Beyond Pigou: Climate Change Mitigation, Policy Making and Distortions

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Abstract

Optimal Carbon and Income Taxation. At what rate should a government tax carbon emissions? This chapter investigates optimal carbon taxation while taking into account that taxes are set by national policy makers. I add two features, namely distortionary income taxation and lack of commitment to future policies, to a standard climate-economy model. I show that there exists a tax-interaction effect: the optimal time-consistent carbon tax is in general not at the Pigouvian level, due to costs and benefits of emitting carbon that only materialize in the presence of income taxes. Quantitatively, I find a monotonic relationship between the cost of climate change and the size and direction of the tax-interaction effect. As a consequence, the higher the damages caused by climate change, the closer is the time-consistent carbon tax to the tax rate chosen under commitment.

Time-Consistent Unilateral Climate Policy. This chapter analyzes unilateral climate change mitigation in a two-region climate-economy model with distortionary income taxation and lack of commitment. I calibrate the model to investigate how the European Union should regulate carbon emissions under the assumption that the rest of the world does not participate in climate policy. I find that when introducing distortionary income taxes into a noncooperative regime, the unilateral carbon tax rate is cut almost in half initially and increases more slowly over time than in a setting with lump-sum taxation. At the same time, the decline in economic activity leads to a decrease in cumulative global emissions and thus mitigates climate change in the long run.

Climate Change Mitigation under Political Instability. This chapter studies climate change mitigation in a setting where the policy maker is subject to probabilistic political turnover. Different types of governments have heterogeneous preferences with respect to the level of greenhouse emissions and hence, commitment to future mitigation policies is not feasible. I show that an incumbent government that takes into account the possibility of losing power has an incentive to reduce the emission level and invest more in clean energy relative to a corresponding myopic policy maker. This result is independent of whether the incumbent derives more or less disutility from emitting carbon than a possible successor. This reflects an incentive to affect the future state of the economy and thus to manipulate the extent of emission mitigation in the future. Quantitatively, I find that having a strategic rather than a myopic government results in a reduction of cumulative carbon emissions until 2100 that is equivalent to emissions being permanently 10 percent lower than under business-as-usual.

To my parents Albrecht and Elsbeth

The learning and knowledge that we have is, at the most, but little compared with that of which we are ignorant.

Plato

There are basically two types of people. People who accomplish things, and people who claim to have accomplished things. The first group is less crowded.

Mark Twain

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I will not claim that this thesis constitutes an accomplishment, but will leave this to others to judge. However, it does mark the end of an important and defining period in my life. Six years ago, while I was determined to do a Ph.D. in Economics, Stockholm was admittedly not my most preferred choice. Having spent a year in Canada for my Master's degree, I would have given a lot to be able to stay in a country that I fell in love with. Today I am glad and without any remorse that I got the opportunity to spend this time at Stockholm University. In every aspect - academically, socially and in terms of increasing my knowledge and my learning, as little as it still is – it was a wonderful, positively intense and highly rewarding experience. (And despite my – very much regretted – failure to get a firm grasp on the Swedish language, I did fall in love with Sweden as well.)

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No acknowledgements of a Ph.D. thesis would be complete without stating what every student learns quickly: doing a Ph.D. would be much less pleasant and rewarding without having your fellow students around. I was extremely lucky to have met and interacted with a great group of friends and colleagues throughout my time in Stockholm.

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Contents

Chapter 1

Introduction

This thesis consists of three essays on the economics of climate change. Despite being self-contained, they share a unifying theme – the inability of policy makers to credibly commit to climate change mitigation in the future – and a common methodology, the use of climate-economy modeling.

Climate change has long been viewed as an important problem among natural scientists. Over the last decade, in particular since the publication of the Stern Review (Stern, 2006) and the 4th IPCC Assessment Report, it has also attracted increasingly more attention from policy makers and economists. On the political level, despite a long history of climate negotiations between countries, there has not yet been any comprehensive climate agreement beyond the Kyoto Protocol. While policies to mitigate climate change have been implemented unilaterally in a few places, most notably in the European Union, most industrialized countries have so far not participated in the mitigation of global climate change.

Economists have analyzed the consequences of and strategies against climate change using many different instruments and approaches. A popular tool have been so-called "integrated assessment models" (IAMs), also referred to as climate-economy models. While these models come in many varieties, with notable differences regarding modeling assumptions, level of detail and questions they aim to answer, their common feature is the combination of stylized representations of the "climate", usually captured by changes in the mean global surface temperature, with traditional macroeconomic frameworks. Their use has been pioneered by the seminal work of William Nordhaus (e.g. Nordhaus and Yang, 1996; Nordhaus, 2008) in the context of the DICE and RICE models.

This thesis employs climate-economy models to address a particular aspect of climate policy making. A common assumption in many studies is the idea that a government today not only chooses policy instruments such as a carbon tax or an emission quota for the next few years, for example over the span of a legislative period, but also in the possibly very distant future. I refer to this as the assumption of a government being able to "commit" to future policies. This is a particularly important assumption in the context of climate change, since greenhouse gases, such as carbon dioxide, stay in the atmosphere for hundreds of years. Hence, assuming that governments put some positive weight on the welfare of future generations, the current amount of emissions which is considered optimal depends to a large extent on how much carbon will be emitted in the future. Loosely speaking, cutting emissions by half today will not have much of an effect on how the climate evolves if from tomorrow onwards, people release double the amount of carbon into the air. Hence, whether or not a policy maker today is able to regulate or affect future emission levels has an impact on her current policy choice. How much of an impact, and in what direction this pushes the stringency of climate change mitigation, is among the questions that this thesis aims to answer. Throughout its chapters, I consider different mechanisms that prevent commitment to future policies from being feasible and investigate how they affect climate change and policy outcomes in the long run.

The second chapter, titled "**Optimal Carbon and Income Taxation**", studies an economy where the government taxes labor and capital income in order to finance a public consumption good, and where it does not have access to a commitment device. The combination of these two features causes a commitment problem with respect to climate policy in the following way: first, the optimal level of climate change mitigation – and hence, with a market-based approach, the optimal carbon tax rate – depends on the rates at which the government taxes income. Second, in dynamic models with capital taxation, a tax policy that is chosen optimally at time 0 for all future periods t is not "time-consistent": in the absence of a commitment device, once the economy enters period $t > 0$, the government has an incentive to renege on the previously announced policy.

The first link is related to a well-known result in environmental economics concerning the interaction between labor taxation and pollution control in static models, which has given rise to an extensive literature initiated by Bovenberg and de Mooij (1994). Chapter 2 generalizes this mechanism to a dynamic setting with capital taxation. The argument with respect to capital accumulation is straightforward: if fossil fuel is used as an input in the production process, taxing carbon emissions lowers output and hence the income of the agents in the economy, which in turn has a negative effect on household savings. This exacerbates the distortion generated by the tax on capital income, thus causing a loss in welfare. In essence, this represents a "second-best" cost of taxing carbon. Taking this into account, a government that internalizes the social cost of emitting carbon must set the carbon tax below the Pigouvian rate, i.e., the level of marginal emission damage. A similar argument can be made for labor taxation. Moreover, in contrast to static models, a dynamic setting gives rise to additional channels through which emission reductions affect the government's incentives under distortionary taxation. Importantly, some of these channels can give rise to second-best benefits of carbon taxation, which in isolation would induce the government to set a carbon tax that exceeds the Pigouvian rate. In general, distortionary income taxation gives rise to a "tax-interaction effect", which drives a wedge between the optimal carbon tax and the Pigouvian rate. The direction of the tax-interaction effect, i.e., whether the tax rate is above or below the Pigouvian level, is ambiguous.

The second link described above represents a classical result in the context of dynamic public finance, first shown in a seminal paper by Fischer (1980), which comes from the fact that a government's incentives with respect to capital taxation change over time.[1] When solving the model, a straightforward way to deal with the time inconsistency is to assume the existence of a commitment device. While this facilitates the numerical analysis, it is arguably a very strong assumption, in particular given the long time horizon of climate change. Instead, I solve for a time-consistent equilibrium, following the approach by Klein et al. (2008). A quantitative evaluation of the model shows that the magnitude and the direction of the tax-interaction effect depend on the size of the carbon tax and hence on the cost of climate change. Thus, the tax-interaction effect results in an optimal time-consistent carbon tax below the Pigouvian rate only if the impact of climate change on social welfare is sufficiently detrimental. Moreover, comparing the outcome with a setting in which the government can credibly commit to future tax rates, I find that the difference between the optimal carbon tax rates is potentially large, depending on the calibration. In particular, for moderate climate damages, having access to a commitment device leads to considerably smaller carbon tax rates in the long run.

The third chapter of my thesis, "**Time-Consistent Unilateral Climate Policy**", further investigates the link between climate change mitigation and income taxation. More specifically, it addresses the question of how introducing distortionary taxes into a calibrated climate-economy model affects policy outcomes, in particular the level of carbon taxes, as well as climate change. Conceptually, this analysis builds on the framework introduced in the previous chapter. However, using a one-region model of the global economy is problematic in this context, since it assumes an unrealistically high level of cooperation with respect to both fiscal policy and climate change mitigation. On the other hand, calibrat-

[1] Since the capital stock in a given period t is inelastic, a tax on capital income is *ex post* non-distortionary. Prior to period t, however, taxing capital discourages household savings, and hence, *ex ante*, the government has an incentive to announce a low tax rate.

ing the model to a single country abstracts from the fact that climate change is a global public good, which is only marginally affected by the actions of an individual country or region.

In other words, obtaining quantitatively meaningful estimates of the optimal carbon tax requires the use of a model with multiple regions. In this chapter, I restrict the analysis to the simplest example of such a framework, an economy consisting of two regions. I calibrate the model such that one region represents the European Union, while the other one is assumed to combine the rest of the world. Dividing the global economy along these lines is motivated by the current state of global climate change mitigation, with the EU being the only large industrialized country or region that has unilaterally implemented some type of comprehensive climate policy.[2] In line with this observation, I assume that the rest of the world not only abstains from cooperating with the EU, at least for the foreseeable future, but it does not even participate in climate change mitigation, i.e., it does not internalize the cost of emitting carbon.

Ideally, one would want to model a noncooperative game between the two regions, in which either region takes the behavior of the other one into account, and the optimal policy of one policy maker is affected by the behavior of the other. When solving a model with distortionary taxation, but without a commitment device, however, this would result in two dimensions of strategic interaction: within a region, a policy maker plays a game with her successor, which ensures that the resulting equilibrium is time-consistent. On the international level, the policy maker interacts strategically with her counterpart in the other region. Finding an equilibrium in such a setup is not only numerically demanding, it is also not guaranteed to be unique. In this chapter, to facilitate the analysis, I abstract from strategic interaction between regions. Instead, I assume that only the EU is a large open economy with a government that chooses income and carbon tax rates optimally, while taking the effect on

[2]Compare figure B.1 in the appendix to chapter 3.

the other region into account. In contrast, the rest of the world does not feature a strategically acting government. Instead, tax rates are given exogenously. In other words, the rest of the world can be interpreted as consisting of a large number of small open economies.

Solving for a time-consistent equilibrium under the assumption that capital is perfectly mobile between regions, I find that the initial carbon tax rate in a setting with distortionary taxation is only half as high as the tax rate that would be optimal if the government were able to use lump-sum taxes. Moreover, compared to a "first best" regime with global cooperation, the carbon tax rate is reduced by a factor of seven. Over time, the optimal carbon tax increases more slowly than under lump-sum taxation, which translates into carbon emissions falling at a slower rate. However, cumulative emission levels in this scenario are closer to the first best than to a noncooperative regime with lump-sum taxes, illustrating the fact that distortionary taxation reduces economic activity and thus dampens carbon emissions. In conclusion, this exercise shows that the outcome in climate-economy models, both in terms of policy variables and with respect to the extent of climate change, can change considerably when second-best features are introduced into the model.

The fourth and final chapter of the thesis, titled "**Climate Change Mitigation under Political Instability**", considers a different source of time inconsistency, that is, a different reason why the commitment assumption fails. Most industrialized countries are democracies, where governments are subject to political turnover, facing the risk of being voted out of office. Intuitively, this precludes any form of credible commitment to the implementation of policies in the future, unless the legislative process makes it impossible or very costly to abolish existing laws. With respect to climate change mitigation, this particular constraint to policy making may not matter much if the platforms or preferences of different parties are closely aligned. This appears to be the case for most countries within the European Union. In contrast, in several countries outside Europe, there appears to exist considerable disagreement between parties about the importance of climate change and the appropriate policies to address it. A prime example in this regard are the United States, where the Democrats and the Republicans have been unable to agree on any kind of meaningful climate policy.[3]

With these examples in mind, this chapter studies how the incentives to mitigate carbon emissions are affected when incumbent governments behave "strategically"; that is, they take the risk of losing power in the future into account when choosing their actions. For tractability, I restrict the analysis to two types of policy makers and assume that they are heterogeneous with respect to their preferred level of mitigation. In such a setting, incumbent governments cannot directly set policies in future periods. However, they can affect their successor's policy choice by manipulating the state of the economy in the future. This notion of a policy maker adjusting her behavior in order to "create facts" for her successor has been extensively studied in other areas of public policy making, starting with the seminal paper by Persson and Svensson (1989) in the context of public debt accumulation.

The analysis proceeds in two steps. First, I employ a stylized model in which the economy exists for only two periods, and where policy makers have a particular type of preferences. This setting allows me to solve the model analytically. The main focus is on the question if and how a strategic policy maker adjusts her policy choices relative to a "myopic" government that perceives to remain in office with certainty. I find that a strategic incumbent implements policies that result in more pronounced emission reductions and, in a setting with different energy sources, more investment in relatively "clean" forms of energy production. Notably, this is true for both a "green" incumbent, who experiences a higher disutility from emitting carbon than her opponent, and a "skeptic" incumbent, whose utility cost is relatively low. The intuition for this finding is that either type affects her successor's policy by manipulating both the future state of the climate – by reducing current emissions – and the future production structure of the economy, by shifting investment away from

[3] In addition, representatives of the Republican Party have repeatedly voiced their indifference or disbelief regarding the occurrence of climate change.

fossil-based capital.

More specifically, a green incumbent wishes to keep the future cumulative stock of emissions low; since she anticipates high emission levels implemented by a skeptic successor, she compensates those with more pronounced emission cuts in the current period. Moreover, she is able to "tie the hands" of her successor, that is, to weaken the incentive to emit by reducing the capacity of fossil-based energy in the future. A skeptic incumbent on the other hand has an incentive to smooth emission reductions over time. Hence, by reducing current carbon emissions, she avoids steep emission cuts by a green successor in the future. Moreover, she realizes that such emission reductions would lower the rate of return to current investment in fossil-based energy. Hence, she has an incentive to restructure her investment decision.

The second part of the chapter quantifies the effects of strategic government behavior using the example of the United States. I calibrate a one-region neoclassical growth model with energy use and probabilistic political turnover. The production structure in this economy is a simplified version of the integrated assessment model WITCH (Bosetti et al., 2006), featuring two types of energy, each of which is produced using a specific type of capital. This exercise shows that the difference in expected cumulative US emissions by 2100 between a setting with strategic policy makers and one with myopic agents can be substantial: in the baseline calibration, I find a reduction that is equivalent to emissions along a business-as-usual path – without any climate policy – being permanently lowered by 10%. A large share of this reduction would materialize even without the government adjusting its investment behavior towards clean energy, indicating that the main channel through which an incumbent manipulates future policy is the stock of cumulative carbon emissions.

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Chapter 2

Optimal Carbon and Income Taxation*

2.1 Introduction

At what rate should a policy maker tax emissions of greenhouse gases such as CO_2 in order to internalize climate change? In this paper, I address this question while taking into account that climate policy is chosen by national governments that also use income taxes to finance public goods. Specifically, I show how optimal carbon taxes are affected when adding two real-world features, distortionary income taxation and the inability of the government to commit to future policies, to an otherwise standard climate-economy model. Previous studies focusing on optimal carbon taxation have typically abstracted from these features. Hence, this paper also sheds some light on the question of how useful such "first-

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best" models are in guiding policy makers: if their results are sensitive to the introduction of arguably realistic features, then this limits their policy relevance.

The main findings of this paper are the following. First, resorting to distortionary income taxes rather than first-best lump-sum taxation to finance public goods gives rise to a "tax-interaction effect", which drives a wedge between the level of marginal climate damage - i.e., the Pigouvian rate - and the social cost of emitting carbon, which equals the optimal carbon tax. This effect is caused by costs and benefits of reducing emissions that only materialize in "second best". In addition to the well-known static effect on labor supply, I identify further channels through which emission reductions affect the government's incentives under distortionary taxation. Second, a quantitative evaluation shows that the magnitude and the direction of the net tax-interaction effect depend on the size of the carbon tax and hence on the cost of climate change. If the impact of climate change on social welfare is sufficiently small, the tax-interaction effect results in an optimal time-consistent carbon tax equal to or even above the Pigouvian rate. This also implies that the lower the cost of climate change, the closer is the optimal carbon tax to the first-best rate. For high damages, I find that the time-consistent carbon tax can amount to less than half of the first-best rate, indicating that first-best models may not be reliable estimates for the social cost of carbon when distortionary taxation is taken into account. Third, comparing these results with a setting in which the government can credibly commit to future tax rates, I find that the difference between the optimal carbon tax rates is potentially stark, depending on the calibration. In particular, for moderate climate damages, having access to a commitment device leads to considerably smaller carbon tax rates in the long run.

This paper builds on "integrated assessment models" (IAM), such as, for example, the DICE model (Nordhaus, 2008) or Golosov et al. (2014), that are widely used to inform policy makers about the size of the social cost of carbon and hence the optimal carbon fee.[1][2] These models typically prescribe a Pigouvian tax that equals the marginal global climate damage, which is defined as the present value of the damage caused globally by emitting an additional unit of carbon. As in these studies, I analyze optimal carbon taxation in a standard deterministic neoclassical growth model. However, I take into account that a government's role is not limited to implementing climate policy, but it must also raise revenue in order to finance expenditures on public goods, by taxing labor and capital income.[3] This introduces distortions into the economy that make the first-best allocation unfeasible, even if the government is assumed to be benevolent. When modeling distortionary taxation, I assume that all tax rates are optimally chosen.[4] In addition, it is well-known that in models with distortionary income taxes, one has to take a stand on whether the government is able to credibly commit to future policies (Klein et al., 2008). I assume that there is no such commitment device.[5] This assumption is arguably more realistic and plausible than allowing a government to commit to all future tax rates.

I start by providing an analytical characterization of the social cost of carbon which shows that the optimal second-best carbon tax is in gen-

[1]In this paper, a carbon fee could be either a direct carbon tax or the price of tradable emission permits. I will use the terms "tax" or "fee" as synonyms. Note that in order to optimally correct a pollution externality, the emission fee must be set equal to the marginal social cost of pollution evaluated at the efficient emission level (Kolstad, 2000). The question of what carbon tax is optimal is therefore equivalent to asking what is (a good estimate for) the marginal social cost of carbon.

[2]For example, an Interagency Working Group of the US government recently published a report determining the social cost of carbon to be used in cost-benefit analysis (IWG, 2010, 2013). They have used the DICE as well as the PAGE model (Hope, 2006, 2008) and the FUND model (Tol, 2002a,b; Anthoff et al., 2009).

[3]Throughout this paper, I assume that the government is restricted to a total income tax, and has no access to lump-sum taxation. If a lump-sum tax were feasible, a Pigouvian tax would be obtained.

[4]There is a large literature in environmental economics that instead analyzes partial tax reforms, where non-environmental tax rates, and possibly the pollution tax, are exogenously given. An example is Glomm et al. (2008) for a dynamic growth model. Compare also the quantitative results in Barrage (2013).

[5]Note that throughout this paper, I focus on Markov-perfect equilibria when solving the model with distortionary taxation.

eral not equal to the marginal climate damage and hence is not at the Pigouvian rate. I refer to this as a "tax-interaction effect". It is caused by additional effects of carbon taxation that only materialize in a setting with distortionary income taxes, and that are caused by the interaction of carbon emissions with current and future "wedges", that is, distortions of a first-best margin. For example, under certain conditions, an emission tax leads to a decrease in labor supply, which results in a welfare loss if the intratemporal labor-leisure margin is distorted by a labor income tax. Similarly, taxing carbon has a negative effect on household savings, thereby exacerbating the intertemporal distortion caused by the capital income tax. These effects represent second-best costs of emission reductions and thus decrease the optimal carbon tax. In addition, I show that there are future wedges that are affected by contemporaneous carbon emissions.

The deviation of the optimal emission tax from the Pigouvian rate was a prominent finding in earlier studies, which considered second-best environmental taxation in a static model with a labor income tax (Bovenberg and de Mooij, 1994; Parry, 1995; Bovenberg and Goulder, 1996) and hence focused on the labor-leisure wedge.[6] In a dynamic model, however, taking into account only the second-best effect of carbon emissions on current labor supply gives an incomplete characterization of the social cost of carbon.

A quantitative assessment shows that the second-best effects go in different directions. In other words, some constitute costs of emission reduction, while others represent benefits. The net effect depends on the size of the carbon tax and hence on the welfare effect of climate damages. In the baseline calibration of my global climate-economy model, where damages are calibrated such that they are comparable to DICE, I find that the optimal second-best carbon tax is initially 3% above the Pigouvian fee. Thus, if the disutility of climate damages is sufficiently

[6]Those studies usually found that the tax-interaction effect dominates "revenue recycling", that is, using the revenue raised with the emission tax to lower distortionary income taxes, which results in an efficiency gain.

low, the second-best costs of reducing carbon emissions are more than offset by the benefits, implying that the carbon tax is higher than the Pigouvian level. In contrast, if preferences are calibrated such that global temperature change in the long run stabilizes at a sufficiently low level and the Pigouvian tax rate is high, the second-best costs outweigh the benefits, and the optimal carbon tax is lower than the Pigouvian level. In other words, there exists a monotonic relationship between the cost of climate change and the tax-interaction effect.

From this, it follows that the relation between the time-consistent carbon tax and both the first-best tax and the tax chosen under commitment, respectively, depends on the severity of climate change. For the scenarios considered here, I find that the time-consistent tax rate can be up to 46% below the first-best rate in the long run. With respect to the commitment outcome, for sufficiently high damages, the carbon tax rates with and without commitment are very close. This points to a corollary for climate-economy modeling: when aiming at obtaining an approximation of the realistic, but computationally more intensive outcome in the absence of commitment, the error when using the commitment solution decreases in the cost of climate change. In contrast, for small climate impacts, the first-best economy may yield a better approximation.

2.1.1 Related Literature

This paper is related to different strands of the literature, both in climate-economy modeling and public finance. In the context of climate change, numerous studies have used IAMs to compute the social cost of carbon and the optimal carbon tax, often in a global planner model without distortionary taxation.[7] One of the earliest and most influential IAMs is the DICE model (Nordhaus, 2008), which features a neoclassical growth

[7] One example of a "second-best" model is Gerlagh and Liski (2012) They compute Markov-perfect optimal carbon fees in a setting without distortionary taxes, but where the government is unable to commit to future policies due to time-inconsistent preferences, that is, hyperbolic discounting.

model similar to the one used below.[8][9] The estimates for the SCC in DICE have increased over the past versions. The newest version, DICE-2013R, finds an optimal carbon price of 66$/tC in 2015 (Nordhaus, 2013). A multi-region version of this framework is the RICE model (Nordhaus and Yang, 1996; Nordhaus, 2010). Here, in a cooperative regime, a planner sets carbon prices optimally in all regions to maximize global welfare for a given set of welfare weights.[10] Nordhaus (2010) finds an optimal carbon tax of 29$/tC in 2010.

In addition, RICE can be used to analyze a setting without cooperation among regions. Specifically, Nordhaus and Yang (1996) compute a full-information "open loop" Nash equilibrium. An IAM related to RICE is the WITCH model (Bosetti et al., 2006), which also consists of multiple regions that play a noncooperative game. However, WITCH features a more detailed representation of energy production. Moreover, technical change is endogenous.

Golosov et al. (2014) consider a climate-economy model similar to DICE, although with a different formulation of the carbon cycle and an explicit modeling of fossil fuel use. Notably, they derive a closed-form expression for the expected social cost of carbon under certain conditions - in particular, logarithmic utility and full depreciation - and show that the optimal tax as a share of contemporaneous output is constant. Quantitatively, they find an optimal carbon tax 57$/tC in 2010.

As indicated above, the present model is a generalization of the literature on static models initiated by Bovenberg and de Mooij (1994). While Bovenberg and de Mooij (1994) analyze a model with a pollution-

[8] A notable difference is that in DICE, fuel use is not explicitly modeled. Instead, carbon emissions are linked proportionally to output. The planner can invest in abatement, which reduces the amount of pollution for a given output level (Nordhaus, 2008).

[9] Other examples of frequently used IAMs are the PAGE model (Hope, 2006, 2008) and the FUND model (Tol, 2002a,b; Anthoff et al., 2009). Note that these are not optimal growth models, but instead take output scenarios as given.

[10] Hence, in the cooperative regime, the RICE model does not explicitly model climate agreements. See Barrett (2005) for an overview of the literature on environmental agreements and Harstad (2012, 2013) for recent work on agreements in a dynamic climate model.

intensive consumption commodity, Parry (1995) and Bovenberg and Goulder (1996) examine the case of a “dirty” input in the production process, similar to the setting in this paper.[11]

In addition, this paper is related to more recent work by Barrage (2013). She also considers the interaction between optimal income and carbon taxation in a neoclassical climate-economy model with distortionary income taxes. However, her analysis differs from this paper in three key dimensions. First, throughout her paper, she studies a setting where the government is assumed to be able to commit to future tax rates. In her baseline model, this results in a zero capital tax.[12] Second, her model comprises one region only and hence focuses on global climate policy. Finally, with regard to the research question, Barrage (2013) is interested in the qualitative difference between climate damages to utility and productivity, and under which conditions they are not fully internalized. In contrast, my main qualitative result does not make a distinction between utility and production damages, but instead relates the tax-interaction effect to different wedges.

Methodologically, this paper is related to Klein et al. (2008), Azzimonti et al. (2009), and Martin (2010) who analyze time-consistent Markov-perfect equilibria in a standard neoclassical growth model without environmental quality.[13] Analogous to Klein et al. (2008), I derive the current government’s generalized Euler equations, which are weighted sums of intertemporal and intratemporal wedges that the government trades off against each other. Similar to Azzimonti et al. (2009), this paper analyzes a *stock* of a public good, rather than a pure flow.[14] Note

[11] Compare also Bovenberg and van der Ploeg (1994), Goulder (1995), Goulder et al. (1997) and Bovenberg and Goulder (2002).

[12] She also considers extensions to her model where capital taxes can either be temporarily non-zero, due to an upper bound that binds for a finite number of periods, or where a permanently positive capital tax is exogenously given.

[13] See Fischer (1980) and Lucas and Stokey (1983) for earlier work on the time inconsistency of optimal policy in the presence of distortionary incomes taxes. Kehoe (1989) extended the model in Fischer (1980) to a two-country setting.

[14] Battaglini and Coate (2007, 2008) also consider an environment with distortionary income taxation and public good provision, but their focus is on the political economy of fiscal policy, in particular on legislative decision making.

that while the application here is with respect to an environmental public good, the analysis would be similar to the case of the stock of a non-environmental public good. For example, one could think of infrastructure such as public roads and buildings as a persistent public good, i.e., expenditures today are of importance for the stock tomorrow.

The remainder of this paper is structured as follows. Section 2.2 presents the framework. In section 2.3, I analyze a global climate-economy model with distortionary taxation. Section 2.5 concludes the paper.

2.2 The Framework

In this section, I introduce a simple dynamic framework where I analyze optimal carbon and income taxation. Consider the standard neoclassical growth model, extended by "fossil fuel" or "energy" and "environmental quality", that is, the state of the climate. Fossil fuel is used as a factor of production, in addition to capital and labor. Burning fuel causes emissions of a pollutant, here carbon. Hence, the amount of fuel used in production is a determinant of climate change, which affects both the utility function of the representative household – as in the static second-best literature following Bovenberg and de Mooij (1994) – and the productivity of the representative firm, as, for example, in Golosov et al. (2014). Producers do not take into account how their decisions affect the climate; hence, carbon emissions represent an externality.

Note that throughout this paper, I employ deterministic models and abstract from all uncertainty related to the climate or economic development. Moreover, technological growth is exogenous.[15]

2.2.1 Utility and Household Problem

The representative household's per-period utility is given by $u(C, 1-h, G, T)$, where C denotes private consumption of a final good, h hours worked and G public consumption. T is an indicator of climate change.

[15]These assumptions are discussed more thoroughly in the conclusion.

Specifically, it represents the change in mean global surface temperature relative to the preindustrial period. The two latter variables are not chosen by the household; hence, they represent public goods. u is increasing in its first three arguments and decreasing in T. In other words, a higher T corresponds to a "worse" state of the climate. There are several channels through which permanently warmer temperatures cause disutility (Barrage, 2013), for example, by affecting health and general well-being, as well as through the possible loss of biodiversity.

Note that in contrast to many papers in public finance, I have assumed that the public consumption good is valued by the household; therefore, the amount provided is a choice variable of the government or planner. This assumption is important for the infinite-horizon version of the model in section 2.3 for technical reasons.[16] For the two-period model in 2.3, it is not essential and therefore, I will simplify the analysis by assuming exogenous government expenditures.

The population size is constant. Let A_t denote the level of labor-enhancing productivity, which grows exogenously at the rate ζ.[17] From here on, I express variables in efficiency levels. That is, $c_t \equiv C_t/A_t$ and $g_t \equiv G_t/A_t$.

Households maximize lifetime utility, subject to their budget constraint, taking price and tax sequences as given:

$$\max_{\{c_t,h_t,k_{t+1}\}_{t=0}^{\bar{t}}} \sum_{t=0}^{\bar{t}} \beta^t u(c_t, 1-h_t, g_t, T_t), \tag{2.1}$$

subject to

$$c_t + k_{t+1} \leq [1 + (1-\tau_t^k)(r_t - \delta)]k_t + (1-\tau_t^h)w_t h_t, \tag{2.2}$$

where $\bar{t} \leq \infty$. $k_t \equiv K_t/A_t$ denotes the capital stock in period t. r_t and $w_t \equiv W_t/A_t$ are the factor prices of capital and labor, respectively,

[16] Compare the discussion in the appendix, section A.3, for details.

[17] That is, $A_{t+1} = \zeta A_t$. For the theoretical analysis, to save on notation, I will assume that $\zeta = 1$.

while τ^k and τ^h are the corresponding linear tax rates. δ denotes the rate of capital depreciation. Solving this problem yields two standard optimality conditions, one intertemporal (consumption-savings) and one intratemporal (consumption-leisure).

When solving the model numerically in section 2.3, I need to choose a functional form for the per-period utility function. In the baseline model, following Klein et al. (2008), u is additively separable and logarithmic in the first three arguments.[18] Moreover, I assume a quadratic utility damage due to the externality:

$$u(c,l,g,T) = [(1-\alpha_g)\alpha_c \ln c + (1-\alpha_g)(1-\alpha_c)\ln l + \alpha_g \ln g] - \frac{\alpha_T}{2}T^2. \quad (2.3)$$

As is standard in the environmental economics literature, I let preferences between private consumption and environmental quality be additively separable (for example Cremer and Gahvari, 2001) and assume that disutility is convex in temperature change (Weitzman, 2010). The assumption of additivity is convenient, since it facilitates the analytical and numerical analysis. Moreover, relaxing this assumption is not straightforward. While there is some evidence that higher temperatures have an effect on the marginal utility of leisure (for example Zivin and Neidell, 2010), it is unclear whether, on aggregate, leisure and climate are substitutes or complements. In addition, how to specify a non-separable utility function with temperature change in a macroeconomic model is an open research question.

2.2.2 Production, Fuel Use and Firm's Problem

The consumption good is produced with a technology represented by a function F, which uses as inputs capital, labor and fuel, denoted by M. Moreover, the temperature change T does not only affect utility, but also has an impact on the production process. "Net" output - taking damages from climate change into account - is given by $Y_t =$

[18] This specification is convenient since it allows for the existence of a balanced growth path (King et al., 2002).

$F(K_t, A_t h_t, B_t M_t, T_t)$. B_t denotes energy-augmenting productivity or "energy efficiency", which grows exogenously. Hence, there is a second source of technological progress, apart from the labor-enhancing productivity A_t. I assume that A_t and B_t grow at the same exogenous rate ζ, which is necessary for a balanced growth path, as discussed in more detail in section 2.4.2.1 below.

More specifically, let net output be given by:

$$Y_t = F(K_t, A_t h_t, B_t M_t, T_t) = [1 - d(T_t)] f(K_t, A_t h_t, B_t M_t) - \kappa B_t M_t. \tag{2.4}$$

Following Nordhaus (2008) and Golosov et al. (2014), I assume that T enters the production function multiplicatively. The "damage function" d captures damages to productivity, with $0 \leq d(T) \leq 1$. It is assumed to be convex and increase in temperature ($d_T > 0$, $d_{TT} > 0$). Moreover, I let the *private* marginal cost of fuel use be paid in terms of the final good;[19] it is given by κB_t. This could, for example, be interpreted as a per-unit extraction cost, which is assumed to grow at the same rate as energy-augmenting productivity. The function f is assumed to exhibit constant returns to scale. Hence, dividing both sides of (2.4) by A_t gives the output in efficiency units:

$$y_t = \frac{Y_t}{A_t} = [1 - d(T_t)] \tilde{f}(k_t, h_t, m_t) - \kappa m_t, \tag{2.5}$$

where $m_t \equiv B_t M_t / A_t$. Note that in efficiency units, using one unit of m is then associated with the constant cost κ.

Regarding fuel use, to simplify the exposition, I assume that the resource m is not exhaustible and hence does not have a scarcity rent. In other words, I abstract from the Hotelling problem of how to optimally extract a finite resource. Fuel should here be interpreted as coal rather than (conventional) oil or gas. While the amount of coal left in the ground

[19] Alternatively, one could let the cost be a function of the resources left in the ground, or model energy production as a separate production sector that uses labor and possibly capital as in Golosov et al. (2014) or Barrage (2013).

is finite, these resources are sufficiently large that they will not be used up in any sensible parameterization of the present model.[20] Therefore, coal can be considered to be in virtually "infinite" supply. This is not only a common assumption in the literature (Golosov et al., 2014), but also supported by empirical evidence: coal prices do not display any upward trend over time (Gaudet, 2007), indicating that the Hotelling model is not a suitable framework for analyzing coal extraction.[21] A representative firm then solves the following problem:

$$\max_{k_t,h_t,m_t} [1-d(T_t)]f(k_t,h_t,m_t)-\kappa m_t-r_tk_t-w_th_t-\theta_tm_t, \tag{2.6}$$

where θ_t denotes a tax on fuel use (per efficiency unit) and hence on carbon emissions. From the first-order condition, it follows that the carbon tax is given by $\theta_t = f_m(t)-\kappa$.[22] The economy's resource constraint in efficiency units is given by:

$$c_t+g_t+k_{t+1}+\kappa m_t = F(k_t,h_t,m_t,T_t)+(1-\delta)k_t. \tag{2.7}$$

For the quantitative analysis, I assume a Cobb-Douglas production function (Golosov et al., 2014):

$$\tilde{f}(k,h,m) = k^{\rho}m^{\xi}h^{1-\rho-\xi}, \tag{2.8}$$

with $\rho = \nu(1-\xi)$. Finally, a common functional form for the damage function is:

$$d(T) = (1+\gamma T^2)^{-1}\gamma T^2. \tag{2.9}$$

This specification is used, for example, in the DICE model (Nordhaus, 2008).

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[20]Note that the climate model used here indicates that burning all the estimated coal resources would lead to a long-term temperature increase of up to $7^{\circ}C$, depending on the estimate.

[21]This type of argument does not apply to oil and conventional gas. In particular, using up all the oil that is estimated to be left in the ground would have a minor impact on temperature change (about $0.35^{\circ}C$ in the climate model used here).

[22]Note that $B_t\theta_t$ gives the carbon tax in $\$/GtC$.

2.2.3 Climate Change

In addition to the private extraction cost, using fuel has a social cost: it causes carbon emissions, which negatively affect the state of the climate by increasing the mean global surface temperature. Many IAMs model this mechanism in two steps (Nordhaus, 2008; Golosov et al., 2014): first, past (and possibly current) carbon emissions, plus a vector of initial carbon concentrations in the atmosphere and other reservoirs like the upper and lower oceans, translate into current carbon concentrations. Second, the current vector of carbon stocks, $\mathbf{s}_t$, maps into the mean global temperature change in period t: $T_t = \mathcal{F}(\mathbf{s}_t)$.[23] One consequence of this modeling strategy is that many IAMs typically feature multiple variables summarizing the state of the climate (Nordhaus, 2008; Cai et al., 2013).

To keep the number of state variables low, I use a more reduced-form approach in this paper. Specifically, I assume a direct mapping $T_t = q(\mathbf{m}^t)$, where $\mathbf{m}^t = \{m_t, m_{t-1}, ..., m_{t_0}\}$ denotes the history of past global CO_2 emissions back to period t_0, and $\partial q / \partial m_j > 0 \; \forall j$. In words, the current *flow* of carbon has an impact on the state of the climate in future periods. This is a reasonable assumption, given that carbon stays in the atmosphere for a very long time.

The functional form for q that is chosen below is based on Matthews et al. (2009). They define the "climate-carbon response" (CCR) as the ratio of global mean temperature change and total cumulative carbon emissions over some period of time. Using both historical emission data and an ensemble of climate models, they show that this variable is almost constant over time and, in particular, it is independent of the atmospheric carbon concentration. From this observation, it follows that the increase in the global mean surface temperature can be written recursively as:

$$T_{t+1} - T_t = \text{CCR} \cdot m_t. \tag{2.10}$$

[23] Carbon is sometimes referred to as a "stock pollutant", since the stock in the atmosphere, rather than the flow, matters for climate change.

For the quantitative analysis, this specification is convenient, since it summarizes the climate side of the model in one state variable, T_t, while abstracting from the carbon concentrations in the different reservoirs. Note that in contrast to other climate-economy models (Nordhaus, 2008; Golosov et al., 2014; Gerlagh and Liski, 2012), this specification implies that an increase in the global mean temperature due to carbon emissions is irreversible. This has quantitative implications for the size of the optimal carbon tax, as discussed in more detail in section 2.4.2.3.

2.2.4 Government

The government must finance the public good by taxing labor and capital income. By assumption, lump-sum taxes are not available. Its budget constraint reads:

$$g_t \leq \tau_t^k (r_t - \delta) k_t + \tau_t^h w_t h_t + \theta_t m_t. \tag{2.11}$$

Note that throughout this paper, I assume that the government has to balance its budget in every period. In other words, it can neither borrow from nor lend to households. The latter assumption is crucial, as pointed out by Azzimonti et al. (2006). They show that if the government were allowed to accumulate assets, it would be able to dispense with distortionary taxation after a finite number of periods. Hence, even in the absence of commitment, a government would set a zero tax rate on capital income in the long run. The intuition for this result is that the government could confiscate all income in the first period, and then lend to households every period and accumulate assets over time. After a sufficiently large number of periods, the government's wealth would be large enough to finance the public good without resorting to distortionary taxation. Therefore, since I want income tax rates to be non-zero in every period, I abstract from government assets.

2.3 A Finite-Horizon Setting

In this section, I consider two finite-horizon versions of the framework introduced in the previous section, a static model where $\bar{t} = 0$ and a two-period model where $\bar{t} = 1$. The purpose of this section is twofold. First, it allows me to review the main result in the literature that started with Bovenberg and de Moij (1994) and illustrate its key mechanism that will be generalized in the infinite-horizon setting in the next section. Second, it introduces some notation and provides some intuition for the results found later.

Throughout the section, for simplicity, assume that the public good is not valued by the household and hence its per-period utility $u(c, l, T)$ depends on private consumption, leisure and the state of the climate. Instead, government expenditures are exogenously given.

2.3.1 The One-Period Model Revisited

In the one-period model, investment is zero and the capital stock is given. Environmental quality is a flow variable. That is, assume that temperature change is given by $T = q(m)$. Note that such a static model is not really appropriate to analyze long-term effects on the climate: as mentioned above, greenhouse gases are stock rather than flow pollutants.

Start by defining two "wedges", which are here defined as distortions of first-best margins. Let ω_{LL} denote the "labor-leisure wedge" and ω_{Env} the "environmental wedge", respectively. They are given by:

$$\omega_{LL} \equiv u_c F_h - u_l \tag{2.12}$$

$$\omega_{Env} \equiv u_c(F_m - \kappa) + q_m[u_T + u_c F_T]. \tag{2.13}$$

The first-best equilibrium, when lump-sum taxes are available, is characterized by both wedges being zero. For the environmental wedge, this just implies that the marginal benefit of increasing emissions net of private cost - the first term on the right-hand side of (2.13) - in terms of utility equals the marginal climate damage, captured by the second term.

Turning to the second-best setting with distortionary taxation, I use these wedges to express the government's optimality condition, which characterizes optimal policy. This approach follows that of Klein et al. (2008) and will be at the core of the analysis in the remainder of the paper.

The government's problem in this economy is given by

$$\max_{m,h} u(F(k,h,m) - g - \kappa m, 1-h, q(m))$$

s.t. an "implementability constraint" which is derived from the household's optimality condition and its budget constraint:[24]

$$\begin{aligned}\chi(h,m) \equiv u_c\big(F(k,h,m) - g - \kappa m, 1-h, q(m)\big)\cdot \\ \cdot\,[F(k,h,m) - g - \kappa m]\frac{F_h h}{F_h h + F_k k} \\ -u_l\big(F(k,h,m) - g - \kappa m, 1-h, q(m)\big)h = 0.\end{aligned}$$

Note that I have assumed a "total income tax", that is, both capital and labor income are taxed at the same rate $\tau = \tau^k = \tau^h$.[25]

Define the function $\mathcal{H}$ implicitly by

$$\chi(\mathcal{H}(m), m) = 0. \tag{2.14}$$

In words, for a given fossil fuel use m, $\mathcal{H}(m)$ gives the household's optimal labor supply, i.e. the labor choice that satisfies its optimality condition. In a sense, this is the household's "best response" to the fossil fuel use announced by the government, assuming within-period commitment. Using

[24] That is, from consolidating $u_c F_h(1-\tau) - u_l = 0$ and $c = (1-\tau)(F_k k + F_h h)$. Note that if both the household's budget constraint and its resource constraint, $c = F(k,h,m) - g - \kappa m$, are satisfied, so is the government's budget constraint, $g \leq \tau(F_h h + F_k k) + (F_m - \kappa)m = \tau(F_h h + F_k k) + \tau_m m$.

