Resource extraction and the Green Paradox: Accounting for political economy issues and climate policies in a heterogeneous world

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Chapter 2

Unilateral Climate Policies: Incentives and Effects*

2.1 Introduction

Global carbon emissions are largely due to the combustion of fossil fuels. Reducing the greenhouse gas emissions that contribute to climate change, and thus averting damages and costs related to the effects of global warming has been on the international policy agenda for the last 25 years.[1] Various policies directed at reducing carbon emissions have been proposed, most of them affecting the demand side or consumer side of the fossil fuel markets. In a theoretical contribution, Sinn (2008) directs the readers' attention to the so far largely neglected supply side responses to climate policies, entailing possible adverse effects on the climate. His so called "Green Paradox" hypothesis states that climate policies designed to decrease carbon output, f.ex. by curbing demand or subsidizing renewable resources, might actually increase short-run or overall emissions. The underlying idea is that a subsidy on renewables or a fast increasing carbon tax can be considered by resource owners as a threat of future expropriation, which provides them with an incentive to extract in greater amounts in earlier periods of time.

The Green Paradox phenomenon has so far been mainly analyzed in the context of a single jurisdiction. Such an approach neglects the potential (strategic) interactions between

[1]The IPCC published its first assessment report in 1990.

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countries that have different climate policies. The objective of this paper is to investigate the occurrence of Green Paradoxes in a two-region setting with resource pools differing in their extraction costs.

The questions we seek to answer are: How do heterogeneous policies or the change in policies affect the extraction path? How do different extraction costs affect the equilibrium extraction? To answer these questions we give numerical examples for a full solution of the model, after obtaining analytical results of the direction of change of our Green Paradox variables of interest, and discuss the occurrence of the Green Paradox. In the theoretical analysis, we find that a backstop subsidy in one region always results in a Green Paradox outcome, whereas a carbon tax does not in general. We are also interested in whether unilateral climate policies are likely to be introduced in the first place. This relates to the welfare effects of unilateral climate policy changes. We study numerically how policy changes affect the different welfare components and give examples of optimal endogenous policies. We find that the regions have different incentives to use climate policies for non-climate purposes, i.e., without accounting for climate costs. In our calibration, we use real world parameter values to examine welfare impacts of carbon taxation and backstop subsidies. This exercise verifies that both green and non-green incentives to introduce climate policies can be substantial.

Literature related to the Green Paradox has been ample since Sinn's seminal paper. In order to position our work we give a brief and selective survey of the papers closest to ours. Comprehensive general surveys can be found in Van der Werf and Di Maria (2012) and Van der Ploeg and Withagen (2015).

Most of the existing literature assesses the Green Paradox effect in a single economy only. This implies that the authors implicitly analyze a world of homogeneous countries having uniform (climate) policies. Yet, these assumptions are clearly oversimplifying. In reality, policies such as carbon taxation and subsidies on backstop technologies are subject to governmental discretion and political calculus and often seem arbitrary from a global perspective. Hoel (2011) addresses this point. He assesses the effect of different climate policies in a world that consists of more than one country. He finds that, with heterogeneity in the countries' climate policies, the effects of changes in climate policies on the emission paths might be very different from those found for a world of identical countries. Hoel's paper inspired both our and the paper of Fischer and Salant (2014). Fischer and Salant (2014) introduce heterogeneous extraction costs and exogenously decreasing backstop production costs into Hoel's framework and analyze the effects of different climate policies in a regulated region (as opposed to an unregulated region with no climate policies) on *cumulative* carbon emissions.

Similar to Fischer and Salant (2014), we also extend Hoel's setup by introducing resource extraction costs which differ among the two regions of our model. This assumption makes the model more realistic as extraction costs of fossil fuels increase over time and vary widely worldwide due to different accessibility and different sorts of the fossil fuels, different geographical conditions, labour and investment costs (IEA, 2011; Oilprice.com, 2012). It also signifies that fossil fuel endowments differ not only quantitatively, but also qualitatively between regions. We introduce other forms of heterogeneity, including differences in production costs of renewables, which are assumed to be non-tradables. Due to the constancy of marginal extraction and backstop production costs, cumulative emissions are fixed, implying that all carbon, that was initially in the crust of the earth, will eventually end up in the atmosphere. This is in contrast to Fischer and Salant (2014). In their setting, declining backstop costs ensure that the scarcity rent of the high cost resource is zero. Hence, they find that cumulative emissions reductions are possible as even unregulated consumers may switch from fossil fuels to the backstop before complete exhaustion occurs. Hence, some climate policies might have innoxious or even positive consequences in their setting, whereas they are detrimental to the climate in ours. Examples encompass a backstop subsidy and, under certain circumstances, a carbon tax. These policies influence the scarcity rents of *both* fuel pools in our model; they can increase *both* regions' initial emissions or induce emission leakage such that total initial emissions rise, resulting in a Green Paradox.

Consequently, we focus on the occurrence of the Green Paradox following from a change in the *global emissions path*. Our definition of the Green Paradox as an increase in *total initial* emissions, and not only the GHG output in the regulated region, accounts for the global consequences of emission path changes. The differing resource extraction costs affect the consumer price of the resource and hence the switching time to the more expensive backstop technology. The presence of spatially separated heterogeneous resource pools alters global trade and therefore extraction patterns, as compared to Hoel (2011). Hence, the effects of climate policies in a setting with multiple regions and extraction costs eventually lead to Green Paradox outcomes that differ as compared to the homogeneous case without extraction costs. In contrast to Hoel (2011), different extraction costs ensure that climate costs do not increase as a result of a change in carbon taxation, even in case the low tax country increases its tax. This is a more optimistic outlook than given in Hoel (2011). Yet, unlike Hoel (2011), we find rare instances of a Green Paradox occurring as a consequence of carbon taxation.

Whereas Hoel (2011) assesses the Green Paradox effects of exogenous climate policies in an otherwise homogeneous world, we take a first step to also assess (non-green) incentives of heterogeneous regions to implement climate policies. The regions' welfare levels are affected by extraction costs and the terms of trade effects arising as the regions supply the non-renewable resource to the global market at different times. These factors give rise to regionally different incentives to employ climate policies. Thus, as opposed to Hoel (2011) and Fischer and Salant (2014), we account for these incentives in our setting and examine the welfare effects of climate policies. Consequently, governments have an incentive to use 'climate' policies for other than climate purposes, enhancing positive terms of trade effects.[2] Carbon taxes, for instance, might not be levied in order to improve green welfare, but to suppress demand for expensive non-renewable resource imports. A similar reasoning applies to a region deciding to subsidize a backstop technology: it might want to shorten its costly non-renewable resource dependence or it might find it more lucrative to export its non-renewable resource while switching earlier to renewables itself. Similar terms of trade effects have been identified by Eichner and Pethig (2013). In their linear-demand, two-country and two-period model, a government chooses a unilateral climate policy to achieve an emissions target in the first period. The idea of their setup is close to ours: their goal is to find cost effective unilateral ceiling policies for a sub-global coalition. Yet, without including extraction costs and without modelling the climate externality, they cannot account for the complete incentive structure, both green and non-green, to introduce climate policies. Nevertheless, we confirm Eichner and Pethig's conclusion that the sign and magnitude of the optimal carbon tax depend on the distribution of ownership of the fossil fuel between the climate bloc and the rest of the world: in order to increase its fuel export revenues, the coalition has higher incentives to set lower taxes (or even emission subsidies) the higher its share of the world fossil fuel stock is. In addition to Eichner and Pethig (2013), we find that policy incentives are highly dependent on the fossil fuel's extraction costs and hence on the *timing* of being exporter and importer of the resource. Furthermore, since climate damages are part of our welfare function, welfare optimization in our setting can involve a direct trade-off between green and non-green welfare, making carbon taxes an optimal policy for a region even though it might lose with respect to its terms of trade. On the