[25] Since the tax on capital income works as a lump-sum tax in this setting, assuming separate tax rates would eliminate the distortion and hence would result in a zero labor tax.

$\mathcal{H}$, the government's problem can be more compactly written as:

$$\max_{m} u(F(\mathcal{H}(m), m) - g - \kappa m, 1 - \mathcal{H}(m), q(m)). \tag{2.15}$$

Taking the derivative of (2.15) w.r.t. m gives the following optimality condition:

$$\underbrace{u_c(F_m - \kappa) + q_m[u_T + u_c F_T]}_{\omega_{Env}} + \mathcal{H}_m \underbrace{(u_c F_h - u_l)}_{\omega_{LL}} = 0. \tag{2.16}$$

This shows that, in equilibrium, the government trades off wedges. In first best, since both wedges are zero, (2.16) holds. In second best where $\tau > 0$, I have that $\omega_{LL} > 0$ and hence the environmental wedge cannot be zero unless $\mathcal{H}_m = 0$. More precisely, if $\mathcal{H}_m > 0$ ($\mathcal{H}_m < 0$), ω_{Env} must be negative (positive) for (2.16) to be satisfied.

Expression (2.16) illustrates that there is an interaction between climate policy and the non-environmental income tax, in the sense that in the presence of a distortionary tax on labor income, environmental quality is not provided at the first-best margin. Moreover, whether or not the climate externality is less than fully internalized, i.e. whether or not $\omega_{Env} < 0$, depends on the sign of $\mathcal{H}_m$.

What is the intuition behind (2.16)? For the sake of the argument, assume that $\mathcal{H}_m > 0$. That is, a marginal increase in fuel use and thus, carbon emissions, raises the labor supply. In first best, where $\omega_{LL} = 0$, a marginal change in hours worked does not affect welfare. In contrast, in second best, it leads to a first-order welfare gain since, in equilibrium, the benefit from a marginal increase in hours worked, $u_c f_h$, is greater than the marginal disutility of working more (u_l). This is only the case if $\omega_{LL} > 0$, i.e. as long as the income tax is positive. In this sense, fuel use mitigates the intratemporal distortion caused by the income tax. The positive effect on labor supply is an additional benefit of fuel use, besides the usual benefit of increasing output and consumption. Thus, it reduces the social cost of carbon below the value of the marginal damage - or, in terms of tax rates, the optimal second-best tax is lower than the corresponding Pigouvian fee.[26] In other words, the margin between private consumption and environmental quality is distorted compared to the first best. In the remainder of this paper, I will refer to this effect on labor supply, represented by $\mathcal{H}_m \omega_{LL}$, as the "static labor effect".

In order to make a statement on the direction of this effect, one must determine the sign of $\mathcal{H}_m$. In the appendix, I show that the general equilibrium effect is given by:

$$\mathcal{H}_m = A^{-1} \left(\epsilon_{h,\tilde{w}} \frac{\partial \tilde{w}h/\partial m}{\tilde{w}h} + \epsilon_{h,y} \frac{\partial y/\partial m}{y} \right), \tag{2.17}$$

where $A > 0$. $\epsilon_{h,w}$ denotes the uncompensated wage elasticity of labor supply, while $\epsilon_{h,y}$ is the elasticity of labor supply with respect to non-labor income. Note that (2.17) shows that the marginal reaction of labor to a change in fuel use is a weighted average of those two elasticities, where the weights are the proportional changes in labor- and non-labor income, respectively.

Consider the special case where preferences are additive-separable and logarithmic in consumption. This implies that $\epsilon_{h,w} + \epsilon_{h,y} = 0$. Moreover, assume a Cobb-Douglas production function and denote the constant income shares of labor and capital by υ_h and υ_k, respectively. Then, (2.17) simplifies to:

$$\mathcal{H}_m = \frac{1}{A + \upsilon_k + \upsilon_h} (F_m - \kappa + F_T q_m) \epsilon_{h,w} \left[\upsilon_h - \frac{\tilde{w}h}{y} \upsilon_k \right]. \tag{2.18}$$

The sign of the first term on the right-hand side of (2.18) is positive. The second term captures the net effect of an increase in emissions on output. It is non-negative since the carbon tax internalizes at least the contemporaneous productivity damage caused by emissions, that is, since

[26]Naturally, the same logic applies if $\mathcal{H}_m < 0$. In that case, there is an additional second-best cost of using fuel, since it decreases labor supply and hence exacerbates the intratemporal distortion.

$\theta \geq -F_T q_m$.[27] This is shown by Barrage (2013). Note that this term reflects the interplay between the tax-interaction effect and the revenue-recycling effect discussed above. As shown in the appendix, a decrease in the carbon tax – and hence a decrease in green revenue – leads to a higher net wage, implying that the tax-interaction effect dominates the revenue-recycling effect.

Then, assuming that the uncompensated elasticity of labor is positive - that is, when the net wage increases, the substitution effect dominates the income effect - the sign of $\mathcal{H}_m$ is determined by the last term on the right-hand side of (2.18). In the case of full capital depreciation and no exogenous income, this term is zero and thus $\mathcal{H}_m = 0$. In the more general case, it can be negative or positive, depending on whether υ_h/υ_k is less or greater than $\tilde{w}h/y$. Intuitively, what matters is whether the proportional change in labor income $\tilde{w}h$ following a marginal increase in fuel use is smaller or larger than the proportional change in non-labor income y. If it is larger, (2.17) shows that more weight is put on wage elasticity and hence, even in the case where the unweighted elasticities offset each other, $\mathcal{H}_m$ is positive.

As a second takeaway from (2.18), note that $F_m - \kappa + F_T q_m$ is decreasing in m, due to both a decreasing marginal return to fuel use and a convex damage function:

$$\frac{\partial}{\partial m}(F_m - \kappa + F_T q_m) = F_{mm} + F_{TT} q_m < 0.$$

[27] In the special case when there are no direct utility damages in the model, I have

$$\omega_{Env} = F_m - \kappa + F_T q_m, \tag{2.19}$$

and hence a zero environmental wedge implies that $\mathcal{H}_m = 0$, which is consistent with (2.16). In other words, as noted by Bovenberg and Goulder (2002), the climate externality is in general not fully internalized only if pollution has a negative effect on utility. Intuitively, in the case of contemporaneous productivity damages only, a marginal increase in fuel use from the first-best level leaves output – and hence the wage – unchanged. In other words, the positive effect on output of burning more fuel is equal to the negative effect. This is not the case if there are direct damages to utility or if there are *future* productivity damages, as in dynamic models with a stock pollutant which will be the focus of the analysis in the remainder of the paper.

Hence, all else equal, the reaction of labor supply to an increase in m, whether positive or negative, is more pronounced for a lower initial emission level. It follows that a higher utility or productivity cost of climate change, which reduces the emission level, is expected to increase the absolute value of $\mathcal{H}_m$.

To summarize, (2.17) and (2.18) show that the direction of the change in labor supply following a marginal increase in emissions is ambiguous, but more pronounced for a higher cost of climate change. These insights will be important for interpreting the findings in the infinite-horizon climate-economy model used below.

2.3.2 A Two-Period Model with Capital

Let $\bar{t} = 1$, thus the representative household lives for two periods and can postpone consumption by saving into an asset, referred to as capital. The government can impose a tax on capital income.

Crucially, I assume that the government in period 0 does not have access to a commitment device which would allow it to commit to future tax rates. From this, it follows that even in the case of separate tax rates on labor and capital income in period 1, the capital tax will be non-zero.[28] Hence, there is an intertemporal distortion, implying that the "consumption-savings wedge", i.e. the distortion of the consumption-savings margin, is positive:[29]

$$\omega_{CS} \equiv -u_c + \beta u_c'[F_k' + 1 - \delta] > 0. \tag{2.20}$$

Under lack of commitment, the government's problem is solved using backwards induction. In the appendix, I show that this results in a linear

[28] In the case of separate tax rates, the capital tax acts as a de-facto lump-sum tax since the tax base is inelastic. Hence, the labor tax is zero, while government expenditures are solely financed through capital taxation. If I instead allowed for commitment, the capital tax rate might be zero. This is discussed in more detail in section 2.4.1.2.

[29] Throughout this paper, primes denote future variables. For example, $c' = c_{t+1}$, $u_c' = u_c(t+1)$, $c'' = c_{t+2}$, $u_c'' = u_c(t+2)$ etc.

combination of wedges, similar to (2.16) in the static setting with labor taxation:

$$\omega_{Env} + \mathcal{H}_m \omega_{LL} + \mathcal{K}_m \omega_{CS} = 0. \tag{2.21}$$

Here, the function $\mathcal{K}(m)$ is defined analogous to $\mathcal{H}(m)$, but with respect to current savings. That is, it gives the best-response function for households' savings in period 0 given an emission level m. Note that (2.21) contains the derivatives of the policy functions for savings and labor and hence, following Klein et al. (2008), I refer to this as a *generalized* Euler equation. This equation shows that, as in the one-period model, optimal environmental policy interacts with fiscal policy. This implies that as long as current savings and labor supply are affected by current fuel use, $\mathcal{K}_m \neq 0$ and $\mathcal{H}_m \neq 0$, emissions are not in general at the Pigouvian level.

The last term on the left-hand side of (2.21), $\mathcal{K}_m \omega_{CS}$, reflects what I will call the "savings effect". To understand the mechanism, abstract from labor taxation, and hence let $\omega_{LL} = 0$. Then, the sign of the environmental wedge depends on the sign of $\mathcal{K}_m$: if current savings increase (decrease) in current fuel use, the wedge is negative (positive), i.e., the carbon tax is below (above) its Pigouvian level. The intuition is similar to the static case above. First, note that since households understand that capital will be taxed in the following period and thus their return to savings will be lower, they consume more and save less than in first best.

Then, if $\mathcal{K}_m > 0$, by increasing fossil fuel use and thus "underproviding" the environmental public good, i.e. by not fully internalizing climate damages, the first-period government can increase current savings. This has a first-order welfare gain in second best since $\omega_{CS} > 0$ and hence the discounted marginal increase in utility due to more consumption in the subsequent period is higher than the marginal utility loss due to less consumption today. It follows that using fossil fuel has an additional benefit which is not present in first best and hence the social cost of carbon does not fully internalize the utility damage caused by the climate externality.

In the case with labor taxation, fossil fuel use affected labor supply through a change in the return to labor. Here, the mechanism is slightly different. The return to current savings is determined by the fuel use in the next period, which is not directly affected by the current government. Instead, more fuel use today affects the amount of resources available to the household by increasing today's capital income, i.e. the return to past savings. Note that this result is analogous to Klein et al. (2008) who only consider not-environmental public consumption. In general, underproviding a public good today dampens underinvestment and thus mitigates the intertemporal distortion caused by the positive tax on capital income.

Returning to the more general case with both $\omega_{LL} > 0$ and $\omega_{CS} > 0$, whether the optimal carbon tax is below or above the Pigouvian rate depends on the sign of $\mathcal{H}_m \omega_{LL} + \mathcal{K}_m \omega_{CS}$. This is in general ambiguous. Note that under particular assumptions - logarithmic utility, a Cobb-Douglas production structure, endogenous government expenditures and a flow pollutant - one can solve for ω_{Env} analytically. In this case, $\mathcal{H}_m = 0$, while $\mathcal{K}_m > 0$ and hence, $\omega_{Env} < 0$. Under more general assumptions, numerical simulations indicate that this result still holds for reasonable parameter values.

To summarize, this section has illustrated that in finite-horizon settings without commitment, carbon taxation interacts with fiscal policy, in the sense that a distortion of the non-environmental margins affects the environmental margin. This possibly leads to an optimal carbon tax which is below the Pigouvian level and hence the climate externality is not fully internalized. In the following sections, I will turn to an infinite-horizon framework. Increasing the number of periods gives rise to additional dynamic effects and adds more terms to the equation (2.21). Each of them is linked to a distorted margin in the future and will reflect how a change in current fuel use affects these future wedges, in addition to the contemporaneous wedges that are at the root of the savings and the static labor effect.

2.4 The Infinite-Horizon Model

I now consider an infinite-horizon version of the simple global climate-economy model outlined above. I derive the government's generalized Euler equations and show that the result obtained in the previous section carries over to the longer horizon: in dynamic models without commitment, climate policy interacts with distortionary taxation and the optimal carbon tax is in general not at the Pigouvian level.[30] In addition to the second-best effects of emissions that were present in the two-period model above, I identify further benefits and costs from current fuel use.

2.4.1 Theoretical Analysis

2.4.1.1 First Best

In the presence of lump-sum taxation, the first-best equilibrium is characterized by the following set of equations:

$$\omega_{CS} \equiv u_c - \beta u_c'[F_k' + 1 - \delta] = 0 \tag{2.22}$$

$$\omega_{LL} \equiv u_l - u_c F_h = 0 \tag{2.23}$$

$$\omega_{PG} \equiv u_g - u_c = 0 \tag{2.24}$$

$$\omega_{Env} \equiv u_c(F_m - \kappa) + \beta q_m \left[u_T' + u_c' F_T' - \frac{q_T'}{q_m'} u_c'(F_m' - \kappa) \right] = 0. \tag{2.25}$$

As before, I define wedges for the consumption-savings margin (ω_{CS}), the labor-leisure margin (ω_{LL}), and the environmental margin (ω_{Env}). In addition, since public consumption is endogenous, there is a wedge for the public-private good margin, denoted by ω_{PG}. The first-best equilibrium is characterized by all these wedges being simultaneously zero.

Note that (2.25) is a compact way of writing the first-best environ-

[30] For simplicity, I derive the analytical results in an infinite-horizon setting where fossil fuel never stops. In the calibrated model below, fossil fuel stops after a finite number of periods.

mental margin. Since

$$u_c'(F_m' - \kappa) = -\beta q_m' \left[u_T'' + u_c'' F_T'' - \frac{q_T''}{q_m''} u_c''(F_m'' - \kappa) \right],$$

(2.25) can be rewritten as

$$\begin{aligned}
\omega_{Env} &= u_c(F_m - \kappa) + \beta q_m \cdot \\
&\left[u_T' + u_c' F_T' + \frac{q_T'}{q_m'} \left(\beta q_m' \left[u_T'' + u_c'' F_T'' - \frac{q_T''}{q_m''} u_c''(F_m'' - \kappa) \right] \right) \right] \\
&= u_c(F_m - \kappa) + \beta q_m \cdot \\
&\left[u_T' + u_c' F_T' + q_T' \beta \left(u_T'' + u_c'' F_T'' - \frac{q_T''}{q_m''} u_c''(F_m'' - \kappa) \right) \right],
\end{aligned}$$

and thus,

$$\begin{aligned}
\omega_{Env} &= u_c(t)(F_m(t) - \kappa) + q_m(t) \cdot \\
&\sum_{i=t+1}^{\infty} \beta^{i-t} \left(\prod_{j=t+1}^{i-1} q_T(j) \right) [u_T(i) + u_c(i) F_T(i)] = 0.
\end{aligned} \tag{2.26}$$

The first term captures the marginal benefit of carbon emissions in utils, the second term the discounted marginal utility and productivity damages in the future. From this, it follows that the Pigouvian tax is defined as:

$$\theta_t^p = -\frac{q_m(t)}{u_c(t)} \sum_{i=t+1}^{\infty} \beta^{i-t} \left(\prod_{j=t+1}^{i-1} q_T(j) \right) (u_T(i) + u_c(i) F_T(i)). \tag{2.27}$$

2.4.1.2 Second Best without Commitment

Next, I relax the assumption that lump-sum taxation is feasible. Instead, the government must resort to a distortionary tax on labor and capital income to finance a public consumption good. As before, I assume that it does not have access to a technology that allows it to commit to all future tax rates. When solving for the outcome under lack of commitment, I look for the time-consistent differentiable Markov-perfect equilibrium in this economy.[31] The basic idea of this equilibrium concept is that only current payoff-relevant states, but not the history of states and actions, matter for a player's action choice.

Note that in this setting, the current government plays a game with its successor.[32] This implies that the current government takes into account the optimal behavior of next period's government when solving its problem. While the current government cannot directly choose policies in the following period, it can affect them by choosing the economy's future state variables.

I define the Markov-perfect equilibrium in a setting where the government has access to a total income tax. That is, it is restricted to impose the same tax rate on labor and capital income. This assumption ensures a setting where both the intertemporal consumption-savings margin and the intratemporal labor-leisure margin are distorted simultaneously, i.e. where I have positive tax rates on both labor and capital income. As shown by Martin (2010), in a setting where the government has ex-ante access to two separate tax rates, the equilibrium features a zero tax rate on labor income, assuming that labor taxes are bounded to be non-negative and that the capital income tax is not bounded from above. This is intuitive: recall that taxes on capital are ex post non-distortionary and thus, can be considered as de facto lump-sum taxes. Hence, in the presence of such a tax, assuming that it is unbounded, it cannot be optimal to have a positive distortionary tax on labor income.[33] Empirically, a setting with a total income tax appears more realistic than an equilib-

[31] An alternative approach would be to look for all sustainable equilibria, along the lines of Phelan and Stacchetti (2001) or Reis (2011).

[32] If governments in different periods are identical, the current government actually plays a game "against itself". That is, even though I have the same government making the decisions in both periods, it must be treated as different players, due to the lack of commitment. Equivalently, announcements in the current period about how the government will behave in the following period are not credible.

[33] In other words, the government is not allowed to subsidize labor. Martin (2010) shows that subsidizing labor is optimal in a setting with unrestricted separate tax rates on labor and capital. However, this appears to be empirically less relevant than zero labor taxes.

rium in which the government finances its expenditures only using a tax on capital or on labor income.[34]

The analysis is a straightforward extension of Klein et al. (2008) and Azzimonti et al. (2009), adding a second public good, environmental quality, which in contrast to the other good does not only affect utility, but also the production process. Hence, there is a second state variable in addition to capital, here the current state of the climate T. Moreover, by comparing the Markov-perfect carbon tax to the outcome under commitment, I will show that in the presence of distortionary taxes, the optimal pollution price is in general not time-consistent. That is, the tax schedule set by a government which had access to a commitment device is different than the one chosen under lack of commitment. Note that this time inconsistency is due to the interaction between environmental and non-environmental taxes: as seen above, the optimal pollution price depends on the optimal tax structure. If other taxes are time-inconsistent - for example a positive tax on labor income in a scenario where separate tax rates on labor and capital are feasible - so is the carbon tax.

2.4.1.3 Equilibrium Definition

A stationary Markov-perfect equilibrium is defined as a value function v, differentiable policy functions ψ and ϕ, a savings function n^k and a labor-supply function n^h such that for all k and T, $\psi(k,T)$, $\phi(k,T)$, $n^k(k,T)$ and $n^h(k,T)$ solve

$$\max_{k',T',h,g,m} u(\mathcal{C}(k,k',h,g,m,T), 1-h, g, T) + \beta v(k',T'), \tag{2.28}$$

[34]There are other ways of modifying the model such that one would get positive tax rates on both production factors in equilibrium. Martin (2010) considers an exogenous upper bound on the capital tax, as well as making the utilization rate of capital endogenous. The former is somewhat unsatisfying since it leaves the origin of the bound unmodeled. The latter slightly changes the logic of the mechanism in this paper.

subject to

$$\begin{aligned}
&\beta u_c'\left(\mathcal{C}\left(\begin{array}{c} k', n^k(k',T'), n^h(k',T'), \\ \psi(k',T'), \phi(k',T'), T' \end{array}\right), 1-n^h(k',T'), \psi(k',T'), T'\right)\cdot \\
&\cdot\left[1+\left[1-\mathcal{T}\left(\begin{array}{c} k', n^h(k',T'), \psi(k',T'), \\ \phi(k',T'), T' \end{array}\right)\right]\right. \\
&\quad\cdot\left.\left[F_k\left(\begin{array}{c} k', n^h(k',T'), \\ \phi(k',T'), T' \end{array}\right)-\delta\right]\right] \\
&-u_c\big(\mathcal{C}(k,k',h,g,m,T), 1-h, g, T\big)=0,
\end{aligned} \tag{2.29}$$

$$\begin{aligned}
&\frac{u_l\big(\mathcal{C}(k,k',h,g,m,T), 1-h, g, T\big)}{u_c\big(\mathcal{C}(k,k',h,g,m,T), 1-h, g, T\big)} \\
&-F_h(k,h,m,T)[1-\mathcal{T}(k,h,g,m,T)]=0,
\end{aligned} \tag{2.30}$$

and $T'=q(T,m)$. $\mathcal{C}$ yields private consumption from the resource constraint, while $\mathcal{T}$ gives the income tax rate that balances the government's budget:

$$\mathcal{C}(k,k',h,g,m,T)=F(k,h,m,T)+(1-\delta)k-g-\kappa m-k', \tag{2.31}$$

$$\mathcal{T}(k,h,g,m,T)=\frac{g-(F_m(k,h,m,T)-\kappa)m}{(F_k(k,h,m,T)-\delta)k+F_h(k,h,m,T)h}. \tag{2.32}$$

Moreover, for all k and T,

$$\begin{aligned}
v(k,T)=u&\left[\mathcal{C}\left(\begin{array}{c} k, n^k(k,T), n^h(k,T), \\ \psi(k,T), \phi(k,T), T \end{array}\right), 1-n^h(k,T), \psi(k,T), T\right] \\
&+\beta v(n^k(k,T), q(T,\phi(k,T))).
\end{aligned}$$

As outlined above, the current government plays a game against its successor, possibly itself. Following the one-stage deviation principle, the current government's strategy constitutes an equilibrium if it maximizes its objective function, subject to all relevant constraints, taking the strategies of the other player - the future government - as given.

In other words, assuming that the future government chooses policies according to the equilibrium decision rules, it must be optimal for the current government to follow the same policy functions.

2.4.1.4 Solution

When solving the model, I follow Klein et al. (2008). Denote the left-hand side of (2.29) as $\eta(k, T, g, m, k', h)$ and the left-hand side of (2.30) as $\epsilon(k, T, g, m, k', h)$, respectively. Define the functions $\mathcal{K}(k, T, g, m)$ and $\mathcal{H}(k, T, g, m)$ implicitly as

$$\eta(k, T, g, m, \mathcal{K}(k, T, g, m), \mathcal{H}(k, T, g, m)) = 0 \tag{2.33}$$

$$\epsilon(k, T, g, m, \mathcal{K}(k, T, g, m), \mathcal{H}(k, T, g, m)) = 0. \tag{2.34}$$

As in the finite-horizon models above, $\mathcal{K}$ ($\mathcal{H}$) can be interpreted as the household's response function for savings (hours worked) to the current government's policy choice, assuming that future governments follow the equilibrium policies: it gives the household's optimal savings level if the current governments set expenditures g and a carbon tax that results in emission level m. In equilibrium, $\mathcal{K}(k, T, \psi(k, T), \phi(k, T)) = n^k(k, T)$ and $\mathcal{H}(k, T, \psi(k, T), \phi(k, T)) = n^h(k, T)$.

Solving the government's problem, taking $\mathcal{K}$ and $\mathcal{H}$ as given, results in the following system of optimality conditions that characterize the stationary Markov-perfect equilibrium:[35]

$$u_c - \beta u_c'[1 + (1 - \mathcal{T}(k', T', h', g', m'))(F_k' - \delta)] = 0 \tag{2.35}$$

$$u_l - u_c(1 - \mathcal{T}(k, T, h, g, m))F_h = 0 \tag{2.36}$$

[35] Compare the appendix, section A.3, for details. Note that deriving the generalized Euler equations for the less general case with a capital income tax only is completely analogous, but with $\omega_{LL} = \omega_{LL}' = 0$.

$$\begin{aligned} u_g - u_c + \mathcal{H}_g(u_c F_h - u_l) + \mathcal{K}_g[-u_c + \beta u_c'(F_k' + 1 - \delta)] \\ + \beta \mathcal{K}_g \mathcal{H}_k'(F_h' u_c' - u_l') \\ - \beta \mathcal{K}_g \frac{\mathcal{K}_k'}{\mathcal{K}_g'} \left[\mathcal{H}_g'(F_h' u_c' - u_l') + u_g' - u_c'\right] = 0. \end{aligned} \tag{2.37}$$

$$\begin{aligned} u_c(F_m - \kappa) + \beta q_m \left[u_T' + u_c' F_T' - \frac{q_T'}{q_m'} u_c'(F_m' - \kappa)\right] \\ + \mathcal{K}_m[-u_c + \beta u_c'(F_k' + 1 - \delta)] \\ + \beta(u_g' - u_c') \left[-\mathcal{K}_m \frac{\mathcal{K}_k'}{\mathcal{K}_g'} - q_m \frac{\mathcal{K}_T'}{\mathcal{K}_g'} + q_m \frac{q_T'}{q_m'} \frac{\mathcal{K}_m'}{\mathcal{K}_g'}\right] \\ + \mathcal{H}_m(u_c F_h - u_l) + \beta \mathcal{K}_m(u_c' F_h' - u_l') \left[\mathcal{H}_k' - \frac{\mathcal{K}_k'}{\mathcal{K}_g'} \mathcal{H}_g'\right] \\ + \beta(u_c' F_h' - u_l') q_m \left[\mathcal{H}_T' - \frac{\mathcal{K}_T'}{\mathcal{K}_g'} \mathcal{H}_g' - \frac{q_T'}{q_m'} \mathcal{H}_m' + \frac{q_T'}{q_m'} \frac{\mathcal{K}_m'}{\mathcal{K}_g'} \mathcal{H}_g'\right] \\ = 0 \end{aligned} \tag{2.38}$$

where the two latter equations are once more generalized Euler equations. Using the wedges defined in (2.22)-(2.25) above, I can write (2.37) and (2.38) as a linear combination of wedges:

$$\begin{aligned} \omega_{PG} + \mathcal{K}_g \omega_{CS} - \beta \mathcal{K}_g \frac{\mathcal{K}_k'}{\mathcal{K}_g'} \omega_{PG}' + \mathcal{H}_g \omega_{LL} \\ + \beta \omega_{LL}' \mathcal{K}_g \left[\mathcal{H}_k' - \frac{\mathcal{K}_k'}{\mathcal{K}_g'} \mathcal{H}_g'\right] = 0, \end{aligned} \tag{2.39}$$

$$\begin{aligned} \omega_{Env} + \mathcal{K}_m \omega_{CS} - \beta \omega_{PG}' \mathcal{K}_m \frac{\mathcal{K}_k'}{\mathcal{K}_g'} - \beta \omega_{PG}' \left[q_m \frac{\mathcal{K}_T'}{\mathcal{K}_g'} - q_m \frac{q_T'}{q_m'} \frac{\mathcal{K}_m'}{\mathcal{K}_g'}\right] \\ + \mathcal{H}_m \omega_{LL} + \beta \omega_{LL}' \mathcal{K}_m \left[\mathcal{H}_k' - \frac{\mathcal{K}_k'}{\mathcal{K}_g'} \mathcal{H}_g'\right] \\ + \beta \omega_{LL}' q_m \left[\mathcal{H}_T' - \frac{\mathcal{K}_T'}{\mathcal{K}_g'} \mathcal{H}_g' - \frac{q_T'}{q_m'} \mathcal{H}_m' + \frac{q_T'}{q_m'} \frac{\mathcal{K}_m'}{\mathcal{K}_g'} \mathcal{H}_g'\right] = 0. \end{aligned} \tag{2.40}$$

As before, the government trades off wedges in equilibrium. In first best, as $\omega_{CS} = \omega_{LL} = \omega_{PG} = \omega_{env} = 0$, (2.39) and (2.40) are satisfied. If the government has to resort to distortionary taxation, the household's optimality conditions (2.35) and (2.36) imply that if $\mathcal{T}(\cdot) > 0$, the consumption-savings and labor-leisure wedges are positive. Then, assuming that the derivatives of the best-response functions are non-zero, it follows from (2.39) and (2.40) that ω_{PG} and ω_{env} cannot be zero at the same time: in optimum, neither public good is provided at the first-best margin. Recall that for the environmental public good, the result that $\omega_{env} \neq 0$ just says that the social cost of carbon is not equal to the marginal climate damage.

Equations (2.39) and (2.40) are useful in computing stationary Markov-perfect equilibria. To facilitate the interpretation, I show in the appendix that they can be rewritten as:[36]

$$\begin{aligned} & u_c(t)(F_m(t) - \kappa) - \bar{q}_m \sum_{i=t+1}^{\infty} \Xi(i) \left[-u_T(i) - u_c(i) F_T(i) \right] \\ & \quad + \mathcal{K}_m(t)\omega_{CS}(t) - \beta\omega_{PG}(t+1)\mathcal{K}_m(t)\frac{\mathcal{K}_k(t+1)}{\mathcal{K}_g(t+1)} + \mathcal{H}_m(t)\omega_{LL}(t) \\ & \quad + \beta\omega_{LL}(t+1)\mathcal{K}_m(t)\left[\mathcal{H}_k(t+1) - \frac{\mathcal{K}_k(t+1)}{\mathcal{K}_g(t+1)}\mathcal{H}_g(t+1)\right] \\ & \quad + \bar{q}_m \sum_{i=t+1}^{\infty} \Xi(i) \left[\omega_{LL}(i) \left(\mathcal{H}_T(i) - \frac{\mathcal{K}_T(i)}{\mathcal{K}_g(i)}\mathcal{H}_g(i) \right) - \omega_{PG}(i)\frac{\mathcal{K}_T(i)}{\mathcal{K}_g(i)} \right] \\ & \quad = 0, \end{aligned} \tag{2.41}$$

with

$$\Xi(i) \equiv \beta^{i-t} \left(\prod_{j=t+2}^{i} q_T(j) \right)$$

[36] Note that in the special case of a flow pollutant (and contemporaneous damages), (2.40) directly characterizes the tax-interaction effect. With $q_m = 0$ in every period, (2.40) can be rewritten as

$$\omega_{Env} + \mathcal{K}_m\omega_{CS} - \beta\omega'_{PG}\mathcal{K}_m\frac{\mathcal{K}'_k}{\mathcal{K}'_g} + \mathcal{H}_m\omega_{LL} + \beta\omega'_{LL}\mathcal{K}_m\left[\mathcal{H}'_k - \frac{\mathcal{K}'_k}{\mathcal{K}'_g}\mathcal{H}'_g\right] = 0,$$

where ω_{Env} is the difference between the social cost of emissions and the marginal damage.

and where I have assumed that:[37]

$$q_m(t) = q_m(t+1) = q_m(t+2) = ... = \bar{q}_m.$$

Expression (2.41), together with (2.40), represents the main theoretical result in this paper. Note that the first term in (2.41) is the marginal benefit of pollution (in utils), while the second term is the present value of the sum of future marginal damages when increasing current emissions or, more concisely, the current marginal climate damage. Denote the difference between the latter and the former, that is, the tax-interaction effect, by $Q(t)$:

$$\begin{aligned} Q(t) \equiv & -u_c(t)(F_m(t) - \kappa) \\ & -\bar{q}_m \sum_{i=t+1}^{\infty} \beta^{i-t} \left(\prod_{j=t+2}^{i} q_T(j) \right) \left[u_T(i) + u_c(i) F_T(i) \right]. \end{aligned}$$

For further interpretation, divide both sides of this expression by the current marginal utility of consumption, $u_c(t)$. On the left-hand side, this gives the difference between the Pigouvian carbon fee, θ^p, and the social cost of carbon (in dollar terms) and hence the optimal carbon tax. Denote this by Δ:

$$\Delta_t = \theta_t - \theta_t^p = -\frac{Q(t)}{u_c(t)}. \quad (2.42)$$

In first best, $Q(t) = 0$, and hence $\theta = \theta^p$, as seen above. In second best,

[37] In words, an additional unit of emissions affects the pollutant stock in the same way, independently of when it occurs. This is a standard assumption in many climate models (Nordhaus, 2008; Golosov et al., 2014).

(2.41) shows that the tax-interaction effect is given by

$$
\begin{aligned}
Q(t) = {} & \underbrace{\mathcal{H}_m(t)\omega_{LL}(t)}_{Q_1} + \underbrace{\mathcal{K}_m(t)\omega_{CS}(t)}_{Q_2} \\
& + \underbrace{\beta\omega_{LL}(t+1)\mathcal{K}_m(t)\left[\mathcal{H}_k(t+1) - \frac{\mathcal{K}_k(t+1)}{\mathcal{K}_g(t+1)}\mathcal{H}_g(t+1)\right]}_{Q_3} \\
& + \underbrace{\left(-\beta\omega_{PG}(t+1)\mathcal{K}_m(t)\frac{\mathcal{K}_k(t+1)}{\mathcal{K}_g(t+1)}\right)}_{Q_4} \\
& + \underbrace{\bar{q}_m \sum_{i=t+1}^{\infty} \beta^{i-t}\left(\prod_{j=t+1}^{i} q_T(j)\right)\omega_{LL}(i)\left[\mathcal{H}_T(i) - \frac{\mathcal{K}_T(i)}{\mathcal{K}_g(i)}\mathcal{H}_g(i)\right]}_{Q_5} \\
& + \underbrace{\bar{q}_m \sum_{i=t+1}^{\infty} \beta^{i-t}\left(\prod_{j=t+1}^{i} q_T(j)\right)\left[-\omega_{PG}(i)\frac{\mathcal{K}_T(i)}{\mathcal{K}_g(i)}\right]}_{Q_6} \\
= {} & \sum_{n=1}^{6} Q_n(t).
\end{aligned}
$$

The questions of whether there is a tax-interaction effect and in what direction it goes can then be asked in terms of $Q(t)$: is it different from zero, and if so, what is the sign? Moreover, to what extent do the different components of $Q(t)$ move in the same direction or cancel each other out?

At this point, note that the wedges and derivatives that show up in (2.4.1.4) are endogenous and solved for simultaneously when computing the equilibrium. Moreover, for most of these terms, it is not possible to determine the sign analytically. Hence, the questions just asked are ultimately quantitative questions and therefore require a numerical analysis. This is done in the next subsection. Before solving for the terms Q_1 through Q_6, I proceed with a qualitative interpretation of the different terms.

2.4.1.5 Interpretation

The first component of $Q(t)$, $\mathcal{H}_m\omega_{LL}$, captures the static labor effect of current fuel use on labor supply, described in section 2.3.1. Recall from above that if $\mathcal{H}_m > 0$, an increase in current fuel use has a positive impact on current labor supply, which mitigates the intratemporal distortion and hence has non-zero impacts on utility in second best.

Similarly, the second component, $\mathcal{K}_m\omega_{CS}$, is the savings effect that was present in the two-period model. For $\mathcal{K}_m > 0$, a higher fuel use today increases the resources available for the household and allows it to move more resources to the next period, thereby mitigating the intertemporal distortion. With a slight abuse of terminology, call Q_1 and Q_2 the "contemporaneous second-best effects" of carbon emissions.

The remaining components of Q did not show up in the one- and two-period models considered above. Q_3 reflects the second-best effect of an increase in current fuel use on tomorrow's labor-leisure wedge through a change in the future capital stock. A higher k' affects future labor supply in two ways. First, there is a direct effect, captured by the term $\mathcal{H}_k'$: a higher capital stock increases tomorrow's real wage which, in turn, affects the amount of hours worked.

To understand the second channel, note that a change in current savings affects future savings. For example, assuming that $\mathcal{K}_k' > 0$, a higher capital stock tomorrow leads to more savings. This, in turn, dampens the intertemporal distortion *in the future* and hence reduces the incentive for the future government to "underprovide" public goods in order to increase savings. This may imply a higher income tax (to finance the non-environmental good) and a higher emission fee (to increase the provision of the environmental public good), which will affect labor supply. This channel is captured by the term $\frac{\mathcal{K}_k'}{\mathcal{K}_g'}\mathcal{H}_g'$

The same logic applies to Q_4. This component reflects the direct welfare effect of a change in future public goods provision due to a change in the capital stock. For example, assume that the public consumption good tomorrow is underprovided, and that a change in current fuel use increases tomorrow's capital stock, which has a positive effect on tomorrow's savings and public goods provision. Formally, this implies that $-\mathcal{K}_m \frac{\mathcal{K}'_k}{\mathcal{K}'_g} > 0$. Then, by underproviding public goods today, the current government is able to dampen the desire of the successive government to underprovide public goods tomorrow, by increasing savings in the future and thereby reducing the need to provide additional resources in the subsequent period. This would be an additional benefit of current fuel use.

Note that these channels were also present in the model by Klein et al. (2008). Hence, they do not depend on the public good being persistent. Therefore, I will refer to Q_3 and Q_4 as the "second-best flow effects".

The two remaining terms in (2.4.1.4) reflect the effect of a change in current fuel use on the future pollutant stock and thus, on the labor-leisure and public-good margins in all future periods, due to the persistence of the pollutant. These terms will be referred to as "second-best stock effects" of current emissions. More specifically, Q_5 captures the impact of current fuel use on future labor supply decisions. Once more, this component can be disentangled in a direct effect of a change in s on hours worked ($\mathcal{H}'_T$), and its effect on future savings and hence public goods provision and taxation ($-\frac{\mathcal{K}'_T}{\mathcal{K}'_g}\mathcal{H}'_g$), analogous to a change in the capital stock. For example, through its impact on productivity, a higher pollutant stock has a negative impact on output and thus wages and household income and thus on future labor supply and savings.

2.4.2 Quantitative Analysis

Above, I have characterized the tax-interaction effect in a dynamic infinite-horizon model without commitment. I have identified the second-best benefits and costs of emissions that affect the social cost of carbon. However, this section has given no indication of how important the tax-interaction effect is and in what direction it goes. As argued above, this is a quantitative question. Therefore, I now compute the optimal Markov-perfect carbon tax in a calibrated climate-economy model and compare it to both the tax in first best and to the Pigouvian rate. Moreover, for comparison, I also compute the outcome if the government had access to a commitment device and thus could credibly commit to all future tax rates.[38]

2.4.2.1 Calibration

I calibrate the model using 2011 as the base year. That is, I assume that in 2011, there is no climate policy, and the world economy is on a balanced growth path (BGP), featuring a total income tax. I solve the global model in second best without any climate damages, and calibrate the labor-augmenting productivity level A_{2011} such that annual output equals world GDP in 2011, which amounted to 70 trillion US\$. Moreover, I calibrate the energy efficiency level B_{2011} such that emissions equal 9 GtC (Olivier et al., 2013). Recall that labor- and energy-augmenting productivity are assumed to grow at the same rate. I set the annual growth rate to be 1.8% ($\zeta = 1.018$). Note that one period in the model equals two years.

When using a Cobb-Douglas production function, a standard choice for the income share of capital, θ, is between 0.3 and 0.36. I set $\rho = 0.35$, to get a capital-output ratio of around 3 along the business-as-usual BGP. As for the income share of fossil fuel, I follow Golosov et al. (2014) and set $\xi = 0.03$.[39] Note that without climate policy, the marginal product of fuel is equal to the private extraction cost and hence:

$$\kappa_{2011} = \frac{\xi y_{2011}}{m_{2011}} = 0.03 \frac{70 \cdot 10^{12}}{8.5 \cdot 10^9} = 233\$/tC. \tag{2.43}$$

This value is between what is found by Golosov et al. (2014) for the private cost of using oil and coal, respectively.

With respect to the utility function, I choose the parameter values

[38] Compare the appendix, section A.5, for how to compute the second-best equilibrium under commitment.

[39] Other studies use a higher income share. For example, Fischer and Springborn (2011) choose $\xi = 0.09$.

for α_c and α_g to target hours worked and the ratio of government expenditures to output. Following Klein et al. (2008), the latter should be about 0.2. With the total time endowment normalized to unity, the labor supply is typically assumed to be between 0.22 and 0.25 (Klein et al., 2008; Barrage, 2013).

Regarding the calibration of parameters γ and α_T, Barrage (2013) finds that production damages account for about 74% of total output damages if $T = 2.5°C$. From this, she calibrates $\gamma = 0.00172$. In my baseline calibration, I fix this value and choose α_T to match the first-best long-run temperature change that the model delivers when the parameterization of the damage parameters follows the DICE model (Nordhaus, 2008). In other words, I first run the model with lump-sum taxation with $\gamma = 0.00284$ and $\alpha_T = 0$ - note that the DICE model does not feature utility damages. In a second step, I calibrate α_T such that a model run with $\gamma = 0.00172$ gives the same temperature increase as the first run. I also conduct some sensitivity analysis by varying the target value for temperature and check for the impact on the results. In particular, the baseline calibration results in a long-run global temperature increase of about $4°C$ above the pre-industrial level.[40] For comparison, I also run versions of the model in which global mean temperature instead stabilizes at $3°C$ and $4.5°C$, respectively.

The following table lists the parameter settings for the baseline calibration.

2.4.2.2 Solution Method

For simplicity, in the analytical analysis above, I have characterized optimal income and carbon taxation in a stationary economy. When quantitatively analyzing climate change, however, stationarity is a problematic assumption if it implies that fossil fuel is used forever. Therefore, in this section, I turn to a non-stationary framework. Nevertheless, the

[40] Since temperature change does not depreciate, it stays constant once carbon emissions stop, as discussed below.

Parameter	Description	Value	Source
Preferences			
α_c	utility weight consumption	.255	Calibration
α_g	utility weight public good	.12	Calibration
α_T	utility weight climate	$1.1e^{-3}$	Calibration, sensitivity
Production			
ρ	income share capital	.35	
ξ	income share fuel	.03	Hassler et al. (2012)
Other			
δ	depreciation rate	.08	Klein et al. (2008)
β	time discount rate	.985	Nordhaus (2010)
γ	damage function	.00172	Barrage (2013)

Table 2.1: Baseline Calibration

key equation derived above, (2.4.1.4), can still be used to quantify the tax-interaction effect and its individual components.

I follow a common modeling strategy (Golosov et al., 2014; Barrage, 2013; Cai et al., 2012) and assume that in the long run, energy use does no longer cause carbon emissions. More specifically, I impose a deterministic number of J periods, after which the one-to-one mapping between the amount of fuel used and the amount of carbon emitted is no longer valid.[41] In the baseline model, I let $J = 120$. From this period onwards, T is constant, and the economy converges to a balanced growth path (BGP). Let $\bar{v}$ denote the terminal value function (Cai et al., 2012):

$$\bar{v}(k_{J+1}, T_{J+1}) = \sum_{t=J+1}^{\infty} \beta^{t-J+1} u(c_t, 1 - h_t, g_t, T_t). \qquad (2.44)$$

This function gives the continuation value for the stationary phase of the economy.