[2]The link between strategic environmental policy and international trade has been extensively discussed in the literature, see e.g. Rauscher (1994) and Ulph (1997).

other hand, the same mechanism causes backstop subsidies to be an optimal policy for some parameter values, namely as long as non-green welfare gains compensate for green welfare losses. Eichner and Pethig (2013) cannot consider backstop subsidies as a viable policy concept as they would violate their policy goal which is an exogenous emissions ceiling, and due to the lack of a post-fossil fuel period in their model.
By identifying the terms of trade effects, both our and Eichner and Pethig's papers unravel possible strategic incentives that the countries face, without yet considering it in a game theoretic model. A game theoretic approach is taken by a separate strand of literature such as Wirl (2012) and Strand (2013). In a static setup with a 'policy bloc' and a fringe of fossil fuel importers versus an exporter bloc, Strand (2013) contrasts the performance of a carbon tax and a cap-and-trade scheme for the policy bloc. The Nash equilibrium where the policy bloc uses the carbon tax is preferred. Karp et al. (2015) extend this static setting to study Markov perfect equilibria of a dynamic game, where they analyze the effectiveness of taxes versus quotas. Wirl (2012) also derives Markov perfect equilibria in a stock externality game between cartelized fossil fuel suppliers and consumers, the instruments being quantities and prices. His model, however, does not account for scarcity rents, extraction costs and backstop technologies.

The remainder of the paper is structured as follows: We give a brief discussion of the model's setup in Section 2.2.1, before deriving the first-best in Section 2.2.2 and contrast our findings with the market equilibrium outcome in Section 2.2.3. In Section 2.2.4 we introduce exogenous climate policies and conduct the main analysis of the changes in carbon taxation and backstop subsidy on the resource usage and resource price paths. We comment on endogenous policies and welfare effects of climate policy changes in Section 2.2.5. The model is calibrated in Section 2.3, and welfare effects of policy changes are discussed as deviations of the calibrated benchmark case. We summarize our findings and conclude in Section 2.4.

2.2 Model

2.2.1 Model Description

We assess the effects of unilateral climate policies on the paths of global carbon emissions, while accounting for heterogeneity in extraction costs in a multi-region setting.

For simplicity, we employ a two-region partial equilibrium model of resource extraction; one of the regions is called home, the other is called foreign. All of the fossil fuel originates from mines in these two regions and all of the world demand arises from these regions. Variables pertaining to foreign are denoted by asterisks. Both regions are in the possession of a stock of fossil fuel. The fossil fuels extracted are homogeneous energy bearers and serve directly as consumption good. However, the fossil fuels differ in two respects. One of them is more expensive to extract and one of them can be more polluting. We will make specific assumptions on this in due course. Further sources of heterogeneity encompass the regions' climate policies and the amounts of the initial non-renewable resource stocks.

We assume constant marginal extraction costs. This is a simplification with non-negligible consequences: in this framework, unlike in Fischer and Salant (2014), the whole non-renewable resource stock is exhausted. What matters for the climate effects is solely the resource usage path. The real-world trend of extraction costs which are increasing with the amount of total previously extracted resources (IEA, 2008) is partly captured by the presence of heterogeneity in constant marginal extraction costs between the regions. The assumption that *all* the resources in one region are extracted at a different cost than *all* of the resources in the other region is not a strong assumption. The extraction costs of Saudi Arabia's conventional oil, the oil from tar sands in Canada or offshore oil in Norway are quite different and vary between the countries, while being quite homogeneous within one country due to geological differences in extraction and other costs, such as labour (IEA, 2011; Oilprice.com, 2012).[3]

The initial stock of fossil fuel in the home region is denoted by X_0. Global consumption of this fuel is composed of consumption at home, x_c, and foreign consumption, x_c^*. The constant marginal extraction cost is c_x. Since the two regions cover the entire earth and since no storage possibilities exist, total extraction of this type of fossil fuel equals $x_c + x_c^*$. For the foreign region the stock is Y_0^*, home consumption is y_c, foreign consumption is y_c^*, with a constant marginal extraction cost c_y^*. Energy is also provided by a backstop

[3]Extraction costs vary widely due to different accessibility and different sorts of the fossil fuels, different geographical conditions, labour and investment costs (IEA, 2011; Oilprice.com, 2012).

technology that is not hampered by stock limitations. Production and consumption of the backstop, or renewables, is denoted by z_c for the home region and z_c^* for the foreign region. The constant marginal production costs for the backstop technology are b and b^*, and energy from the backstop technology is used only locally, which stands in contrast to the global renewables market of Fischer and Salant (2014), where policies affect the single *global* backstop price. The production technology for renewables is purely local due to the different availability of solar radiation and wind, difficulties in storage and transportation, for instance. The assumption of constant marginal backstop production costs is a simplification since production costs of renewable resources have been and still are declining.[4] Our assumption is helpful for the scarcity rent of the high-cost resource not to be zero as it is in Fischer and Salant (2014).

Utility from consumption is represented by utility functions U and U^* that are continuously differentiable and concave. The fossil fuels in the home and in the foreign region and the renewable energy from the backstop technology are assumed to be perfect substitutes in utility. Consumption of energy leads to CO_2 emissions that are proportional to the use of energy. Per unit of energy from the home (foreign) fossil fuel the emission factor equals ψ (ψ^*). Climate costs at time t are an increasing convex function of the stock of carbon in the atmosphere above the pre-industrial level. We draw upon Archer (2005) and model the carbon stock in the following way: a share α of total emissions stays in the atmosphere forever as the stock S_1, whereas part $(1-\alpha)$ adds to a transient stock S_2 with a constant rate of decay δ. The damage function for the home (foreign) region, $C(S_1 + S_2)$ ($C^*(S_1 + S_2)$), depends on the sum of stocks of CO_2.

The regions have two climate policy measures at hand: a carbon tax, levied on the use of the non-renewable, and a backstop subsidy, which lowers the backstop production cost. Both, the carbon tax and the subsidy, determine the competitiveness of the backstop resource and thus the renewable and non-renewable resource usage profile of the regions. The enforcement of these climate policies in both regions and their interplay are of major importance for the regions' welfare and play a key role regarding the possible occurrence of a Green Paradox.