Numerically, both the first-best and the second-best equilibrium with commitment are straightforward to solve for, by maximizing over all

[41]This could be interpreted in different ways. For example, at a given point in time, "clean" energy, i.e. a perfect substitute for fossil fuel whose production and use does not cause carbon emissions, becomes available. Alternatively, one could assume the employment of technologies like Carbon Capture and Storage (CCS).

variables for J periods, given the terminal value function. This is the approach employed by Golosov et al. (2014) or Barrage (2013), among others. Under lack of commitment, this method is not feasible. Instead, I have to resort to dynamic programming, following Cai et al. (2012, 2013). The problem is formally described in the appendix in section A.6. As discussed above, when choosing its optimal policy, the current government takes as given the next period's value function, as well as its successor's time-consistent decision rules. When solving the problem, I approximate these functions using Chebyshev polynomials. Computations are performed in AMPL, using the KNITRO optimization solver (Ziena, 2013) for the maximization problems.

2.4.2.3 Results

	$\$/tC$		$\log(\theta/\theta^{FB})$		$\log(\theta/\theta^{p})$		τ	
Year	2010	2100	2010	2030-2130	2010	2030-2130	2010	2030-2130
Baseline								
First Best	88.74	797.97	-	-	-0.00	-0.00	-	-
Markov	76.99	509.79	-0.14	-0.44	0.03	-0.04	0.25	0.25
Commitment	77.53	450.04	-0.14	-0.57	0.01	-0.12	0.25	0.31
Target 3°C								
First Best	179.75	1512.46	-	-	-0.00	-0.00	-	-
Markov	144.76	948.22	-0.22	-0.46	-0.14	-0.17	0.25	0.25
Commitment	147.06	935.59	-0.20	-0.48	-0.11	-0.09	0.25	0.31
No util damages								
First Best	57.65	532.97	-	-	-0.00	-0.00	-	-
Markov	54.61	355.70	-0.05	-0.40	0.20	0.09	0.25	0.25
Commitment	54.51	277.83	-0.06	-0.65	0.13	-0.15	0.25	0.32
No prod damages								
First Best	38.78	377.66	-	-	-0.00	-0.00	-	-
Markov	41.00	262.47	0.06	-0.35	0.19	0.05	0.25	0.25
Commitment	40.56	177.34	0.04	-0.75	0.19	-0.26	0.25	0.32

Table 2.2: Results

The first three rows of table 2.2 contain the numerical results for the baseline model. In first best, the tax schedule starts at 89$/tC in 2011 and rises to about 800$/tC in 2100. In the presence of distortionary taxation, by contrast, the carbon tax increases from about 77$/tC in 2010 to 450$/tC under commitment and 510$/tC in the Markov-perfect equilibrium, respectively.

The second column of table 2.2 shows the relative deviation of the optimal carbon tax under distortionary income taxation from the first-best rate. The third column displays the deviation from the corresponding Pigouvian rate and hence captures the tax-interaction effect. Note that the tax-interaction effect does not fully account for the change in θ relative to the first best. For example, in the baseline model, the optimal carbon tax in 2011 is 3% above the Pigouvian level, but 14% below the first-best tax. The difference is caused by a "distortion-level effect": due to the distortions in the consumption-savings and the consumption-labor margin, the second-best equilibria both with and without commitment feature lower output and lower consumption than the first-best outcome. This, in turn, reduces the damages from climate change and hence the absolute level of the marginal damages, i.e. the Pigouvian carbon tax. This can be formally expressed as:

$$\underbrace{\log(\theta/\theta^{FB})}_{\text{total change}} = \underbrace{\log(\theta^{p}/\theta^{FB})}_{\text{TIE}} + \underbrace{\log(\theta/\theta^{p})}_{\text{distortion-level effect}}$$

In other words, the distortion-level effect reduces the Pigouvian fee, while the tax-interaction effect shifts the optimal tax above or below the Pigouvian level. Figure 2.1, which shows the time path of the optimal carbon price for the first best and the Markov-perfect equilibrium, as well the corresponding level of the marginal climate damage in the latter setting, further illustrates this relationship.

Focusing on the second row of table 2.2, the tax-interaction effect under lack of commitment is small in the baseline model: in 2011, the optimal carbon tax exceeds the Pigouvian level by 3%, which in absolute terms amounts to \$1.95. The table also displays the average deviation between 2030 and 2130: in this period, the optimal tax is on average 4% below the Pigouvian level. To shed some light on these results, recall the expression for the absolute deviation Δ of the social cost of carbon from

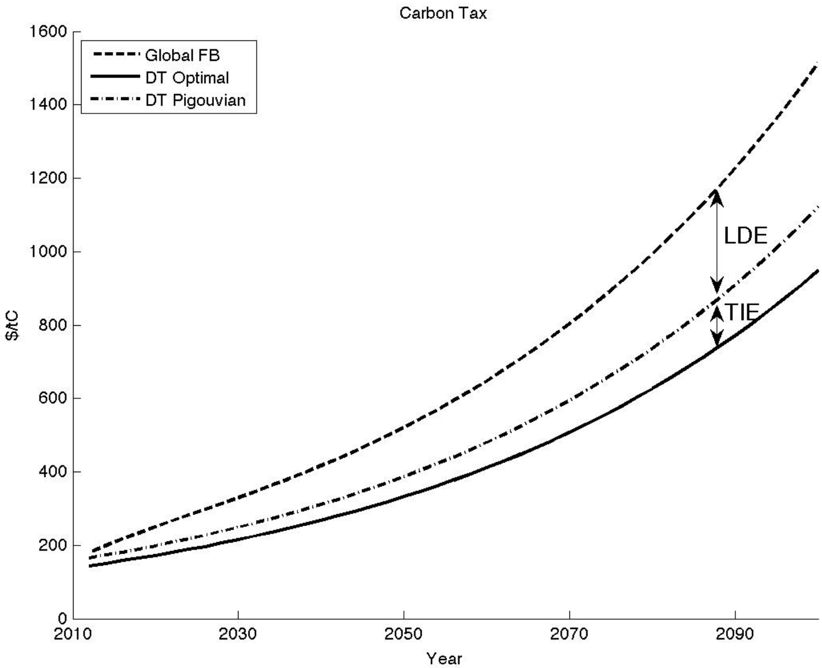

Figure 2.1: Optimal carbon tax - Scenario “Target 3°C”

the marginal climate damage (in dollar terms), derived above:

$$\Delta_t = \theta_t - \theta_t^p = -\frac{1}{u_c(t)} \sum_{j=1}^{6} Q_j(t) \equiv \sum_{j=1}^{6} \tilde{Q}_j(t).$$

Table 2.3 shows the values of the components of Δ in 2011. Looking at the different components, first note that $\tilde{Q}_1$ and $\tilde{Q}_2$ are both negative. Recall that $\tilde{Q}_1$ quantifies the static labor effect: disregarding all other effects, the government would have an incentive to decrease the optimal carbon tax in order to account for the positive effect of fuel use on the labor supply in second best. By itself, the static labor effect would prescribe an optimal carbon tax that is more than 3$/tC below the Pigouvian level. Similarly, $\tilde{Q}_2$ captures the second-best benefit of stimulating savings, which induces the government to lower the tax by 1.57$/tC relative to the Pigouvian fee.

	θ	Δ	$\tilde{Q}_1$	$\tilde{Q}_2$	$\tilde{Q}_3$	$\tilde{Q}_4$	$\tilde{Q}_5$	$\tilde{Q}_6$
Baseline	76.99	1.95	-3.09	-1.57	11.80	-11.56	4.74	1.63
Target 3°C	144.76	-21.36	-22.54	-4.05	30.73	-29.98	4.23	0.24
No util damages	54.61	9.68	3.42	-0.73	5.45	-5.35	4.94	1.94
No prod damages	41.00	7.12	7.49	-0.20	1.48	-1.46	-0.03	-0.17

Table 2.3: Results

In contrast, the stock effects $\tilde{Q}_5$ and $\tilde{Q}_6$ are both positive, reflecting the negative impact of a higher pollutant stock on labor supply and savings in the future. Hence, these effects by themselves would suggest an above-Pigouvian carbon tax. Overall, the combined sign of $\tilde{Q}_1$ through $\tilde{Q}_6$ is positive. Since $\tilde{Q}_3$ and $\tilde{Q}_4$ – despite being the largest effects in absolute value – go in different directions and have an almost-zero net effect, the small positive total effect is due to the fact that the stock effects, reflecting second-best considerations in the future, more than offset the contemporaneous second-best benefits of emitting carbon.

The remainder of tables 2.2 and 2.3 show how these results change when varying some of the key parameters. For the "Target 3°C" scenario, I set α_T, the weight on temperature change in the utility function, such that the global mean temperature stabilizes at $3°C$ in first best, rather than at about $3.75°C$ in the baseline model. Since this results in a higher cost of climate change, the level of the carbon tax in 2011 increases to about 180$/tC under lump-sum taxation and 145$ in the Markov-perfect equilibrium, respectively. The tax-interaction effect is now negative: in 2011, the optimal carbon tax is 14% below the Pigouvian level, while between 2030 and 2130, the average gap increases to 17%.

Table 2.3 shows that while the signs of $\tilde{Q}_1$ through $\tilde{Q}_6$ are the same as in the baseline scenario, the absolute values of the contemporaneous second-best effects $\tilde{Q}_1$ and $\tilde{Q}_2$ are larger, which accounts for almost the entire decrease in Δ. As in the baseline calibration, $\tilde{Q}_3$ and $\tilde{Q}_4$ almost completely offset each other, while $\tilde{Q}_5$ and $\tilde{Q}_6$ are positive and only slightly smaller than before.

The scenarios "No utility damages" and "No productivity damages" contain the results when setting the parameters governing utility and productivity damages, α_T and γ, respectively, equal to zero. In either scenario, climate change is less costly than in the baseline scenario and hence the optimal carbon tax is lower, both in first and second best. With regard to the tax-interaction effect, in both cases the optimal carbon tax is around 20% higher than the Pigouvian fee in 2011, and still exceeds the marginal damage level by 9% and 5%, respectively, between 2030 and 2130. Looking at the decomposition in table 2.3, note that $\tilde{Q}_1$ is positive, implying that the static labor effect now drives up the optimal carbon tax and thus captures a second-best *cost* of burning carbon. Moreover, $\tilde{Q}_2$ is close to zero. Hence, in contrast to the baseline model, the contemporaneous effects do not offset the positive stock effects, but rather reinforce them, which results in a strong positive tax-interaction effect.[42]

Hence, these results suggest that there is a monotonic relationship between the cost of climate change and the tax-interaction effect. What explains this finding? As indicated by table 2.3, what determines the size and direction of the TIE are mainly the contemporaneous effects captured by $\tilde{Q}_1$ and $\tilde{Q}_2$. Recall their definitions from (2.42) and (2.4.1.4):

$$\tilde{Q}_1 = -\mathcal{H}_m(t)\frac{\omega_{LL}(t)}{u_c(t)}, \quad \tilde{Q}_2 = -\mathcal{K}_m(t)\frac{\omega_{CS}(t)}{u_c(t)}.$$

Therefore, $\tilde{Q}_1 < 0$ if $\mathcal{H}_m(t) > 0$ and vice versa. Similarly, $\mathcal{K}_m(t) > 0$ implies $\tilde{Q}_2 < 0$, which is the case in all scenarios in all periods. In other words, the savings effect is always negative and represents a force that drives the optimal carbon tax below the Pigouvian level. What is different across scenarios is the size of $\mathcal{K}_m$: the reaction of savings to a marginal increase in fossil fuel use is greater for higher utility or a higher productivity cost of climate change and hence for lower fossil fuel

[42]Note that in the "No productivity damages" scenario, the stock effects are approximately zero, as indicated above.

use. Intuitively, the smaller is m_t, the larger is the marginal product F_m. This translates into a larger increase in household income which, in turn, causes savings to rise more sharply.

With respect to the sign of $\mathcal{H}_m(t)$, recall from the insights from the one-period model that the change in labor supply following an increase in emissions can be positive or negative, depending on whether the income or the substitution effect dominates. Here, the higher the cost of climate change, the stronger is the latter relative to the former: in the baseline and the "Target 3°C" scenario, the substitution effect dominates and hence $\mathcal{H}_m(t) > 0$, while the reverse is true in the two other scenarios. Note that higher output leads to an increase in the household's labor and non-labor income, giving rise to the income effect, but also raises the net wage and induces higher savings, which generates the substitution effect. The impact of $\mathcal{K}_m$ on $\mathcal{H}_m$ can be formalized in the following way:

$$\mathcal{H}_m(t) = \Lambda_0(t) + \Lambda_1(t)\mathcal{K}_m(t), \tag{2.45}$$

where Λ_0 and Λ_1 depend on the derivatives of functions η and ϵ defined in (2.33) and (2.34) above. In the scenarios considered here, I find that $\Lambda_0 < 1$ and $\Lambda_1 > 0$. For small m_t and a large $\mathcal{K}_m(t)$, the second term on the right-hand side of (2.45) dominates the first term, resulting in $\mathcal{H}_m$ being positive. In other words, when fossil fuel use is low, the large increase in savings and thus a strong reduction in disposable income lead to an increase in labor supply. In contrast, for high levels of fossil fuel use, the increase in savings following an increase in m_t is not strong enough to offset the income effect and hence labor supply falls, exacerbating the intratemporal distortion.

Figure 2.2 shows how the tax-interaction effect evolves over time in the four scenarios. In the baseline calibration, between 2011 and 2130, the relative deviation of the second-best carbon tax from the Pigouvian level decreases monotonically over time from 3% to about −6%. The finding that the time path of $\log(\theta/\theta^p)$ has a negative slope is consistent across the different scenarios. The intuition for this is the following. Due

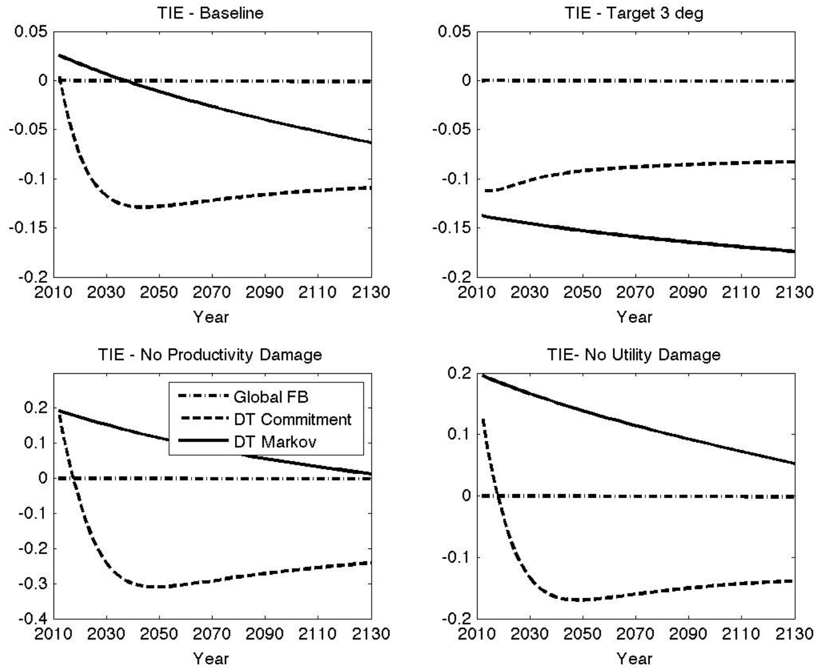

Figure 2.2: Tax-Interaction Effect - Baseline Scenario

to the convexity of productivity and utility damages, the marginal cost of climate change is increasing the cumulative emissions, even without taking into account exogenous output growth. Hence, the Pigouvian level of the carbon tax rises over time, which leads to lower fuel use and thus more pronounced reactions in labor supply and savings, $\mathcal{K}_m$ and $\mathcal{H}_m$.

Comparing the Markov-perfect carbon tax rates with the outcome under commitment, table 2.2 shows that the difference in absolute levels is initially very small, but increases over time, featuring higher rates under lack of commitment in 2100. The reason for this is twofold: first, the commitment solution features more public consumption and hence a higher income tax rate than the Markov-perfect equilibrium.[43] This results in a lower output and consumption level and hence a smaller

[43] Compare Klein et al. (2008).

Pigouvian rate, as seen in figure 2.1. For example, in the baseline scenario, the Pigouvian tax in 2100 amounts to $504\$/tC$ under commitment, compared to $534\$/tC$ in the Markov-perfect case.

Second, this gap is further widened by the tax interaction effect, as is illustrated by figure 2.2 for the baseline setting. In other words, the difference between the optimal tax rate and the Pigouvian level is larger (in absolute terms) under commitment than in the setting without commitment. More precisely, $\log(\theta/\theta^p)$ starts close to zero in 2011, but then drops to around -0.12 during a transition period and then increases slightly over time. In contrast, the tax-interaction effect decreases smoothly in the Markov-perfect equilibrium. In 2100, the corresponding tax levels are $450\$/tC$ and $510\$/tC$ with and without commitment, respectively.

To understand this result, it is useful to first consider the case where the government imposes a tax only on labor income. As shown in the appendix, solving the government's problem yields the following first-order condition with respect to consumption for all periods $t \geq 1$:

$$u_c(t) - \lambda_t + \mu_t[u_{cc}(t)c_t + u_c(t)] + u_{cc}(t)k_{t+1}[\mu_t - \mu_{t+1}] = 0, \qquad (2.46)$$

where λ_t and μ_t are the Lagrange multipliers with respect to the resource constraint and the government budget constraint, respectively. Note that in the special case considered here, where utility is additively separable and logarithmic in c, $u_{cc}(t)c_t + u_c(t) = 0$, and hence the third term in (2.46) is zero. Since the last term is quantitatively small in the long run,[44] (2.46) boils down to $u_c(t) \approx \lambda_t$. The first-order condition is given by $\lambda_t(F_m(t) - \kappa) - \xi_t = 0$, where ξ_t denotes the Lagrange multiplier with respect to the law of motion for temperature change. Together, these two equations boil down to the first-best optimality condition (2.26), which implies that the tax-interaction effect is close to one. The intuition for this result is analogous to Klein et al. (2008): while decreasing fuel in

[44] If the economy were to reach a steady state where $\mu_t k_t = \mu_{t+1}k_{t+1}$, it would be zero.

period t use has a negative effect on contemporaneous labor supply, it leads to an increase in hours worked in the previous periods $t-1$, $t-2$, etc., which counteracts the incentive to increase fuel use. In contrast, without commitment, a given government does not take into account the effect on household behavior in previous periods.

In the case of a total income tax, on the other hand, the tax-interaction effect is considerably less than one in the long run. Intuitively, increasing fuel use in period t raises the return to savings (since $F_{km} > 0$) and hence has a positive effect on savings in the previous periods. In contrast to labor supply, however, there are no offsetting effects. Therefore, the government has an incentive to decrease the carbon tax in order to increase savings. Formally, letting ρ_t denote the Lagrange multiplier with respect to the tax constraint and again assuming logarithmic preferences, the first-order condition with respect to consumption is given by:

$$\begin{aligned} & u_c(t) - \lambda_t + u_{cc}(t)k_{t+1}[\mu_t - \mu_{t+1}] \\ & \qquad + u_{cc}(t)\left[\rho_t \frac{F_h(t)}{u_l(t)} - \rho_{t+1}\frac{F_h(t+1)}{u_l(t+1)}\right] = 0, \end{aligned} \tag{2.47}$$

where the last two terms are close to zero in the long run. As before, this gives $u_c(t) \approx \lambda_t$. The first-order condition for fuel use reads:

$$\lambda_t(F_m(t)-\kappa)-\xi_t+\rho_t\left[F_{km}(t)+\frac{u_c(t)-\beta^{-1}u_c(t-1)}{u_l(t)}F_{hm}\right]=0. \tag{2.48}$$

Without the last term, this would be the corresponding expression in first best and the setting with only a labor tax. Since $\rho_t > 0$, however, the first-best margin is distorted and the tax-interaction effect is positive.

When comparing the size of the tax-interaction effect under commitment across the different scenarios described above, it is worthwhile to note that the gap between the optimal carbon tax and the Pigouvian level decreases in climate damage and thus in the level of the carbon tax rate. Here, the optimal carbon tax is 9% lower than the Pigouvian rate in the “Target 3°C” scenario where tax rates are high, but 26% lower in the setting without productivity damages. Intuitively, when taxes are low, more fuel is used and hence the marginal impact of increasing fuel use on the return to capital is smaller, i.e. $\partial^2 F_k / \partial m^2 < 0$. Thus, for low carbon taxes, the government must provide a larger increase in fuel use, relative to the Pigouvian level, in order to create an incentive for the household to increase savings.

Returning to the baseline model, note that the global first-best carbon tax in this paper is within the range of what other studies have found. In particular, Golosov et al. (2014) find an optimal carbon tax of 57\$/tC in 2010, while the newest version of the DICE model (Nordhaus, 2013) reports a tax of 66\$/tC in 2015 (18$\$/tCO_2$). The revised estimate of the Interagency Working Group on Social Cost of Carbon of the US government is higher, amounting to 121\$/tC in 2010 (33$\$/tCO_2$) for a comparable discount rate (IWG, 2013). The main difference to these studies, as explained above, is the law of motion for global mean temperature change: they explicitly model an atmospheric carbon stock that determines temperature change, and assume that some carbon leaves the atmosphere over time. In contrast, my model, based on Matthews et al. (2009), assumes that the effect of emitting carbon on temperature is permanent.

To summarize, I have shown that introducing distortionary income taxation in a global climate-economy model gives rise to a tax-interaction effect, which results in a wedge between the optimal carbon tax and the Pigouvian fee. This wedge is caused by the presence of second-best costs and benefits of burning fossil fuel. Quantitatively, the size and direction of this effect depend on the level of the carbon tax and hence on the socially desired temperature change.

2.5 Conclusion

This paper has analyzed optimal carbon taxation in a world where governments have to resort to distortionary taxation to finance public expenditures and where regions do not cooperate when setting climate policy.

I have added these features to an otherwise standard dynamic climate-economy model and computed optimal carbon tax schedules for different settings.

The main findings of this paper are the following. First, I have characterized optimal policy analytically in a global planner model. I have illustrated that the optimal second-best carbon tax is in general not at the Pigouvian level, due to the presence of additional costs and benefits of carbon emissions that only materialize under distortionary income taxation. In contrast to previous studies, I have shown that it is not only the current labor-leisure margin that is affected by climate policy, but there are other current and future wedges that interact with carbon taxes. Second, a quantitative analysis has shown that the size and direction of the net tax-interaction effect depend on the level of the carbon tax and hence on the cost of climate change. In the baseline model, the overall effect is positive, resulting in an optimal second-best carbon tax which is initially about 3% above the Pigouvian rate. Moreover, I have found a considerable variation between a time-consistent estimate of the social cost of carbon and the corresponding first-best outcome.

In order to facilitate the analysis, I have made a number of simplifying assumptions. Relaxing those assumptions could result in potentially interesting extensions of the above framework. Most notably, in this paper I have considered a global economy. Since fiscal policy is typically set at the country level, extending the model to multiple regions would deliver more reliable quantitative results. In the next chapter of this thesis, I make a first step in this direction by modeling an economy with two regions, calibrated to the European Union and the rest of the world.

Moreover, the framework in this paper is deterministic and has abstracted from uncertainty, both with respect to climate change and long- and short-run economic growth. Regarding the latter, it is straightforward to add exogenous productivity or taste shocks to the model, in the tradition of the real business cycle literature. Previous work by Heutel (2012) has shown that in a first-best setting, climate policy is procyclical in the sense that a carbon tax optimally increases during expansion, while it must be reduced in a recession. The framework used in this paper would allow me to analyze how robust this finding is to the introduction of distortionary income taxes in the economy.

Given its long-term nature and its complexity, climate change gives rise to many types of uncertainty, both related to the science and to the economic damages.[45] Integrated assessment models are usually either deterministic, or consider parametric uncertainty (Nordhaus, 2008; Golosov et al., 2014). Some recent papers instead focus on "intrinsic" uncertainty, that is, uncertainty caused by the random occurrence of exogenous events (Cai et al., 2012). In particular, studies by Lemoine and Traeger (2013) and Cai et al. (2013) incorporate so-called "tipping points", defined as irreversible and abrupt shifts in the climate system, in stochastic versions of the DICE model. Jensen and Traeger (2013) analyze optimal carbon mitigation under long-term growth uncertainty. While such questions are beyond the scope of this paper, it is important to keep in mind that these channels have a potentially large quantitative impact on optimal carbon taxes.

Integrated assessment models such as the one used in this paper have other limitations. Two important areas of ongoing research are the modeling of economic growth and the representation of climate damages. The above framework has built upon the neoclassical growth model, assuming an exogenously given progress of both general-purpose technology and energy efficiency. A recent strand of the literature has instead considered optimal environmental policy in endogenous-growth models. Using a model of directed technical change, Acemoglu et al. (2012) endogenize productivity growth for both a clean and a dirty production input. They show that optimal climate policy in such a setting consists of both a carbon tax and a research subsidy to the clean type of energy. Hemous (2013) embeds this framework in a setting with two regions and analyzes unilateral policy. He also finds that research subsidies are an important component of optimal policy. These results suggest that incorporating

[45] Compare Stern (2013) for a recent summary.

endogenous growth along similar lines would affect the results in this paper qualitatively and quantitatively.

Moreover, Stern (2013) notes that integrated assessment models usually assume that economic growth is not affected by climate damages. Instead, the multiplicative damage function that is used in this paper, as well as in many others studies, relates contemporaneous damages to the current flow of output, but not to, for example, the stock of capital or other factors determining the growth potential of the economy.[46] This shortcoming is exacerbated by the fact that the damage function as used in the DICE model yields quantitatively small damages.[47] These issues are summarized by Stern (2013), arguing that the "exogeneity of a key driver of growth, combined with weak damages" is one of the key weaknesses of current integrated assessment modeling. While this paper had a different focus and did not attempt to contribute to advances in climate-economy modeling in these areas, one should keep these limitations in mind when interpreting its results.

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[46] A recent paper by Moyer et al. (2013) analyzes a model in which climate change has direct effects on productivity. They find that this leads to a considerable increase in the social cost of carbon.

[47] As shown by Ackerman et al. (2010), the damage function in Nordhaus (2008) would imply a decrease in output by only 50% when the temperature increases by $19°C$ relative to the preindustrial level. However, it should be noted that William Nordhaus warns that there is not sufficient evidence to reliably use this damage function for temperature changes above $3°C$ (Stern, 2013).

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A Appendix

A.1 $\mathcal{H}_m$ in the Static Model

In this section, I derive the expression for $\mathcal{H}_m$, the derivative of the household's response function for labor supply that is given by (2.17). Let $h = \sigma(\tilde{w}, y)$ be the Marshallian (uncompensated) labor supply, as a function of the net wage $\tilde{w}$ and non-labor income y. Note that these are themselves functions of h and m. Then, totally differentiating

$$h = \sigma(\tilde{w}(h, m), y(h, m))$$

yields

$$dh = \frac{\partial\sigma}{\partial\tilde{w}}\left[\frac{\partial\tilde{w}}{\partial h}dh + \frac{\partial\tilde{w}}{\partial m}dm\right] + \frac{\partial\sigma}{\partial y}\left[\frac{\partial y}{\partial h}dh + \frac{\partial y}{\partial m}dm\right].$$

Rearranging gives

$$\mathcal{H}_m \equiv \frac{dh}{dm} = \frac{\sigma_{\tilde{w}}\frac{\partial\tilde{w}}{\partial m} + \sigma_y\frac{\partial y}{\partial m}}{1 - \sigma_{\tilde{w}}\frac{\partial\tilde{w}}{\partial h} - \sigma_y\frac{\partial y}{\partial h}} = \frac{\epsilon_{h,\tilde{w}}\frac{h}{\tilde{w}}\frac{\partial\tilde{w}}{\partial m} + \epsilon_{h,y}\frac{h}{y}\frac{\partial y}{\partial m}}{1 - \epsilon_{h,\tilde{w}}\frac{h}{\tilde{w}}\frac{\partial\tilde{w}}{\partial h} - \epsilon_{h,y}\frac{h}{y}\frac{\partial y}{\partial h}}, \tag{2.49}$$

where the denominator is positive. Note that if the proportional change in labor income following from an increase in fuel use is the same as the change in non-labor income, that is, if

$$\frac{\partial\tilde{w}/\partial m}{\tilde{w}}h = \frac{\partial y/\partial m}{y},$$

the sign of $\mathcal{H}_m$ is given by the sign of the sum of the wage and the income elasticity:

$$\mathcal{H}_m = \frac{\frac{h}{\tilde{w}}\frac{\partial\tilde{w}}{\partial m}}{1 - \epsilon_{h,\tilde{w}}\frac{h}{\tilde{w}}\frac{\partial\tilde{w}}{\partial h} - \epsilon_{h,y}\frac{h}{y}\frac{\partial y}{\partial h}}(\epsilon_{h,\tilde{w}} + \epsilon_{h,y}).$$

Next, note that with a total income tax,

$$\begin{aligned}(1-\tau)F_h &= \left(1 - \frac{g - (F_m - \kappa)m}{F_k k + F_h h}\right)F_h = \left(\frac{F - g - \kappa m}{F_k k + F_h h}\right)F_h \\ &= \frac{\upsilon_h h^{-1}(F - g - \kappa m)}{\upsilon_k + \upsilon_h},\end{aligned}$$

where $F_k k = \upsilon_k F$, $F_k k = \upsilon_k F$, $F_k k = \upsilon_k F$ and $\upsilon_k + \upsilon_h + \gamma_m = 1$ by Euler's theorem. Similarly,

$$y = (1-\tau)F_k k = \frac{\upsilon_k(F - g - \kappa m)}{\upsilon_k + \upsilon_h}.$$

Assume that $\frac{\upsilon_k}{\upsilon_k + \upsilon_h}$ is constant, which is the case for many CES functions.

Then,

$$\frac{\partial \tilde{w}}{\partial m} = \frac{\partial (1-\tau) F_h}{\partial m} = \frac{\upsilon_h h^{-1}}{\upsilon_k + \upsilon_h}(F_m + F_T q_m - \kappa m) \tag{2.50}$$

and

$$\frac{\partial y}{\partial m} = \frac{\partial (1-\tau) F_k k}{\partial m} = \frac{\upsilon_k}{\upsilon_k + \upsilon_h}(F_m + F_T q_m - \kappa m) \tag{2.51}$$

Substituting (2.50) and (2.51) in (2.49) yields:

$$\begin{aligned}\mathcal{H}_m &= \frac{\epsilon_{h,\tilde{w}} \frac{\upsilon_h}{\upsilon_k+\upsilon_h} + \epsilon_{h,y} \frac{\tilde{w}h}{y} \frac{\upsilon_k}{\upsilon_k+\upsilon_h}}{\tilde{w} - \epsilon_{h,\tilde{w}} h \frac{\partial \tilde{w}}{\partial h} - \epsilon_{h,y} \frac{\tilde{w}h}{y} \frac{\partial y}{\partial h}}(F_m + F_T q_m - \kappa m) \\ &= \frac{\epsilon_{h,\tilde{w}} + \epsilon_{h,y}}{A} \frac{\upsilon_h}{\upsilon_k + \upsilon_h}(F_m + F_T q_m - \kappa m)\end{aligned}$$

If $\epsilon_{h,w} + \epsilon_{h,y} > 0$ ($\epsilon_{h,w} + \epsilon_{h,y} < 0$), the former dominates (is dominated by) the latter and hence the static labor effect results in a carbon tax below (above) the Pigouvian level.

Note that in the case without capital and hence exogenous non-labor income, this becomes

$$\mathcal{H}_m = \frac{\epsilon_{h,\tilde{w}}}{\tilde{w} - \epsilon_{h,\tilde{w}} \tau F_h}(F_m + F_T q_m - \kappa m).$$

A.2 The GEE in the Two-period Model

This section shows how to derive the government's generalized Euler equation in the two-period model without commitment. Assume that the stock of the pollutant s evolves in the following way:

$$s_0 = q_0(m_0), \quad s_1 = q(s_0, m_1). \tag{2.52}$$

That is, s_t denotes the pollutant stock *at the end* of period t.

Similarly to the static setting above, the environmental wedge in period 0 is defined as the sum of the direct marginal benefit and cost of pollution, now taking stock effects into account:

$$\omega_{Env} \equiv u_c(F_m - \kappa) + q_m[u_s + u_c F_s] + \beta q_m q_s' \left[u_s' + u_c' F_s'\right] = 0. \quad (2.53)$$

I solve the model using backwards induction. For simplicity, assume that there are separate feasible tax rates on labor and capital income in the final period. The government's problem in period 1 can then be written compactly as:

$$\max_{h_1, m_1} u[F(k_1, h_1, m_1, q(s_0, m_1)) - g_1, 1 - h_1, q(s_0, m_1)]. \quad (2.54)$$

Note that since the tax on capital income is a de-facto lump-sum tax, this is identical to the problem of a social planner that takes the capital stock and the stock of the pollutant as given. The labor tax is optimally zero.

Let $M(k_1, s_0)$ and $H(k_1, s_0)$ denote the policy rules that solve the government's problem in period 1. Since government expenditures are financed by the revenue generated from the tax on capital income and the pollution tax, the tax rate on capital in $t = 1$ is given residually by:

$$\mathcal{T}(k_1, s_0) = \frac{g_1 - F_m[k_1, M(k_1, s_0), H(k_1, s_0), q(s_0, M(k_1, s_0))]}{F_k[k_1, M(k_1, s_0), H(k_1, s_0), q(s_0, M(k_1, s_0))]k_1}. \quad (2.55)$$

I assume that this tax is always positive, i.e. government expenditures are large enough so that they cannot be financed by the revenue from the emission tax alone. To simplify the notation, let $M(k_1, s_0) = M_1$, $H(k_1, s_0) = H_1$ and $\mathcal{T}(k_1, s_0) = \mathcal{T}_1$.

The government in period 0 takes these functions as given when solving its problem:

$$\begin{aligned} \max_{k_1, m_0, h_0} & u[F(k_0, h_0, m_0, q_0(m_0)) - \kappa m_0 - g_0 - k_1, 1 - h_0, q_0(m_0)] \\ & + \beta u\left[F(k_1, H_1, M_1, q(q_0(m_0), M_1)) - \kappa M_1 - g_1, \right. \\ & \left. 1 - H_1, q(q_0(m_0), M_1)\right] \end{aligned}$$

subject to implementability constraints. Assuming that the government imposes a tax on total income in period 0, and hence $\omega_{LL} > 0$, there are two such constraints.[48] The first comes from the intratemporal optimality condition and is analogous to the one-period model, but with savings k_1 as an additional argument. Hence, it can be compactly written as $\chi(k_1, h_0, m_0) = 0$. The second combines the household's budget constraint with the household's intertemporal optimality condition:

$$\begin{aligned} 0 \geq & \beta u_c\big(F_h(1)H_1 + (1-\mathcal{T}_1)F_k(1)k_1, 1 - H_1, q(q_0(m_0), M_1)\big) \\ & \cdot \big(F_k(k_1, H_1, M_1, q(q_0(m_0), M_1))(1-\mathcal{T}_1\big) \\ & - u_c\big(F_h(0)h_0 + (1-\tau_0)F_k(0)k_0, 1 - h_0, q_0(m_0)\big). \end{aligned}$$

Using the definition of $\mathcal{T}_1$ above, and a similar definition for the tax in period 0, one can rewrite this as:

$$\begin{aligned} 0 \geq & \beta u_c \begin{pmatrix} F(k_1, H_1, M_1, q(q_0(m_0), M_1)) - g_1 - \kappa M_1, \\ 1 - H_1, q(q_0(m_0), M_1) \end{pmatrix} \\ & \cdot \big(F_k(1)(1-\mathcal{T}_1\big) - u_c\big(F(0) - g_0 - \kappa m_0 - k_1, 1 - h_0, q_0(m_0)\big) \\ & \equiv \eta(k_1, h_0, m_0), \end{aligned} \tag{2.56}$$

where I have omitted the arguments of the production function.

Let $\mathcal{H}(m)$ and $\mathcal{K}(m)$ denote the decision rules implicitly defined by the solutions to the two constraints:

$$\epsilon(\mathcal{K}(m), \mathcal{H}(m), m) = 0 \tag{2.57}$$

$$\eta(\mathcal{K}(m), \mathcal{H}(m), m) = 0. \tag{2.58}$$

Similar to $\mathcal{H}$, $\mathcal{K}$ can be interpreted as the household's response function to the current fossil fuel choice. Then, the government's problem can be rewritten as

[48] If instead there were a separate tax on labor and capital income, it would follow that $\omega_{LL} = 0$, and there would be only one distortion and implementability constraint.

$$\max_{m_0} \begin{array}{l} u[F(k_0, m_0, \mathcal{H}(m_0), q_0(m_0)) - \kappa m_0 - g_0 - \mathcal{K}(m_0), \\ \quad 1 - \mathcal{H}(m_0), q_0(m_0)] \\ +\beta u\,[\,F(\mathcal{K}(m_0), M_1, H_1, q(q_0(m_0), M_1)) - \kappa M_1 - g_1, \\ \qquad\quad , 1 - H_1, q(q_0(m_0), M_1)\ ] \end{array} \tag{2.59}$$

where $M_1 = M(\mathcal{K}(m_0), s_0)$ etc. Taking derivatives with respect to m and using the envelope theorem gives the generalized Euler equation (2.21).

A.3 Derivation of the GEE in the Infinite-horizon Model

Let the equilibrium policy functions for saving, hours worked, fuel use and government expenditures be denoted by $n^k(k,T)$, $n^h(k,T)$, $\psi(k,T)$ and $\phi(k,T)$, respectively.