[4]Much of the literature employs backstop costs declining in time (Gerlagh, 2011; Fischer and Salant, 2014). We assume constant backstop costs which does not preclude the possibility of decreasing production costs of the renewable resource once the switch occurrs and the backstop technology is used.

2.2.2 First-best

The first-best optimum is found by maximizing the unweighted sum of the total welfare of both regions using a common rate of pure time preference and taking into account the constraints imposed by the limited stocks of fossil fuels and the accumulation of CO_2 in the atmosphere. In mathematical terms, the problem is to maximize:

$$\begin{aligned} W = \int_0^\infty & e^{-\rho t}\{U(x_c + y_c + z_c) + U^*(x_c^* + y_c^* + z_c^*) \\ & - c_x(x_c + x_c^*) - c_y^*(y_c + y_c^*) - bz_c - b^* z_c^* - C(S_1 + S_2) - C^*(S_1 + S_2)\}dt \end{aligned} \tag{2.1}$$

subject to

$$\dot{X} = -(x_c + x_c^*),\ X(0) = X_0,\ \text{given}, \tag{2.2}$$

$$\dot{Y}^* = -(y_c + y_c^*),\ Y^*(0) = Y_0^*,\ \text{given}, \tag{2.3}$$

$$\dot{S}_1 = \alpha[\psi(x_c + x_c^*) + \psi^*(y_c + y_c^*)],\ S_1(0) = S_{10},\ \text{given}, \tag{2.4}$$

$$\dot{S}_2 = (1-\alpha)[\psi(x_c + x_c^*) + \psi^*(y_c + y_c^*)] - \delta S_2,\ S_2(0) = S_{20},\ \text{given}, \tag{2.5}$$

and subject to the usual non-negativity constraints on energy use and fossil fuel stocks. S_{10} and S_{20} denote the initial permanent and transient stocks of carbon in the atmosphere. We omit the time arguments where there is no danger of confusion. The Lagrangian reads:

$$\begin{aligned} L = e^{-\rho t}\{ & U(x_c + y_c + z_c) - c_x(x_c + x_c^*) - bz_c - C(S_1 + S_2) \\ & + U^*(x_c^* + y_c^* + z_c^*) - c_y^*(y_c + y_c^*) - b^* z_c^* - C^*(S_1 + S_2)\} \\ & + \lambda_x\,(-x_c - x_c^*) + \mu_1 \alpha\,(\psi(x_c + x_c^*) + \psi^*(y_c + y_c^*)) \\ & + \lambda_y^*\,(-y_c - y_c^*) + \mu_2(1-\alpha)\,(\psi(x_c + x_c^*) + \psi^*(y_c + y_c^*) - \delta S_2)\,. \end{aligned}$$

Necessary conditions are:

$$e^{-\rho t}\{U'(x_c+y_c+z_c)-c_x\}-\lambda_x+\mu_1\alpha\psi+\mu_2(1-\alpha)\psi\leqslant 0,\ x_c\geqslant 0,\ c.s., \tag{2.6}$$

$$e^{-\rho t}\{U^{*\prime}(x_c^*+y_c^*+z_c^*)-c_x\}-\lambda_x+\mu_1\alpha\psi+\mu_2(1-\alpha)\psi\leqslant 0,\ x_c^*\geqslant 0,\ c.s., \tag{2.7}$$

$$e^{-\rho t}\{U'(x_c+y_c+z_c)-c_y^*\}-\lambda_y^*+\mu_1\alpha\psi^*+\mu_2(1-\alpha)\psi^*\leqslant 0,\ y_c\geqslant 0,\ c.s., \tag{2.8}$$

$$e^{-\rho t}\{U^{*\prime}(x_c^*+y_c^*+z_c^*)-c_y^*\}-\lambda_y^*+\mu_1\alpha\psi^*+\mu_2(1-\alpha)\psi^*\leqslant 0,\ y_c^*\geqslant 0,\ c.s., \tag{2.9}$$

$$e^{-\rho t}\{U'(x_c+y_c+z_c)-b\}\leqslant 0,\ z_c\geqslant 0,\ c.s., \tag{2.10}$$

$$e^{-\rho t}\{U^{*\prime}(x_c^*+y_c^*+z_c^*)-b^*\}\leqslant 0,\ z_c^*\geqslant 0,\ c.s., \tag{2.11}$$

$$-\dot\mu_1=-e^{-\rho t}[C'(S_1+S_2)+C^{*\prime}(S_1+S_2)], \tag{2.12}$$

$$-\dot\mu_2=-e^{-\rho t}[C'(S_1+S_2)+C^{*\prime}(S_1+S_2)]-\delta\mu_2, \tag{2.13}$$

$$-\dot\lambda_x=0, \tag{2.14}$$

$$-\dot\lambda_y^*=0, \tag{2.15}$$

$$\lim_{t\to\infty}\mu_1(t)S_1(t)+\mu_2(t)S_2(t)+\lambda_x(t)X(t)+\lambda_y^*(t)Y^*(t)=0. \tag{2.16}$$

Here *c.s.* stands for complementary slackness. The following example helps us in interpreting these conditions. Consider, for instance, equation (2.6). Suppose the home country is actually consuming some of its own fossil fuel at instant of time t: $x_c(t)>0$. Equation (2.6) then says that discounted marginal benefits equal discounted marginal cost. To see this, let us solve for the multipliers of the transient and permanent carbon stocks. The general solution for (2.12) is

$$\mu_1(t)=\int_0^t e^{-\rho s}[C'(S_1+S_2)+C^{*\prime}(S_1+S_2)]ds+\mu_{10}.$$

From the transversality condition in (2.16), we arrive at the following expression for the multiplier:

$$-\mu_1(t)=\int_t^\infty e^{-\rho s}\left(C'(S_1+S_2)+C^{*\prime}(S_1+S_2)\right)ds. \tag{2.17}$$

The solution for $\mu_2(t)$ is

$$-\mu_2(t)=e^{\delta t}\int_t^\infty e^{-(\rho+\delta)s}\left(C'(S_1+S_2)+C^{*\prime}(S_1+S_2)\right)ds. \tag{2.18}$$

Whereas $-\mu_1(t)$ in equation (2.17) denotes the total discounted marginal damage from a higher permanent CO_2 stock, $-\mu_2(t)$ in equation (2.18) is the total discounted marginal damage from a higher transient CO_2 stock. Using this in (2.6) we get

$$U'(x_c + y_c + z_c) = c_x + e^{\rho t}\lambda_x + \alpha\psi e^{\rho t}\int_t^{\infty} e^{-\rho s}\left(C'(S_1+S_2) + C^{*\prime}(S_1+S_2)\right)ds \qquad (2.19)$$
$$+ (1-\alpha)\psi e^{\rho t}e^{\delta t}\int_t^{\infty} e^{-(\rho+\delta)s}\left(C'(S_1+S_2) + C^{*\prime}(S_1+S_2)\right)ds \text{ if } x_c > 0.$$

This signifies that the home region's marginal utility equals its marginal cost, consisting of four parts: the marginal extraction cost c_x, the current value of the fossil fuel stock $e^{\rho t}\lambda_x$, the total marginal damage resulting from the increase in the permanent CO_2 stock, and, finally, the total marginal damage from the increase in the transient CO_2 stock.[5] The interpretation of the other necessary conditions is similar.