Define the residual functions that capture the household's optimality conditions when set to zero:

$$\begin{aligned} &\eta(k,T,g,m,k',h) = u_c[\mathcal{C}(k,k',h,g,m,T), 1-h, g, T] \\ &- \beta u_c'[\mathcal{C}\left(\begin{array}{c} k', n^k(k',T'), n^h(k',T'), \\ \psi(k',T'), \phi(k',T'), T' \end{array} \right), 1 - n^h(k',T'), \psi(k',T'), s'] \\ &\cdot \{\, 1 + [1 - T(k', n^h(k',T'), \psi(k',T'), \phi(k',T'), s')] \\ &\quad [F_k(k', n^h(k',T'), \phi(k',T'), s') - \delta]\ \}, \end{aligned} \tag{2.60}$$

and

$$\begin{aligned} \epsilon(k,T,g,m,k',h) = & \frac{u_l[\mathcal{C}(k,k',h,g,m,T), 1-h, g, T]}{u_c[\mathcal{C}(k,k',h,g,m,T), 1-h, g, T]} \\ & - F_h(k,h)[1 - T(k,h,g,m,T)]. \end{aligned} \tag{2.61}$$

That is, $\eta(k,T,g,m,k',h) = 0$ gives the household's Euler equation and $\epsilon(k,T,g,m,k',h) = 0$ the household's labor-leisure condition. Define functions $\mathcal{K}(k,T,g,m)$ and $\mathcal{H}(k,T,g,m)$ implicitly by

$$\eta(k,T,g,m,\mathcal{K}(k,T,g,m),\mathcal{H}(k,T,g,m)) = 0 \tag{2.62}$$

$$\epsilon(k,T,g,m,\mathcal{K}(k,T,g,m),\mathcal{H}(k,T,g,m)) = 0. \tag{2.63}$$

Using those functions and

$$\mathcal{C}(k,T,k',h,g,m) = F(k,h,m,T) + (1-\delta)k - g - k',$$

write the government's problem in t compactly as:

$$\max_{k',T',h,g,m} u(\mathcal{C}(k,T,k',h,g,m), 1-h, g, T) + \beta v(k',T'),$$

s.t.

$$\begin{aligned} s' &= q(T,m) \\ k' &= \mathcal{K}(k,T,g,m) \\ h &= \mathcal{H}(k,T,g,m). \end{aligned}$$

or

$$\max_{g,m} u[\mathcal{C}(k,T,\mathcal{K}(k,T,g,m),\mathcal{H}(k,T,g,m),g,m), 1-\mathcal{H}(k,T,g,m), g, s] \\ + \beta v[\mathcal{K}(k,T,g,m), q(T,m)],$$

where

$$v(k,T) = u[\mathcal{C}\begin{pmatrix} k, n^k(k,T), n^h(k,T), \\ \psi(k,T), \phi(k,T), T \end{pmatrix}, 1-n^h(k,T), \psi(k,T), T)] \\ + \beta v(n^k(k,T), q(s,\phi(k,T))).$$

Taking f.o.c. yields:

$$-u_c(\mathcal{K}_g - F_h\mathcal{H}_g + 1) - u_l\mathcal{H}_g + u_g + \beta v'_k\mathcal{K}_g = 0 \tag{2.64}$$

$$-u_c[\mathcal{K}_m - F_h\mathcal{H}_m - (F_m - \kappa)] - u_l\mathcal{H}_m + u_m + [\beta v'_k\mathcal{K}_m + v'_s q_m] = 0. \tag{2.65}$$

The derivatives of the value function $v(k, T)$ with respect to k and s read:

$$v_k = u_c[F_k + 1 - \delta - \mathcal{K}_k + F_h \mathcal{H}_k] - u_l \mathcal{H}_k + \beta v_k' \mathcal{K}_k, \tag{2.66}$$

and

$$v_s = u_c[F_s - \mathcal{K}_s + F_h \mathcal{H}_s] - u_l \mathcal{H}_s + u_s + \beta[v_k' \mathcal{K}_s + v_T' q_T]. \tag{2.67}$$

Note that, at this point, one can see why I need a second *endogenous* public good in addition to environmental quality. If government expenditures were exogenous, I would have only one first-order condition above, namely (2.65). However, in order to substitute for v_k' and v_T' in (2.66) and (2.67), I need two equations; (2.65) alone would not be sufficient. From (2.64) and (2.65):

$$\beta v_k' = \frac{1}{\mathcal{K}_g} \left[u_c(\mathcal{K}_g - F_h \mathcal{H}_g + 1) + u_l \mathcal{H}_g - u_g\right] \tag{2.68}$$

$$\begin{aligned} \beta v_T' &= \frac{1}{q_m} \left[u_c(\mathcal{K}_m - F_h \mathcal{H}_m - (F_m - \kappa)) + u_l \mathcal{H}_m\right] \\ &\quad + \frac{1}{q_m} \left[-\frac{\mathcal{K}_m}{\mathcal{K}_g} \left[u_c(\mathcal{K}_g - F_h \mathcal{H}_g + 1) + u_l \mathcal{H}_g - u_g\right]\right] \\ &= -\frac{1}{q_m} \Big[u_c(F_h \mathcal{H}_m + (F_m - \kappa)) - u_l \mathcal{H}_m \\ &\qquad + \frac{\mathcal{K}_m}{\mathcal{K}_g} \left[u_c(1 - F_h \mathcal{H}_g) + u_l \mathcal{H}_g - u_g\right]\Big] \end{aligned} \tag{2.69}$$

Inserting (2.68) in (2.66) and updating gives:

$$\begin{aligned} v_k' &= u_c'(F_k' + 1 - \delta) + \mathcal{H}_k'(u_c' F_h' - u_l') \\ &\qquad - \frac{\mathcal{K}_k'}{\mathcal{K}_g'} \left[u_g' - u_c' + \mathcal{H}_g'(u_c' F_h' - u_l')\right] \end{aligned} \tag{2.70}$$

Similarly, (2.69) in (2.67) yields:

$$\begin{aligned} v_T' =& u_T' + u_c'F_T' - \frac{q_T'}{q_m'}u_c'(F_m' - \kappa) + (u_g' - u_c')\left[-\frac{\mathcal{H}_T'}{\mathcal{H}_g'} + \frac{q_T'}{q_m'}\frac{\mathcal{H}_m'}{\mathcal{H}_g'}\right] \\ &+ (u_c'F_h' - u_l')\left[\mathcal{H}_T' - \frac{\mathcal{K}_T'}{\mathcal{K}_g'}\mathcal{H}_g' - \frac{q_T'}{q_m'}\mathcal{H}_m' + \frac{q_T'}{q_m'}\frac{\mathcal{K}_m'}{\mathcal{K}_g'}\mathcal{H}_g'\right] \end{aligned} \tag{2.71}$$

Finally, substituting (2.70) for v_k' in (2.64) gives:

$$\begin{aligned} &u_g - u_c + \mathcal{H}_g(u_cF_h - u_l) + \mathcal{K}_g[-u_c + \beta u_c'(F_k' + 1 - \delta)] \\ &+ \beta\mathcal{K}_g\left\{\mathcal{H}_k'(F_h'u_c' - u_l') - \frac{\mathcal{K}_k'}{\mathcal{K}_g'}\left[\mathcal{H}_g'(F_h'u_c' - u_l') + u_g' - u_c'\right]\right\} = 0. \end{aligned}$$

Moreover, substituting (2.71) for v_T' in (2.65) yields:

$$\begin{aligned} &u_c(F_m - \kappa) + \beta q_m\left[u_T' + u_c'F_T' - \frac{q_T'}{q_m'}u_c'(F_m' - \kappa)\right] + \mathcal{H}_m(u_cF_h - u_l) \\ &+ \mathcal{K}_m[-u_c + \beta u_c'(F_k' + 1 - \delta)] \\ &+ \beta(u_g' - u_c')\left[-\mathcal{K}_m\frac{\mathcal{K}_k'}{\mathcal{K}_g'} - q_m\frac{\mathcal{K}_T'}{\mathcal{K}_g'} + q_m\frac{q_T'}{q_m'}\frac{\mathcal{K}_m'}{\mathcal{K}_g'}\right] \\ &+ \beta\mathcal{K}_m(u_c'F_h' - u_l')\left[\mathcal{H}_k' - \frac{\mathcal{K}_k'}{\mathcal{K}_g'}\mathcal{H}_g'\right] \\ &+ \beta(u_c'F_h' - u_l')q_m\left[\mathcal{H}_T' - \frac{\mathcal{K}_T'}{\mathcal{K}_g'}\mathcal{H}_g' - \frac{q_T'}{q_m'}\mathcal{H}_m' + \frac{q_T'}{q_m'}\frac{\mathcal{K}_m'}{\mathcal{K}_g'}\mathcal{H}_g'\right] \\ &= 0 \end{aligned}$$

Using the wedges defined above, these two equations can be written as

$$\begin{aligned} \omega_{PG} + \mathcal{K}_g\omega_{CS} - \beta\mathcal{K}_g\frac{\mathcal{K}_k'}{\mathcal{K}_g'}\omega_{PG}' + \mathcal{H}_g\omega_{LL} \\ + \beta\omega_{LL}'\mathcal{K}_g\left[\mathcal{H}_k' - \frac{\mathcal{K}_k'}{\mathcal{K}_g'}\mathcal{H}_g'\right] = 0, \end{aligned} \tag{2.72}$$

and

$$\omega_{Env} + \mathcal{K}_m \omega_{CS} - \beta \omega'_{PG} \mathcal{K}_m \frac{\mathcal{K}'_k}{\mathcal{K}'_g} - \beta \omega'_{PG} \left[q_m \frac{\mathcal{K}'_T}{\mathcal{K}'_g} - q_m \frac{q'_T}{q'_m} \frac{\mathcal{K}'_m}{\mathcal{K}'_g} \right] + \mathcal{H}_m \omega_{LL} + \beta \omega'_{LL} \mathcal{K}_m \left[\mathcal{H}'_k - \frac{\mathcal{K}'_k}{\mathcal{K}'_g} \mathcal{H}'_g \right] + \beta \omega'_{LL} q_m \left[\mathcal{H}'_T - \frac{\mathcal{K}'_T}{\mathcal{K}'_g} \mathcal{H}'_g - \frac{q'_T}{q'_m} \mathcal{H}'_m + \frac{q'_s}{q'_m} \frac{\mathcal{K}'_m}{\mathcal{K}'_g} \mathcal{H}'_g \right] = 0. \tag{2.73}$$

A.4 Derivation of the Tax-Interaction Effect

In this section, I derive the explicit version of the environmental GEE, given by (2.4.1.4), from the implicit version (2.40). To keep the notation simple, start by defining $X(t)$ as the sum of the current second-best benefit and cost of pollution; that is,

$$\begin{aligned} X(t) =& \mathcal{K}_m \omega_{CS} - \beta \omega'_{PG} \mathcal{K}_m \frac{\mathcal{K}'_k}{\mathcal{K}'_g} - \beta \omega'_{PG} \left[q_m \frac{\mathcal{K}'_s}{\mathcal{K}'_g} - q_m \frac{q'_s}{q'_m} \frac{\mathcal{K}'_m}{\mathcal{K}'_g} \right] \\ &+ \mathcal{H}_m \omega_{LL} + \beta \omega'_{LL} \mathcal{K}_m \left[\mathcal{H}'_k - \frac{\mathcal{K}'_k}{\mathcal{K}'_g} \mathcal{H}'_g \right] \\ &+ \beta \omega'_{LL} q_m \left[\mathcal{H}'_s - \frac{\mathcal{K}'_s}{\mathcal{K}'_g} \mathcal{H}'_g - \frac{q'_s}{q'_m} \mathcal{H}'_m + \frac{q'_s}{q'_m} \frac{\mathcal{K}'_m}{\mathcal{K}'_g} \mathcal{H}'_g \right]. \end{aligned}$$

Then, (A.4) can be written as $\omega_{Env}(t) + X(t) = 0$. Using the definition of ω_{Env}, this implies that in period $t + 1$,

$$\begin{aligned} &u_c(t+1)(F_m(t+1) - \kappa) = -X(t+1) - \beta q_m(t+1) \cdot \\ &\left[u_s(t+2) + u_c(t+2) F_s(t+2) - \frac{q_s(t+2)}{q_m(t+2)} u_c(t+2)(F_m(t+2) - \kappa) \right]. \end{aligned}$$

Inserting this repeatedly in the GEE (A.4) and assuming that $q_m(t+1) = q_m(t+2) = ... = q_m(t)$ gives

$$\begin{aligned}\omega_{Env}(t) + X(t) = u_c(t)(F_m(t) - \kappa) \\ + q_m(t) \sum_{i=t+1}^{\infty} \beta^{i-t} \left(\prod_{j=t+2}^{i} q_s(j) \right) (u_s(i) + u_c(i)F_s(i)) \\ + \sum_{i=t+1}^{\infty} \beta^{i-t-1} \left(\prod_{j=t+2}^{i} q_s(j) \right) X(i) = 0.\end{aligned}$$

A.5 Second-best With Commitment

Once more, I assume that the government is restricted to impose a total income tax. In the commitment case, if it could instead impose separate tax rates on income from labor and capital, the seminal work by Judd (1985) and Chamley (1986) has shown that capital taxes are zero in the long run (steady state). Moreover, if per-period utility is separable in consumption and leisure, and has a constant intertemporal elasticity of substitution with respect to consumption, capital taxes are zero as of the second period.

The household takes the sequences of before-tax factor prices and taxes as given. As before, solving its problem gives rise to the usual optimality conditions:

$$u_c(t) - \beta u_c(t+1)[1 + (1 - \tau_{t+1})(r_{t+1} - \delta)] = 0 \quad (2.74)$$

$$u_l(t) - u_c(t)(1 - \tau_t)w_t = 0.. \quad (2.75)$$

The government's problem can be written as

$$\max_{c_t, k_{t+1}, T_{t+1}, h_t, g_t, m_t, \tau^k_{t+1}, \tau^h_t} \sum_{t=0}^{\infty} \beta^t u(c_t, 1 - h_t, g_t, T_t)$$

s.t.

$$c_t + g_t + k_{t+1} \leq F(k_t, h_t, m_t, T_t) + (1-\delta)k_t \tag{2.76}$$

$$g_t \leq F_m(t)m_t + \tau_t^h F_h(t)h_t + \tau_t^k (F_k(t) - \delta)k_t, \tag{2.77}$$

$$T_{t+1} \geq q(T_t, m_t) \tag{2.78}$$

as well as (2.74) and (2.75), with $w_t = F_h(t)$ and $r_t = F_k(t)$. That is, the government maximizes its objective function, lifetime utility, subject to the resource constraint, its budget constraint and the household's optimality conditions.

In the spirit of the so-called "primal approach" (Ljungqvist and Sargent, 2004), I can substitute (2.74) and (2.75) in (2.76) to eliminate taxes from the problem:

$$\begin{aligned} g_t \leq F_m(t)m_t + \left(1 - \frac{u_l(t)}{u_c(t)}\right) F_h(t)h_t \\ + \left[1 - (F_k(t)-\delta)^{-1}\left(\frac{u_c(t)}{\beta u_c(t+1)} - 1\right)\right](F_k(t)-\delta)k_t \end{aligned}$$

for $t \geq 1$. Using the resource constraint and the fact that $F_m m + F_k k + F_h h = F(k, h, m)$, this implementability constraint can be written as

$$u_c(t)c_t + u_c(t)k_{t+1} - \beta^{-1}u_c(t-1)k_t - u_l(t)h_t \geq 0. \tag{2.79}$$

Then, assigning Lagrange multipliers $\beta^t \lambda_t$ to (2.76) and $\beta^t \mu_t$ to (2.79), the first-order condition with respect to c_t reads:

$$u_c(t) - \lambda_t + \mu_t[u_{cc}(t)c_t + u_c(t)] + u_{cc}(t)k_{t+1}[\mu_t - \mu_{t+1}] = 0. \tag{2.80}$$

This applies to the case where the government has access to two separate tax rates levied on labor and capital income, respectively. In case the labor tax is restricted to be non-positive: $\tau_t^h \leq 0$, I have the additional constraint

$$u_c(t)F_h(t) \leq u_l(t). \tag{2.81}$$

On the other hand, if the government taxes labor and capital income at the same rate, the additional constraint reads:

$$F_h(t)[u_c(t-1) - \beta u_c(t)] - \beta[F_k(t) - \delta]u_l(t) = 0. \tag{2.82}$$

A.6 Algorithm

This algorithm for finite-horizon value function iteration follows Cai et al. (2012).

Initialization

- For each period $t \leq J+1$, choose m_t^k approximation nodes for the capital stock and m_t^T nodes for temperature change:

  $$X_t^k = \{x_{it}^k : 1 \leq i \leq m_t^k\},\ X_t^T = \{x_{it}^T : 1 \leq i \leq m_t^T\}.$$

  Here, I solve the first-best problem sequentially using KNITRO, and then choose Chebyshev approximation nodes from an interval around the first-best outcome for k and T, i.e. $x_{1t}^k = a_{min}^k k_t$ and $x_{mt}^k = a_{max}^k k_t$, with $a_{min}^k < 1$ and $a_{max}^k > 1$.

- Choose a functional form for approximating value and policy functions. Here, I apply Chebyshev polynomial approximation (Judd, 1998; Cai et al., 2012), using complete Chebyshev polynomials as basis functions. That is, for a function $v(k,T)$, the degree-n complete Chebyshev approximation is given by $P_n(k,T;\mathbf{b})$, where $\mathbf{b}$ is a vector of coefficients.

Step 1 - Continuation Value

1. Maximization step. For any $(x_{i,J+1}^k, x_{j,J+1}^T)$, $1 \leq i \leq m_{J+1}^k$, $1 \leq j \leq m_{J+1}^T$ solve the stationary problem in period $J+1$:

   $$\max_{\{c_t^{i,j}, h_t^{i,j}, k_{t+1}^{i,j}, g_t^{i,j}, m_t^{i,j}\}_{t=J+1}^{\infty}} \sum_{t=J+1}^{\infty} \beta^{t-J+1} u(c_t^{i,j}, 1-h_t^{i,j}, g_t^{i,j}, x_{j,J+1}^T)$$

s.t.

$$c_t^{i,j} + g_t^{i,j} + k_{t+1}^{i,j} + \kappa m_t^{i,j} = F(k_t^{i,j}, h_t^{i,j}, m_t^{i,j}, x_{j,J+1}^T) + (1-\delta)k_t^{i,j},$$

and $k_{J+1}^{i,j} = x_{i,J+1}^k$. The continuation value is given by:

$$v_{J+1}^{i,j} = \sum_{t=J+1}^{\infty} \beta^{t-J+1} u(c_t^{i,j}, 1 - h_t^{i,j}, g_t^{i,j}, x_{j,J+1}^T). \tag{2.83}$$

2. Fitting step. Approximate $v_{J+1}(k,T)$ with $P_n(k,T;\mathbf{b}_{J+1})$. That is, compute $\mathbf{b}_{J+1}$ such that $P_n(x_{i,J+1}^k, x_{j,J+1}^T; \mathbf{b}_{J+1})$ approximates $v_{J+1}^{i,j}$.

Step 2 - Backwards Induction For $t = J, J-1, ..., 0$, iterate through the following steps.

1. Maximization step. For any $(x_{i,t}^k, x_{j,t}^T)$, $1 \leq i \leq m_t^k$, $1 \leq j \leq m_t^T$, solve the maximization problem, given the approximated policy functions and the value function in $t+1$.

2. Fitting step. Choose coefficients to approximate

$$\begin{aligned}
v_t(k,T) &\approx P_n(k,T;b_t^v) \\
\psi_t(k,T) &\approx P_n(k,T;b_t^\psi) \\
\phi_t(k,T) &\approx P_n(k,T;b_t^\phi) \\
n_t^k(k,T) &\approx P_n(k,T;b_t^k) \\
n_t^h(k,T) &\approx P_n(k,T;b_t^h)
\end{aligned}$$

Chapter 3

Time-Consistent Unilateral Climate Policy*

3.1 Introduction

Climate change is the prototypical example of a global public good: the evolution of the climate and the possible damages caused by it depend on the total stock of greenhouse gases, such as carbon dioxide, in the atmosphere, but not on the location of the emission source. In the absence of a "global government", the most efficient way to internalize the social cost of emitting carbon would require some form of coordination or agreement between industrialized countries. Despite a long history of negotiations and annual climate summits, policy makers have not yet been able to agree on almost any kind of comprehensive cooperation beyond the Kyoto protocol. Instead, most initiatives to mitigate climate change up to now have been implemented unilaterally, comprising a region, a single country or even only a province or state. When climate policy is set on the national level, however, the policy maker's incentives change relative to a setting of international cooperation: not only is it likely that

*I am very grateful to John Hassler, Per Krusell, Rick van der Ploeg, and seminar participants at the MCC Workshop on Public Finance and Climate Policy in Berlin for their useful comments. All errors are my own.

her objective will be mainly on increasing domestic welfare, but she will also take into account how climate policy is affected by, and changes the effects of, other national policies.

This paper marks a first step in the direction of analyzing unilateral climate change mitigation while taking into account interactions with fiscal policy, and more specifically with income taxation, using the example of the European Union. Based on previous work in Schmitt (2014), I use a simple climate-economy with two regions, where only the EU engages in climate change mitigation, while the rest of the world does not internalize the cost of emitting carbon. In other words, I take a pessimistic view by assuming that the rest of the world not only refuses to join any cooperative regime, at least in the foreseeable future, but also does not participate in climate change mitigation at all. Instead, the regions interact with each other in a noncooperative regime.

Ideally, one would want either region to choose policies optimally, taking the behavior of the other region into account. In other words, governments should play a simultaneous game with each other: without cooperation, the optimal policy of one policy maker is affected by the behavior of the other, and vice versa. In the absence of distortionary income taxes or if policy makers are able to commit to future tax rates, it is straightforward to compute the open-loop, non-cooperative Nash equilibrium in such a setting. This is the solution concept used in the multi-region models RICE (Nordhaus and Yang, 1996; Nordhaus, 2010) and WITCH (Bosetti et al., 2006). When solving a model with distortionary taxation and lack of commitment, however, there is a second dimension along which a game occurs, in addition to the one on the international level. Within each region, a government plays a game with its successor, in the style of Klein et al. (2008) and Schmitt (2014). In other words, if commitment is not feasible, the current policy maker has to take into account the behavior of future governments when choosing its policy.[1]

[1]In such a setting, one can also find the optimal policy in period t for all future periods $t+1, t+2, \ldots$ that would be realized under commitment. However, such

Finding an equilibrium in such a setting with a long time horizon is numerically demanding. Moreover, even in a simpler framework without distortionary taxation, Nash equilibria are in general not unique. Therefore, in order to keep the analysis tractable, I abstract from strategic interaction in this paper, at least for the main quantitative exercise.[2] Instead, I assume that only the policy maker in the EU chooses climate and fiscal policies optimally. In the rest of the world, however, income taxes are given exogenously and there is no regulation of carbon emissions. This implies that the EU government takes into account the behavior of agents in the rest of the world when choosing its policies, but not vice versa. Such a model could be interpreted as the EU interacting with a continuum of open economies which (i) are small in the sense that they do not take into account how their actions affect the global aggregate, (ii) are subject to exogenous income taxation, and (iii) do not mitigate climate change. Hence, while assumption (iii) may be too pessimistic and therefore most likely overestimates the amount of cumulative emissions that the model delivers, assumption (i) biases the model in the opposite direction.

In this setting, I compute the time path of the optimal carbon tax for the EU under the assumption that capital is perfectly mobile between regions. Moreover, I assume that the EU internalizes only climate damages in its own region, while disregarding impacts in the rest of the world. I consider different scenarios regarding the tax system – i.e. whether or not lump-sum taxes are available – and whether the economy is in a cooperative or noncooperative regime. With respect to policy variables, I find that the initial carbon tax rate in the "realistic" scenario with distortionary taxation and unilateral climate policy amounts to slightly more than half the rate that would be optimal in the presence of lump-sum taxes. Moreover, in the "first best", a cooperative regime with

an outcome is in general not time-consistent: once the economy is in period $t+1$, the government has an incentive to renege on its previously announced policy and reoptimize.

[2] In section 3.2, for illustrative purposes, I compute the equilibria with strategic interaction in a two-period economy.

lump-sum taxes, the optimal tax would be greater by a factor of seven. In terms of emission levels and climate change, the realistic scenario is much closer to the first best than to the noncooperative regime with lump-sum taxes, illustrating the fact that distortionary taxation reduces economic activity and thereby dampens carbon emissions. With respect to climate-economy modeling, this underlines the importance of incorporating second-best features in the model in order to get more reliable policy recommendations.

How realistic is the assumption of no climate change mitigation in the rest of the world? Figure B.1 in the appendix gives an overview over current carbon-tax or tradable-permit systems. It illustrates that a large majority of countries, including most major polluting countries such as the US or China, do not impose a price on carbon emissions. A notable exception is the European Union which has had a system of tradable permits, the EU Emissions Trading System (ETS), since 2005. With a share in global carbon emissions of about 11 percent in 2010, this makes it the largest jurisdiction with some type of comprehensive, market-based climate policy in place. The fact that this policy has been initiated unilaterally almost a decade ago and does not seem to have facilitated cooperation with other high-emission countries motivates the question of how stringent the domestic regulation of carbon emissions should be, in particular when taking into account the incentive for other countries to free ride.

This paper is related to a number of studies that feature climate-economy models in a setting with multiple regions.[3] Due to the different solution concepts, both WITCH and RICE are much more detailed than my model, with each of them including 12 regions rather than two. Moreover, they feature multiple dimensions of interaction between regions in addition to carbon emission levels. In the WITCH model, regions are also linked through trade of an exhaustible resource and, given the en-

[3]Other papers analyze the economics of climate change in a one-region global model, for example Nordhaus (2008) and Golosov et al. (2014) in a first-best setting, or Barrage (2013), who considers distortionary income taxation under commitment.

dogeneity of technical change, through technology spillovers.

The remainder of the paper is structured as follows. In section 3.2 I present the model and discuss different equilibrium concepts for games with two regions behaving strategically. I also contrast a small with a large open economy. Section 3.3 contains the main quantitative exercise of the model, in which I compute the time-consistent unilateral policy that the European Union should adopt in a setting without participation by the rest of the world. Section 3.4 concludes.

3.2 Preliminaries

3.2.1 The Model

The model presented here is a two-region version of Schmitt (2014).[4] For the remainder of this paper, the regions will be indexed by $j = EU, ROW$. Each region is populated by a continuum of identical agents with mass υ^{EU} and υ^{ROW}, respectively. Both regions are assumed to have identical preferences and production technologies. Lifetime utility of an agent in region j is given by:

$$\sum_{t=0}^{\infty} \beta^t u(c_t^j, 1 - h_t^j, g_t^j, T_t),$$

where c_t^j denotes private consumption and g_t^j consumption of a public good, both expressed in labor-efficiency units. Moreover, $1 - h_t^j$ denotes leisure. T_t captures climate change: it represents the mean change in global surface temperature, relative to the preindustrial level. For most of the paper, I assume that climate change causes damages only to productivity, as outlined below, but not to utility. This assumption is mainly due to the lack of data: to my knowledge, little work has been done on how to formalize a utility function that includes temperature change as an argument. For the quantitative analysis, I follow Klein et al. (2008)

[4]Compare chapter 2 of this thesis for a more detailed exposition.

and assume an additively-separable functional form:

$$u(c,l,g) = (1-\alpha_g)\alpha_c \ln c + (1-\alpha_g)(1-\alpha_c)\ln l + \alpha_g \ln g. \tag{3.1}$$

I calibrate the parameters α_c and α_g such that in the equilibrium with distortionary taxation and lack of cooperation, the share of output spent on public expenditures in the EU is between 0.2 and 0.3, while the labor supply is between 0.22 and 0.25 (Klein et al., 2008; Barrage, 2013).

Output y_t^j of a single consumption good is given by

$$y_t^j = [1-d^j(T_t)]F(k_t^j, h_t^j, m_t^j) = [1-d^j(T_t)]k^\rho m^\phi h^{1-\rho-\phi} - \kappa m_t^j, \tag{3.2}$$

where F is a constant-returns-to-scale production technology, which I assume has a Cobb-Douglas form. m_t denotes the level of fossil fuel use, which in absence of a clean energy source is proportional to the amount of carbon emitted. I assume that fossil fuel is a non-exhaustible resource. κ is interpreted as the share of gross output spent on extraction. With respect to parameter values, I set $\rho = 0.35$, as is standard. I calibrate the income share of fossil fuel ϕ such that the marginal product to fossil fuel in 2010, without climate policy in place, equals the observed price. Golosov et al. (2014) report a coal price of around $105\$/tC$, together with global output of 70 trillion $US\$$. Moreover, global carbon emissions amounted to about 9 GtC (Olivier et al., 2013). Hence, I set ϕ such that

$$\frac{\phi Y_{2011}}{M_{2011}} = \phi \frac{70 \cdot 10^{12}}{9 \cdot 10^9} = 105\$/tC, \tag{3.3}$$

which gives $\phi = 0.015$. Note that this is smaller than what is typically assumed for the income share of the energy sector. However, I interpret this as the income share for fossil fuel, while capital and labor used in the energy sector are captured by k and h in the production function.

With respect to climate damages, I follow Nordhaus (2008), Golosov et al. (2014) and others in assuming that temperature change affects productivity through a damage function. In other words, d^j is an increasing and convex function that gives the share of gross output lost because of climate change. Here, this function will differ across regions. For the calibration, I use the specification from the RICE model (Nordhaus, 2010). For the EU, it reads:

$$d^{EU}(T) = \frac{0.01(\gamma_1^{EU} T + \gamma_2^{EU} T^2)}{1 + \left(0.01(\gamma_1^{EU} T + \gamma_2^{EU} T^2)\right)^{10}}, \tag{3.4}$$

with $\gamma_1^{EU} = 0$ and $\gamma_1^{EU} = 0.1591$. For the rest of the world, I use the global damage function:

$$d^{ROW}(T) = \frac{\gamma_1^{ROW} T + \gamma_2^{ROW} T^2}{1 + \gamma_1^{ROW} T + \gamma_2^{ROW} T^2}, \tag{3.5}$$

with $\gamma_1^{ROW} = 0.0018$ and $\gamma_1^{ROW} = 0.0023$.

The model features two channels through which the regions are linked with each other. First, climate change is a global externality. That is, the state of the climate, represented by temperature change, is a function of aggregate global carbon emissions. Since productivity in either region depends on T, emitting carbon in one region affects welfare in the other and vice versa. This link is present even if the two regions are otherwise closed economies. With respect to the carbon cycle, I use a model based on Matthews et al. (2009). The main idea is that there exists a direct mapping between carbon emissions and temperature change, formalized in the following way:

$$T_{t+1} = q(T_t, m_t^{EU} + m_t^{ROW}) = T_t + CCR \cdot (m_t^{EU} + m_t^{ROW}). \tag{3.6}$$

The parameter CCR denotes the "climate-carbon response", which is defined as the ratio of global mean temperature change to cumulative carbon emissions over some period of time. It is assumed to be constant and independent of the atmospheric concentration of carbon. Importantly, (3.6) implies that there is no natural decay of carbon in the atmosphere. In other words, once emitted, a unit of carbon will stay in the atmosphere forever. The assumption of a zero decay rate is different from the type of carbon cycle typically used in other climate economy models (Nordhaus, 2008; Golosov et al., 2014, e.g.). All else equal, it would imply higher marginal damage for emitting a unit of carbon and therefore a higher carbon tax rate. Using formulation (3.6) allows me to reduce the number of state variables in my model, which facilitates the analysis when using recursive models.

The second channel arises from assuming that capital is perfectly mobile between the two regions. The motivation for this assumption is twofold. First, capital mobility is empirically relevant and important in the context of climate change. In particular, it allows for "carbon leakage", i.e. carbon emissions may rise in one region as a result of emission reductions in another. Here, if productive capital moves to the rest of the world due to the carbon tax in the EU, this may increase output and hence fuel use in the rest of the world. Moreover, by allowing for capital mobility, the equilibrium outcome can feature distinct, positive tax rates on labor and capital income. In a global model, I would need to restrict the analysis to a total income tax, since for separate tax rates, the labor tax would optimally be zero (Schmitt, 2014). In the two-region model, if capital can be reallocated between regions after the tax rates have been (credibly) announced, this results in an *endogenous* upper bound on the capital income tax.[5] More specifically, I assume the same timing as in Kehoe (1989): in period $t-1$, households save for the subsequent period. At the beginning of period t, governments announce tax rates, which they are assumed to be able commit to throughout the period. Consumers then decide on how to allocate their savings across the two regions.

Assuming capital mobility requires a distinction between the capital stock of a region, i.e., the capital owned by its households, and the amount of capital used in production. Let z_t^{EU} and z_t^{ROW} denote the levels of utilized capital in EU and ROW, respectively.[6] Then, region j's capital exports in period t are given by the difference between owned

[5]Martin (2010) shows that assuming an exogenous upper bound on the capital tax results in positive labor tax rates.

[6]Output is then a function of z rather than k: $y^j = F(z^j, h^j, m^j, T)$.

and utilized capital, $x_t^j = k_t^j - z_t^j$. If $x_t^j > 0$ ($x_t^j < 0$), region j owns more (less) capital than it uses in production. The amount of capital exported in one region must equal the amount imported in the other, resulting in a clearing condition for global capital market:

$$x_t^{EU} + x_t^{ROW} = k_t^{EU} - z_t^{EU} + k_t^{ROW} - z_t^{ROW} = 0. \tag{3.7}$$

The resource constraint in j is given by:

$$c_t^j + k_{t+1}^j + g_t^j + \kappa m_t^j = F(z_t^j, h_t^j, m_t^j, T_t) + (1-\delta)k_t^j + r_t^*(k_t^j - z_t^j), \tag{3.8}$$

where r_t^* denotes the world market interest rate. Note that if j is a capital exporter (importer), the last term on the right-hand side is positive (negative); hence, there is an inflow (outflow) of resources.

Finally, I assume that carbon is emitted until an exogenously given period J, after which a backstop technology is available. The main motivation for having two phases, a non-stationary fossil-based phase and a stationary "clean" phase is that carbon should not be used forever. Since my model does not feature endogenous technical change, I have to take a stand on how whether and when the backstop kicks in and carbon emissions stop. Note that due to the modeling of the carbon cycle, temperature change will stay constant from period $J + 1$ onwards.

3.2.2 Strategic Interaction Between Regions

In this section, I discuss the two different notions of open economies. First, I look at the limiting case where both regions in the model behave as small open economies (SMOPECs): they choose their policies given the behavior of the other region, without taking into account how their actions affect this behavior. This is the setting which is commonly used in multi-region models, for example in RICE (Nordhaus and Yang, 1996). Naturally, in the case of two regions, this is an overly strong assumption. Nevertheless, it illustrates how the type of tax system and whether or not regions cooperate affect the evolution of climate change. In addition, this exercise also illustrates different ways to define an equilibrium in a setting where regions act strategically, depending on what type of taxation is used. I then discuss the generalization towards a large open economy, in which each region realizes that it can affect the state of the global economy. I show how the equilibrium definition changes compared to the SMOPEC case. Moreover, I illustrate how in such a setting, even in a scenario with lump-sum taxes, a policy maker has an incentive to tax carbon emissions below the Pigouvian level. In the quantitative analysis in section 3.3, I effectively combine a large open economy, the EU, with a continuum of small open economies, shaping the rest of the world.

3.2.2.1 Small Open Economies

Consider a world consisting of two small open economies. There are several different scenarios. Start with the case where regions do not cooperate and lump-sum taxes are feasible. Due to both the climate externality and capital mobility, a government faces a number of additional choice variables and constraints compared to a one-region economy. Let

$$\mathbf{q}^j = \{\hat{c}_t^j, \hat{k}_{t+1}^j, \hat{z}_t^j, \hat{h}_t^j, \hat{g}_t^j, \hat{m}_t^j\}_{t=0}^J \tag{3.9}$$

denote the optimal policy vector of the government in region j. It solves the sequential problem of the government in j in period $t = 0$, given that the other region implements $\mathbf{q}^{-j}$:

$$\begin{aligned}\mathbf{q}^j = \underset{\substack{c_t^j, k_{t+1}^j, z_t^j, h_t^j,\\ g_t^j, m_t^j, T_{t+1}}}{\arg\max} & \sum_{t=0}^{J} \beta^t \big(u(c_t^j, 1-h_t^j, g_t^j) + \varphi u(\hat{c}_t^{-j}, 1-\hat{h}_t^{-j}, \hat{g}_t^{-j})\big) \\ & + \beta \bar{v}^j(k_{J+1}^j, \hat{k}_{J+1}^{-j}, T_{J+1}) + \beta\varphi \bar{v}^j(k_{J+1}^j, \hat{k}_{J+1}^{-j}, T_{J+1}),\end{aligned} \tag{3.10}$$

subject to the law of motion for climate change (3.6), the resource constraint (3.8), and the return to utilized capital being equal the world rental rate r_t^*:[7]

$$r_t^* = F_z^j(t). \tag{3.11}$$

$\bar{v}^j$ denotes the terminal value function for the stationary phase after period J. Note that for generality, I have allowed for the case that the government in j puts some weight φ on the welfare of the households in the rest of the world. In the quantitative analysis below, I will focus on the extreme, but arguably relevant case that $\varphi = 0$, implying that the EU government only cares about the welfare of the domestic household, but not about the agents in the other region. In contrast, if $\varphi = 1$, there are equal weights on both regions, and hence the domestic government is benevolent in the sense that it maximizes global welfare. Naturally, the extent to which a country mitigates carbon emissions depends crucially on φ.[8]

An open-loop Nash equilibrium is obtained if (3.10) holds for both regions, the return to capital – the price of the mobile factor – is equalized across regions ($r_t^* = F_z^{EU}(t) = F_z^{ROW}(t)$), and the world market for capital is cleared, i.e., (3.7) is satisfied.[9]

If lump-sum taxation is not feasible and a government has to resort to distortionary taxes on labor and capital income, it is possible to solve the model sequentially if both governments have access to a commitment device that allows them to credibly announce their optimal policy $\mathbf{q}^{Com}$ in period 0. In this paper, I focus on scenarios where such a commitment device does not exist. Then, due to the well-known problem of capital taxation, the allocation that is optimal under commitment is not time-consistent (Chamley, 1986; Chari and Kehoe, 1999; Klein et al., 2008). In other words, if a government were to announce $\mathbf{q}^{Com}$ in period 0 for

[7] Without capital mobility, this condition is replaced with the constraint that utilized capital must always equal the domestic capital stock: $z_t^j = k_j^t$.

[8] In a policy report, a US government interagency working group argued that a proper estimate of the social cost of carbon should include all damages, domestic and foreign (IWG, 2010), arguing that climate policy should be done by international agreements. However, in the absence of such cooperation, the question of which value for φ is more relevant is ambiguous, and eventually comes down to moral judgement.

[9] I solve for the Nash equilibrium using a simple iteration algorithm Nordhaus and Yang (cp 1996).

all $t > 0$, it would have an incentive to reoptimize when entering period t.

Let $\tau_t^{k,j}$ and $\tau_t^{h,j}$ denote the tax rates on capital and labor income, respectively, in region j. Households in j then face the following budget constraint:

$$c_t^j + k_{t+1}^j \leq [1 + (1 - \tau_t^{k,j})(r_t^* - \delta)]k_t^j + (1 - \tau_t^{h,j})w_t^j h_t^j, \tag{3.12}$$

where w_t^j denotes the wage rate. The government's budget constraint reads:

$$g_t \leq \tau_t^{k,j}(r_t^* - \delta)z_t^j + \tau_t^{h,j} w_t^j h_t^j + \theta_t^j m_t^j, \tag{3.13}$$

with θ_t^j denoting the carbon tax. In equilibrium, having profit-maximizing firms on the production side implies that $w_t^j = F_h^j(t)$ and $\theta_t^j = F_m^j(t) - \kappa$.

A non-stationary Markov-perfect equilibrium consists of the following set of functions:

$$\left\{ \{V_t^j, \mathcal{K}_t^j, \mathcal{C}_t^j, \mathcal{Z}_t^j, \mathcal{H}_t^j, \mathcal{G}_t^j, \mathcal{M}_t^j, \mathcal{T}_t^{k,j}, \mathcal{T}_t^{h,j}\}_{t=0}^J \right\}_{j \in \{EU, ROW\}},$$

That is, an equilibrium is composed of value and policy functions for savings ($\mathcal{K}$), private consumption ($\mathcal{C}$), capital input ($\mathcal{Z}$), hours ($\mathcal{H}$), public consumption ($\mathcal{G}$), emissions ($\mathcal{M}$) and taxes on capital ($\mathcal{T}^k$) and labor income ($\mathcal{T}^h$), such that for all k_t^{EU}, k_t^{ROW} and T_t, the policy functions $\mathcal{C}_t^j = \mathcal{C}_t^j(k_t^{EU}, k_t^{ROW}, T_t)$, $\mathcal{Z}_t^j = \mathcal{Z}_t^j(k_t^{EU}, k_t^{ROW}, T_t)$ etc. solve

$$\begin{aligned} \max_{\substack{k_{t+1}^j, c_t^j, z_t^j, h_t^j, m_t^j, \\ g_t^j, \tau_t^{k,j}, \tau_t^{h,j}, T_{t+1}}} \quad & u(c_t^j, 1 - h_t^j, g_t^j) \\ & + \beta V_t \left(k_{t+1}^j, \mathcal{K}_t^{-j}(k_t^{EU}, k_t^{ROW}, T_t), T_{t+1} \right), \end{aligned} \tag{3.14}$$

subject to the law of motion for temperature change:

$$T_{t+1} = q(T_t, m_t^j + \mathcal{M}_t^{-j}), \tag{3.15}$$

the resource constraint in j:

$$F(z_t^j, h_t^j, m_t^j, T_t) + (1-\delta)k_t^j - c_t^j - g_t^j - \kappa m_t^j - k_{t+1}^j + r_t^*(k_t^j - z_t^j) = 0 \quad (3.16)$$

the household's intratemporal optimality condition,

$$\frac{u_l(c_t^j, 1-h_t^j, g_t^j, T_t)}{u_c(c_t^j, 1-h_t^j, g_t^j, T_t)} - F_h^j(z_t^j, h_t^j, m_t^j, T_t)[1-\tau_t^h] = 0, \quad (3.17)$$

and the household's Euler equation:

$$u_c(c_t^j, 1-h_t^j, g_t^j, T_t) - \beta(1+r_t^*)u_c\left(\mathcal{C}_{t+1}^j, 1-\mathcal{H}_{t+1}^j, \mathcal{G}_{t+1}^j, T_{t+1}\right) \quad (3.18)$$

for all periods t and $j \in \{EU, ROW\}$. Moreover, in each period t, the continuation value for all k_t^{EU}, k_t^{ROW} and T_t is given by

$$\begin{aligned} V_t^j\left(k_t^{EU}, k_t^{ROW}, T_t\right) &= u_c\left(\mathcal{C}_t^j, 1-\mathcal{H}_t^j, \mathcal{G}_t^j, T_t\right) \\ &\quad + \beta V_{t+1}^j\left(\mathcal{K}_t^{EU}, \mathcal{K}_t^{ROW}, q(T_t, \mathcal{M}_t^j + \mathcal{M}_t^{-j})\right), \end{aligned} \quad (3.19)$$

the world capital market clears

$$k_t^j - z_t^j + k_t^{-j} - \mathcal{Z}_t^{-j} = 0, \quad (3.20)$$

and the after-tax returns to utilized capital in both region are equalized:

$$\begin{aligned} &\left(1-\tau_t^{k,j}\right)\left[F_z\begin{pmatrix} z_t^j, h_t^j, \\ m_t^j, T_t \end{pmatrix} - \delta\right] \\ &\quad - \left(1-\mathcal{T}_t^{k,-j}\right)\left[F_z\begin{pmatrix} \mathcal{Z}_t^{-j}, \mathcal{H}_t^{-j}, \\ \mathcal{M}_t^{-j}, T_t \end{pmatrix} - \delta\right] = 0, \end{aligned} \quad (3.21)$$

Note that the constraints contain both the *future* decision rules for region j, as well the *current* decision rules for the other region. This illustrates the fact that the policy maker in j must take into account the behavior both by its successor and by the government in the other region. The former dependence is caused by the lack of commitment and/or the infeasibility of lump-sum taxes. The latter depends on capital mobility and the fact that climate change is a global externality. Note that without capital mobility, the constraints (3.20) and (3.21) are replaced by $k_t^j - z_t^j = 0$. This eliminates all decision rules for the other region from the problem apart from the one for $\mathcal{M}^{-j}$ in the law of motion for temperature change.

Below, I solve for the different equilibrium concepts outlined here in a setting with two periods, i.e. for $J = 1$. This is obviously a restrictive case, and does not have any quantitative meaning for climate change, with damages occurring over a long period of time in the future. However, this exercise serves as an illustration of how the relevant outcomes, in particular cumulative emissions, change when going from the social optimum with cooperation and lump-sum taxes to the second-best scenarios. Moreover, while finding the cooperative equilibria in this setting is not an issue even for large J, one problem with the non-cooperative regimes is that the Nash equilibria may not be unique. For the sequential problems with lump-sum taxes or commitment, one can easily check for multiple equilibria by varying initial conditions (Nordhaus and Yang, 1996; Bosetti et al., 2006). While this is also possible in the recursive formulation, the higher computational complexity makes such a procedure very time-intensive. In contrast, for a small number of periods, the running time is negligible.

Following the approach laid out in Schmitt (2014), I solve for the Markov-perfect equilibrium using finite-horizon dynamic programming. That is, in every period t I compute the Nash equilibrium for the subgame that starts in t, using the decision rules and the value functions found by solving the subgame in $t + 1$. By definition, the resulting decision rules constitute a Markov-perfect equilibrium since they constitute a Nash equilibrium for each possible subgame. Regarding the computation of the Nash equilibrium in t, I start with an initial guess for the policy vector for *ROW* along a grid, compute the optimal response for *EU* and then use this to compute the optimal response for *ROW*. I iterate until both policy vectors converge.

Finally, for comparison, I also compute the corresponding cooperative equilibria for both the setting with lump-sum and with distortionary taxation. Following, for example, Kehoe (1989), under policy cooperation a single policy maker maximizes global welfare, that is, the sum of welfare over regions. With lump-sum taxes, this is a simple example of a social planner economy. I will refer to this as the first-best scenario. Under distortionary taxation and lack of commitment, solving for the Markov equilibrium is conceptually equivalent to the algorithm outlined in in Schmitt (2014), but with twice the amount of variables and constraints[10]

Note that in this exercise, I assume that climate change has a direct impact on the utility function, rather than an effect on productivity. I add a quadratic damage term, $-\alpha_T T_t^2$, to the utility function as specified in (3.1). Having utility damages facilitates the modeling of unilateral climate policy: a region does not mitigate climate change when $\alpha_T = 0$.

Figures 3.1 and 3.2 show the results of this exercise. They plot the deviation of the cumulative emission level from the first-best equilibrium with cooperation and lump-sum taxation ("Coop/LS") against the damage parameter α_T. The range of α_T goes from 0 – no climate policy – to a value that implies a reduction of cumulative emissions in "Coop/LS" of 30% relative to the business-as-usual scenario. Consider first a setting with two identical regions, and in particular with the same preferences regarding climate change. If $\alpha_T = 0$, there is no disutility from climate change, and thus no incentive to reduce emissions. Under lack of cooperation and lump-sum taxation ("NoCoop/LS"), the emission level is then the same as in first best. In the scenarios with distortionary taxes, "Coop/DT" and "NoCoop/DT", emissions are lower. This is due to what is referred to as the "distortion-level effect" in Schmitt (2014): proportional income taxes reduce the output level and hence decrease the demand for fossil fuel, resulting in less emissions. Note that this effect is stronger in the scenario with cooperation, as it features higher income taxes and hence a greater level of distortion. Without coopera-

[10]It is straightforward to show that if the two regions are identical, the aggregate outcome in this setting is the same as in a one-region model.

tion, tax rates on capital income are constrained by the tax level in the other region, due to capital mobility. Hence, in equilibrium, both regions feature lower tax rates than under cooperation. This result was shown prominently in Kehoe (1989).

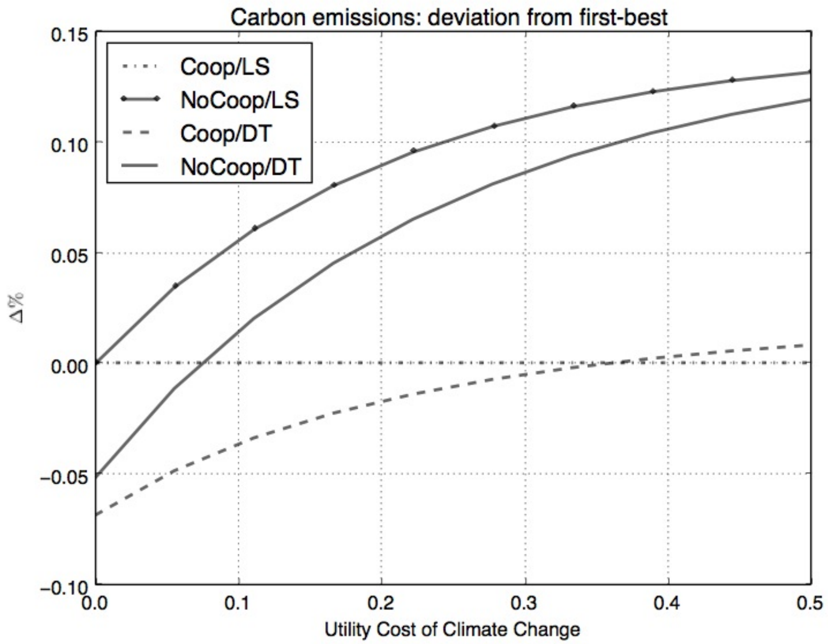

Figure 3.1: Two-period Model - Emissions

As α_T rises, emissions in all three second-best scenarios increase relative to the social optimum. In "Coop/LS", either policy maker does not internalize damages caused by climate change in the other region, and therefore considers a higher emission level optimal. In other words, each region has an incentive to free ride on climate change mitigation in the other region. In "Coop/DT", the relative increase in emissions reflects a "tax-interaction effect", as analyzed in Schmitt (2014): in the presence of distortionary income taxes, emissions are in general not taxed at the Pigouvian rate. Instead, the higher the cost of climate change, the more the optimal tax falls relative to the Pigouvian level. The exercise here confirms the result that the tax-interaction effect is more prevalent for more severe climate damages. Finally, "NoCoop/DT" combines the effects present in the previous scenarios. Intuitively, for zero or low damages, the distortion-level effect dominates and emissions are less than in the social optimum. As α_T increases, the incentive to free ride becomes stronger, as does the tax-interaction effect. For sufficiently high damages, the emission level exceeds the first best, while approaching the case with lump-sum taxes.

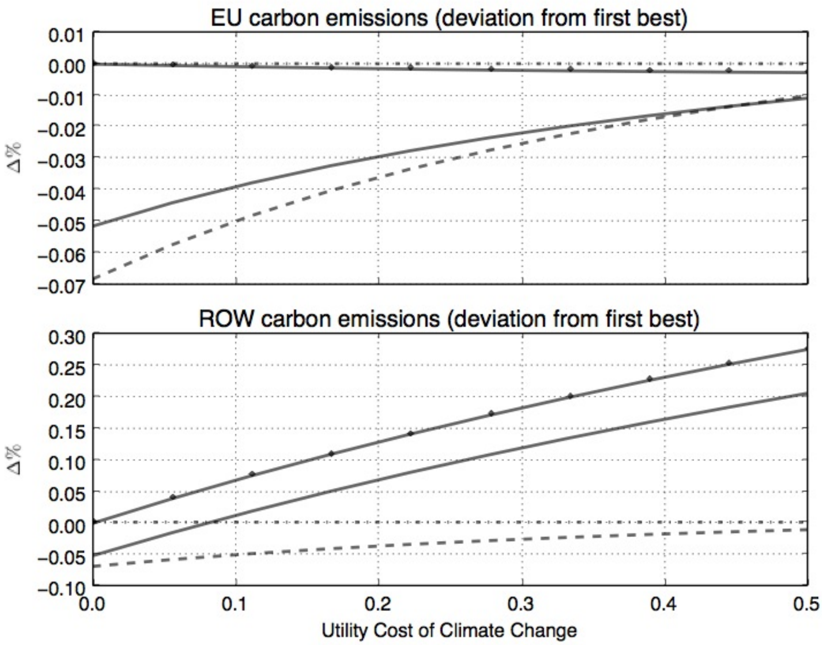

Figure 3.2: Two-period Model - Unilateral Setting

Figure 3.2 displays the corresponding graph for a setting with unilateral policy: only one of the regions, the EU, suffers a disutility from climate change, while the other one is not affected ($\alpha_T = 0$). For the scenarios with cooperation, the outcome is very close to the previous setting in both regions, with slightly higher emission levels, since the overall cost of climate change is smaller. In the noncooperative regimes, intuitively, emissions in the rest of the world relative to the first best grow faster than before. More interestingly, the relative emission level in the EU under "NoCoop/LS" decreases, although weakly, in α_T. This can be interpreted as the EU offsetting some of the emission increases in the rest of the world by implementing larger emission cuts. For the same reason, while relative emissions still increase in the cost of climate change in the "NoCoop/DT" scenario, they do so considerably slower than in the setting with two-sided climate policy.

To summarize, this exercise has shown that how the second-best level of cumulative emissions, and thus the extent of climate change, relates to the first-best outcome depends crucially on which distortions are present. This result will also be reflected in the quantitative analysis in section 3.3. It will build on the scenario with unilateral policy considered here, while assuming that the EU is a large open economy.

3.2.2.2 Large Open Economy

In the equilibrium definitions in the previous section I have assumed that either policy maker takes the outcome in the other region as given when choosing her policies. For a large region such as the European Union, this is a strong assumption. I now discuss briefly how the equilibrium in a large open economy is characterized, and show that in contrast to a SMOPEC, even a setting with lump-sum taxation gives rise to a tax-interaction effect, i.e. the fee on carbon emissions does not equal a Pigouvian tax.[11]

Conceptually, the main difference between this and the previous setting is that the policy maker in region j takes into account how her actions affect the behavior of households in the other region. For example, all else equal, increasing fuel use in j increases the domestic marginal product to utilized capital, which leads to a temporary differential between the domestic and the foreign interest rate. This will induce foreign households to reallocate savings to j, up to the point where return rates

[11] The discussion here is related to Gross (2014) who analyzes optimal income taxation under commitment in large open economies.

are equalized. In a SMOPEC, this additional effect of increasing fossil fuel use would not be accounted for, since the world market interest rate is viewed as being independent from the actions in j. In other words, in a large open economy, a policy maker still takes as given the actions by the policy maker in the other regions, but not the behavior of foreign households. Formally, this extends its set of controls by the variables chosen by the foreign households, while at the same time adds their optimality conditions as constraints (Gross, 2014). For reasons that will become apparent later on, let $\sigma_t^{h,j}$ denote a subsidy on labor income in region j, which is financed by a lump-sum tax. The optimal policy vector in region j is then given by:

$$\mathbf{q}^j = \{\hat{c}_t^j, \hat{c}_t^{-j}, \hat{k}_{t+1}^j, \hat{k}_{t+1}^{-j}, \hat{z}_t^j, \hat{z}_t^{-j}, \hat{h}_t^j, \hat{h}_t^{-j}, \hat{g}_t^j, \hat{m}_t^j\}_{t=0}^J. \tag{3.22}$$

Note that this set does not contain fuel use and government expenditures in the other region, since they are chosen by the foreign policy maker. Given $\hat{m}^{-j}$, $\hat{g}^{-j}$ and $\sigma_t^{h,-j}$, $\mathbf{q}^j$ solves the following sequential problem:

$$\begin{aligned}\mathbf{q}^j = \underset{\substack{c_t^j, c_t^{-j}, k_{t+1}^j, k_{t+1}^{-j}, z_t^j, z_t^{-j},\\ h_t^j, h_t^{-j}, g_t^j, m_t^j, T_{t+1}}}{\arg\max} & \sum_{t=0}^J \beta^t u(c_t^j, 1-h_t^j, g_t^j, T_t) \\ & + \beta \bar{v}(k_{J+1}^j, \hat{k}_{J+1}^{-j}, T_{J+1}),\end{aligned} \tag{3.23}$$

subject to (3.6), the domestic and the foreign resource constraints:

$$c_t^j + k_{t+1}^j + g_t^j + \kappa m_t^j = F(z_t^j, h_t^j, m_t^j, T_t) + (1-\delta)k_t^j + F_k^j(t)(k_t^j - z_t^j), \tag{3.24}$$

$$\begin{aligned}c_t^{-j} + k_{t+1}^{-j} + \hat{g}_t^{-j} + \kappa \hat{m}_t^{-j} = {} & F(z_t^{-j}, h_t^{-j}, \hat{m}_t^{-j}, T_t) \\ & + (1-\delta)k_t^{-j} + F_k^{-j}(t)(k_t^{-j} - z_t^{-j}),\end{aligned} \tag{3.25}$$

the first-order conditions of the foreign households:

$$u_l^{-j}(t) - (1 + \sigma_t^{h,-j}) F_h^{-j}(t) u_c^{-j}(t) = 0, \tag{3.26}$$

$$u_c^{-j}(t) - \beta u_c^{-j}(t+1)(1 + F_k^{-j}(t+1) - \delta) = 0, \tag{3.27}$$

as well as conditions representing the world market clearing for capital and the factor price equalization:

$$k_t^j - z_t^j + k_t^{-j} - z_t^{-j} = 0, \tag{3.28}$$

$$F_z^j(t) - F_z^{-j}(t) = 0. \tag{3.29}$$

Again, an open-loop Nash equilibrium is characterized by (3.23) being satisfied for both regions.

In this setting, one can show that carbon emissions are not taxed at the Pigouvian level. For exposition, assume that damages from climate change occur to utility and only for one period after the emission of carbon.[12] Let λ_t^j, ξ^t and μ^t denote the Lagrange multipliers associated with constraints (3.24), (3.28) and (3.29), respectively. Assuming an interior solution, consider the first-order conditions of the policy maker's problem with respect to $k_{u,t}^j$ and m_t^j:

$$\lambda_t^j F_{kk}^j(t)(k_t^j - k_{u,t}^j) - \xi_t + \mu_t F_{kk}^j(t) = 0. \tag{3.30}$$

$$\beta u_T^j(t+1) + \lambda_t^j(F_m^j(t) - \kappa + F_{km}^j(t)(k_t^j - k_{u,t}^j)) + \mu_t F_{km}^j(t) = 0. \tag{3.31}$$

By definition, emissions are at the Pigouvian level when the marginal benefit of emitting is equal to the marginal damage. Here, this translates to the following condition:

$$\beta u_T^j(t+1) + u_c^j(t)(F_m^j(t) - \kappa) = 0. \tag{3.32}$$

Suppose a first-best equilibrium is obtained, characterized by the usual set of first-order conditions, including (3.32). Then, λ_t^j equals the marginal utility of consumption, $\lambda_t^j = u_c^j(t)$. From (3.31), since $F_{km}^j > 0$, it is straightforward to see that (3.32) holds only if

$$u_c^j(t)(k_t^j - k_{u,t}^j) + \mu_t = 0. \tag{3.33}$$

[12] The argument generalizes to less restrictive assumptions.

By (3.30), however, this cannot be satisfied as long as $\xi_t > 0$, i.e. as long as the constraint imposed by world capital market clearing binds. Hence, emissions are not at the Pigouvian level, and the economy does not yield a first-best equilibrium. To understand the intuition, assume that the economy is initially at a point without capital exports, i.e. $k_t^j - k_{u,t} = 0$. (3.31) then reads:

$$\beta u_T^j(t+1) + u_c^j(t)(F_m^j(t) - \kappa) + \mu_t F_{km}^j(t) = 0.$$

With $\mu_t > 0$, the sum of the first two terms must be negative, implying that the marginal damage of emitting carbon exceeds the marginal benefit, which equals the carbon tax. In other words, the policy maker has an incentive to use more fossil fuel than dictated by the Pigouvian principle, in order to increase the domestic interest rate and thus attract capital. (3.31) also indicates that in the more general case when the region is a capital exporter, this effect is reinforced. In contrast, in the case of a capital importer, the sign of $u_c^j(t)(k_t^j - k_{u,t}^j) + \mu_t$ is ambiguous. Intuitively, when importing capital, any policy that increases the rate of return increases the factor payments to foreign capital holders. In the opposite case, a higher interest rate at home raises the foreign rate of return, thus benefitting the domestic households that hold capital abroad. An equivalent effect can be found for labor: increasing hours worked, for example by paying a subsidy, increases the net inflow of capital. For this reason, I have allowed for subsidies on labor and as part of the policy vector above. Note also that this result is reminiscent of the tax-interaction effect under distortionary income taxation as discussed in Schmitt (2014). However, in the present setting, distortionary taxes are not needed for such an effect to arise.

Unfortunately, solving the model presented in this section numerically has proven difficult, even in the case with two periods. A simple iterative algorithm where each region solves its problem while taking the policy variables in the other region as given does not yield convergence. I leave the task of finding a more suitable algorithm to future research.

Instead, in the next section I perform a quantitative analysis of climate policy in the EU in a framework which has the spirit of the model presented in this section, but with one essential simplification, namely the abstraction from strategic interaction.

3.3 Quantitative Analysis

In this section, to facilitate the numerical analysis, I abstract from strategic interaction between regions. More specifically, I assume that fiscal and climate policy are set endogenously only in the EU, while the rest of the world does not participate in climate change mitigation.

3.3.1 The Government's Problem

Assuming exogenous policy in *ROW* implies that there is no explicit government and the economy is in a competitive equilibrium, with the households taking the behavior by the policymaker and the households in the EU as given. The equilibrium can be characterized by the following set of equations:

$$\begin{aligned}\beta u_c^{ROW}(t+1)[1-(1-\tau_t^{k,ROW})(F_z^{ROW}(t+1)-\delta)]\\ -u_c^{ROW}(t)=0,\end{aligned} \tag{3.34}$$

$$u_l^{ROW}(t)-u_c^{ROW}(t)(1-\tau_t^{h,ROW})F_h^{ROW}(t)=0, \tag{3.35}$$

$$F_m^{ROW}(t)-\kappa=0, \tag{3.36}$$

and

$$\begin{aligned}c_t^{ROW}+k_{t+1}^{ROW}+g_t^{ROW}+\kappa m_t^{ROW}=F(z_t^{ROW},h_t^{ROW},m_t^{ROW},T_t)\\ +(1-\delta)k_t^{ROW}+r_t^*(k_t^{ROW}-z_t^{ROW}),\end{aligned} \tag{3.37}$$

representing the foreign household's Euler equation, its labor-leisure optimality condition, the foreign firm's first-order condition for fuel use and the resource constraint, with public expenditures g_t^{ROW} being equal to tax revenues. Since there is no climate policy, (3.37) states that the price of fossil fuels must equal the private extraction cost.

As before, I solve for the Markov-perfect equilibrium in the setting with unilateral policy and distortionary income taxes using backward induction. The main conceptual difference to the previous section is that there is no strategic interaction, and hence I do not need to compute a Nash equilibrium. Instead, the policy maker in the EU also "chooses" policies in ROW, but has to satisfy the conditions (3.34) - (3.37) that ensure a competitive equilibrium. Formally, the Markov-perfect equilibrium consists of a set of value and policy functions,

$$\{V_t^j, \mathcal{K}_t^{EU}, \mathcal{C}_t^{EU}, \mathcal{Z}_t^{EU}, \mathcal{H}_t^{EU}, \mathcal{G}_t^{EU}, \mathcal{M}_t^{EU}, \mathcal{T}_t^{k,EU}, \mathcal{T}_t^{h,EU}, \\ \mathcal{K}_t^{ROW}, \mathcal{C}_t^{ROW}, \mathcal{Z}_t^{ROW}, \mathcal{H}_t^{ROW}, \mathcal{M}_t^{ROW}, \}_{t=0}^J,$$

such that for all possible states and periods, the policy functions solve

$$\max_{\substack{c_t^{EU}, k_{t+1}^{EU}, z_t^{EU}, h_t^{EU}, g_t^{EU}, m_t^{EU}, \\ \tau_t^{k,EU} c_J^{ROW}, k_{t+1}^{ROW}, z_t^{ROW}, h_t^{ROW}, m_t^{ROW}, T_{t+1}}} u(c_t^{EU}, 1 - h_t^{EU}, g_t^{EU}, T_t) \\ + \beta V_t^{EU}(k_{t+1}^{EU}, k_{t+1}^{ROW}, T_{t+1}),$$

subject to the same constraints as above, plus the equilibrium conditions in ROW.[13] In contrast, if lump-sum taxation is feasible, the problem can again be solved sequentially:

$$\max_{\substack{c_t^{EU}, k_{t+1}^{EU}, z_t^{EU}, h_t^{EU}, g_t^{EU}, m_t^{EU}, \\ c_t^{ROW}, k_{t+1}^{ROW}, z_t^{ROW}, h_t^{ROW}, m_t^{ROW}, T_{t+1}}} \sum_{t=0}^{J} \beta^t \big(u(c_t^{EU}, 1 - h_t^{EU}, g_t^{EU}, T_t) \\ + \beta \bar{v}(k_{J+1}^{EU}, k_{J+1}^{ROW}, T_{J+1}),$$

subject to the same constraints as before, as well as (3.34) - (3.37).

When calibrating the model, I use the year 2010 as the first model period and assume that the economy enters this year in a Markov-perfect

[13]The full problem is listed in the appendix.

equilibrium without climate damages and mitigation policies in place. One model period equals two years. Since I abstract from optimal taxation in the rest of the world, I also have to take a stand on the size of the exogenous income tax rate there. Carey and Rabesona (2002) report average effective tax rates on labor income of 20 – 25% for the US and Japan between 1980 and 2000. Effective capital tax rates are higher, in the range of 35 – 45% for the US and up to 50% for Japan. To account for smaller tax rates in emerging economies, I set both tax rates to 20% in the baseline model. Running robustness checks using higher tax rates on capital in the rest of the world has only small effects on the results presented below.

3.3.2 Results

Figure 3.3 shows the annual global emission levels between 2010 and 2200 for the first best scenarios and the two noncooperative scenarios. Several features are noteworthy. First, with neither cooperation nor distortionary taxes, carbon emissions are considerably higher than in the other scenarios, initially rising from around 12 GtC in 2010, and then decreasing over time after a transitional period.[14] Second, with cooperation, global emissions start at a lower level of about 7.3 GtC, with a steep decline thereafter. This is not surprising since in the first-best setting, the rest of the world takes into account the climate damage caused by their emissions. In other words, the "no-climate-policy" constraint (3.36) does not apply in the cooperative regime.

Finally, the scenario with distortionary income taxes and no cooperation has an initial emission level of 8.7 GtC in the beginning and a much slower decline over time. Figure 3.4 shows how this affects climate change: by 2200, mean global temperature relative to the preindustrial level is at $3°C$ in the first-best setting, and at around $3.6°C$ in the "NoCoop/DT"

[14]The initial rise in emissions can be explained by the fact that the economy is initiated in a second-best state, with capital taxes and thus a capital stock which is too low from a first-best perspective. Hence, the economy experiences a period of fast capital accumulation during the first few periods, which increases output and thus emissions.

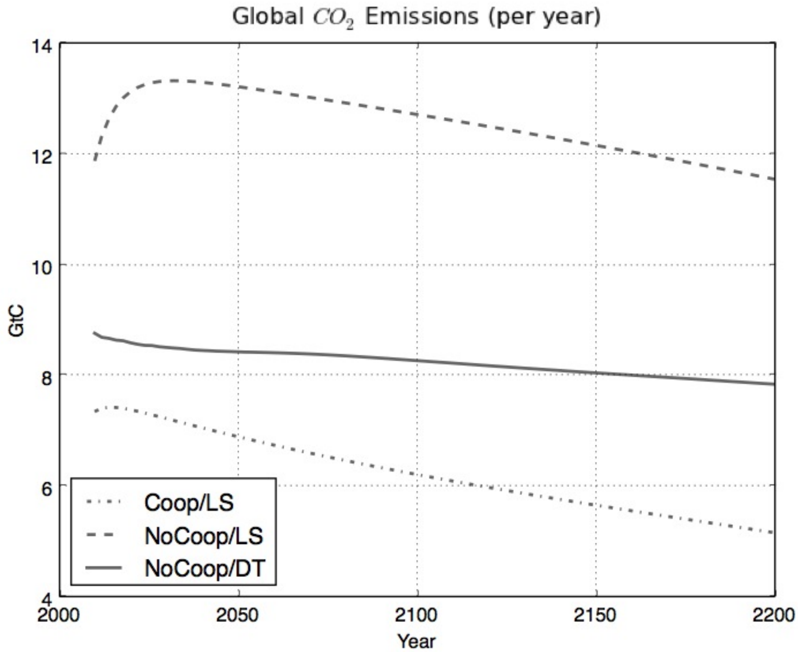

Figure 3.3: Baseline Model - Emissions

scenario. With lump-sum taxes instead of distortionary taxation, the temperature increase is considerably higher, at $5°C$.

Intuitively, the lower emission level is caused by the presence of taxes on labor and capital income that introduce distortions in the economy which disrupts economic activity and hence lowers the demand for fossil fuel in production. I find rates of close to 30 percent for the capital tax throughout the time period considered here, while the labor tax increases from 34 to 37 percent over time.[15] Figure 3.5 illustrates how the emission levels translate into carbon taxes. Unsurprisingly, the global carbon tax rate under cooperation is much higher than in the noncooperative regimes, starting at 82.40$/tC$ in 2010 and reaching 750$/tC$ at the end

[15]The labor tax rate is close to the estimates for the average effective tax rate reported by Carey and Rabesona (2002) for the EU-15 up to 2000. In contrast, the capital tax rate given by the model is about 10 percent lower than the corresponding estimates.

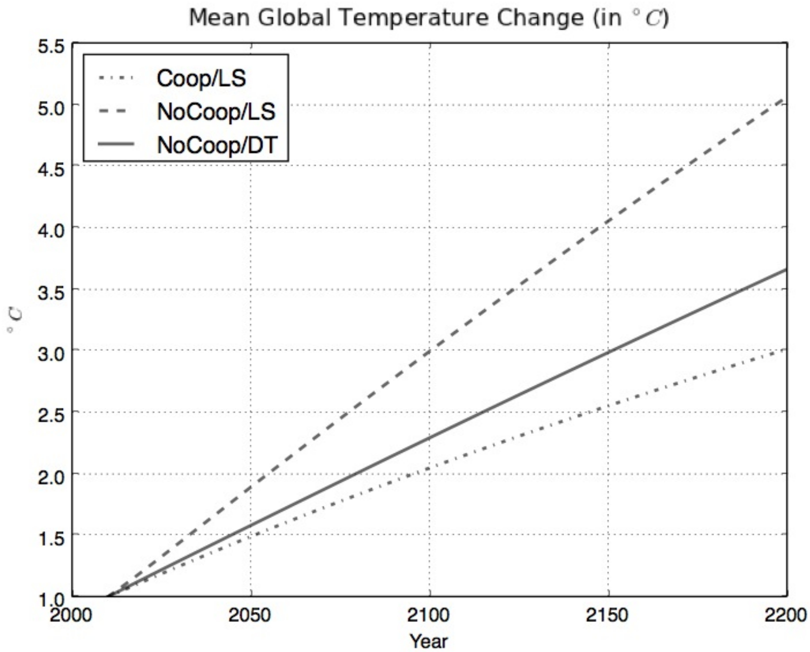

Figure 3.4: Baseline Model - Temperature Change

of the century. This is close to the result in an equivalent one-region global model with a social planner in Schmitt (2014), with a small deviation due to differences in calibration. It is also comparable to estimates found by other studies, ranging from 57\$/tC (Golosov et al., 2014) to 120$\$/tC$ (IWG, 2013), when using integrated assessment models with a nonzero rate of decay of carbon in the atmosphere. Notably, for the RICE model, Nordhaus (2010) reports a surprisingly low carbon tax of 29$\$/tC$ (in 2005 prices) for an optimal setting with full participation. This leads to a faster temperature increase than in my model, with temperature change reaching a peak of $3°C$ in around 2130 and slowly decreasing afterwards.[16]

[16] In a scenario with limited participation, including rich countries such the US, Japan and Russia in addition to the European Union, Nordhaus (2010) finds a temperature increase of $4.5°C$ by 2200, about half a degree lower than a in model with only the EU adopting climate policy.

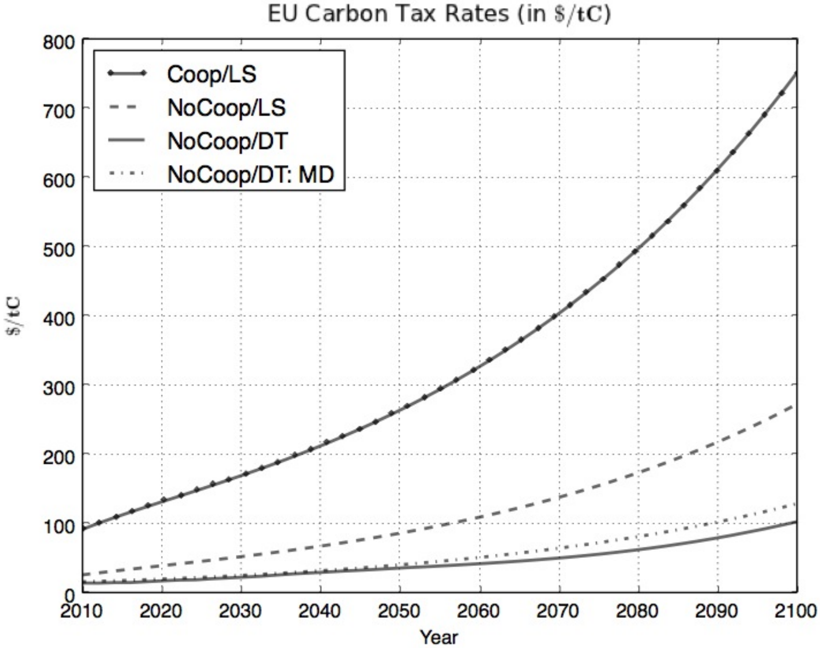

Figure 3.5: Baseline Model - Carbon Taxes

Without cooperation, carbon taxes fall considerably. In the setting with lump-sum taxation, the carbon tax rate starts at $23.40\$/tC$ in 2010 and increases to $272\$/tC$ in 2100, reflecting the fact that the EU internalizes only climate damages to their own economy, but not to the rest of the world. Introducing distortionary income taxes causes an additional fall, leading to carbon tax rates of $13\$/tC$ in 2010 and $103\$/tC$ in 2100, respectively. Hence, there is a slower increase in the carbon tax rate over time compared to the other scenarios, mirroring the slower fall in carbon emissions. For comparison, the price for emission allowances in the ETS was in the range of $15-20EUR/tCO_2$, which corresponds to about $85-110\$/tC$.[17] Hence, real-world prices appear to be closer to the first best than to the second-best scenarios in the model.

[17]Prices have fallen considerably since then to below $3EUR/tCO_2$, before reaching levels of around $7EUR/tCO_2$ in 2014.

Figure 3.6 identifies the distortion-level effect as the main driver of this result: relative to a setting with lump-sum taxation, initial GDP falls considerably and then grows more slowly.[18] Since the cost of climate change is measured as a fraction of output, this reduces the marginal damage level and thus the size of the carbon tax. This effect is reinforced by a tax-interaction effect, as figure 3.5 illustrates by plotting the level of marginal damage for the "NoCoop/DT" scenario: the optimal carbon tax does not equal the Pigouvian rate. Instead, I find that it is initially around 10% below the Pigouvian level; between 2010 and 2100, the average gap amounts to 17%. This deviation is slightly higher than the size of the tax-interaction effect found for a comparable calibration in Schmitt (2014). Note that compared to the one-region model where the economy's capital input was equal to its capital stock, the elastic supply of capital in this model creates an additional channel for the tax-interaction effect: increasing fuel use has a positive effect on the domestic return to capital, which attracts more capital used for domestic production. As shown above, this may introduce a wedge between the optimal carbon tax and the Pigouvian rate even in the setting with lump-sum taxes. With distortionary taxation, attracting more capital also widens the tax base, thereby increasing the incentive for the government to lower the carbon tax. More generally, emitting more carbon creates an additional second-best benefit, which is very similar to the static labor effect discussed Schmitt (2014).

The results presented so far implicate some lessons for climate-economy modeling. Most notably, distortionary tax systems have a negative effect on carbon emissions and thus dampen climate change, even in the absence of specific climate policies. In some sense, at least with respect to emissions, "two wrongs make a right": the setting with one distortion, lack of cooperation, leads to high levels of emissions and a large temper-

[18] Note that the model slightly overestimates the size of the EU economy. However, this could be interpreted as accounting for the fact that the rest of the world does not completely follow business-as-usual when it comes to climate change mitigation. Instead, some other countries like Australia and parts of the United States have some policy in place.

ature increase. Having a second source of distortion in form of income taxes partially offsets this effect.[19] This implies that models that feature only lack of cooperation may overestimate the extent of climate change that would occur in a business-as-usual scenario. As a consequence, such models would prescribe too steep reductions in emissions and thus too high and quickly increasing carbon taxes, thereby inflating the cost of climate policy. In order to account for these effects, it would be advisable for modelers to include some representation of distortionary tax systems – at the very least captured by exogenous income tax rates – when studying optimal climate policy.

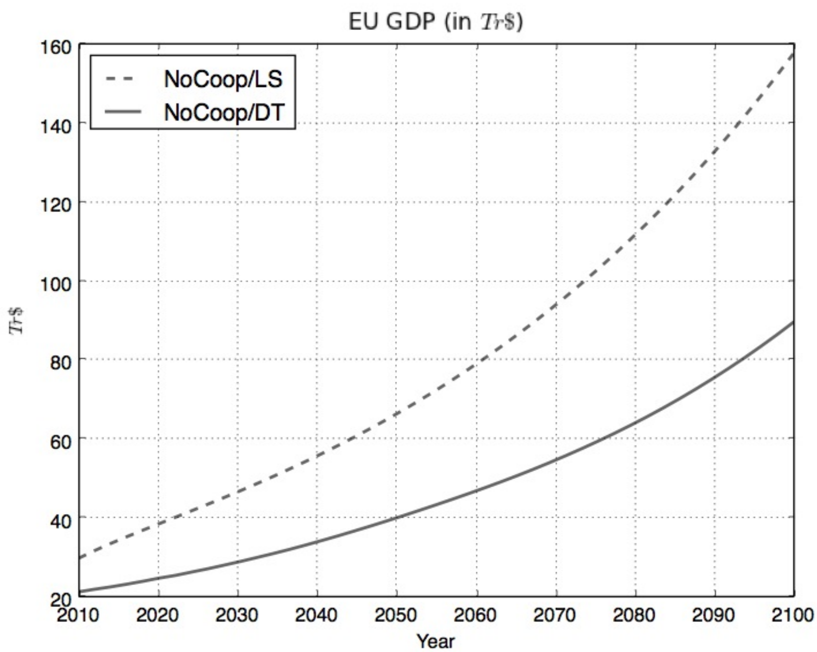

Figure 3.6: Baseline Model - Output

The results presented above have been derived in a setting with perfect capital mobility. Figure 3.7 plots EU capital exports, defined as the

[19]Naturally, this argument is valid only in terms of emission levels, not in terms of welfare. Eliminating lump-sum taxes from the "NoCoop/LS" scenario causes a loss in welfare, despite the smaller increase in temperature.

difference between capital stock k_t^{EU} and utilized capital z_t^{EU}, over time, both in absolute terms and as a share of the total global capital stock. As expected, in the scenario with distortionary taxation, the EU is a net capital exporter. In other words, there is capital flight to the rest of the world, reflecting the fact that distortionary taxes in the EU are higher and carbon emissions are taxed. With lump-sum taxation, the opposite is true, and capital moves into the EU, with the largest inflow in case of the no-cooperation scenario. At first glance, this may seem counter-intuitive, since even without income taxes, carbon taxation is in place only in the EU, suggesting that without capital mobility, the return to capital should be lower. Due to the carbon tax, however, households in the rest of world have higher income and thus save more than in the EU. Therefore, after a short initial phase of being importers, the capital stock in the rest of the world is high enough to decrease the return rate below the one in the EU, and hence capital moves in the other direction.

Since fossil fuel use features only a small income share, the effect of a moderate carbon tax is not strong enough to distort the marginal product of capital sufficiently.

When comparing emission levels with and without capital mobility, I find only marginal differences, even in the setting with distortionary taxes. The reasoning for this is twofold. After opening borders to capital flows, there is an initial phase of a few periods in which the difference in the net rate of return to capital between the two regions is high. Hence, capital flows to the rest of the world, which sees a rise in production and thus fossil fuel use relative to the outcome without capital mobility. However, while production in the rest of the world is more emission intensive than in the EU, this difference is not large in second best, as illustrated by the moderate size of the carbon tax. Hence, the resulting increase in global emissions caused by the reallocation of capital is small. In the "NoCoop/DT" scenario, shutting down capital mobility decreases emissions on average by 0.14 GtC each year between 2010 and 2150, which amounts to 1.5% of the initial emission level.[20] In the longer run,

[20]Note that when running the model without capital mobility, I need to assume a

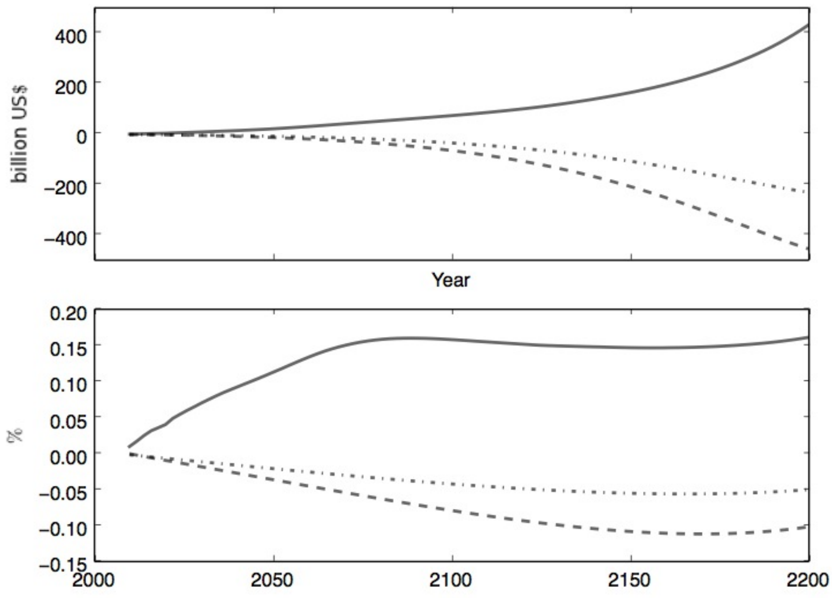

Figure 3.7: Baseline Model - Capital Exports

the allocation of utilized capital under capital mobility approaches the corresponding levels in a setting without capital mobility. As a consequence, the differences in output and thus fossil fuel use and emissions are negligible.

Finally, in addition to the case without capital mobility, I run a number of further robustness checks. The results presented here are only marginally affected by increasing capital tax rates in the rest of the world by a reasonable amount, as well as by restricting the EU to a total income tax instead of separate tax rates on labor and capital income. The same is true when calibrating the model with a higher income share of fossil fuel of $\phi = 0.03$ (Golosov et al., 2014).

total income tax rather than separate tax rates on labor and capital. In the latter case, since capital taxes would no longer be bounded by tax competition, they effectively work as lump-sum taxes. Therefore, labor tax rates are optimally zero or, if not bounded from below, negative (Martin, 2010).

3.4 Conclusion

Mitigating climate change is a global problem, whose solution requires some form of international agreement or coordination. This paper has analyzed a setting where such cooperation is not feasible. Instead, climate change mitigation is undertaken unilaterally by a single region, the European Union, while the rest of the world is assumed to have no incentive to reduce emissions of greenhouse gases relative to a business-as-usual scenario. I have calibrated a two-region climate-economy model, in which for reasons of tractability I have abstracted from strategic interaction. I have shown that while carbon taxes fall considerably when introducing distortionary income taxes into a setting without cooperation, the initial emission level is closer to the first best than to a noncooperative regime with lump-sum taxation. Over time, however, carbon taxes increase less than under lump-sum taxation, which causes emissions to fall slower. An implication from this exercise is that models of unilateral climate policy making that abstract from a realistic representation of income tax systems may overestimate the level of carbon emissions in the absence of mitigation and therefore prescribe too stringent policies.

As outlined above, the model used here has been considerably simplified relative to an ideal model of two-sided strategic interaction. Modeling the rest of the world as a small open economy most likely introduces a downward bias with respect to carbon emissions. On the other hand, preventing it to participate or cooperate in climate change mitigation at some later point in time may overestimate the extent of climate change. The net effect is unclear. Dealing with these shortcomings of the model should be a goal of future research.