The implementation of the social optimum in a decentralized economy requires two different taxes that are uniform across the two regions. One tax on the use of fossil fuel extracted in the home region and one on the use of fossil fuel extracted in the foreign region. These taxes differ according to the emission intensity of the fossil fuels. As long as CO_2 accumulates, the CO_2 taxes increase. They definitely decrease as soon as renewables take over in both countries. In order to avoid complicated tax patterns, we assume from here on that marginal damages are constant and equal across regions: $C'(S_1 + S_2) = C^{*\prime}(S_1 + S_2) = \nu$. The first-best tax rates are hence of the following simple form:

$$\tau_x = \tau_x^* = \alpha\psi\frac{2\nu}{\rho} + (1-\alpha)\psi\frac{2\nu}{\rho+\delta}, \qquad (2.20)$$
$$\tau_y = \tau_y^* = \alpha\psi^*\frac{2\nu}{\rho} + (1-\alpha)\psi^*\frac{2\nu}{\rho+\delta}. \qquad (2.21)$$

The shadow prices of the non-renewable resources, if used, are non-zero in our setup. Moreover, these shadow prices will typically differ. This and the linearity of the model also imply that there is never simultaneous use of two or more types of energy in an optimum. Finally, the necessary conditions indicate that no subsidy on renewables is required to implement the first-best outcome.

2.2.3 Market Equilibrium

We next consider the market economy where both types of fossil fuel are traded on a world market. It is important to note that pollution taxes are only levied on consumers. Fossil

[5] Hotelling's rule holds: extraction today goes at the cost of future extraction.

fuel producers are suppliers on the world market where the prices are p_x and p_y for fossil fuel from the home and the foreign region, respectively. We assume that fossil fuel of the home region is more expensive to extract, whereas the home region has a cost advantage in producing renewable energy.

Assumption 1 $c_x > c_y^*$

Assumption 2 $b < b^*$

In the analysis that follows, we restrict ourselves to cases where pollution taxes are not too high and renewables' costs are not too low, such that both the low and the high cost fossil fuels are supplied and demanded in equilibrium for some period of time in both regions.

According to the Herfindahl rule, first only the foreign fossil fuel, then only the home fossil fuel is supplied. Producers of the home (foreign) region's non-renewable resource maximize profits taking the world market price of their fossil fuel p_x (p_y) as given. They also use a common world market interest rate that is assumed to be equal to the rate of time preference ρ. This yields Hotelling's rule: there exists a constant λ_x (λ_y^*) such that:

$$p_x = c_x + e^{\rho t}\lambda_x \qquad \text{if } x_c + x_c^* > 0, \tag{2.22}$$
$$p_y = c_y^* + e^{\rho t}\lambda_y^* \qquad \text{if } y_c + y_c^* > 0. \tag{2.23}$$

Consumers are confronted with the world market price of fossil fuel as well as with potentially differentiated emission taxes. Utility maximization then yields:

$$U'(x_c) = p_x + \tau_x, \qquad \text{if } x_c > 0, \tag{2.24}$$
$$U'(y_c) = p_y + \tau_y, \qquad \text{if } y_c > 0, \tag{2.25}$$
$$U'(z_c) = b, \qquad \text{if } z_c > 0. \tag{2.26}$$

Similarly,

$$U^{*\prime}(x_c^*) = p_x + \tau_x^*, \qquad \text{if } x_c^* > 0, \tag{2.27}$$
$$U^{*\prime}(y_c^*) = p_y + \tau_y^*, \qquad \text{if } y_c^* > 0, \tag{2.28}$$
$$U^{*\prime}(z_c^*) = b^*, \qquad \text{if } z_c^* > 0. \tag{2.29}$$

The fact that there is never simultaneous supply of the two types of fossil fuel, together with the fact that there has to be a unique global fossil fuel price, has an interesting consequence for the optimal tax rates in a decentralized general equilibrium. To see this, let the shadow prices λ_x and λ_y^* be given and positive. Then T_1, the moment of the transition from cheap fossil fuel to expensive fossil fuel, is determined by:

$$p_x(T_1) = c_x + e^{\rho T_1}\lambda_x = p_y(T_1) = c_y^* + e^{\rho T_1}\lambda_y^*. \tag{2.30}$$

In order to have an equilibrium, all demand for cheap oil should be concentrated before T_1 and all demand for expensive fossil fuel is exerted only after T_1. The low and high cost resource producers are confronted with the same price due to the fossil fuel world market. Perfect competition implies that consumers can buy any amount of fossil fuel at a given price; if one kind of fossil fuel were taxed heavier than the other, the consumers would simply not buy it. Hence, no local government can differentiate the taxes according to the origin of oil, and it has to hold that $\tau = \tau_x = \tau_y$ and similarly $\tau^* = \tau_x^* = \tau_y^*$.

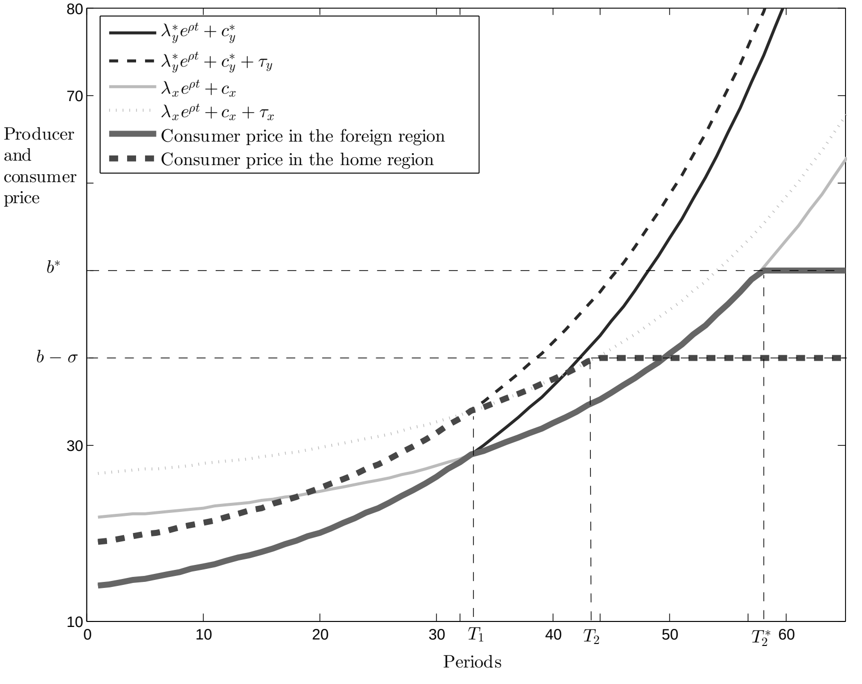
Fischer and Salant (2014), in contrast, obtain different switching times for the different regions from the low to the high cost non-renewable resource. They do not model a *global* market where the non-renewable resources are competitively supplied, but their regulated and unregulated regions are able to purchase oil from a low and a high cost pool on separated markets.