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A Equilibrium Definition

The non-stationary Markov-perfect equilibrium consists of a set of value and policy functions,[21]

[21] In period J, the last period with carbon emissions, the government's problem reads

$$\max_{\substack{c_t^{EU}, k_{t+1}^{EU}, z_t^{EU}, h_t^{EU}, g_t^{EU}, m_t^{EU}, \tau_t^{k,EU} \\ c_t^{ROW}, k_{t+1}^{ROW}, z_t^{ROW}, h_t^{ROW}, m_t^{ROW}, T_{t+1}}} u(c_t^{EU}, 1-h_t^{EU}, g_t^{EU}, T_t) + \beta \bar{v}^j(k_{t+1}^{EU}, k_{t+1}^{ROW}, T_{t+1}),$$

$$\{V_t^j, \mathcal{K}_t^{EU}, \mathcal{C}_t^{EU}, \mathcal{Z}_t^{EU}, \mathcal{H}_t^{EU}, \mathcal{G}_t^{EU}, \mathcal{M}_t^{EU}, \mathcal{T}_t^{k,EU}, \mathcal{T}_t^{h,EU}, \\ \mathcal{K}_t^{ROW}, \mathcal{C}_t^{ROW}, \mathcal{Z}_t^{ROW}, \mathcal{H}_t^{ROW}, \mathcal{M}_t^{ROW}, \}_{t=0}^{J},$$

such that for all k_t^{EU}, k_t^{ROW} and T_t, the policy functions $\mathcal{C}_t^j$, $\mathcal{Z}_t^j$ etc. solve

$$\max_{\substack{c_t^{EU}, k_{t+1}^{EU}, z_t^{EU}, h_t^{EU}, g_t^{EU}, m_t^{EU}, \tau_t^{k,EU} \\ c_J^{ROW}, k_{t+1}^{ROW}, z_t^{ROW}, h_t^{ROW}, m_t^{ROW}, T_{t+1}}} u(c_t^{EU}, 1 - h_t^{EU}, g_t^{EU}, T_t) \\ + \beta V_t^{EU}(k_{t+1}^{EU}, k_{t+1}^{ROW}, T_{t+1}),$$

subject to the law of motion for temperature change:

$$T_{t+1} = q(T_t, m_t^{EU} + m_t^{ROW}),$$

the resource constraint in for the EU:

$$F(z_t^{EU}, h_t^{EU}, m_t^{EU}, T_t) + (1-\delta)k_t^{EU} - c_t^{EU} - g_t^{EU} - \kappa m_t^{EU} - k_{t+1}^{EU} \\ + \left[\left(1 - \tau_t^{k,EU}\right) F_z \begin{pmatrix} z_t^{EU}, h_t^{EU}, \\ m_t^{EU}, T_t \end{pmatrix} + \tau_t^{k,EU}\delta\right](k_t^{EU} - z_t^{EU}) = 0$$

the domestic household's intratemporal optimality condition:

$$\frac{u_l(c_t^{EU}, 1 - h_t^{EU}, g_t^{EU}, T_t)}{u_c(c_t^{EU}, 1 - h_t^{EU}, g_t^{EU}, T_t)} - F_h^{EU}(z_t^{EU}, h_t^{EU}, m_t^{EU}, T_t)[1 - \tau_t^{h,EU}] = 0,$$

the domestic household's Euler equation:

$$u_c(c_t^{EU}, 1 - h_t^{EU}, g_t^{EU}, T_t) - \beta u_c\left(\mathcal{C}_{t+1}^{EU}, 1 - \mathcal{H}_{t+1}^{EU}, \mathcal{G}_{t+1}^{EU}, T_{t+1}\right) \cdot \\ \cdot \left[1 + [1 - \mathcal{T}_{t+1}^{k,j}]\left[F_z \begin{pmatrix} \mathcal{Z}_{t+1}^{EU}, \mathcal{H}_{t+1}^{EU}, \\ \mathcal{M}_{t+1}^{EU}, T_{t+1} \end{pmatrix} - \delta\right]\right] = 0,$$

the resource constraint in for the rest of the world:

$$
\begin{aligned}
0 = {} & F(z_t^{ROW}, h_t^{ROW}, m_t^{ROW}, T_t) + (1-\delta)k_t^{ROW} \\
& - c_t^{ROW} - g_t^{ROW} - \kappa m_t^{ROW} - k_{t+1}^{ROW} \\
& + \left[\left(1 - \tau_t^{k,ROW}\right) F_z \left(\begin{array}{c} z_t^{ROW}, h_t^{ROW}, \\ m_t^{ROW}, T_t \end{array} \right) + \tau_t^{k,ROW} \delta \right] (k_t^{ROW} - z_t^{ROW})
\end{aligned}
$$

the foreign household's intratemporal optimality condition:

$$
\begin{aligned}
& \frac{u_l(c_t^{ROW}, 1 - h_t^{ROW}, g_t^{ROW}, T_t)}{u_c(c_t^{ROW}, 1 - h_t^{ROW}, g_t^{ROW}, T_t)} \\
& - F_h^{ROW}(z_t^{ROW}, h_t^{ROW}, m_t^{ROW}, T_t)[1 - \tau_t^{h,ROW}] = 0,
\end{aligned}
$$

the foreign household's Euler equation:

$$
\begin{aligned}
& u_c(c_t^{ROW}, 1 - h_t^{ROW}, g_t^{ROW}, T_t) - \beta u_c \left(\mathcal{C}_{t+1}^{ROW}, 1 - \mathcal{H}_{t+1}^{ROW}, \mathcal{G}_{t+1}^{ROW}, T_{t+1} \right) \cdot \\
& \quad \cdot \left[1 + [1 - \mathcal{T}_{t+1}^{k,j}] \left[F_z \left(\begin{array}{c} \mathcal{Z}_{t+1}^{ROW}, \mathcal{H}_{t+1}^{ROW}, \\ \mathcal{M}_{t+1}^{ROW}, T_{t+1} \end{array} \right) - \delta \right] \right] = 0,
\end{aligned}
$$

the firm's optimality condition for fuel use in the rest of the world:

$$
F_m(z_t^{ROW}, h_t^{ROW}, m_t^{ROW}, T_t) - \kappa = 0,
$$

the clearing condition for the world capital market:

$$
k_t^{EU} - z_t^{EU} + k_t^{ROW} - z_t^{ROW} = 0,
$$

and a constraint to ensure equalized rates of return:

$$
\begin{aligned}
& \left(1 - \tau_t^{k,EU}\right) \left[F_z \left(\begin{array}{c} z_t^{EU}, h_t^{D}, \\ m_t^{EU}, T_t \end{array} \right) - \delta \right] \\
& \qquad - \left(1 - \tau_t^{k,ROW}\right) \left[F_z \left(\begin{array}{c} z_t^{ROW}, h_t^{ROW}, \\ m_t^{ROW}, T_t \end{array} \right) - \delta \right] = 0.
\end{aligned}
$$

Moreover, in each period t, the continuation value for all k_t^{EU}, k_t^{ROW} and T_t is given by

$$V_t^{EU}\left(k_t^{EU}, k_t^{ROW}, T_t\right) = u_c\left(\mathcal{C}_t^{EU}, 1 - \mathcal{H}_t^{EU}, \mathcal{G}_t^{EU}, T_t\right) + \beta V_{t+1}^{EU}\left(\mathcal{K}_t^{EU}, \mathcal{K}_t^{ROW}, q(T_t, \mathcal{M}_t^{EU} + \mathcal{M}_t^{ROW})\right).$$

B Figures

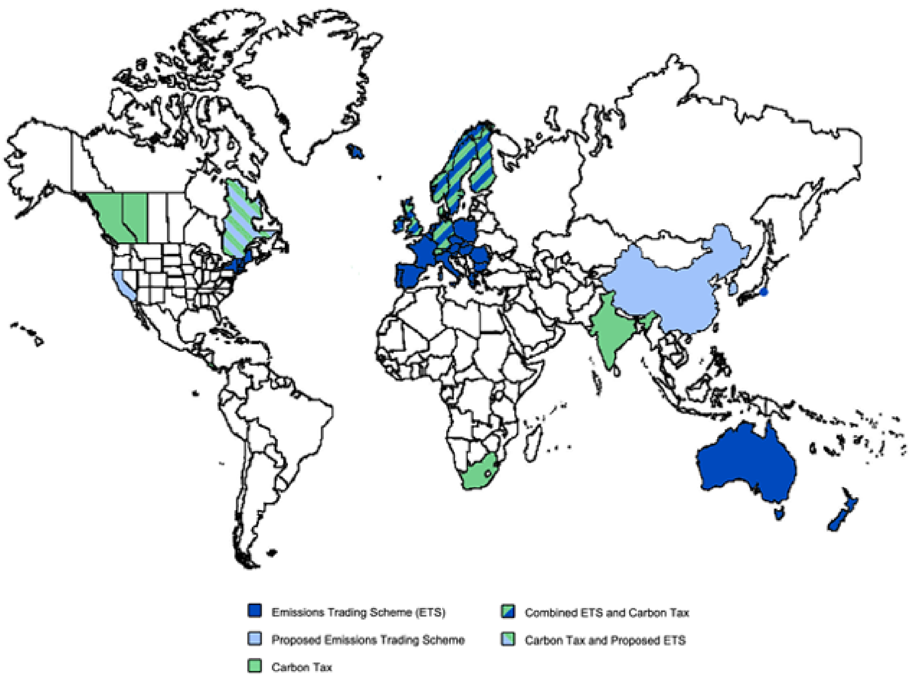

Figure B.1: Source: EESI (2012)

Chapter 4

Climate Change Mitigation under Political Instability*

4.1 Introduction

How does "political instability" - the risk of losing power in the future - affect the incentives of a policy maker in the context of climate change mitigation? In this paper, I analyze the regulation of greenhouse gas emissions such as CO_2 under the assumption that an incumbent government may, at some point in the future, be replaced by a government with different preferences with respect to the extent of climate change mitigation. Hence, policy measures such as carbon taxes in the future may differ from what the current government considers optimal. In other words, the incumbent government cannot commit to future policies. A "strategic" policy maker that takes this risk into account will behave differently from a "myopic" government that does not perceive the possibility of losing power. Hence, the analysis below addresses the question of how strategic policy making affects carbon emissions and hence climate change.

A large number of studies use climate-economy models to analyze

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the global or regional impacts of climate change and to derive "optimal" mitigation policies (for example Nordhaus, 2008; Golosov et al., 2014). Since the aim of this literature is usually to make a normative analysis, it abstracts from political processes and instead assumes that policy makers, either on a global level or within a country, are able to commit to policies over long periods of time. However, in both democracies and autocracies, incumbent governments face the possibility of losing power, as a result of either an election or a revolt. This makes the assumption of commitment to future policies beyond the short- to medium-run unrealistic. Nevertheless, this lack of commitment may not be of importance in practice as long as there is a consensus between different parties or factions competing for political power about their preferred policies. If this is not the case and parties are heterogeneous with respect to what policy choices they consider optimal, an incumbent government must take into account the possibility of – from their perspective – non-optimal policies in the future, which in turn affects its current policy choice.

This paper analyzes climate change mitigation in a setting with political instability and heterogeneous policy makers. I use a one-region neoclassical growth model where the production of the final consumption goods requires energy as an input. In order to analyze the effect of political stability on investment behavior, I assume that the energy sector uses fossil fuel and two different types of capital: "dirty" capital is a complement to fuel in producing fossil-based energy, which, in turn, is a substitute for "clean" capital in the production of total energy.[1] Carbon emissions increase proportionally with fossil fuel use. Note that a one-region framework does not allow me to explicitly model damages from climate change as a function of global mean temperature change relative to the pre-industrial level, which represents the usual approach in the literature. Instead, I assume that government types have preferences over the level of cumulative US emissions. On the political side, for reasons

[1] The production structure in my model is based on the WITCH model (Bosetti et al., 2006), but with a considerably lower level of detail in order to keep the numerical analysis tractable.

of tractability, I restrict myself to a two-party system, which is the usual setting for analyzing political instability in the literature (Persson and Tabellini, 2002): a relatively "green" incumbent puts a higher weight on climate change mitigation than its relatively "skeptic" opponent. I consider both the case when the probability of losing power in the future is exogenous and when it is endogenous.[2]

The main findings of this paper are the following. Conceptually, political instability and strategic behavior induce a policy maker to adjust her policy in order to manipulate the future state of the economy and thus "create facts" for her successor (Persson and Tabellini, 2002). These adjustments occur in two ways. First, even without different types of capital, the risk of losing political power in the future creates an incentive to reduce current emissions below the level that would be optimal for a myopic incumbent. I refer to this behavior as "precautionary emission saving". Intuitively, a green government wishes to keep the future cumulative stock of emission low; since it anticipates high emission levels implemented by a skeptic successor, it compensates those with more pronounced emission cuts. A skeptic incumbent on the other hand has an incentive to smooth emission reductions over time. Hence, by reducing emissions today, it avoids steep emission cuts by a green successor in the future. In other words, either type affects its successor's policy by manipulating tomorrow's stock of cumulative emissions. Second, with two energy sources and capital types, political instability induces both parties to manipulate the future production structure of the economy by shifting the investment from dirty to clean capital. The motives for this behavior are different across types. A green incumbent wishes to "tie the hands" of a skeptic successor, that is, to weaken its incentive to emit by reducing (increasing) the capacity of fossil-based energy (clean energy) in the future. In contrast, a skeptic government realizes that emission

[2]Note that it is not clear which assumption is more realistic. While allowing the turnover probability to be endogenous is the more general approach, it has been suggested that environmental policy represents a "secondary" rather than a "frontline" policy issue (List and Sturm, 2006), so that divergent platforms may only have a limited effect on election results.

cuts by a green successor would reduce the rate of return to investment in dirty capital and hence reoptimizes in order to “cushion the blow”.

To quantify the effect of strategic government behavior, I use a model of the economy of the United States and consider two types of policy makers, representing the Democratic and the Republican Party. Anecdotal evidence, as well as the inability of the US Congress to agree on any meaningful climate change legislation, suggests that both parties disagree to a considerable extent about the importance of climate change and about what policy measures (if any) should be employed to mitigate it.[3] For the Democrats, I calibrate the utility function using estimates for the social cost of carbon (SCC) published by the Obama administration (IWG, 2010). For the Republicans, due to the lack of better data, I assume that they put zero weight on cumulative emissions, that is, their preferred allocation is identical to the business-as-usual (BAU) outcome.

In the baseline calibration of the model, I find that the difference in expected cumulative emissions by 2100 between a setting with strategic policy makers and one with myopic agents amounts to a decrease that is equivalent to emissions along a BAU path being permanently reduced by 10%. A large share of this reduction would materialize even without the government adjusting its investment behavior towards clean energy, indicating that the main channel through which an incumbent manipulates future policy is the emission stock. Running a number of robustness checks shows that the findings are sensitive to the elasticity of substitution in the production of fossil-based energy. In the extreme case of a Leontief production function, the reduction in cumulative emissions corresponds to a BAU cut of 5%.

The effects of political instability and strategic interaction on a pol-

[3]For example, then-presidential candidate Mitt Romney remarked in 2012 while delivering a speech at the Republican convention: “President Obama promised to begin to slow the rise of the oceans and to heal the planet. My promise [...] is to help you and your family.” In contrast, in June 2014 President Barack Obama stated: “As president, and as a parent, I refuse to condemn our children to a planet that’s beyond fixing.” It should also be noted that while the attitudes reflected in these statements are representative for the parties’ stances on climate change, neither party is completely homogeneous.

icy maker's incentives have been extensively studied in the context of public debt accumulation (Persson and Svensson, 1989; Alesina and Tabellini, 1990; Aghion and Bolton, 1990) and other areas of public policy (see Persson and Tabellini, 2002, for an overview). In the context of climate change, this paper relates to the large literature on climate-economy modeling. Prominent examples of such "integrated assessment models" are DICE/RICE (Nordhaus and Yang, 1996; Nordhaus, 2008, 2010), WITCH (Bosetti et al., 2006, 2009), PAGE (Hope, 2006, 2008) and FUND (Tol, 2002a,b), as well as Golosov et al. (2014). While these models feature considerable differences in terms of structure, scope and level of detail, they have a "first-best" spirit in common, in the sense that climate policy is set by a global or regional planner whose long-run policy choices are time-consistent, even in the absence of formal commitment. More recently, some papers have introduced features in their models that cause the time-consistent equilibrium to be different from the commitment solution. Gerlagh and Liski (2012) assume that a policy maker faces time-inconsistent preferences, due to hyperbolic discounting. Schmitt (2014) considers distortionary income taxes as the source of the time inconsistency of the commitment solution.[4]

4.2 Insights From Two-period Models

In this section, I use a simple framework with two periods and two government types to generate some insights into the mechanisms that will be in play in the quantitative model in section 4.3. I proceed in two steps. First, I employ a model adopted from Harstad (2013) that allows for an analytical solution, in order to illustrate how strategic policy makers react to political instability with respect to emission levels and investment in one type of capital that serves as a substitute for fossil fuel use. In the second part of this section, I use numerical analysis to confirm that these results carry over to a model with two types of capital and functional forms that are more standard in macroeconomic modeling.

[4] Compare chapter 2 of this thesis.

4.2.1 An Analytical Model

Consider an economy that lasts two periods, indexed by $t = 1, 2$. Let m_t denote the amount of fossil-based fuel consumed in period t, chosen by the policy maker that is in power in t.[5] In addition, consider a source of "clean" or renewable energy, which can be used as a substitute for fossil fuel in period 2, given that an investment has been made in period 1. Let k_r denote the capacity of clean energy.

The world is populated by different types of agents, as described below. An agent of type j has the following per-period utility functions in period 1 and period 2, respectively:

$$u_1(m_1, k_r) = -\frac{b}{2}(\bar{m} - m_1)^2 - \kappa\frac{k_r^2}{2} \tag{4.1}$$

$$u_2(m_2, k_r, m_1; \gamma) = -\frac{b}{2}(\bar{m} - m_2 - k_r)^2 - \frac{\gamma^j}{2}(m_2 + \phi m_1)^2. \tag{4.2}$$

The first term on the right-hand side of (4.1) captures the benefit of using energy in period 1, while the first term of the right-hand side of (4.2) represents the benefit in period 2. $\bar{m}$ denotes a bliss point, which gives the preferred energy level in the absence of climate change. b is a parameter that indicates the importance of energy use: the greater b, the larger is the disutility of not being at the bliss point. For simplicity, I let $\bar{m}$ and b be the same across time and types. Moreover, clean energy acts as a perfect substitute for fossil fuel: ceteris paribus, a larger capacity reduces the optimal amount of fossil fuel consumed in period 2, i.e. changes the effective bliss point. The second term on the right hand side of (4.1) represents the assumption that in order to use clean energy at an amount of k_r in period 2, an investment cost of $\kappa k_r^2/2$ (in utility

[5] Ulph and Ulph (2013) show that in a setting where a government cannot commit to future policies, decentralization of the planner equilibrium requires further policy instruments in addition to a carbon price set by a tax or a system of tradable permits. In the appendix, I illustrate this finding in my model and show that an incumbent can use an investment subsidy in order to decentralize the equilibrium. Throughout the paper, I assume that a policy maker has access to the necessary instruments and hence, the planning solution is always feasible.

terms) has to be born in period 1.

To simplify the exposition, I assume that climate change only occurs in the second period. The second term on the right-hand side of (4.2) captures the utility cost of climate change. It depends on the stock of emitted carbon, that is, on the cumulative emissions in both periods. The stock at the beginning of period 2 is given by m_1 and is assumed to depreciate at the rate $1-\phi$, $0 \leq \phi \leq 1$. The parameter γ^j measures the utility weight that an agent of type j associates with climate damages. There will be heterogeneity across policy makers with respect to the weight they put on the disutility of climate change.

Let β denote a discount factor and q the probability of political turnover. For what follows, it is useful to define the functions

$$Q(x;\gamma,q) = q\frac{\gamma}{b+\gamma} + (1-q)\frac{x^2+b\gamma}{(b+x)^2} \tag{4.3}$$

and

$$\Psi(x;\gamma,q) = \frac{\beta b Q(x;\gamma,q)}{\kappa + \beta b Q(x;\gamma,q)}. \tag{4.4}$$

4.2.1.1 Benchmark: Social Planner

Consider a social planner who chooses fossil fuel use in both periods as well as investment in clean energy in period 1. Assume that she puts weight γ^{PL} on the disutility of climate change. Hence, her problem then reads:

$$\max_{m_1,k_r,m_2} -\frac{b}{2}(\bar{m}-m_1)^2 - \kappa\frac{k_r^2}{2} - \beta\frac{b}{2}(\bar{m}-m_2-k_r)^2 - \frac{\gamma^{PL}}{2}(m_2+\phi m_1)^2.$$

The optimal policy is given by $\{m_1^{PL}, m_2^{PL}, k_r^{PL}\}$, where

$$m_1^{PL} = \frac{1-\beta\phi Q^{PL}(1-\Psi^{PL})}{1+\beta\phi^2 Q^{PL}(1-\Psi^{PL})}\bar{m}, \tag{4.5}$$

$$k_r^{PL} = \Psi^{PL}(\bar{m}+\phi m_1^{PL}), \tag{4.6}$$

and

$$m_2^{PL} = \frac{b(\bar{m} - k_r^{PL}) - \phi\gamma^{PL}m_1^{PL}}{b + \gamma^{PL}}. \tag{4.7}$$

with $Q^{PL} = Q(\gamma^{PL}; \gamma^{PL}, p) = \gamma^{PL}/(b+\gamma^{PL})$ and $\Psi^{PL} = \Psi(\gamma^{PL}; \gamma^{PL}, p)$.

4.2.1.2 Political Instability

Assume now that there are two types of policy makers. For the sake of exposition, I will also refer to them as parties and label them as "green" (g) and "skeptic" (s), with $\gamma^s < \gamma^g$. Instead of a planner who chooses the complete policy vector $\{m_1, m_2, k_r\}$, different parties may be in power in different periods. A policy maker of type j has the per-period utility functions (4.1) and (4.2), with $\gamma = \gamma^j$.[6] The type-j party in power in period 1 chooses m_1 and k_r to maximize the expected discounted sum of per-period utility:

$$\max_{m_1, k_r} = -\frac{b}{2}(\bar{m}-m_1)^2 - \kappa\frac{k_r^2}{2} - \beta\mathsf{E}_{m_2}\left[\frac{b}{2}(\bar{m} - m_2 - k_r)^2 - \frac{\gamma^j}{2}(m_2 + \phi m_1)^2\right].$$

In period 2, the (possibly new) government chooses m_2 to maximize (4.2), while taking m_1 and k_r as given. Working backwards, solving this problem yields the following decision rule for a party of type-j in power in period 2, as a function of m_1 and k_r:

$$m_2(m_1, k_r; \gamma^j) = \frac{b(\bar{m} - k_r) - \phi\gamma^j m_1}{b + \gamma^j}. \tag{4.8}$$

Intuitively, fossil-based energy use in period 2 is a decreasing function of both m_1 and k_r. A higher emission level in period 1 increases the carbon stock and hence induces the period-2 government to lower the fossil fuel use, assuming that $\phi > 0$ and $\gamma^j > 0$. A higher capacity of clean energy reduces the need for fossil-based energy. With (4.8), the carbon stock in

[6] Policy makers should here be interpreted as citizen candidates, who derive utility from policies even when they are not in power.

period 2 can be written as:

$$m_2(m_1, k_r; \gamma^j) + \phi m_1 = \frac{b(\bar{m} - k_r + \phi m_1)}{b + \gamma^j}. \tag{4.9}$$

Thus, a higher emission level in period 1 translates into a higher carbon stock and hence more climate change.

4.2.1.3 Exogenous Turnover Probability

For now, assume that the probability of remaining in power is exogenous and given by q. To facilitate the notation, I omit indices for the cost parameter where possible. Instead, let $\hat{\gamma}$ denote the cost of the party that is in power in period 1, while $\tilde{\gamma}$ is associated with the opposition party. The problem of the incumbent in period 1 can then be written as:

$$\begin{aligned}\max_{m_1, k_r} \; & -\frac{b}{2}(\bar{m} - m_1)^2 - \kappa\frac{k_r^2}{2} \\ & +\beta\left[q\left(-\frac{b}{2}[\bar{m} - m_2(m_1, k_r; \hat{\gamma}) - k_r]^2 - \frac{\hat{\gamma}}{2}[m_2(m_1, k_r; \hat{\gamma}) + \phi m_1]^2\right)\right. \\ & \quad +(1-q)\left(-\frac{b}{2}[\bar{m} - m_2(m_1, k_r; \tilde{\gamma}) - k_r]^2\right. \\ & \qquad \left.\left. - \frac{\hat{\gamma}}{2}[m_2(m_1, k_r; \tilde{\gamma}) + \phi m_1]^2\right)\right].\end{aligned} \tag{4.10}$$

Inserting the reaction function given by (4.8), taking derivatives and solving for m_1 and k_r yields the following decision rules:

$$\hat{m}_1 = \frac{1 - \beta\phi Q(\tilde{\gamma}; \hat{\gamma}, q)(1 - \Psi(\tilde{\gamma}; \hat{\gamma}, q)))}{1 + \beta\phi^2 Q(\tilde{\gamma}; \hat{\gamma}, q)(1 - \Psi(\tilde{\gamma}; \hat{\gamma}, q))}\bar{m}, \tag{4.11}$$

and

$$\hat{k}_r = \Psi(\tilde{\gamma}; \hat{\gamma}, q)(\bar{m} + \phi\hat{m}_1). \tag{4.12}$$

Note that (4.11) and (4.12) nest a number of special cases. First, consider the case where the *perceived* probability of remaining in power is $q = 1$. Hence, $Q(\tilde{\gamma}; \hat{\gamma}, 1) = c/(b+\hat{\gamma}) \equiv Q^*$ and $\Psi = (\beta b Q^*)/(\kappa + \beta b Q^*) \equiv$

Ψ^*. Then, these decision rules give the same emission and investment levels that the policy maker would choose in "first best", that is, if she remained in power for two periods:

$$m_1^* = \frac{1-\beta\phi Q^*}{1+\beta\phi^2 Q^*} = \frac{b+\gamma-\beta\phi c(1-\Psi^*)}{b+\gamma+\beta\phi^2 c(1-\Psi^*)},\ k_r = \Psi^*(\bar{m}+\phi m_1^*). \quad (4.13)$$

An incumbent government that perceives the probability of a turnover as 0 – and hence does not take into account the possibility of losing power – will be referred to as a "myopic" government.

Second, assume that the cost of investing in clean energy goes to infinity, and hence $\Psi \to 0$. Then, $k_r = 0$ and

$$\hat{m}_1 = \frac{1-\beta\phi\hat{Q}}{1+\beta\phi^2\hat{Q}}\bar{m}.$$

In this case, it is easy to see that $\partial\hat{m}_1/\partial\hat{Q} < 0$. Moreover, it can be shown that for a given $\hat{\gamma}$, $Q(\tilde{\gamma};\hat{\gamma},q)$ can never be lower than $Q(\hat{\gamma};\hat{\gamma},q)$.[7] Hence, for $\tilde{\gamma} \neq \hat{\gamma}$, $\hat{Q} > Q^*$ and $\hat{m}_1 < m_1^*$. In words, compared to a myopic incumbent, a "strategic" government that takes into account political instability and heterogeneity always chooses a lower emission level in period 1.

Note that this "precautionary emission savings" effect holds for any $\tilde{\gamma} \neq \hat{\gamma}$ and hence for both a relatively skeptic and a relatively green incumbent in period 1. Start with a green government. If there is a non-zero probability that a skeptic government will get into power in period 2, the carbon stock $m_2 + \phi m_1$ is, in expectation, higher than what the incumbent considers to be optimal. From (4.9), $\partial(m_2+\phi m_1)/\partial m_1 > 0$; hence, a green government has an incentive to lower the current emissions, in order to partially offset a possibly high increase in the future.

For a skeptic incumbent in period 1, a non-zero probability of a green successor results in possibly suboptimally low fossil fuel use m_2. By (4.8), $\partial m_2/\partial m_1 < 0$. Thus, by reducing emissions in period 1, a skeptic government can mitigate the emission cuts that a green successor would choose

[7] See the appendix for the proof.

to implement. Trading off emissions today with emissions tomorrow only has an effect on utility if m_1 and m_2 are not perfect substitutes. In other words, the utility function assumed here makes it optimal to smooth fuel use and thus emissions over time.

For the general case with investments in clean energy, the following proposition summarizes the main findings:

Proposition 1. *Consider the above model with $q \in (0,1)$, $\phi \in (0,1)$ and $\kappa \in (0,\infty)$. Then, for any $\hat{\gamma}$, $\tilde{\gamma}$, with $\hat{\gamma} \neq ga\tilde{m}ma$, the following statements about the optimal policy $\{\hat{m}_1, \hat{k}_r\}$ hold:*

1. *Let m_1^* and k_r^* denote the optimal choices of a myopic incumbent that does not account for the possibility of losing power. Then,*

$$\hat{m}_1 < m_1^*, \hat{k}_r > k_r^*.$$

2. *Let $\check{m}_1$ and $\check{r}_2$ denote the optimal choices of the incumbent if the policies in period 2 were chosen by a planner who puts weight ρ on the incumbent's preference. Define $\check{\gamma} = \rho\hat{\gamma} + (1-\rho)\tilde{\gamma}$ and let $\bar{q}$ denote a threshold given by:*

$$\bar{q} \equiv \left[\frac{\tilde{\gamma}^2 + b\hat{\gamma}}{(b+\tilde{\gamma})^2} - \frac{\check{\gamma}^2 + b\hat{\gamma}}{(b+\check{\gamma})^2}\right] / \left[\frac{\tilde{\gamma}^2 + b\hat{\gamma}}{(b+\tilde{\gamma})^2} - \frac{\hat{\gamma}}{b+\hat{\gamma}}\right].$$

Then, if $q < \bar{q}$,

$$\hat{m}_1 < \check{m}_1, \hat{k}_r > \check{k}_r.$$

Proof. See the appendix. ∎

The first part of the proposition compares the optimal policy $\{\hat{m}_1, \hat{k}_r\}$ to a setting with myopic incumbents. The intuition for the change in fossil fuel use was discussed above. Regarding clean capital, I find that both types have an incentive to increase investment relative to the myopic outcome. For the green type, the intuition follows a similar logic as before: since by (4.9), the stock of cumulative emissions decreases in clean energy, $\partial(m_2 + \phi m_1)/\partial k_r < 0$, the incumbent invests more in clean energy to lower a possibly skeptic successor's bliss point and to induce her to reduce emissions. In the remainder of this paper, I will refer to this mechanism as "(partially) tying the successor's hands": by appropriately choosing the future state of the economy, the current incumbent can move her successor's policy closer to her own preferred policy choice. In the next section, I will discuss a setting where today's investment directly determines tomorrow's emission level. In that case, the incumbent can completely tie her successor's hands.

With respect to the skeptic type, the intuition behind proposition 1 is different. Since from (4.8), $\partial m_2/\partial k_r < 0$, one could think that a skeptic incumbent would want to reduce the investment level relative to the myopic outcome. However, note an asymmetry between the two types: while the green type derives a disutility from future emissions, a skeptic type incumbent does not put a positive weight on emissions. Instead, she cares about emissions relative to the bliss point $\bar{m} - k_r$. Hence, by increasing the investment in clean energy, she moves this bliss point closer to the emission level set by a possibly green successor. I will refer to this mechanism as "cushioning the blow", meaning that the incumbent chooses the future state of the economy in order to align her preferred policy with her successor's policy choice. Note that both mechanisms described here, tying the hand and cushioning the blow, affect the emission-savings effect, and vice versa.

The second part of proposition 1 relates $\{\hat{m}_1, \hat{k}_r\}$ to what could be interpreted as a "cooperative regime": whichever party is in power in period 2 chooses m_2 to maximize a weighted average of the two parties' utilities. Note that this requires that in period 1, both types can commit to what policy they will set in period 2 if they get into power.

The following proposition gives the condition for both parties being willing to commit to the cooperative outcome:

Proposition 2. *Define $\underline{q}$ as the following threshold:*

$$\underline{q} \equiv \left[\frac{\check{\gamma}^2 + b\tilde{\gamma}}{(b+\check{\gamma})^2} - \frac{\tilde{\gamma}}{b+\tilde{\gamma}}\right] \Big/ \left[\frac{\hat{\gamma}^2 + b\tilde{\gamma}}{(b+\hat{\gamma})^2} - \frac{\tilde{\gamma}}{b+\tilde{\gamma}}\right].$$

Then, if $\underline{q} < q < \bar{q}$*, both the incumbent and the opposition prefer cooperation* $\{\check{m}_1, \check{k}_r\}$ *to the non-cooperative outcome.*

Proof. See the appendix. ■

Intuitively, if the probability of remaining in power is sufficiently low, the incumbent prefers cooperation in order to avoid a possible successor of a different type to set policy in the future. Similarly, if there is a small probability of getting into power, the opposition prefers to settle for the cooperative outcome. By proposition 2, while cooperation is beneficial for both parties, it leads to higher emissions and less investment in clean energy.

What are the welfare implications of proposition 1? Assume that a planner puts a higher utility weight on cumulative emissions than either of the types, i.e. $\gamma^s < \gamma^g < \gamma^{PL}$,[8] and that γ^{PL} is sufficiently greater than γ^g such that $\hat{m}_1^g \geq m_1^{PL}$ and $\hat{k}_r^g \leq k_r^{PL}$. Then, relative to both a setting with myopic policy makers and the cooperative outcome, political instability and heterogeneous preferences lead to an increase in welfare.[9] Intuitively, if either party remains in power for two periods, emissions are too high ($m_1^{s*} > m_1^{g*} > m_1^{PL}$) and the investment in clean energy is too low from a social perspective. Since political uncertainty reduces emissions and induces more investment, it moves the economy closer to the social optimum.

4.2.1.4 Endogenous Turnover Probability

Next, I endogeneize the probability of remaining in power in period 2. Consider a probabilistic voting model along the lines of Persson and Tabellini (2002). There is a continuum of voters or households that differ with respect to their valuation of climate change. In other words, voter j's preferences are represented by (4.1) and (4.2), with utility cost γ_j^h

[8] This assumption is further motivated in subsection 4.2.1.4.

[9] From proposition 1, it follows that $m_1^{g*} > \hat{m}_1^g$. Moreover, $Q(\gamma^{PL}; \gamma^{PL}, p) > Q(\hat{\gamma}^g; \hat{\gamma}^g, p)$ yields that $m_1^{g*} > m_1^{PL}$. If γ^{PL} is close to γ^g, one could also have $\hat{m}_1^g < m_1^{PL}$.

put on the carbon stock. Assume that γ_j^h is uniformly distributed on $[\gamma_{min}, \gamma_{max}]$, with mean $\bar{\gamma}^h = 0.5(\gamma_{min} + \gamma_{max})$. Moreover, let $\bar{\gamma}^h$ be bracketed by γ^s and γ^g:

$$\gamma^s \leq \bar{\gamma}^h \leq \gamma^g < \gamma^{PL}.$$

Note that this implies that the mean household does not put the same cost on climate change as the social planner. This may seem counterintuitive, but is explained by the fact that climate is a global public good. Hence, the social planner here implements the global optimum, which is different from only taking domestic voters into account. Formally, consider a representative foreign household with the same utility structure as a domestic agent, but with $b = 0$ – it derives no benefit from domestic fossil fuel use – and $\gamma = \gamma^{ROW}$. Then, the global planner's problem (assuming equal welfare weights on the domestic households) reads:

$$\max_{m_1, k_r, m_2} -\frac{b}{2}(\bar{m} - m_1)^2 - \kappa\frac{k_r^2}{2}$$
$$-\beta\left[\frac{b}{2}(\bar{m} - m_2 - k_r)^2 + \frac{\bar{\gamma}^h}{2}(m_2 + \phi m_1)^2 + \frac{\gamma^{ROW}}{2}(m_2 + \phi m_1)^2\right],$$

which is identical to the problem in section 4.2.1.1 if $\gamma^{PL} = \gamma^h + \gamma^{ROW}$.

Households are assumed to be forward-looking and base their voting decisions on which party gives them more utility in period 2. If the period-1 incumbent remains in power, the household's utility is given by:

$$u^h(m_2; m_1, k_r) = -\frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \left[\frac{\hat{\gamma}^2 + b\gamma^h}{(b + \hat{\gamma})^2}\right] + \psi,$$

where ψ can be interpreted as an incumbency bias that indicates the popularity of the incumbent. It is assumed to be uniformly distributed on $\left[-\frac{1}{2\zeta}, \frac{1}{2\zeta}\right]$. A similar expression, but without the incumbency bias, gives the utility if the opposition party gets into power. Using (4.8), the difference in utility reads:

$$\begin{aligned} u_2(m_2, m_1, k_r; \gamma_j^h) + \psi - u^h(\tilde{m}_2, m_1, k_r; \gamma_j^h) \\ &= -\frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \left[\frac{\gamma^2 + b\gamma^h}{(b+\gamma)^2} - \frac{\tilde{\gamma}^2 + b\gamma^h}{(b+\tilde{\gamma})^2} \right] + \psi \\ &\equiv \Xi(m_1, k_r; \gamma_j^h) + \psi. \end{aligned}$$

Hence, household j votes for the incumbent if $\Xi(m_1, k_r; \gamma_j^h) + \psi > 0$.

In the appendix, I show that the probability of remaining in power is given by:

$$q(m_1, k_r) = \frac{1}{2} - \zeta \frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \left[\frac{b}{(b+\hat{\gamma})^2} - \frac{b}{(b+\tilde{\gamma})^2} \right] (\bar{\gamma}^h - \gamma^+), \tag{4.14}$$

where

$$\gamma^+ \equiv \left[\frac{b}{(b+\hat{\gamma})^2} - \frac{b}{(b+\tilde{\gamma})^2} \right]^{-1} \left[\frac{\tilde{\gamma}^2}{(b+\tilde{\gamma})^2} - \frac{\hat{\gamma}^2}{(b+\hat{\gamma})^2} \right]. \tag{4.15}$$

In proposition 3 below, γ^+ will serve as a threshold for when the average household is considered to be relatively green ($\bar{\gamma}^h > \gamma^+$) or skeptic ($\bar{\gamma}^h < \gamma^+$), respectively.

The incumbent's problem in period 1 is similar to the case with an exogenous turnover probability. Using (4.14) in (4.10) gives:

$$\begin{aligned} \max_{m_1, k_r} \; & -\frac{b}{2}(\bar{m} - m_1)^2 - \kappa \frac{k_r^2}{2} \\ & + \beta \left[q(m_1, k_r) \begin{pmatrix} -\frac{b}{2}[\bar{m} - m_2(m_1, k_r; \gamma) - k_r]^2 \\ -\frac{\gamma}{2}[m_2(m_1, k_r; \gamma) + \phi m_1]^2 \end{pmatrix} \right. \\ & \left. + (1 - q(m_1, k_r)) \begin{pmatrix} -\frac{b}{2}[\bar{m} - m_2(m_1, k_r; \tilde{\gamma}) - k_r]^2 \\ -\frac{\gamma}{2}[m_2(m_1, k_r; \tilde{\gamma}) + \phi m_1]^2 \end{pmatrix} \right]. \end{aligned}$$

Solving this problem gives rise to the following proposition:

Proposition 3. *Consider the probabilistic voting model above. If either i) the incumbent government is green ($\hat{\gamma} > \tilde{\gamma}$) and the average household* *is skeptic ($\bar{\gamma}^h < \gamma^+$) or ii) the incumbent government is skeptic ($\hat{\gamma} < \tilde{\gamma}$) and the average household is green ($\bar{\gamma}^h > \gamma^+$), fossil fuel use is lower and the investment in clean energy is higher than in a setting where the incumbent remains in power with exogenous probability $\frac{1}{2}$:*

$$\hat{m}_1^{end} < \hat{m}_1^{exo} < m_1^*, \;\; \hat{k}_r^{end} > \hat{k}_r^{exo} > k_r^*. \tag{4.16}$$

In the opposite cases, the relation between $\hat{m}_1^{end}$ and $\hat{m}_1^{exo}$ ($\hat{k}_r^{end}$ and $\hat{k}_r^{exo}$) is ambiguous.

Proof. See the appendix. ■

The proposition states that if the preferences of the incumbent government in period 1 are sufficiently different from the preferences of the representative household - that is, the government is relatively skeptic, while the household is green, or the other way round - endogenizing the turnover probability strengthens the incentive for precautionary emission saving, tying the hand and cushioning the blow. Hence, it has an unambiguous negative effect on cumulative emissions. The key assumption for this proposition is that households are forward-looking and understand that the future government's policy choice depends on both the carbon stock and the capacity of clean energy. Consider a skeptic household. It is more likely to vote for a green incumbent if it expects it to choose m_2 relatively close to the bliss point $\bar{m} - k_r$. Hence, the probability of remaining in power increases in k_r and decreases in m_1, since by (4.8) $\partial m_2 / \partial m_1 < 0$. A similar argument can be made for a green household and a skeptic government. Since the household prefers a low carbon stock but foresees that a skeptic government would implement relatively high emissions, the probability of the skeptic incumbent remaining in power is higher for a low initial carbon stock and a high capacity for clean energy.

In conclusion, in this section I have derived and illustrated three noteworthy results:

1. Taking into account the possibility of losing power and acting strategically rather than being myopic gives both types an incen-

tive to lower emissions (precautionary emission savings) and increase investment in clean energy (in order to tie the successor's hands or cushion the blow) and hence has an unambiguous positive effect on *global* welfare.

2. From a global perspective, cooperation between policy makers in the future can decrease welfare. In other words, the lack of a commitment device which precludes cooperative behavior in the future is welfare-enhancing in this setting.

3. If the probability of a government change is endogenous, the effects of strategic behavior stated in 1 are exacerbated under certain conditions. In particular, this is true whenever an incumbent faces an electorate with sufficiently different preferences.

4.2.2 A Two-period Model with Two Energy Sources

The above results were derived in a setting with specific preferences and a specific production structure that allowed for an analytical analysis. In particular, this framework did only feature one type of capital, used to produce clean energy. To see whether my findings carry over to a more general setting, I now consider a model where also the production of fossil-based energy uses capital. Hence, a policy maker has to decide not only how much to invest, but also in which type of energy. With respect to preferences and production, the model used in this section features functional forms which are more standard in macroeconomic modeling, in particular a CRRA utility function and CES production functions. In contrast to the previous model, such a framework does not allow for analytical solutions, even in a finite-horizon setting. Instead, I rely on numerical methods.

Consider again two periods, $t = 1, 2$, and let c_t denote the consumption of a final good in period t. As in the previous section, I assume, for simplicity, that climate change occurs only in period 2 but depends on cumulative emissions in both periods. Hence, the lifetime utility of agent j is given by $u_1(c_1) + \beta u_2(c_2, m_1, m_2; \gamma^j)$. Moreover, different types of agents differ with respect to their valuation of climate change, parameterized by γ^j. When solving the model, I assume that u_2 is additively separable in consumption and the level of cumulative emissions and choose the following functional forms:

$$\begin{aligned} &u_1(c_1) + \beta u_2(c_2, m_1, m_2; \gamma^j) \\ &\quad = \frac{c_1^{1-\nu}}{1-\nu} + \beta \left[\frac{c_2^{1-\nu}}{1-\nu} - \frac{\gamma^j}{2}(m_2 + \phi m_1)^2 \right]. \end{aligned} \tag{4.17}$$

Output y_t of the final good is produced using two types of capital, k_r and k_m, as well as fossil fuel according to the production technology f^c that exhibits constant returns to scale. In particular, assume that:

$$y_t = f^c(k_{r,t}, f^e(k_{m,t}, m_t)),$$

where $f^c(0, \cdot) = f^c(\cdot, 0) = 0$. In words, fossil fuel and "dirty" capital are combined as complements to produce an intermediate input, referred to as fossil-based energy, which is then used together with clean capital to produce the consumption good. Assume that, for simplicity, the initial capital stocks are $k_{m,1} > 0$ and $k_{r,1} = 0$, so that output in period 1 is produced only with fossil-based energy.

The capital stocks in period 2 are determined by investment $i_j = k_{j,2} + (1 - \delta_j)k_{j,1}$ for $j \in \{m, r\}$ in period 1, where δ_j denotes the depreciation rate for capital type j. Using fossil fuel is associated with an exogenous per-unit extraction cost p. Hence, the resource constraints in period 1 and period 2, respectively, read:

$$f^c(0, f^e(k_{m,1}, m_1)) = c_1 + k_{r,2} + k_{m,2} + pm_1 - (1 - \delta_m)k_{m,1} \tag{4.18}$$

$$f(k_{r,2}, f^c(k_{m,2}, m_2)) = c_2 + pm_2 - (1 - \delta_m)k_{m,2} - (1 - \delta_r)k_{r,2}. \tag{4.19}$$

A myopic government that anticipates to be in power in both periods maximizes (4.17) subject to (4.18) and (4.19), given the initial capital stocks. Let $k_{j,2}^{g*}$ and $k_{j,2}^{s*}$ denote the investment levels chosen by a myopic green and skeptic incumbent, respectively, for capital type $j \in \{m, r\}$.

As before, I assume that there are two types of governments, with preferences differing in γ^j, $j \in \{g, s\}$. The problem of the incumbent in period 1 reads:

$$\max_{c_1,k_{r,2},k_{m,2},m_1} u_1\left(f^c(0, f^e(k_{m,1}, m_1)) - k_{r,2} - k_{m,2} - pm_1\right) + \beta \mathsf{E}_j\left[u_2(c_2^j, m_1, m_2^j; \gamma^j)\right], \tag{4.20}$$

where c_2^j and m_2^j are functions of $k_{r,2}$, $k_{m,2}$ and m_1. The incumbent in period 2 solves

$$\max_{c_2,m_2} u_2\left(f^c(k_{r,2}, f^e(k_{m,2}, m_2)) + (1-\delta_m)k_{m,2} + (1-\delta_r)k_{r,2} - pm_2\right). \tag{4.21}$$

I solve the model for several scenarios regarding the functional forms chosen for f^c and f^e and, in particular, with respect to the elasticities of substitution both between clean and fossil-based energy in producing the final good, and between fossil fuel and dirty capital in producing fossil-based energy. As a starting point, assume that clean and fossil-based energy are perfect substitutes, while the latter is produced using a Cobb-Douglas technology:[10]

$$f^c(k_{r,2}, f^e(k_{m,2}, m_2)) = A\left[\chi k_{r,2}^{\alpha} + (1-\chi)k_{m,2}^{\theta} m_2^{\xi}\right], \tag{4.22}$$

where A denotes the level of total factor productivity (TFP).