How is then the optimal uniform tax for the home region determined? For every given set of price paths $(p_x(t), p_y(t))$ and demand patterns in the foreign region $(x_c^*(t), y_c^*(t))$, the home region can determine the demand by the home consumers for any tax rate τ from (2.24) and (2.25). Then also total damages are known and the country can determine the optimal tax. In an equilibrium the price paths and demand paths in the presence of the optimal tax are such that the resource market clears. In Section 2.2.5 we will provide some numerical examples of an endogenous optimal tax rate.

Figure 2.1 shows a typical equilibrium, where first the cheap fossil fuel, then the expensive fossil fuel is extracted. Upon exhaustion of the fossil fuel, the regions start using renewables, possibly at different points in time. Here T_1 is the moment of transition from cheap to expensive fossil fuel. At T_2 the home region switches to renewables. The foreign region does so at T_2^*. In the figure $T_2 < T_2^*$ because $b^* > b$.[6]

[6] Of course, $b^* < b$ is an alternative assumption. For a justification of our choice see Section 2.3.

Figure 2.1: Equilibrium paths of the producer and consumer prices in the home and foreign region, $Y_0^* = 3$ and $X_0 = 1$



2.2.4 Exogenous Climate Policies

We begin the climate policy analysis by considering the effects of exogenous carbon taxation and backstop subsidy changes. We assume that the foreign region does not implement any environmental policy. Potential reasons for this environmental faineance are the region's lack of care about climate change, lobbying on the part of the fossil fuel producers, or other political economy considerations. Moreover, we take the tax rate and backstop subsidy imposed by the home region as exogenous. Hence, these policies are not necessarily optimal. Optimal taxation and subsidy in the absence of climate policies in the foreign region are considered in the next section.

In the sequel we employ numerical simulations to illustrate our theoretical findings. For these examples, we need to specify functional forms for the regions' utility and damage functions. For the construction of the graphs we use log-utility. Our damage function is linear in the stock of carbon in the atmosphere. Total carbon costs are hence determined by the discounted sum of carbon emissions over the entire time horizon, multiplied by the constant social cost of carbon. In our baseline case, we set the social discount rate ρ equal to the exogenously given interest rate r and assume them to be $\rho = r = 0.05$. The extraction costs amount to $c_y^* = 10, c_x = 20$ and the backstop production costs to $b = 45$ and $b^* = 50$. In order to concentrate on the policy effects, we assume no difference in the emission factors, i.e., $\psi = \psi^*$. The climate policies initially in place in the home region are a carbon tax $\tau = 5$ and a renewables subsidy $\sigma = 5$. Both are constant over time. No policy is implemented in the foreign region. Since the policy effects depend on the relative abundance of the two resource stocks, we vary the regions' initial resource endowments Y_0^* and X_0. The parameter values are summarized in Table A.2 in Appendix A.4.[7]

As the tax in our example is not prohibitively high, both the cheap and the expensive fossil fuels are used, and we obtain a similar equilibirum as depicted in Figure 2.1. Before we address the questions referring to the appearance of a Green Paradox, we explicitly define what constitutes the Weak and the Strong Green Paradox in our setting, leaning on the distinction in Gerlagh (2011):[8]

Definition 1 *Climate policy changes have a Weak Green Paradox effect if the* initial, global *fossil fuel extraction rate is higher than before the policy change. The Green Paradox is hence defined as a* global *phenomenon.*[9]
For a strong *Green Paradox outcome, the* total climate costs*, i.e. the discounted sum of all climate damages, have to increase* in addition *to the higher initial fossil fuel extraction rate characterizing the Weak Green Paradox.*

We are interested in knowing whether a subsidy on the production cost of renewables in the home region will enhance extraction of foreign fossil fuel, so that the emissions initially increase. Moreover, we analyze the climate effect of a higher tax in the home region.

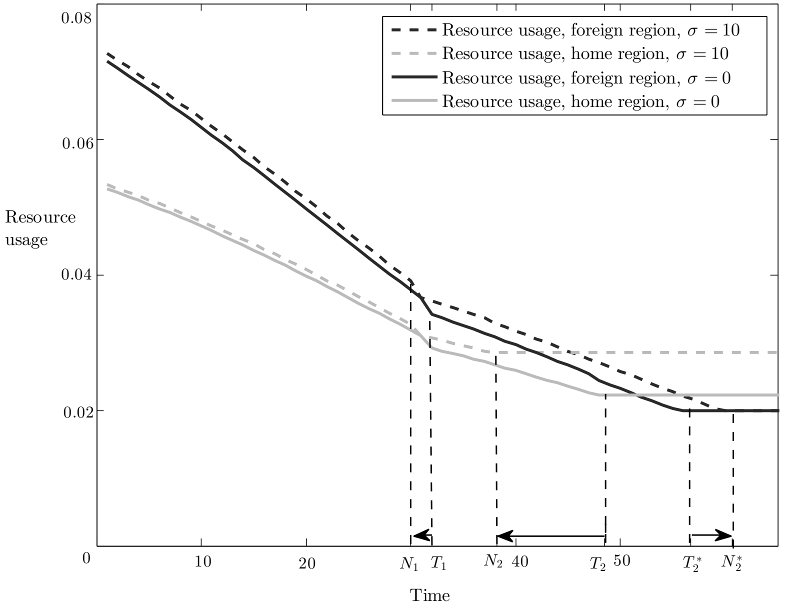
Suppose the already existing renewables subsidy is increased in the home region, while the carbon tax is unchanged. The subsidy change is marginal, so that all fossil fuel from both

[7]The parameter values in this section are arbitrary to a large degree. In contrast, in Section 2.3 we will employ calibrated parameter values.

[8]It is important to note that, in our setting, the amount of cumulative emissions is given. Hence, all fossil fuel resources initially *in situ* are eventually extracted.

[9]A change in climate policies signifies here a reinforcement of already existing policies, or the introduction of climate policies in case climate policies were absent.

Figure 2.2: Resource extraction paths before and after the increase in the home region's subsidy, $X_0 = 1, Y_0^* = 3$, with N_1, N_1^* and N_2^* denoting the new switching points after the policy change



regions is still used up in equilibrium. With a higher subsidy in place, the resource producers are faced with an unchanged demand from the foreign region and a lower demand from the home region as the backstop becomes competitive earlier. In order to match supply and demand, and to fully exhaust the fossil fuels, the shadow prices must go down. More cheap oil is on the market initially and the stock is exhausted sooner: a Weak Green Paradox occurs. Due to the lower backstop price, the home region switches earlier to the renewable resource. More of the high cost resource is left for the foreign region which delays its transition to the renewable energy, given that the costs of backstop production in the foreign region stay unchanged, as can be seen in Figure 2.2.