Figures 4.1 and 4.2 illustrate the main results from the numerical analysis.[11] Define Δ^m, Δ^{k_m} and Δ^{k_r} as the relative deviations of the strategic emission and investment levels, respectively, in period 1 from the respective levels chosen by a myopic incumbent. Figure 4.1 plots the different Δs against the opponent's disutility weight γ^{opp} in the case of a green incumbent, while figure 4.2 shows a skeptic incumbent. Intuitively, when $\gamma^{inc} = \gamma^{opp}$, each type chooses its first-best levels and hence $\Delta = 0$.

[10] While labor is not explicitly modeled, (4.22) can be interpreted as if both sectors use a fixed amount of immobile labor equal to 1, if $\alpha < 1$ and $\theta + \xi < 1$.

[11] I choose the following parameter values when solving the model: $\nu = 1.5$, $\theta = 0.3$, $\xi = 0.03$, $\alpha = 0.5$, $\chi = 0.23$, $A = 4.4$, $p = 0.15$ and $\delta_m = \delta_r = 0.08$.

In contrast, the larger is the difference between γ^{inc} and γ^{opp}, the greater (in absolute values) is Δ. Moreover, these figures show a precautionary emission savings effect: when taking into account the possibility of losing power to an opponent with different preferences, both types reduce current emissions as long as $\phi > 0$. The size of these relative emission cuts increases in $|\gamma^{inc}$ - $\gamma^{opp}|$.

Figure 4.1 also shows that relative to the myopic case, a green incumbent shifts investment towards clean energy, and the more so the greater is $|\gamma^{inc}$ - $\gamma^{opp}|$. The intuition is similar to before: the incumbent government cannot directly choose the future carbon stock. Instead, it can affect it by manipulating the state for a possibly skeptic successor. In other words, by reducing dirty investment, the green type can induce her successor to lower emissions, due to the complementarity between dirty capital and fossil fuel. Once more, the green incumbent partially ties its successor's hand. Note that compared to the model in the previous section, there is a conceptual difference. Consider the case where $\gamma^{opp} = 0$. Then, if the skeptic opponent comes into power in period 2, her optimal emission level is given by $\xi \mu_m k_{m,2}^{\theta} m_2^{\xi-1} = p$ and thus, it is independent of the level of clean energy, due to the assumed separability of f. Hence, in contrast to the previous model, the incumbent does not tie her successor's hand by investing more in clean energy, but instead by investing less in dirty energy. The investment in clean energy is residually determined.

Note that this mechanism is analogous to numerous studies modeling the political economics of public good provision, following the seminal paper by Persson and Svensson (1989). As in their model, the incumbent faces a trade-off between a "volume distortion" and an "intertemporal distortion". Assume that the green incumbent in the first period were to implement the skeptic type's first-best capital stock, $k_{m,2}^{s}$. Then, a skeptic successor would choose its first-best fossil fuel level m_2^s. In this case, there would be no intertemporal distortion, but the emission level would be considerably higher than the first-best level of the the green type, hence resulting in a large volume distortion. Conversely, if the green

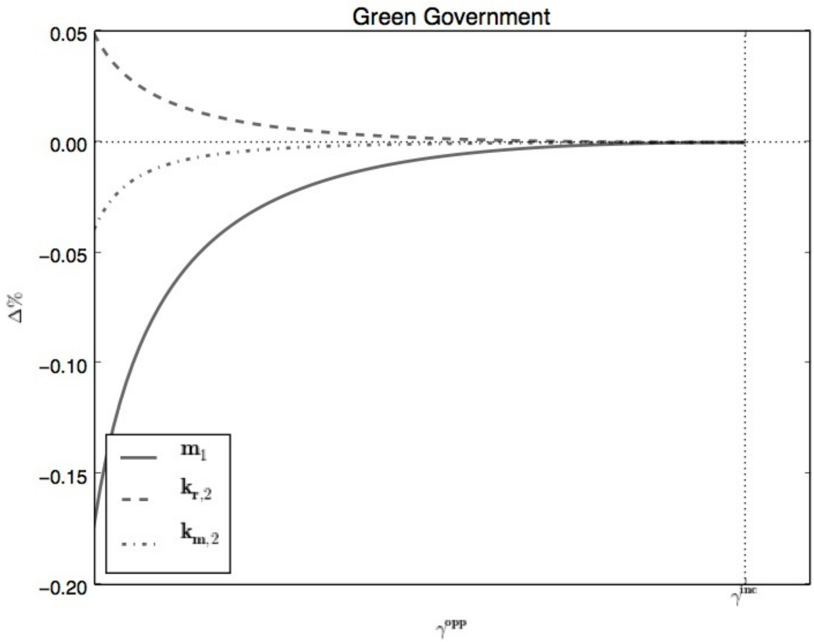

Figure 4.1: Green Incumbent

incumbent's investment choice resulted in a capital stock sufficiently low to induce its successor to set the pollution level to m_2^g, the first-best for the green type, there is no volume distortion from g's perspective, but a high intertemporal distortion.

Finally, figure 4.2 illustrates the idea of cushioning the blow. The greater $|\gamma^{inc}$ - $\gamma^{opp}|$, the less a skeptic incumbent invests in dirty capital. To understand the intuition, abstract from emission saving and assume that the investment decision were the same as in first-best. Since a green successor would cut emissions, the return to investment in dirty capital, given by $A(1-\chi)\theta k_{m,2}^{\theta-1} m_2^{\xi}$, decreases. In other words, due to the possibility of losing power, the return to investing in dirty capital is smaller relative to investing in clean energy. The skeptic incumbent takes this into account by shifting investment from one type of capital to the other.

In the remainder of this section, I discuss how these results are af-

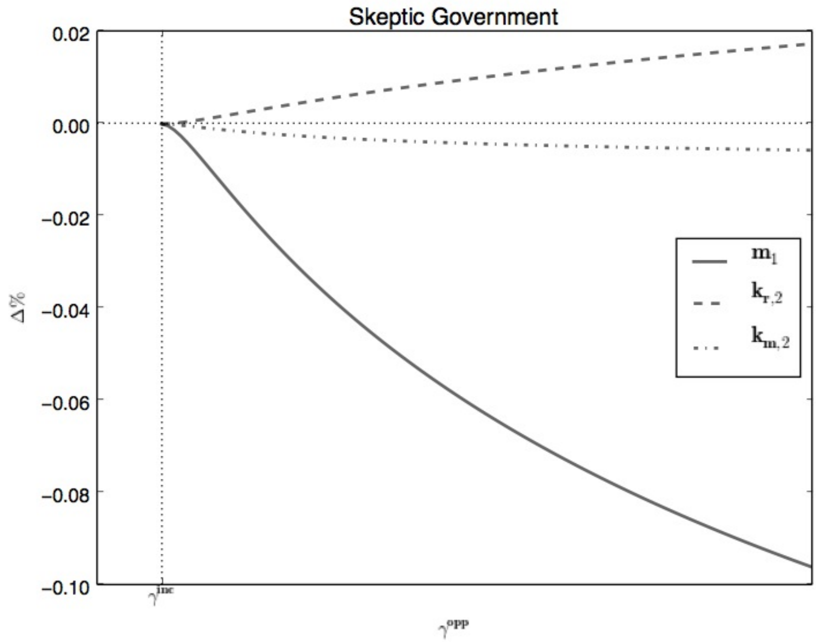

Figure 4.2: Skeptic Incumbent

fected when changing certain key assumptions of the model. In particular, consider the following scenarios:

First, assume that the elasticity of substitution in the production of fossil-based energy is zero, resulting in f^c being a Leontief production function:

$$f^c(k_{r,2}, f^e(k_{m,2}, m_2)) = A\left[\chi k_{r,2}^{\alpha} + (1-\chi)\min\left[k_{m,2}, m_2\right]\right]. \tag{4.23}$$

The implications for the green type are straightforward: since a skeptic successor will always set fossil fuel use equal to the capital stock, a green incumbent can implement its first-best allocation in period 2 by investing $k_{m,2}^{g*}$ and $k_{r,2}^{g*}$, respectively, and thus induce its successor to emit $m_2 = m_2^{g*}$. Hence, in this particular setting, the green type can completely tie its successor's hands. This also eliminates the incentive for precautionary emission saving; hence, $m_1 = m_1^{g*}$.

For a skeptic incumbent in period 1, the same argument holds, at least under certain conditions. Since the Leontief production technology does not impose a lower bound on fossil fuel use, it may be optimal for a green successor to emit less than m_2^{s*} if the marginal benefit of reducing emissions exceeds the marginal cost at $m_2 = m_2^{s*}$.[12] Otherwise, the skeptic type is able to tie a green successor's hands, and does not have an incentive for precautionary emission saving and cushioning the blow.

Next, assume that the elasticity of substitution in producing the final good is unity, resulting in a Cobb-Douglas production function:

$$f(k_{r,2}, f^c(k_{m,2}, m_2)) = Ak_{r,2}^{\upsilon_1} k_{m,2}^{\upsilon_2} m_2^{\upsilon_3}, \tag{4.24}$$

where $\upsilon_1 + \upsilon_2 + \upsilon_3 \leq 1$.[13] Hence, in this setting, clean and fossil-based energy are complements rather than perfect substitutes. Figure B.1 in the appendix illustrates the change in the relative deviations of the strategic emission and investment levels from the myopic outcomes. The dashed lines display the baseline model, as shown in 4.1 and 4.2, while the solid lines show the outcome with production function (4.24). First, note that relative to the myopic setting, both types reduce investment in dirty energy by less than in the baseline case. Intuitively, cutting fossil-based energy production is more expensive, since a perfect substitute is no longer available. As a consequence, while investment in clean energy in the baseline was higher than with myopic types, it is now lower, directly resulting from the complementarity. Moreover, both types cut emissions by less than in the baseline case. The skeptic type has a weaker incentive for precautionary emission saving, since she expects less stringent emission cuts from a green successor.

Finally, consider the same production function as in the baseline model, but let the probability of a political turnover be endogenous.

[12] Formally, as long as $m_2 \leq k_{m,2}$, output in period 2 is simply given by $A(\chi k_{r,2}^{\alpha} + (1-\chi)m_2)$ and thus the marginal cost of reducing emissions is $c_2^{-\nu} A(1-\chi)$, while the marginal benefit is $\gamma(\phi m_1 + m_2)$.

[13] More specifically, in terms of (4.22), $\upsilon_1 = \alpha\chi$, $\upsilon_2 = \theta(1-\chi)$ and $\upsilon_3 = \xi(1-\chi)$.

Analogous to the model in section 4.2, I find the following expression for the probability q of remaining in power:

$$q(k_{m,2}, k_{r,2}, m_1) = \frac{1}{2} - \Big[\zeta\Big(0.5\bar{\gamma}^h((\phi m_1 + m_2^{inc})^2 - (\phi m_1 + m_2^{opp})^2) + (1-\nu)^{-1}((c_2^{opp})^{1-\nu} - (c_2^{inc})^{1-\nu}\Big)\Big], \tag{4.25}$$

where $c_2^{inc} = c_2(k_{m,2}, k_{r,2}, m_1; \gamma^{inc})$ etc. Recall from before that endogeneizing the turnover probability had a reinforcing effect on precautionary emission saving, tying the hands and cushioning the blow if the difference between the preferred policy of the incumbent and the average voter were sufficiently large. An analogous result can be found here, as illustrated by figure B.2 in the appendix. It once more shows the relative deviations of the policies chosen by a strategic incumbent from the myopic case, now for both the baseline model and the model with endogenous turnover probability.[14] For both types, investment in clean energy increases relative to the baseline model, while emissions and investment in fossil-based energy decrease further.

In summary, the extent to which a strategic policy maker deviates from her myopic policy choices when taking political turnover into account crucially depends on the structure of the production technology and on what determines the probability of losing power. In the extreme case of perfect complementarity between capital and fossil fuel in the production of fossil-based energy, political instability does not affect the outcome. As I will show in the next section, however, this result is sensitive to increasing the number of periods.

The models considered in this section have an obvious drawback: the short horizon makes them unsuitable for a quantitative analysis of climate change, the consequences of which will have long-term effects. Therefore, in the next section, I apply a longer-horizon climate-economy model to the US economy in order to quantify the long-run effects of

[14] For each type, $\bar{\gamma}^h$ is set equal to the utility weight of the other type, and ζ is calibrated such that the probability of remaining in power equals 25%.

political instability on emissions and climate change.

4.3 Quantitative Analysis

The framework in this section follows the WITCH model (Bosetti et al., 2006, 2009) in that it features multiple types of capital, each used for the production of a different type of energy. However, the model here is considerably simpler than WITCH in several dimensions. First, WITCH is a "hybrid" model, combining a top-down economic growth model with a detailed bottom-up representation of the energy sector, with seven different technologies and as many types of capital for producing electricity alone. While WITCH can be solved sequentially, my model requires a recursive formulation. Hence, in order to avoid the "curse of dimensionality", I reduce the number of state variables to three, namely two capital stocks and cumulative emissions. Second, WITCH features endogenous technical change by incorporating both learning-by-doing and research and development in energy-producing technologies. I abstract from these mechanisms, once more in order to keep the numerical analysis tractable. Finally, I restrict my model to only one country, the US, in order to focus on the effects of political instability in a two-party system.

4.3.1 The Model

Similar to the model in the previous section, assume that an agent j's utility in period t is an additively separable function of consumption c_t and the level of cumulative emissions, denoted by s_t. Lifetime utility equals the discounted sum of per-period utility:

$$\sum_{t=0}^{\infty} \beta^t u(c_t, s_t) = \sum_{t=0}^{\infty} \beta^t l_t \frac{(c_t/l_t)^{1-\nu}}{1-\nu} - \gamma^j \frac{s_t^2}{2}, \tag{4.26}$$

where l_t denotes population and c_t/l_t consumption per capita in period t.

The consumption good is produced using capital k_c, labor l and total energy e, according to the production function $f(k_c, l, e)$ which exhibits constant returns to scale. Following WITCH, I assume that f is a constant elasticity of substitution (CES) function combining energy and a capital-labor composite, which is produced using a Cobb-Douglas technology:

$$\begin{aligned} y_t &= TFP_t \cdot f(k_{c,t}, l_t, e_t) \\ &= TFP_t \cdot \left[\theta_y \left(k_{c,t}^{\theta_c} l_t^{1-\theta_c}\right)^{\rho_y} + (1-\theta_y) e_t^{\rho_y}\right]^{\frac{1}{\rho_y}}, \end{aligned} \tag{4.27}$$

where TFP denotes total factor productivity, which grows exogenously over time. Note that since I focus on one country, in contrast to WITCH, I do not model global temperature change and hence there are no damages to productivity caused by climate change.

Total energy is a CES composite of two types of energy. The production of fossil-based energy e_b uses both capital and fossil fuel and hence generates carbon emissions. In contrast, since renewable energy is only produced with capital, it does not cause pollution. Formally, energy production is modeled by the following set of equations:

$$e_t = \left(\theta_e e_{m,t}^{\rho_e} + (1-\theta_e) e_{r,t}^{\rho_e}\right)^{\frac{1}{\rho_e}}, \tag{4.28}$$

with

$$e_{m,t} = \left(\theta_m (\mu_m k_{m,t})^{\rho_m} + (1-\theta_m)(\xi m_t)^{\rho_m}\right)^{\frac{1}{\rho_m}}, \tag{4.29}$$

and

$$e_{r,t} = \mu_r k_{r,t}. \tag{4.30}$$

k_m and k_r denote the capital stocks or the "power capacity" (measured in TW) for producing fossil-based and clean energy, respectively, while m denotes fossil fuel use (measured in TWh). Parameters μ_m and μ_r capture plant utilization rates, while the scalar ξ equals the reciprocal of the heat rate, that is, the amount of energy needed to generate a KWh of electricity. The different capital stocks evolve according to the following laws of motion:

$$k_{c,t+1} = (1 - \delta_c)k_{c,t} + i_{c,t} \tag{4.31}$$

$$k_{b,t+1} = (1 - \delta_b)k_{m,t} + \frac{i_{b,t}}{sc_{b,t}} \tag{4.32}$$

$$k_{r,t+1} = (1 - \delta_r)k_{r,t} + \frac{i_{r,t}}{sc_{r,t}}, \tag{4.33}$$

where $i_{j,t}$ denotes investment in capital of type j. As in the WITCH model, investment in energy-related capital involves an investment cost $sc_{j,t}$ (in $\$/TW$) for $j \in \{m, r\}$. Output is used on consumption, investment in the different types of capital and fuel cost. The resource constraint in the economy is then given by

$$y_t = c_t + i_{c,t} + i_{b_t} + i_{r,t} + p_t m_t, \tag{4.34}$$

where p_t denotes the exogenous price of fuel.

4.3.2 Calibration

4.3.2.1 Production

Starting with the production function for the final good, I follow WITCH and set the elasticity of substitution to $\sigma_y = 0.5$, implying that energy and the capital-labor composite are complements. The initial stock of general capital and the time series for total factor productivity and population are taken directly from WITCH.[15]

In the energy sector, I use data from the Energy Information Agency (EIA) for the electricity sector in 2010 to calibrate the initial capacities for fossil-based energy ($k_{m,0} = 0.78$ TW) and clean energy ($k_{m,0} = 0.04$ TW) . Note that since I do not distinguish between different types of fossil fuel, I add the generating capacities for gas and coal. The values for the plant utilization rates μ_m and μ_r are taken from WITCH, as well

[15] Since WITCH is calibrated to a shorter horizon than my model, I assume that both TFP and population remain constant from 2110 onwards.

as the heat rate $1/\xi$ and the rates of depreciation δ_m and δ_r.[16] Finally, in my baseline model, I assume the investment cost sc_m and sc_r and the fuel price p to be constant over time. In the WITCH model, these variables decrease over time due to endogeneous technical change, which I have omitted from the analysis. Note that this leads to an upward bias for the level of cumulative emissions.

As indicated in the discussion in section 4.2, an important variable for the questions at hand is the elasticity of substitution between fossil fuel and capital in the production of fossil-based energy. The WITCH model features a Leontief production function, i.e. $\sigma_m = 0$. In my analysis, I allow for a lower degree of complementarity in the baseline calibration by setting $\sigma_m = 0.5$, but also consider the Leontief case as part of my sensitivity analysis.

4.3.2.2 Utility

Following the calibration of the WITCH model, I assume utility to be logarithmic in consumption ($\nu = 1$) and set the annual discount factor to $\beta = 0.95$. Note that the corresponding *time* discount rate of about 5% is higher than what is usually assumed.[17] The *social* discount rate, however, also depends on the curvature of the utility function, represented by the parameter ν in (4.26), and the growth rate of consumption. In the WITCH model, the assumed TFP growth rate for the US, the region considered here, amounts to about 0.25% per year on average until 2100, much lower than the output growth assumed in the (global) DICE model. This results in a comparable social discount rate of about 5% in the baseline model below. I also report results for a setting with the social discount rate used in Golosov et al. (2014).

In order to calibrate the damage parameter γ, I use the no-turnover version of the model to target the social cost of carbon, which in this

[16] For variables related to fuel, I take weighted averages of the corresponding values for gas- and coal-based plants, using the initial capacities as weights.

[17] For example, the DICE model uses a discount rate of 1.5%. In the Stern review, it was substantially lower, at 0.1% (Stern, 2006).

paper equals the marginal emission damage, that is, the discounted sum of additional utility loss caused by increasing the current emission by a marginal unit. Formally, the SCC in period 0 can be expressed as (in dollar terms):

$$SCC_0 = -\sum_{t=0}^{\infty} \beta^t \frac{u_s(t)}{u_c(0)} = -\sum_{t=0}^{\infty} \beta^t \frac{\gamma s_t}{u_c(0)}. \tag{4.35}$$

Then, I match the SCC from the model to what the two parties in the US have stated as their preferred value. For the Democrats – the "green" type – I use the estimate found by an interagency working group of the current US government (IWG, 2010, 2013), which amounts to 33\$/tCO_2. There is no such estimate for the Republican party. However, since they reject any type of carbon pricing, I assume that $SCC_0 = 0$ and hence $\gamma = 0$. Note from (4.35) that the SCC depends on both γ and β. Hence, when running a sensitivity analysis with respect to the discount factor, I also need to adjust γ accordingly.

4.3.3 Solution Method

Due to the uncertainty of political change, I have to resort to recursive methods for solving the model. I use finite-horizon parametric dynamic programming in the spirit of Cai et al. (2012) and Cai et al. (2013). Starting at period $T = 50$, with one period comprising five years, I compute type j's current value function, taking next period's value function V^j_{T+1} as given.[18] I then go backwards in time and solve for V^j_t given V^j_{t+1}, where V^j_{t+1} is approximated using complete Chebyshev polynomials.[19] Having obtained approximations for the value functions, I then

[18]In the baseline model, I set $V^j_{T+1} = 0$. Having a positive continuation value does not have any effect on V^j_t until t is close to the final period, due to the low annual discount factor of $\beta = 0.95$. When running a sensitivity analysis with respect to β, I assume that from $T+1$ onwards, the economy is in a first-best with $\gamma = 0.5\gamma^g + 0.5\gamma^s$ for another 50 periods. I compute $\tilde{V} = \sum_{t=T+1}^{T+50} \beta^t u(c_t, s_t)$ and use this as the continuation value in $t = T$.

[19]The maximization step is performed in AMPL using the KNITRO solver (Ziena, 2013).

draw shocks from a binary distribution with $q = 0.5$ and simulate the economy 2000 times, reporting the averages below.

Following Cai et al. (2012), I use the results for the emission and capital stocks from solving no-turnover versions of the model sequentially to obtain the approximation grid in each period. Let $\{s_t^j, k_{r,t}^j, k_{b,t}^j\}$ denote the no-turnover outcome in period t when type j is in power. One way of constructing a grid, for example between $k_{r,t}^{\min}$ and $k_{r,t}^{\max}$, would be to set $k_{r,t}^{\min} = \min(k_{r,t}^g, k_{r,t}^s)$ and $k_{r,t}^{\max} = \max(k_{r,t}^g, k_{r,t}^s)$, and equivalently for the other states. However, this results in the approximation grids having an unnecessarily large range, thereby dampening the accuracy. Instead, I take into account that either type, when in power, chooses future capital stocks that are somewhat "close" to its first-best choice. Hence, for type j, I set $k_{r,t}^{\min} = \theta_{\min} k_{r,t}^g$ and $k_{r,t}^{\max} = \theta_{\max} k_{r,t}^g$ and an analogous grid for k_b. As a result, the approximation grids for each type are not the same, but differ along the k_r– and k_b–dimension. Since cumulative emissions are irreversible, the s-dimension is the same. Since this procedure requires that V_t^j is computed along both grids, it essentially doubles the number of maximization and fitting steps, while at the same time increasing the accuracy of the approximation. Note that this method of constructing the approximation grid requires that investment is not constrained to be non-negative, i.e. disinvestment must be feasible.

4.3.4 Results: Baseline Model

Figures 4.3 - 4.6 show the simulated time series for carbon emissions, both annual and cumulative, and clean and dirty capital between 2010 and 2100. The main result from this exercise is illustrated in figure 4.3. The solid lines show the emission levels over time in a setting with strategic incumbents, while the dashed lines correspond to the outcome with myopic incumbents. For comparison, the remaining lines give the first-best emission levels for the green and the skeptic type, respectively, in a setting without political turnover. Throughout the time period under consideration, annual and hence cumulative emissions under strategic incumbents are below the level that they would reach under myopic governments. In order to quantify this effect, I compute the magnitude of the average reduction in the business-as-usual (BAU) emission path that would achieve the same reduction in cumulative emission levels.[20] Formally, letting s_{2100}^{SB} (s_{2100}^{FB}) denote the strategic (myopic) cumulative emission level in 2100, I compute the λ that solves the following equation:

$$\sum_{t=2010}^{2100} (1-\lambda) m_t^{BAU} = s_{2100}^{SB} - s_{2100}^{FB}. \tag{4.36}$$

For the baseline model, I find $\lambda = 0.10$. In words, decreasing BAU emissions permanently by 10% would result in the same reduction in the cumulative emission stock that results from having strategic rather than myopic incumbents.

Figure 4.4 compares the no-turnover case with how the emission level would evolve if an incumbent were to take political uncertainty into account, but never lose power. I refer to this as the "permanent power" (PP) scenario. The graph indicates that, once more, strategic types implement higher emission cuts than myopic incumbents. At least part of the reason for this behavior is the emission saving effect, as outlined above.

Figures 4.5 and 4.6 show the evolution of the green and the dirty capital stock, respectively, over time, comparing the strategic outcome (solid line) to the myopic case (dashed line) and the stocks without political turnover. In addition, it also plots how capital evolves in the permanent-power scenarios. As illustrated by figure 4.5, in the latter case, where incumbents take uncertainty into account, both types invest less in dirty capital than when they remain in office with certainty. As a result, the strategic dirty capital stock is smaller than in the myopic setting. For green capital, figure 4.6 shows that these relationships are just reversed.

Figures 4.3 - 4.5 provide evidence of the same effects being in play as before. In particular, figures 4.5 and 4.6 indicate that both types

[20] The business-as-usual outcome is defined by $\gamma = 0$ in every period.

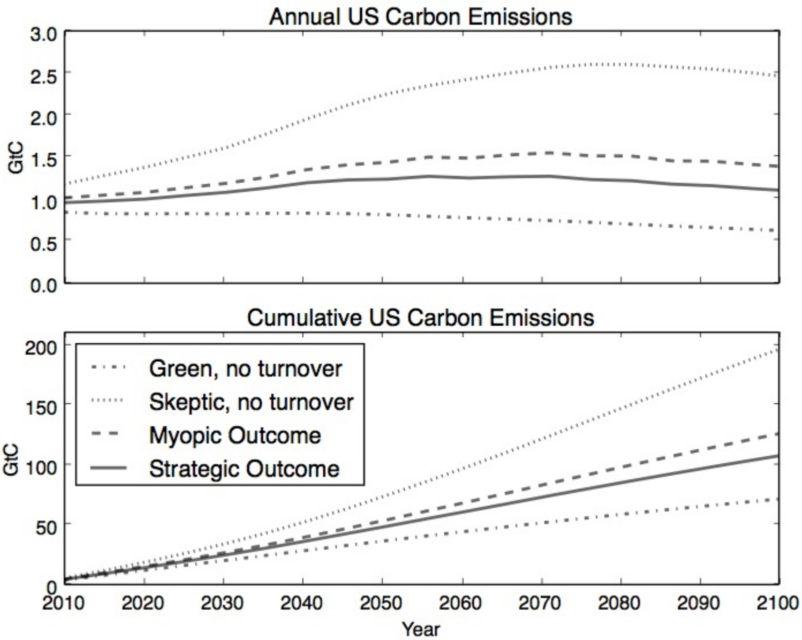

Figure 4.3: Baseline Model - Emissions

shift investment from dirty to green capital, either to tie the successor's hands in case of a green incumbent or to cushion the blow for a skeptic type. Since dirty capital is a complement to fossil fuel, reducing the dirty capital stock contributes to the decrease in carbon emissions illustrated in figures 4.3 and 4.4, further amplifying the emission savings effect. In order to disentangle precautionary emission saving from tying the successor's hands and cushioning the blow, I compute the emission level under "constrained permanent power" (CPP), that is, the incumbent chooses fuel use but is constrained to implement the same investment levels as in the no-turnover case. In some sense, incumbents in this scenario are "partially myopic": they do realize that they may lose power in the future, but they only adjust emission levels, not investment. In this setting, tying the successor's hands and cushioning the blow is not feasible; hence, emission reduction is solely due to precautionary emission saving. Then,

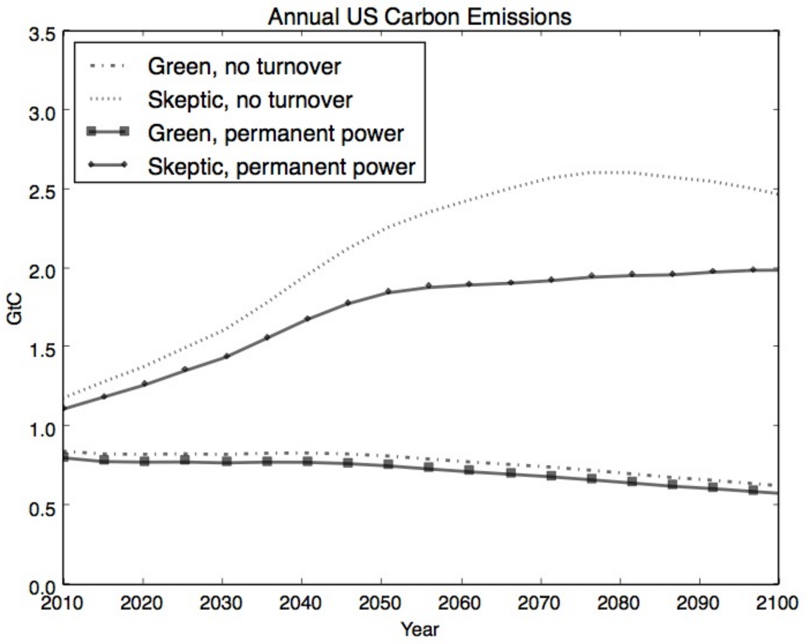

Figure 4.4: Baseline Model - Emissions: FB vs. permanent power

I relate the difference in emission levels between the PP and no-turnover scenarios for both the green and the skeptic type to the corresponding difference between CPP and no-turnover and compute the average over time. Formally, define Δ^j in the following way:

$$\Delta^j = \frac{1}{T} \sum_{t=2010}^{2100} \left(\frac{m_t^{j,CPP} - m_t^{j,FB}}{m_t^{j,PP} - m_t^{j,FB}} \right), \tag{4.37}$$

for $j \in \{g, s\}$. Δ^j serves as a measure for the importance of the emission savings effect: if $\Delta^j = 0$, there is no precautionary emission saving and emission cuts are solely caused by a reduction in the dirty capital stock. On the other hand, if $\Delta^j = 1$, the incumbent being able to adjust investment does not affect the emission level. For the baseline model, I find $\Delta^g = 0.59$ and $\Delta^s = 0.84$, indicating that precautionary emission saving is the dominating effect.

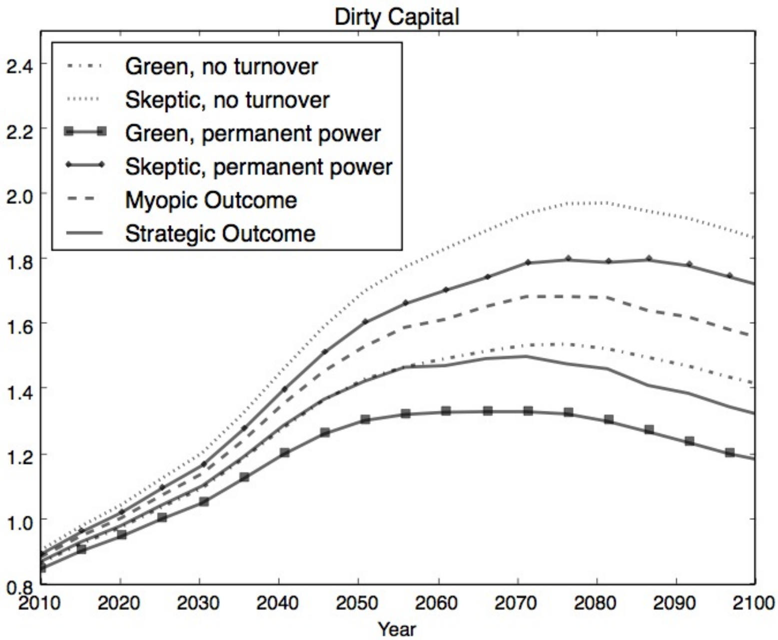

Figure 4.5: Baseline Model - Dirty Capital

4.3.5 Results: Sensitivity Analysis

Table 4.1 gives an overview of the key variables for different model scenarios. Recall that λ measures the quantitative impact of having strategic rather than myopic policy makers, while Δ^j is an indicator of the relative importance of precautionary emission saving.

Scenario	λ	Δ^g	Δ^s
Baseline	0.10	0.59	0.84
Leontief	0.05	0	0
$\beta = 0.985$	0.13	0.62	0.81

Table 4.1: Results

First, I assume that fossil-based energy is produced with a Leontief production function. That is, the elasticity of substitution σ^m between dirty capital and fossil fuel is 0 rather than 0.5 as in the baseline cali-

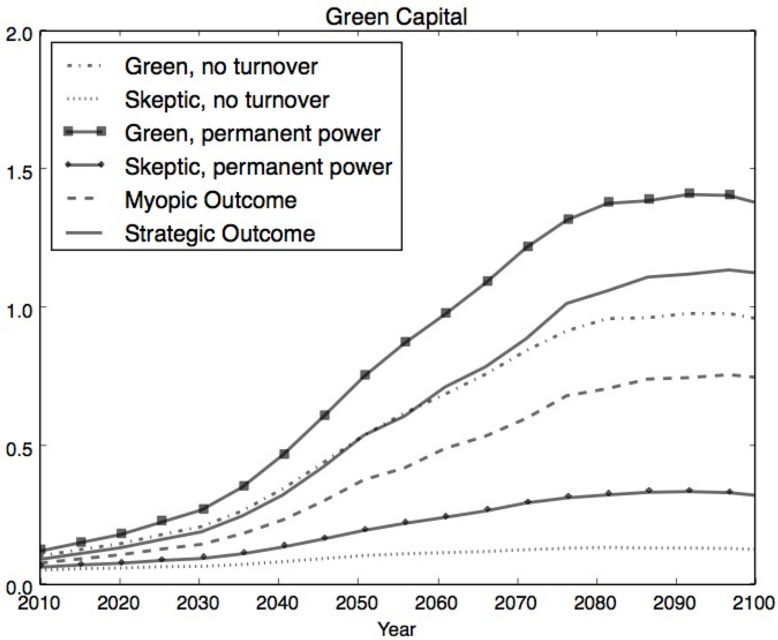

Figure 4.6: Baseline Model - Green Capital

bration. The production function is given by:

$$e_{m,t} = \min(\mu_m k_{m,t}, \xi m_t) \tag{4.38}$$

As discussed above, this essentially allows an incumbent to completely tie its successor's hands: due to perfect complementarity between capital and emissions, the choice of investment also determines fossil fuel use in the subsequent period, unless the marginal benefit of reducing emissions and hence letting some capital lay idle exceeds the cost. Hence, in the CPP scenario where investment adjustments are not possible, emissions are at the no-turnover level and thus $\Delta^j = 0$.

In the two-period model, a consequence of this perfect complementarity was that there was no difference between the strategic and the myopic allocation. Here, while the strategic outcome is closer to the myopic setting than in the baseline model, the two scenarios do not feature identical equilibria, as illustrated in figures B.3 - B.6 in the appendix. The difference in cumulative emissions corresponds to a BAU emission reduction of $\lambda = 5\%$. The intuition is straightforward: if the number of periods exceeds two, the current policy maker takes not only the subsequent period into account, but also the more distant future. Consider the example with a skeptic incumbent in $t = 0$: implementing her no-turnover investment level would induce her preferred emission level in $t = 1$. However, from the perspective of a green successor in $t = 1$, cumulative emissions would then be suboptimally high, inducing her to reduce investment below the no-turnover level in order to tie the hands of the government in $t = 2$. Therefore, the period-0 incumbent has an incentive to reduce investment in dirty capital in order to dampen the tying-the-hands adjustment in period 1. In other words, she is willing to reduce emissions tomorrow in order to have less drastic emissions cuts the day after and thus smooth future emission cuts over time. At the same time, it is not surprising that the strategic emission and investment levels are closer to the myopic allocation, since the perfect complementarity reduces the flexibility of the successor and hence the need for the current incumbent to adjust to future behavior.

The third line in table 4.1 displays the results for λ, Δ^g and Δ^s when increasing the discount factor to $\beta = 0.985$, following, for example, Golosov et al. (2014).[21] As explained above, since the growth rate for the US assumed by WITCH is low, the social discount rate in this setting would be around 1.8%, close to the rate used in the Stern review (Stern, 2006). For comparability, I adjust the utility parameter γ to once more target the SCC in the no-turnover model. I find that all three indicators are close to the baseline model. Most notably, λ is modestly higher, implying a higher impact of strategic policy making on emissions.

[21] Compare also figures B.7 - B.10 in the appendix.

4.4 Conclusion

As of today, there is little to no coordination or cooperation between countries outside the European Union with regard to climate change mitigation. Instead, climate policy is usually set at the national level and is hence affected, like other areas of intertemporal public policy making, by the risk of political turnover.

In this paper, I have analyzed climate policy making under political instability and strategic behavior. I have used a set of standard neo-classical models with two parties and either exogenous or endogenous turnover to show that either party has an incentive to increase the extent of emission mitigation and shift investment away from capital that is complementary to fossil fuel, relative to a corresponding myopic incumbent. To quantify the effect of governments behaving strategically, I have calibrated a model of the US economy and found that the change in cumulative emissions by 2100 is equivalent to reducing BAU emissions permanently by around 10%.

Do policy makers act strategically or myopically? In the context of debt accumulation, some stylized facts as well as evidence on the municipal level indicate that there exists a correlation between policy choices and reelection probabilities (Pettersson-Lidbom, 2001; Persson and Tabellini, 2002). For climate policy, a similar empirical analysis is very difficult, as both the fact that it is usually set by national governments and that it is a rather recent field of policy making lead to there being little to no data available.

The models used in this paper have been stylized and simple in a number of important dimensions, and leave much room for future research. First and foremost, they only included one region, since focusing on a single country appears to be the natural starting point for analyzing the effect of the political process on national climate change mitigation. A next step would add other countries or regions to the framework. This would also allow the modeler to focus on global mean temperature change as a function of global emissions and hence directly on damages caused by climate change, rather than on cumulative emissions. Note, however, that such a model would imply two dimension of strategic interaction: policy makers would not only have to take into account the behavior of possible successors at the national level, but also play a game with other governments. Moreover, as outlined above, the results of the quantitative analysis were biased towards a possibly too pessimistic view, since I have abstracted from endogenous technical change. If investing in clean capital and generating clean energy leads to a cost reduction, this opens an additional channel through which policy makers can affect the future state of the economy and hence may strengthen the incentive for a strategic incumbent to tie its successor's hands. Introducing endogenous technical change, for example along the lines of the WITCH model, might be a worthwhile extension of the framework used in this paper.

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A Theory

A.1 Proof of Proposition 1

Proof. Using (4.4) in (4.11) gives:

$$\hat{m}_1 = \frac{\kappa + \beta\hat{Q}(b - \phi\kappa)}{\kappa + \beta\hat{Q}(b + \phi^2\kappa)}\bar{m}, \tag{4.39}$$

where $\hat{Q} \equiv Q(\tilde{\gamma}; \hat{\gamma}, q)$. Taking the derivative with respect to $\hat{Q}$ yields:

$$\frac{\partial \hat{m}_1}{\partial \hat{Q}} = \frac{\kappa[\beta(b - \phi\kappa) - \beta(b + \phi^2\kappa)}{[\kappa + \beta\hat{Q}(b + \phi^2\kappa)]^2}\bar{m} < 0. \tag{4.40}$$

Moreover, using (4.39) and (4.4) in (4.12)

$$\hat{k}_r = \frac{\beta b\hat{Q}}{\kappa + \beta b\hat{Q}} \cdot \frac{(1 + \phi)(\kappa + \beta b\hat{Q})}{\kappa + \beta\hat{Q}(b + \phi^2\kappa)}\bar{m} = \frac{(1 + \phi)\beta b\hat{Q}}{\kappa + \beta b\hat{Q} + \beta\phi^2\kappa\hat{Q}}\bar{m}. \tag{4.41}$$

Taking the derivative with respect to $\hat{Q}$ gives:

$$\begin{aligned} \frac{\partial \hat{k}_r}{\partial \hat{Q}} &= (1 + \phi)\frac{\beta b(\kappa + \beta b\hat{Q} + \beta\phi^2\kappa\hat{Q}) - \beta b\hat{Q}(\beta b + \beta\phi^2\kappa)}{[\kappa + \beta b\hat{Q} + \beta\phi^2\kappa\hat{Q}]^2}\bar{m} \\ &= \frac{(1 + \phi)\beta b\kappa\bar{m}}{[\kappa + \beta b\hat{Q} + \beta\phi^2\kappa\hat{Q}]^2} > 0. \end{aligned} \tag{4.42}$$

Next, recall the definition of Q:

$$Q(x; \hat{\gamma}, q) = q\frac{\hat{\gamma}}{b + \hat{\gamma}} + (1 - q)\frac{x^2 + b\hat{\gamma}}{(b + x)^2}. \tag{4.43}$$

The first derivative of Q with respect to x reads:

$$Q_x(x; \hat{\gamma}, q) = (1 - q)\frac{2b^2x - 2b^2\hat{\gamma} + 2bx^2 - 2b\hat{\gamma}x}{(b + x)^4}. \tag{4.44}$$

Since $Q_x(\hat{\gamma};\hat{\gamma},q)=0$ (and $Q_{xx}>0$), $Q(x;\hat{\gamma},q)$ has a (local) minimum at $x=\hat{\gamma}$. Hence, for any $\tilde{\gamma}\neq\hat{\gamma}$,

$$Q^*=Q(\hat{\gamma};\hat{\gamma},q)=\hat{\gamma}/(b+\hat{\gamma})<Q(\tilde{\gamma};\hat{\gamma},q).$$

With (4.40) and (4.42) and

$$m_1^*=\frac{\kappa+\beta Q^*(b-\phi\kappa)}{\kappa+\beta Q^*(b+\phi^2\kappa)}\bar{m},\;\; k_r^*=\frac{(1+\phi)\beta bQ^*}{\kappa+\beta bQ^*+\beta\phi^2\kappa Q^*}\bar{m},$$

this proves the first part of the proposition. For the second part, define $\check{\gamma}=\rho\hat{\gamma}+(1-\rho)\tilde{\gamma}$, and let $\check{Q}=\frac{\check{\gamma}^2+b\hat{\gamma}}{(b+\check{\gamma})^2}$. Then, the incumbent's optimal policy in period 1, taking into account that m_2 is chosen to maximize a weighted average of utilities, is given by:

$$\check{m}_1=\frac{\kappa+\beta\check{Q}(b-\phi\kappa)}{\kappa+\beta\check{Q}(b+\phi^2\kappa)}\bar{m},\;\; \check{k}_r=\frac{(1+\phi)\beta b\check{Q}}{\kappa+\beta b\check{Q}+\beta\phi^2\kappa\check{Q}}\bar{m}.$$

Given (4.40) and (4.42), the proposition holds when $\check{Q}<\hat{Q}$, and hence when:

$$\frac{\check{\gamma}^2+b\hat{\gamma}}{(b+\check{\gamma})^2}<q\frac{\hat{\gamma}}{b+\hat{\gamma}}+(1-q)\frac{\tilde{\gamma}^2+b\hat{\gamma}}{(b+\tilde{\gamma})^2}.$$

Rearranging shows that this is the case when $q<\bar{q}$, where $\bar{q}$ is given by:

$$\bar{q}\equiv\frac{\frac{\tilde{\gamma}^2+b\hat{\gamma}}{(b+\tilde{\gamma})^2}-\frac{\check{\gamma}^2+b\hat{\gamma}}{(b+\check{\gamma})^2}}{\frac{\tilde{\gamma}^2+b\hat{\gamma}}{(b+\tilde{\gamma})^2}-\frac{\hat{\gamma}}{b+\hat{\gamma}}}.$$

■

A.2 Proof of Proposition 2

Proof. With (4.39) and (4.41), the objective function in (4.10) can be written as

$$
\begin{aligned}
U &= -\frac{1}{2}\bar{m}\frac{b[\beta\kappa Q(\phi^2+\phi)]^2 + \kappa[(1+\phi)\beta b Q]^2 + \beta b Q[(1+\phi)\kappa]^2}{[\kappa+\beta Q(b+\phi^2\kappa)]^2} \\
&= -\frac{1}{2}\bar{m}\frac{[b\beta^2\kappa^2\phi^2(1+\phi)^2 + \kappa(1+\phi)^2\beta^2 b^2]Q^2 + [\beta b(1+\phi)^2\kappa^2]Q}{[\kappa+\beta Q(b+\phi^2\kappa)]^2} \\
&\equiv \mu(Q)
\end{aligned}
$$

Taking the derivative gives $\mu'(Q) < 0$ and hence utility decreases in Q. For the incumbent, since $\check{Q} < \hat{Q}$ for $q < \bar{q}$, it follows that $\mu(\check{Q}) > \mu(\hat{Q})$: under cooperation in period 2, its total utility is higher than in the non-cooperative regime. ■

A.3 Decentralized Economy

Consider the problem of a representative household with preferences given by (4.1) and (4.2) that produces energy in periods 1 and 2. Since emissions are an externality, it takes into account the private benefit of fossil fuel use, but not the cost. Focusing on the problem in period 2, it makes an investment in clean capital in period 1 and emits carbon in period 2. Let τ^m ($\tilde{\tau}^m$) denote the carbon tax if the current incumbent (the current opposition) is in power in period 2. Moreover, let τ^r denote an investment subsidy, financed by a lump-sum tax. The household's problem then reads:

$$
\begin{aligned}
\max_{k_r, m_2, \tilde{m}_2} \quad & -\frac{\kappa-\tau^r}{2}k_r^2 + \beta\Bigg[q\left(-\frac{b}{2}[\bar{m}-m_2-k_r]^2 - \frac{\tau^m}{2}m_2^2\right) \\
& + (1-q)\left(-\frac{b}{2}[\bar{m}-\tilde{m}_2-k_r]^2 - \frac{\tilde{\tau}^m}{2}m_2^2\right)\Bigg] - C
\end{aligned}
$$

where C captures the cost of expected cumulative emission, taken as given.