Proposition 1 *Let the carbon tax rate in the home region be given. If the home renewables technology receives a subsidy, then*

(i) the initial extraction of the fossil fuel increases, i.e., $\frac{d(y_c+y_c^*)}{d\sigma} > 0$*, and a Weak Green Paradox occurs;*

(ii) the transition for the home region occurs earlier, i.e., $\frac{dT_2}{d\sigma} < 0$ *;*

(iii) the non-renewable resource period for the foreign country is extended, i.e., $\frac{dT_2^*}{d\sigma} > 0$*;*

(iv) the overall resource extraction phase is hence extended and therefore climate costs do not necessarily increase.

Proof. See Appendix A.1.2. □

Proposition 1 states that a Weak Green Paradox *always* occurs in case of a unilateral subsidy rise. This finding contrasts with Fischer and Salant (2014): in their model no Green Paradox occurs as a consequence of faster decreasing backstop production costs if both the low and the high cost pools are used. The reason is that the scarcity rent of the low cost resource is not affected; the cumulative emissions from the low cost pool do not change, whereas emissions from the high cost pool and hence overall emissions *decrease* as the countries switch earlier to the renewable resource.
Yet, despite the inevitable occurrence of the Weak Green Paradox, climate costs do not have to increase necessarily, even if the foreign region (the region with the lower/zero backstop subsidy) increased its subsidy. The reason is that in case the foreign region introduced a backstop subsidy, the home region's high cost resource usage period would be prolonged, i.e., $\frac{\partial T_2}{\partial \sigma^*} > 0$. In case the subsidy is large enough, the extension of the home region's non-renewable resource consumption period might compensate for the foreign region's shortening of its resource usage period.[10]
Thus, whether we are faced with the strong version of the Green Paradox depends primarily on the parameter values used. Our sensitivity analysis shows that the most important variable to determine a Strong Green Paradox outcome is the discount rate: all else equal, a Strong Green Paradox occurs for low discount rates, whereas we obtain the weak version for discount rates above a certain threshold.[11]

Next, we consider an exogenous increase in the carbon tax imposed by the home region. Like Hoel (2011), we employ constant carbon taxes.[12]

[10]Hoel (2011) considers the consequences of a drop in backstop production costs in *both* regions and finds that total climate costs increase if the differences in the countries' carbon tax rates are sufficiently small. The same holds in our setting for initially equal carbon taxes.

[11]The Weak/Strong Green Paradox does not seem to vary with the relative size of the fuel stocks. Thus, with the stock sizes and all other parameters given, we determined the equilibria for different rates of time preference.

[12]Similar to Hoel (2011) we assume constant marginal damages, which reasonably justifies working with

First, note that an increase in τ affects both the low and high extraction cost resource shadow prices. The reason is that, everything else equal, a higher tax in the home region decreases its non-renewable resource demand by increasing the resource consumer price, whereas the demand in the foreign region stays unaffected. The only possibility to match supply and demand is a lower consumer price. With taxes and extraction costs being exogenous for them, all producers accept lower resource rents in equilibrium, i.e., $\frac{d\lambda_y^*}{d\tau} < 0$ and $\frac{d\lambda_x}{d\tau} < 0$.[13]
A change in the tax also affects the switching points. The foreign region faces a lower price path as a consequence of the decrease in the shadow prices. Due to this lower price path it takes longer for the foreign country to attain its renewable resource price b^*. Similar to Hoel (2011) we find that the overall usage time of the expensive non-renewable resource is prolonged as a consequence of increased carbon taxation: $\frac{dT_2^*}{d\tau} > 0$.
Whereas the effect of the carbon tax on T_2^* has an unambiguous sign, the home region's transition to the renewable resource can be accelerated or delayed, like in Hoel (2011). In the numerical analysis, we find that the sign of $\frac{dT_2}{d\tau}$ depends on the relative sizes of the resource stocks. The home region's extraction period tends to shorten in case X_0 is relatively scarce and hence the high cost extraction period is short. In the opposite case, with X_0 being relatively abundant and the extraction period being long, we find $\frac{dT_2}{d\tau} > 0$, as in Figure 2.3.[14] The consumer price is then low enough at the beginning of the usage period of the high extraction cost resource for the increased tax to flatten the consumer price path. The resource use is shifted from the present to the future and climate costs are leveled out even more.

Figure 2.3 shows intra-temporal leakage, i.e., a shift in emissions from the home to the foreign country, as higher non-renewable energy consumption in the foreign region to a certain level offsets the climate effects of a higher carbon tax in the home region. However, this does not always entail higher initial aggregate emissions. No Green Paradox effect can be observed even in the case when the total resource usage period for the home country

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constant carbon taxes. The constancy of carbon taxes is furthermore a less rigid assumption than a fast increasing carbon tax (Sinn, 2008).

[13]The formal derivation can be found in Appendix A.1.1.

[14]The sign of $\frac{dT_2}{d\tau}$ does not only depend on the relative size of the resource stocks, but also on the discount rate. The higher the discount rate, the more probable is $\frac{dT_2}{d\tau} > 0$, all else held equal. Hence, with a stock size Y_0^* which is relative scarce as compared to X_0 (e.g. $Y_0^* = 3, X_0 = 4$), $\frac{dT_2}{d\tau} > 0$ already for intermediate levels of ρ, wheras for relatively abundant Y_0^* (such as $Y_0^* = 4, X_0 = 1$), $\frac{dT_2}{d\tau} > 0$ occurs only for large enough discount rates.

Figure 2.3: Resource extraction paths before and after the increase in the home region's tax rate, $X_0 = 4, Y_0^* = 3$

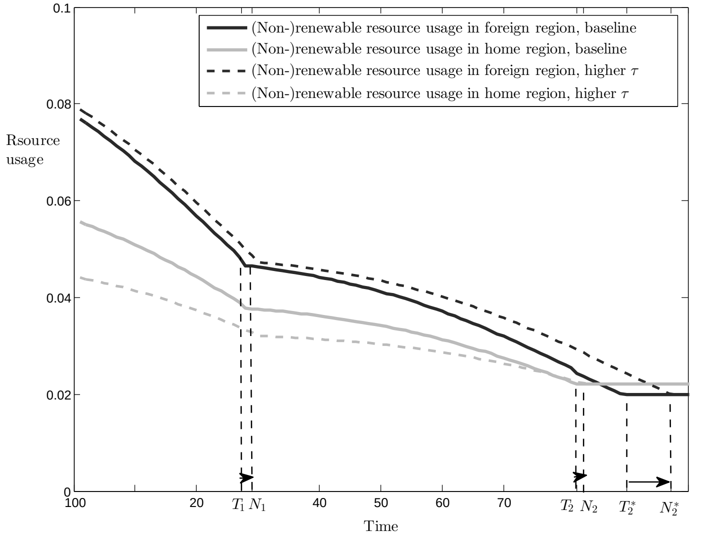
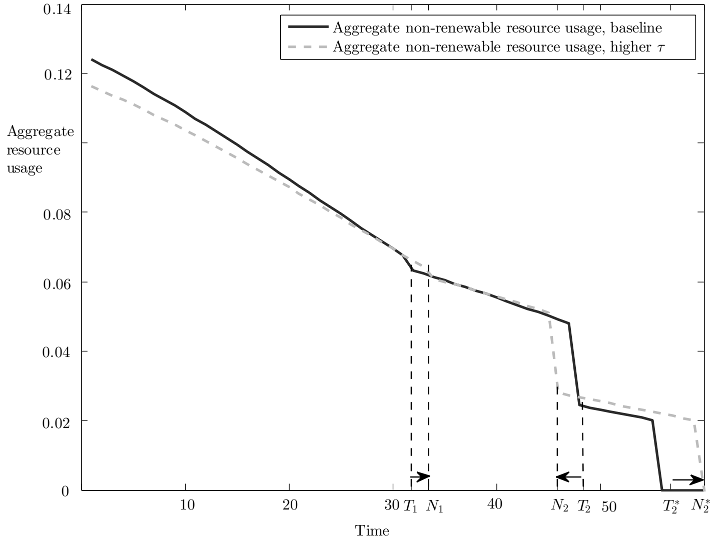