Taking first-order conditions, it is straightforward to show that for any given k_r and m_1, the period-1 incumbent, if remaining in power, can implement its preferred policy rule (4.8) by setting τ^m equal to

$$\tau^m = \frac{b\gamma(\bar{m} - k_r) + b\phi\gamma^j m_1}{b(\bar{m} - k_r) - \phi\gamma^j m_1}. \tag{4.45}$$

An analogous expression holds if the period-1 opposition comes into office. From the first-order condition with respect to k_r, using the fact that m_2 and $\tilde{m}_2$ are chosen according to (4.8), I can solve for the following expression for k_2 given m_1:

$$k_2^d = \frac{\beta b\Gamma}{\kappa - \tau^r + \beta b\Gamma}(\bar{m} + \phi m_1), \tag{4.46}$$

where

$$\Gamma = q\frac{\gamma}{b+\gamma} + (1-q)\frac{\tilde{\gamma}}{b+\tilde{\gamma}}. \tag{4.47}$$

Assume that the carbon tax in period 1 is set such that m_1 is set according to (4.11). Then, from (4.12), it is straightforward to see that k_2^d is equal to the strategic outcome k_2^{SB} if:

$$\frac{\beta b\Gamma}{\kappa - \tau^r + \beta b\Gamma} = \frac{\beta bQ(\tilde{\gamma};\gamma,q)}{\kappa + \beta bQ(\tilde{\gamma};\gamma,q)}. \tag{4.48}$$

Solving for τ^r, I find that the strategic outcome is decentralized by setting:

$$\tau^r = \frac{(Q(\tilde{\gamma};\gamma,q) - \Gamma)\,\kappa}{Q(\tilde{\gamma};\gamma,q)}. \tag{4.49}$$

Note also that if an investment subsidy is not feasible, I have that $k_r^d < k_r^{SB}$ if the incumbent in period 1 is green ($\gamma > \tilde{\gamma}$), since then $\Gamma < Q(\tilde{\gamma};\gamma,q)$. Hence, there is underinvestment in clean energy and implementing the strategic equilibrium in a decentralized economy is not possible. This result was shown by Ulph and Ulph (2013). This finding is reversed in the case of a skeptic incumbent with $\gamma < \tilde{\gamma}$ and thus $\Gamma > Q(\tilde{\gamma};\gamma,q)$, implying that the decentralized solution features more investment in green energy than what the incumbent perceives as optimal.

A.4 Derivation of the turnover probability

The swing voter has the utility cost $\gamma_j^h = \gamma^{sw}$ such that $\Delta(\hat{m}_1, \hat{k}_r; \gamma^{sw}) + \psi = 0$. Using the definition of ψ and rearranging yields:

$$\left[\frac{\hat{\gamma}^2 + b\gamma^{sw}}{(b+\hat{\gamma})^2} - \frac{\tilde{\gamma}^2 + b\gamma^{sw}}{(b+\tilde{\gamma})^2}\right] = \left[\frac{b}{2}(\bar{m} - k_r + \phi m_1)^2\right]^{-1} \psi$$

$$\begin{aligned}\gamma^{sw} &= \left[\frac{b}{(b+\hat{\gamma})^2} - \frac{b}{(b+\tilde{\gamma})^2}\right]^{-1} \left[\frac{b}{2}(\bar{m} - k_r + \phi m_1)^2\right]^{-1} \psi + \gamma \\ &= A^{-1}B^{-1}\psi + \gamma^+,\end{aligned}$$

where

$$\gamma^+ \equiv \left[\frac{b}{(b+\hat{\gamma})^2} - \frac{b}{(b+\tilde{\gamma})^2}\right]^{-1} \left[\frac{\tilde{\gamma}^2}{(b+\tilde{\gamma})^2} - \frac{\hat{\gamma}^2}{(b+\hat{\gamma})^2}\right].$$

Consider first the case of a skeptic incumbent in period 1, i.e. $\hat{\gamma} < \tilde{\gamma}$. Its vote share is then given by:

$$\pi^I = \text{Prob}(\gamma_j^h < \gamma^{sw}) = \frac{\gamma^{sw} - \gamma_{min}}{\gamma_{max} - \gamma_{min}}. \tag{4.50}$$

Hence, the probability of being reelected can be written as:

$$\begin{aligned}q = \text{Prob}\left(\pi^I \geq \frac{1}{2}\right) &= \text{Prob}\left(\gamma^{sw} \geq \frac{1}{2}(\gamma_{min} + \gamma_{max})\right) \\ &= \text{Prob}\left(A^{-1}B^{-1}\psi \geq \frac{1}{2}(\gamma_{min} + \gamma_{max}) - \gamma^+\right) \\ &= \text{Prob}\left(\psi \geq AB(\bar{\gamma}^h - \gamma^+)\right) \\ &= 1 - \text{Prob}\left(\psi \leq AB(\bar{\gamma}^h - \gamma^+)\right) \\ &= 1 - \frac{AB(\bar{\gamma}^h - \gamma^+) + \frac{1}{2\zeta}}{\frac{1}{2\zeta} + \frac{1}{2\zeta}} \\ &= \frac{1}{2} - \zeta AB(\bar{\gamma}^h - \gamma^+) \\ &= \frac{1}{2} - \zeta \frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \left[\frac{b}{(b+\hat{\gamma})^2} - \frac{b}{(b+\tilde{\gamma})^2}\right](\bar{\gamma}^h - \gamma^+).\end{aligned}$$

Next, assume that the incumbent in period 1 is green, i.e. $\hat{\gamma} > \tilde{\gamma}$. Note that this implies that

$$A = \left[\frac{b}{(b+\hat{\gamma})^2} - \frac{b}{(b+\tilde{\gamma})^2} \right] < 0.$$

The incumbent's vote share is given by:

$$\pi^I = \text{Prob}(\gamma_j^h > \gamma^{sw}) = \frac{\gamma_{max} - \gamma^{sw}}{\gamma_{max} - \gamma_{min}}. \tag{4.51}$$

Hence, the probability of remaining in power is:

$$\begin{aligned}
q &= \text{Prob}\left(\pi^I \geq \frac{1}{2}\right) = \text{Prob}\left(\gamma^{sw} \leq \frac{1}{2}(\gamma_{min} + \gamma_{max})\right) \\
&= \text{Prob}\left(A^{-1}B^{-1}\psi \leq \frac{1}{2}(\gamma_{min} + \gamma_{max}) - \gamma^+\right) \\
&= \text{Prob}\left(\psi \geq AB(\bar{\gamma}^h - \gamma^+)\right) \\
&= 1 - \text{Prob}\left(\psi \leq AB(\bar{\gamma}^h - \gamma^+)\right) \\
&= \frac{1}{2} - \zeta \frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \left[\frac{b}{(b+\hat{\gamma})^2} - \frac{b}{(b+\tilde{\gamma})^2} \right] (\bar{\gamma}^h - \gamma^+),
\end{aligned}$$

where the second-last equality is due to the fact that $A < 0$.

A.4.1 Proof of Proposition 3

Proof. To save on notation, denote

$$\Gamma = \left[\frac{b}{(b+\hat{\gamma})^2} - \frac{b}{(b+\tilde{\gamma})^2} \right] (\bar{\gamma}^h - \gamma). \tag{4.52}$$

The objective function can be written as

$$
\begin{aligned}
U = &- \frac{b}{2}(\bar{m} - m_1)^2 - \frac{\kappa}{2}k_r^2 \\
&- \beta \left[\left(\frac{1}{2} - \zeta \frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \Gamma \right) \frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \frac{\hat{\gamma}}{b + \hat{\gamma}} + \right. \\
&\qquad \left. \left(\frac{1}{2} + \zeta \frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \Gamma \right) \frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \frac{\tilde{\gamma}^2 + b\hat{\gamma}}{(b + \tilde{\gamma})^2} \right] \\
= &- \frac{b}{2}(\bar{m} - m_1)^2 - \kappa \frac{k_r^2}{2} - \beta \frac{b}{2}(\bar{m} - k_r + \phi m_1)^2 \left[\frac{1}{2} \frac{\hat{\gamma}}{b + \hat{\gamma}} + \frac{1}{2} \frac{\tilde{\gamma}^2 + b\hat{\gamma}}{(b + \tilde{\gamma})^2} \right] \\
&- \beta \zeta \Gamma \left(\frac{b}{2} \right)^2 (\bar{m} - k_r + \phi m_1)^4 \underbrace{\left[- \frac{\hat{\gamma}}{b + \hat{\gamma}} + \frac{\tilde{\gamma}^2 + b\hat{\gamma}}{(b + \tilde{\gamma})^2} \right]}_{\equiv A}
\end{aligned}
$$

Note that since $\gamma/(b+\hat{\gamma}) < (\tilde{\gamma}^2 + b\hat{\gamma})/(b+\tilde{\gamma})^2$, $A < 0$. Taking derivatives w.r.t. m_1 and k_r yields:

$$
\underbrace{\bar{m} - m_1 - \beta\phi(\bar{m} - k_r + \phi m_1) Q(\tilde{\gamma}; c, 0.5)}_{\equiv f_1(m_1, k_r)} = \underbrace{\beta\phi\zeta b(\bar{m} - k_r + \phi m_1)^3 A\Gamma}_{\equiv g_1(m_1, k_r)} \tag{4.53}
$$

and

$$
\underbrace{-\kappa k_r + \beta b(\bar{m} - k_r + \phi m_1) Q(\tilde{\gamma}; c, 0.5)}_{\equiv f_2(m_1, k_r)} = \underbrace{-\beta\zeta b^2(\bar{m} - k_r + \phi m_1)^3 A\Gamma}_{\equiv g_2(m_1, k_r)}. \tag{4.54}
$$

From (4.53) and (4.54), define the function $\mathbf{h} : \mathbb{R}^2 \to \mathbb{R}^2$ as

$$
\mathbf{h}(m_1, k_r) = \mathbf{f}(m_1, k_r) + \mathbf{g}(m_1, k_r) = \begin{bmatrix} f_1(m_1, k_r) \\ f_2(m_1, k_r) \end{bmatrix} + \begin{bmatrix} g_1(m_1, k_r) \\ g_2(m_1, k_r) \end{bmatrix}.
$$

Note that $\mathbf{f}(m_1, k_r)$ gives the first-order conditions for the case with exogenous turnover probability $p = 0.5$. Let m_1^{exo} and k_r^{exo} denote the optimal policy in this case. Hence, $\mathbf{f}(m_1^{exo}, k_r^{exo}) = \mathbf{0}$. Then, a linear approximation to $\mathbf{h}(m_1, k_r)$ around $\{m_1^{exo}, k_r^{exo}\}$ reads:

$$\mathbf{h}(m_1, k_r) = \mathbf{g}(m_1^{exo}, k_r^{exo}) + \begin{bmatrix} f_{1,m} + g_{1,m} & f_{1,r} + g_{1,r} \\ f_{2,m} + g_{2,m} & f_{2,r} + g_{2,r} \end{bmatrix} \begin{bmatrix} m_1 - m_1^{exo} \\ k_r - k_r^{exo} \end{bmatrix},$$

where $f_{1,m} = \partial f_1(m_1^{exo}, k_r^{exo})/\partial m_1$ etc.

From (4.53) and (4.54), it is easy to verify that taking derivatives for f_1 and f_2 yields:

$$f_{1,m} < 0, \quad f_{1,r} > 0, \quad f_{2,m} > 0, \quad f_{2,r} < 0.$$

The signs of the derivatives of g_1 and g_2 depend on the sign of Γ. Assume that Γ is positive. Then,

$$g_{1,m} < 0, \quad g_{1,r} > 0, \quad g_{2,m} > 0, \quad g_{2,r} < 0,$$

and, moreover, $g_1(m_1^{exo}, k_r^{exo}) < 0$ and $g_2(m_1^{exo}, k_r^{exo}) > 0$. Hence, since $f_{i,j}$ and $g_{i,j}$ have the identical signs for all possible combinations of j and j, the sign of $h_{i,j} = f_{i,j} + g_{i,j}$ is unambiguous. Note that this is not the case if $\Gamma < 0$.

Next, consider the system of linear equations given by

$$\mathbf{h}(m_1, k_r) = \begin{bmatrix} \bar{g}_1 \\ \bar{g}_2 \end{bmatrix} + \begin{bmatrix} h_{1,m} & h_{1,r} \\ h_{2,m} & h_{2,r} \end{bmatrix} \begin{bmatrix} m_1 - m_1^{exo} \\ k_r - k_r^{exo} \end{bmatrix},$$

where $\bar{g}_1 = g_1(m_1^{exo}, k_r^{exo})$ and $\bar{g}_2 = g_2(m_1^{exo}, k_r^{exo})$. Basic algebra shows that

$$m_1 - m_1^{exo} = \frac{h_{1,r}(-\bar{g}_2) - h_{2,r}(-\bar{g}_1)}{h_{1,r}h_{2,m} - h_{2,r}h_{1,m}}, \quad k_r - k_r^{exo} = \frac{h_{2,m}(-\bar{g}_1) - h_{1,m}(-\bar{g}_2)}{h_{1,r}h_{2,m} - h_{2,r}h_{1,m}}$$

Evaluating these expressions shows that

$$h_{1,r}h_{2,m} - h_{2,r}h_{1,m}$$
$$= -[\kappa + \beta(b + \kappa\phi)(Q(\tilde{\gamma}; c, 0.5) + 3\zeta b(\bar{m} - k_r + \phi m_1)^2 A\Gamma)] < 0,$$

$$h_{1,r}(-\bar{g}_2) - h_{2,r}(-\bar{g}_1) = \beta\kappa\zeta\phi b(\bar{m} - k_r + \phi m_1)^3 A\Gamma > 0,$$

$$h_{2,m}(-\bar{g}_1) - h_{1,m}(-\bar{g}_2) = -\beta\zeta b^2(\bar{m} - k_r + \phi m_1)^3 A\Gamma < 0,$$

and hence $m_1 - m_1^{exo} < 0$ and $k_r - k_r^{exo} > 0$.

To complete the proof, it remains to show under what conditions $\Gamma > 0$. From the definition (4.52), it is easy to distinguish two cases. When $\hat{\gamma} > \tilde{\gamma}$, the term in the brackets is negative and hence it must be that $\bar{\gamma}^h < \hat{\gamma}$ for Γ to be positive. The opposite is true for $\hat{\gamma} < \tilde{\gamma}$, which implies that $\bar{\gamma}^h > \hat{\gamma}$.

■

B Figures

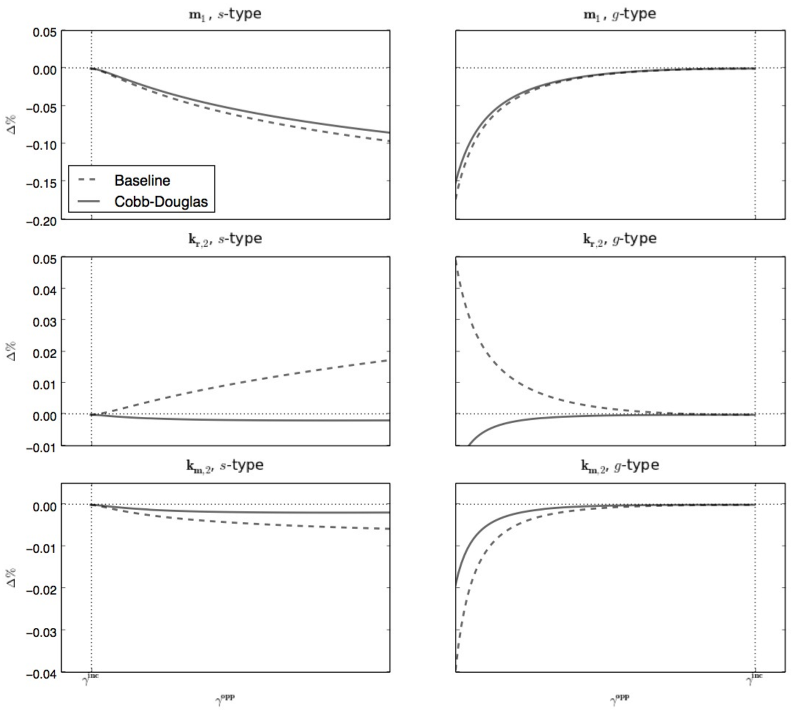

Figure B.1: Cobb-Douglas Production Function

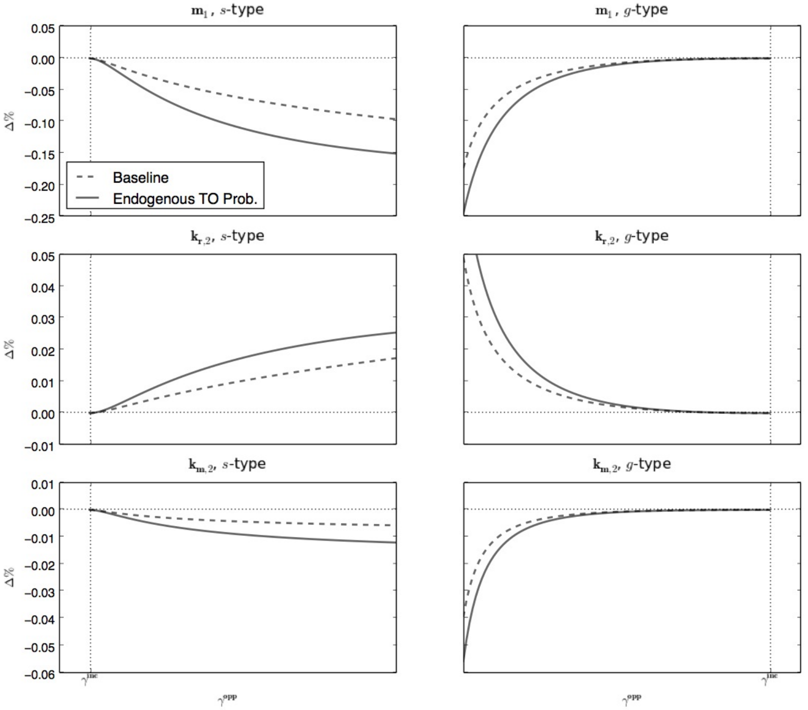

Figure B.2: Endogenous Turnover Probability

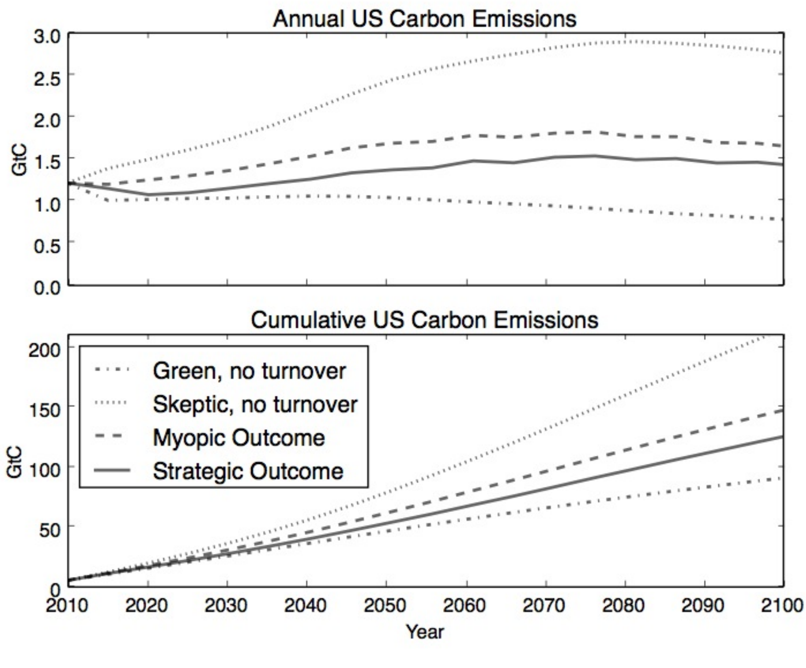

Figure B.3: Leontief production function - Emissions

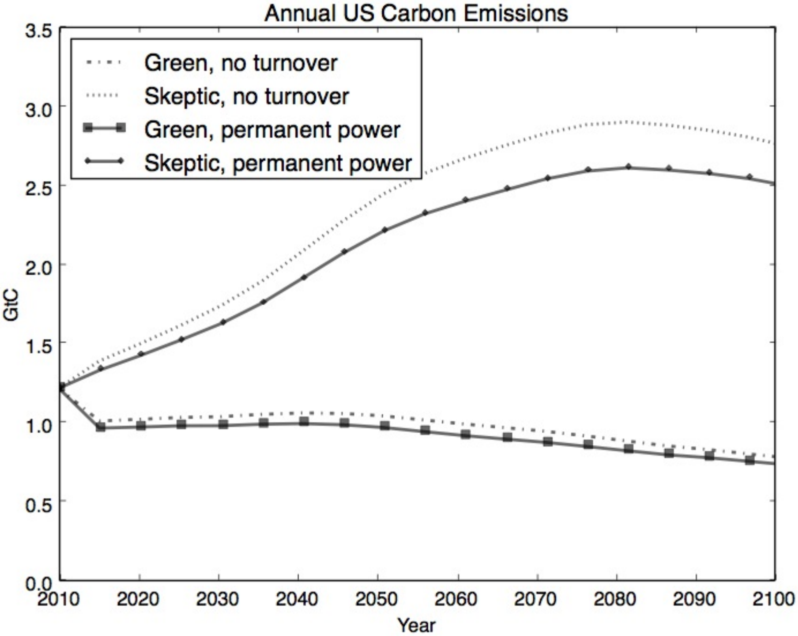

Figure B.4: Leontief production function - Emissions: FB vs. permanent power

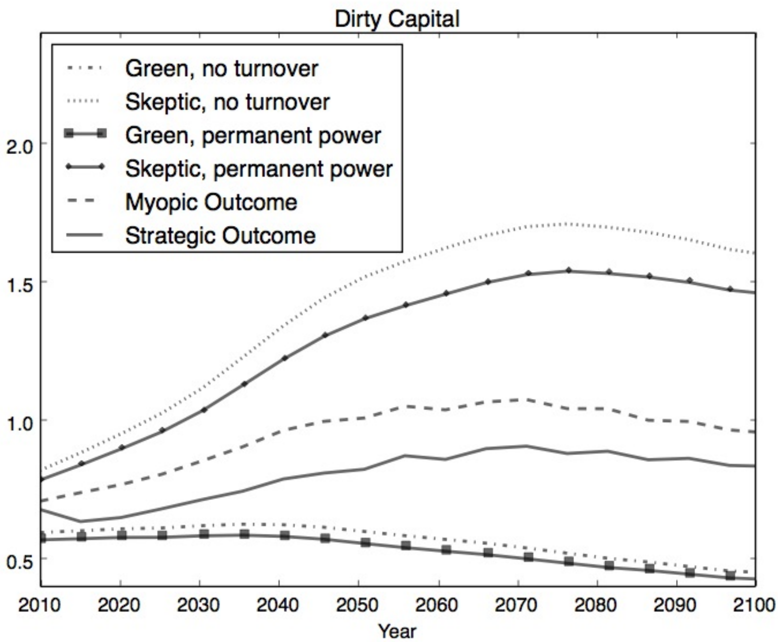

Figure B.5: Leontief production function - Dirty Capital

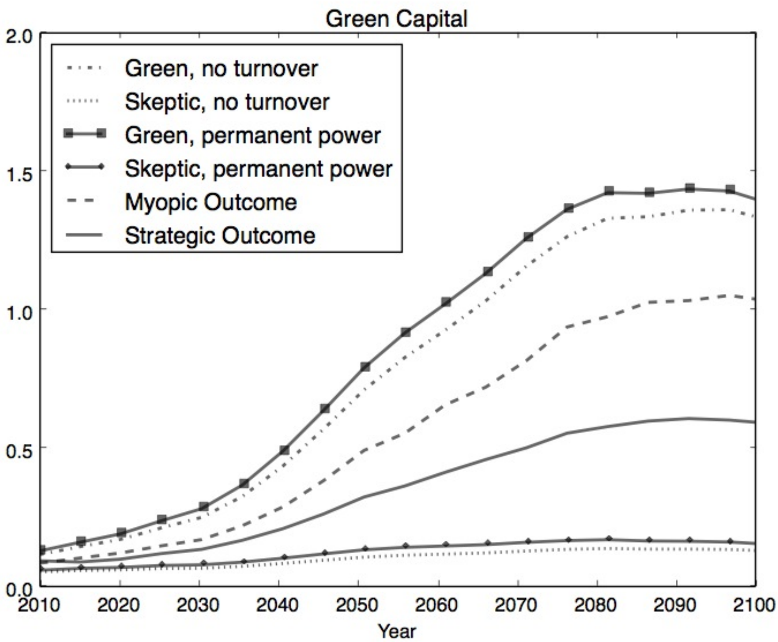

Figure B.6: Leontief production function - Green Capital

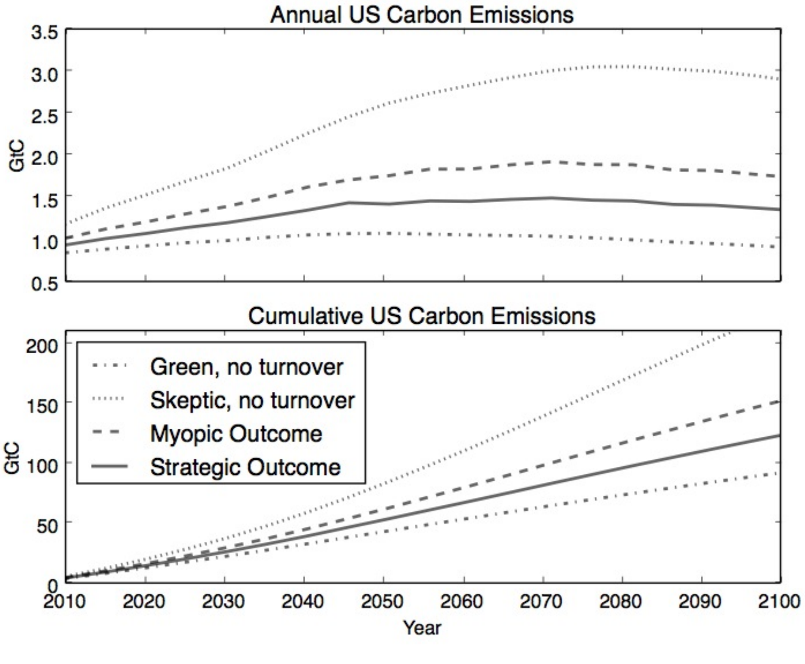

Figure B.7: $\beta = 0.95$ - Emissions

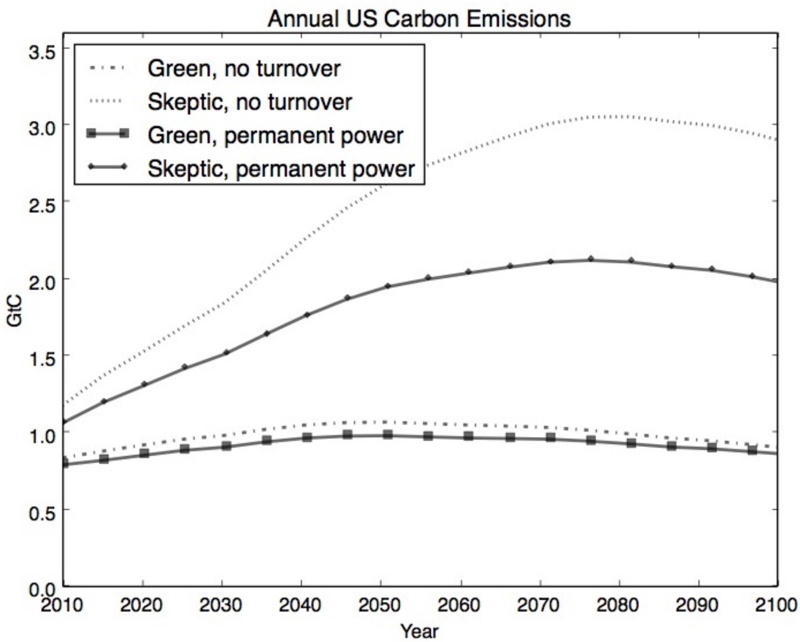

Figure B.8: $\beta = 0.95$ - Emissions: FB vs. permanent power

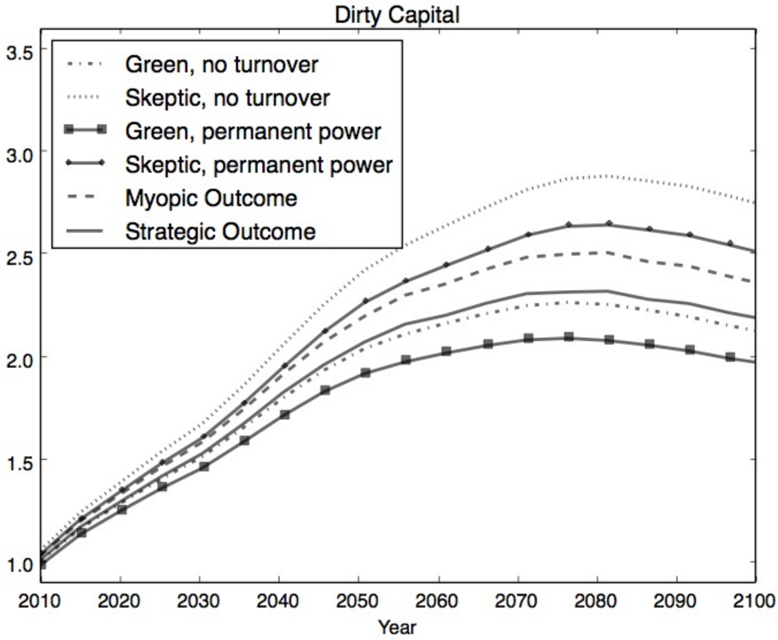

Figure B.9: $\beta = 0.95$ - Dirty Capital

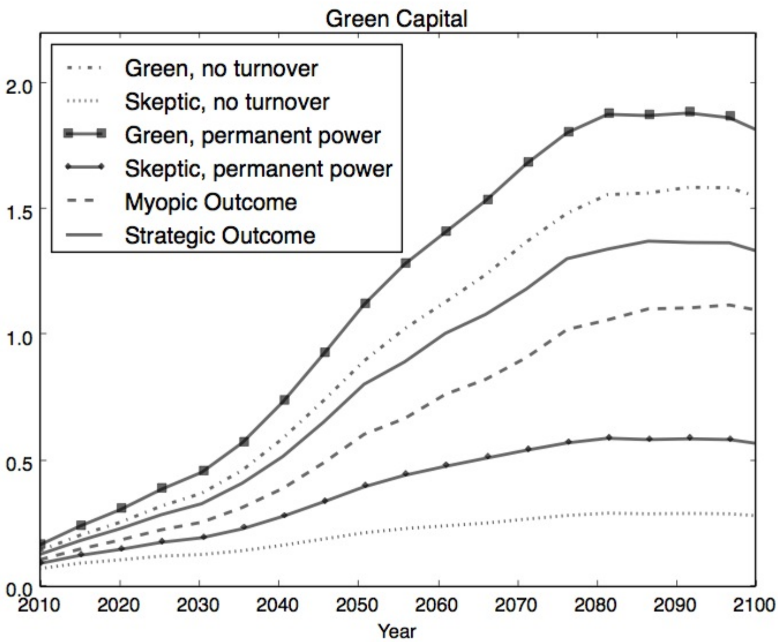

Figure B.10: $\beta = 0.95$ - Green Capital

Sammanfattning

Klimatförändringar har länge ansetts vara ett viktigt problem bland naturvetare och under det senaste årtiondet har de även fått stor uppmärksamhet bland beslutsfattare och ekonomer. Även om det ännu inte har skett några viktiga klimatöverenskommelser mellan länder så har politiska åtgärder för att dämpa klimatförändringarna införts på några ställen, i synnerhet inom EU. Ekonomer har analyserat konsekvenserna av och strategier mot klimatförändringar genom att använda många olika instrument och tillvägagångsätt. Ett populärt instrument har varit så kallade integrerade bedömningsmodeller. Dessa modeller kombinerar stiliserade framställningar av "klimatet" med traditionella makroenomiska ramverk. De finns i många varianter, med skillnader i antagande rörande modell, detaljnivå och de frågor de strävar efter att besvara. Denna avhandling använder klimatekonomiska modeller för att fokusera på en viss aspekt av klimatpolitikens upplägg. Ett vanligt antagande i många studier är tanken att en regering i dag inte enbart kan välja en sådan politisk åtgärd som en koldioxidskatt eller en utsläppsrätt för de nästkommande åren, exempelvis under loppet av en mandatperiod, utan även för en eventuellt mycket avlägsen framtid. Jag hänvisar till detta som antagandet om "åtagande" över tiden. Det är ett speciell viktigt antagande i klimatförändringssammanhang till följd av den långa livstiden för växthusgaser, så som koldioxid, i atmosfären. Som ett exempel, anta att beslutsfattare i dag bryr sig om mängden koldioxid om 100 år. Om koldioxid enbart stannade kvar i atmosfären under 1 år så skulle denna mängd enbart fastställas av den koldioxid som släpps ut om 99 år. Där-

med skulle nuvarande politiska åtgärder inte ha någon effekt på mängden. I verkligheten kommer dagens beslutsfattare att inse att den mängd koldioxid som släpps ut i dag påverkar den framtida koldioxidmängden och de kommer därför att försöka minska utsläppsnivån, exempelvis genom att införa en koldioxidskatt. Hur stor del av minskningen som är "optimal" beror på hur mycket koldioxid som släpps ut mellan nu och då. Om dagens beslutsfattare kunde bestämma dessa framtida utsläppsnivåer och säkerställa att de inte är för höga, så kan de sätta en mycket lägre skattesats än när det föreligger osäkerhet om framtiden och utsläppen sannolikt är mycket höga. Genomgående i denna avhandling så beaktar jag olika skäl till varför antagandet om åtagande kanske inte håller och hur det påverkar klimatförändring och resultatet av politiska åtgärder på lång sikt. I kapitel 1, "Optimal beskattning av koldioxid och inkomst" ("Optimal Carbon and Income Taxation"), visar jag hur inkomstbeskattning hänger samman med koldioxidskatt. För att illustrera huvudidÈn med detta kapitel, beakta ett exempel. Anta att du erhåller en månadsinkomst på USD 1000, av vilken du vill spara en del. Eftersom du vet att en del av räntan på dina besparingar kommer att beskattas kommande år bestämmer du dig för att spara 20 % snarare än de 25 % du skulle spara utan en skatt på räntan. Nu inför din regering en koldioxidskatt för att minska utsläppen. Då detta gör att elektriciteten blir dyrare så sjunker din disponibla inkomst till USD 900, vilket innebär att du sparar USD 180. Anta emellertid att regeringen vill att ditt sparande ligger så nära USD 200 som möjligt. Regeringen står därför inför en avvägning. Å ena sidan vill den minska koldioxidutsläppen, å andra sidan vill den säkerställa att folk sparar tillräckligt. En lösning på detta dilemma kan vara följande: genom att sänka koldioxidskatten så skulle din inkomst vara USD 950 och sålunda uppgår ditt sparande till USD 190. På sätt och vis är detta en kompromiss mellan de två målen: medan utsläppen är större än vad som ursprungligen planerades så ligger sparandet närmare den önskade nivån. Det viktiga att notera här är att om det inte fanns någon inkomstskatt så skulle ditt sparande ha varit USD 250. Även med den ursprungliga koldioxidskatten så skulle du då ha sparat USD 225, dvs mer än det önskade beloppet. På så sätt kan regeringen hålla fast vid det ursprungliga förslaget till koldioxidskatt. Detta exempel illustrerar att den “optimala” klimatpolitiken kan påverkas av hur höga inkomstskatterna är. Hur leder detta till ett problem vad gäller åtagande? Realistiskt sett kan regeringen i dag inte besluta om inkomstskatter i framtiden. Med andra ord, om framtida regeringar höjer eller sänker skatterna så påverkar det också hur mycket koldioxid som släpps ut i framtiden. I sin tur, så som förklaras ovan, är detta viktigt för hur mycket koldioxid som bör släppas ut i dag. Med länken mellan koldioxid och inkomstskatt i åtanke, motiveras kapitel 2, “Tidskonsistent unilateral klimatpolitik” (“Time Consistent Unilateral Climate Policy”) av två observationer: i) de flesta EU-länder använder skatter på arbete och kapitalinkomst, och ii) så här långt är EU den enda stora region som har infört en klimatpolitik. Den andra observationen är viktig då klimatförändringar inte enbart beror på koldioxidutsläppen i ett land över tiden utan även på hur mycket alla andra länder släpper ut. Under dessa förutsättningar beräknar jag till vilken grad EU borde beskatta koldioxidutsläpp. Jag finner att den är ca 13ß/tC, vilket endast är hälften av vad den skulle vara om EU länderna inte hade inkomstskatter. Vidare, om alla länder skulle enas om en global koldioxidskatt skulle denna vara åtta gånger så hög som vad EU skulle fastställa själv. Med andra ord, om inga andra länder gör någonting åt klimatförändringarna borde även EU göra väldigt lite. Slutligen, kapitel 3, med titeln “Dämpande av klimatförändringarna under politisk instabilititet” (“Climate Change Mitigation under Political Instabilitity”) beaktar ett annat och sannolikt mer intuitivt skäl till varför beslutsfattarna inte kan fastställa den framtida nivån på en koldioxidskatt eller en kvot. I demokratier så röstas sittande regeringar normalt bort från makten med regelbundna intervaller och det är inte vanligt att ett parti blir kvar vid makten under en lång tidsperiod. Vidare, i många länder, speciellt utanför EU, är olika partier inte alltid eniga om hur viktiga klimatförändringar är och hur de ska hanteras. USA är ett utmärkt exempel på detta. Jag använder en klimatekonomisk modell för att visa att när beslutsfattare löper risken att förlora makt inför de en mer klimatvänlig politik, exempelvis en högre koldioxidskatt eller fler subventioner för investeringar i ren energi, än i ett hypotetiskt scenario då de inte är det. Tänk exempelvis på den nuvarande amerikanska regeringen. President Obama vet att vid nästa val kan en republikansk kandidat bli president. I detta fall är det sannolikt att USA inte alls kommer att minska koldioxidutsläppen under de närmaste åren. Därför vill Obama släppa ut så lite så möjligt nu som motvikt till höga utsläpp i framtiden. Vidare så vill han lämna så få kolkraftverk som möjligt till sin efterträdare ñ och så många vind- och solkraftverk som möjligt ñ så att det inte finns så stor kapacitet att bränna fossila bränslen i framtiden. Å andra sidan, om Obama visste att han skulle komma att efterträdas av en demokrat så skulle det vara mindre brådskande att agera på klimatförändringar i dag.

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