Figure 2.4: Aggregate resource extraction paths before and after the increase in the home region's tax rate, $X_0 = 3, Y_0^* = 4$: no Weak Green Paradox



is shortened, as is the case in Figure 2.4. The reason is that the usage time of the low extraction cost resource is still prolonged for both regions in Figure 2.4. Hence, in order to analyze the effects of carbon taxation with respect to the Green Paradox as we defined it, we have to turn our attention to the first switching point. In general, $\frac{dT_1}{d\tau} < 0$ is a necessary and sufficient condition for a Weak Green Paradox to occur. Given the partial equilibrium nature and linearity of our model, $\frac{dT_1}{d\tau} < 0$ implies that the initial global extraction rate in the presence of a carbon tax is higher than in the case without policies.

The effects of a tax increase on the transition from the cheap to the expensive fossil fuel are ambiguous; the switch can occur sooner or later as a response to a rise in τ.[15] In order to gain some intuition, let us suppose that, in a world where the home country's initial tax rate equals zero, the home country introduces a large carbon tax. As a consequence of this tax increase the home region almost ceases to use the high cost resource, whereas its demand for the low cost resource is not dramatically affected. Then we might have that $\frac{d\lambda_y^*}{d\tau} < \frac{d\lambda_x}{d\tau}$ which is a necessary and sufficient condition for $\frac{dT_1}{d\tau} < 0$.[16] The intuition is that the producers in the home region are faced with a decrease of the home region's demand to almost no demand for the high cost resource and thus have to accept a lower resource rent in equilibrium. This ensures that the foreign country's demand is sufficiently stimulated in order to make up for the demand loss from the home region. Also, having initially a relatively high λ_y^* as compared to λ_x, i.e., a relatively scarce low cost resource, makes a bigger drop in λ_x more probable. If both resources are equally abundant or the low cost resource is even more abundant than the high cost resource, there is not much scope for λ_x to decrease more than λ_y^* due to a tax increase. Although a relatively scarce low cost resource stock seems to be the only general condition for a Weak Green Paradox to occur, it is very hard to find combinations of parameter values that actually yield the Weak Green Paradox. In Appendix A.2.2 we provide such an example for linear demand functions. The low extraction cost resource usage phase is however mostly prolonged in our examples or T_1 stays unchanged at best. We conclude hence that the conditions for $\frac{dT_1}{d\tau} < 0$ are rather restrictive and summarize our findings in the following proposition:

[15] For the ambiguity in the sign of $\frac{dT_1}{d\tau}$ for non-specified functional forms see also equation (A.16) in the Appendix A.1.1. In Appendix A.2 we present this ambiguity analytically using linear demand functions, and display a numerical example for $\frac{dT_1}{d\tau} < 0$.

[16] This can be seen already in equation (2.30): if T_1 is to decrease, $(\lambda_y^* - \lambda_x)$ needs to go up as a consequence of the tax increase such that, $(\lambda_y^* - \lambda_x)e^{rT_1} = c_x - c_y > 0$ is still satisfied.

Proposition 2 *Let the carbon tax rate and backstop subsidy in the home region be given. If the carbon tax of the home country increases, then*

(i) a Weak Green Paradox occurs only if $\frac{d\lambda_x}{d\tau} > \frac{d\lambda_y^*}{d\tau}$ *and consequently* $\frac{dT_1}{d\tau} < 0$*, which is the case if the low cost resource is sufficiently scarce;*

(ii) no Green Paradox occurs if $\frac{dT_1}{d\tau} > 0$*, i.e., the usage period of the low extraction cost resource is prolonged, which is typically the case.*

(iii) the extraction time for the foreign region is prolonged, i.e., $\frac{dT_2^*}{d\tau} > 0$*;*

(iv) the extraction time for the home region is prolonged, i.e., $\frac{dT_2}{d\tau} > 0$*, if the high cost resource* X_0 *is relatively abundant;*

(v) the extraction time for the home region is shortened, i.e., $\frac{dT_2}{d\tau} < 0$*, if the high cost resource* X_0 *is relatively scarce.*

Proof. See Appendix A.1.1, equations (A.16) and (A.17), and the analytical reasoning and numerical example in Appendix A.2. □

Proposition 2 also has an interesting implication with respect to changes in climate costs as a consequence of a tax increase: Hoel (2011) argues that a tax increase in the *low tax* country likely leads to a shorter overall extraction period and hence to higher total climate costs if the present value of the social cost of carbon is decreasing over time.[17] The case of a tax increase in the lower tax country is not in the centre of our analysis as we focus on the case of a non-environmentally concerned region, characterized by low resource costs, versus an environmentally concerned region with high resource cost. We think that this is a more realistic scenario. However, our analytical results regarding the sign of $\frac{dT_1}{d\tau}$ derived in Appendix A.1.1 do not depend on the initial tax rates in the countries and hold thus for the case of a tax increase in the low-tax country. In contrast to Hoel (2011) we find that higher climate costs are not a necessary consequence in our setting: with different extraction costs, we have an additional switching point from the low to the high cost resource extraction period. Our analysis has shown that the low cost extraction period is likely to be extended as a result of a tax increase, independent of the initial tax rates in the regions, which precludes a Weak Green Paradox and reduces climate costs in the low cost resource phase.

[17] Hoel (2011) illustrates this assuming inelastic demand, but his reasoning is valid for cases of various demand elasticities.

This extension of the low cost resource usage phase countervails the eventually shortened overall extraction period.
Yet, this small, but non-zero likelihood of a Green Paradox occurring sets our result contrary to Fischer and Salant (2014): in their setting, a higher tax only affects the scarcity rent and price of the low cost resource. A higher demand from the unregulated region cannot fully offset the reductions in resource use of the regulated users. Overall, a tax increase flattens out the extraction path of the low cost resource, whereas aggregate emissions decrease due to less intensive and shorter use of the high cost resource pool.

2.2.5 Endogenous Climate Policies and Welfare Effects

In the introduction we have stressed that the effects of climate policies may vary between one- and multiple region settings, between the case with and without extraction costs. Furthermore, the preceding analysis has shown that climate policies affect both the regions' switching times and the producers' resource rents. So far we refrained from statements on the welfare effects of these policy changes. Yet, it is obvious that changes in climate policies alter the resource prices and hence the terms of trade of the regions, the regions' switching points and their green welfare. All these changes have immediate impact on the regions' overall welfare, which we write in the following way:[18]

$$W = \int_0^\infty e^{-\rho t}\{U(x_c + y_c + z_c) - c_x(x_c + x_c^*) + p_x x_c^* - p_y y_c - (b - \sigma)z_c - \sigma z_c\}dt - G, \tag{2.31}$$

$$W^* = \int_0^\infty e^{-\rho t}\{U^*(x_c^* + y_c^* + z_c^*) - p_x x_c^* - c_y^*(y_c + y_c^*) + p_y y_c - b^* z_c^*\}dt - G^*, \tag{2.32}$$

where the sum of G and G^* equals the total climate costs, with

$$G = G^* = \left(\frac{\alpha}{\rho} + \frac{(1-\alpha)}{\rho + \delta}\right)\nu \int_0^\infty e^{-\rho t}\left(\psi(x_c + x_c^*) + \psi^*(y_c + y_c^*)\right)dt. \tag{2.33}$$

where ν equals the constant marginal damage from atmospheric CO_2, whereas the term to the left hand side of ν accounts for the depreciation of atmospheric carbon stock. The derivation of the climate costs in (2.33) follows closely Hoel (2011) and can be found in Appendix A.3. In order to evaluate climate policies, we have to consider the changes in the three components of welfare as described in equations (2.31) and (2.32): the changes

[18]The welfare functions are different from the welfare function depicted in (2.1) as each region accounts only for the climate costs it itself incurs, and its terms of trade.

in utility from resource consumption minus extraction costs, the changes in the terms of trade and the changes in the climate costs. We call the two former changes in the regions' "non-green welfare", whereas the changes in the climate costs are referred to as changes in "green welfare". The notions that countries might have strategic incentives to employ environmental policies, and that climate policies induce terms of trade changes are not new. A large literature deals with strategic climate policies: Strand (2013) compares a carbon tax to a cap-and-trade scheme in a static model where resource importers consisting of a 'policy bloc' and a lethargic fringe, and a bloc of resource exporters set their policies strategically. He finds that the policy bloc prefers the tax over the cap as it reduces the fuel export price. Karp et al. (2015) extend this static setting to study Markov perfect equilibria of a dynamic game where they analyze the effectiveness of taxes versus quotas. A setup closest to ours can be found in Eichner and Pethig (2013): in a two-period model they distinguish between a global climate coalition which wants to take unilateral climate action in order to meet an emission ceiling, taking the market response of the climate passive region into account. They are hence looking for the least cost ceiling policy for the climate coalition, given this coalition's exogenous target, without actually solving for a Nash equilibrium. Similar to Eichner and Pethig (2013), we assume that the foreign region is environmentally inactive and disregard the game theoretic dimension. Our setting, however, is too complex to provide analytical welfare results. The difficulties are rooted in our dynamic, infinite time horizon setting, which contrasts with Eichner and Pethig's two-period model with linear demand and Strand's static model. Moreover, as opposed to Strand (2013), we do not distinguish between a pure importer and exporter bloc, but our regions both import and export the non-renewable resource at different times. Therefore, this section will rely on numerical examples of optimal climate policies in order to unravel some mechanisms that are at play when optimally setting the home region's tax and backstop subsidy. Also, we will try to relate our numerical findings to the insights generated by simpler models in the papers mentioned above.

Consumers are price takers and maximize utility subject to a budget constraint. The world market price for the home and the foreign region's fossil fuel equals $p_x = c_x + e^{\rho t}\lambda_x$ and $p_y = c_y^* + e^{\rho t}\lambda_y^*$ respectively. As before, we assume that the foreign country neither levies a carbon tax nor subsidizes renewables. The tax rate in the home country equals τ whereas the renewables subsidy is σ. As in the previous section we suppose that the taxes and subsidies are constant over time.[19] Although both regions are equally affected by the climate costs, we assume that the foreign country does not account for green welfare. It neglects the existence of climate costs and hence we take $G^* = 0$ in its welfare optimization problem in equation (2.32).[20]

In the following numerical example we assume the social cost of carbon to be equal to 5 and take the total actual climate costs to be the sum of G and G^* from equation (2.33), i.e., equal to the social cost of carbon times the discounted sum of resources extracted.[21] The first-best tax rates in equations (2.20) and (2.21) are hence equal to the social cost of carbon.

Our numerical example shows that a rise in the carbon tax can benefit the home region not only in terms of increased green welfare, but also with regard to its terms of trade, as implied by the literature.[22] A higher tax in the home region lowers its demand for the resource imports from the foreign region, while increasing benefits from non-renewable resource exports to the foreign region after an earlier switch of the home region to backstop consumption. In contrast, the foreign region's welfare deteriorates with increasing taxation in the home region, as can be seen in our numerical example in Figure 2.5.[23]

The positive terms of trade effect in the home region might not dominate for all possible tax rates.[24] At one point, it might be outweighed by the utility loss from decreased resource consumption in the home region and the home region's losses in the period when it is resource exporter itself. This is the case in our numerical example underlying Figure 2.6 where we depict the green and non-green components of the home region's welfare as a

[19] In the following analysis we abstract from issues of dynamic inconsistency. The policy tools considered here are constant taxes and subsidies. Thus, we implicitly assume that commitment is possible or that a policy path determined at the beginning of the time horizon is enforced at all times.

[20] Note that setting $G^* = 0$ does not imply that the 'endogenous' climate policies are also zero in the foreign country. The foreign country might have non-green incentives to pursue climate policies. In this section, however, both the foreign country's climate concerns and its climate policies are exogenously set to zero to match the setup in the previous sections; only the home country's policies are endogenized.

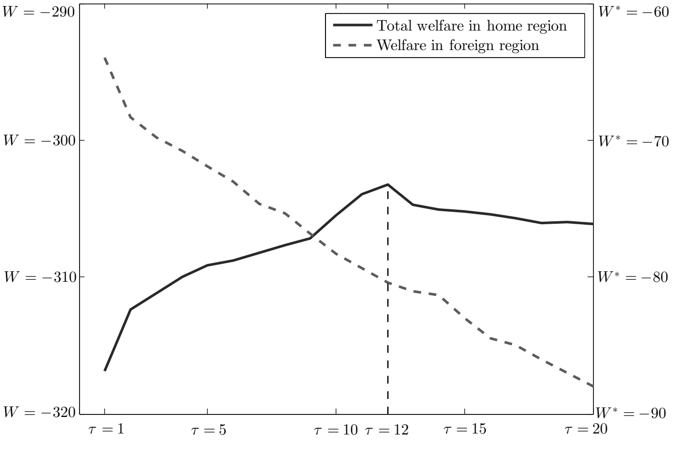
[21] This value of the SCC is arbitrary. Yet, this is inconsequential as we do not compare overall welfare inter-regionally. For intra-regional welfare comparison it is also unimportant as it is just a scaling parameter. In contrast to the numerical exercises of Sections 2.2.4 and 2.2.5, we use a social cost of carbon estimate which corresponds to 30 $ per ton of carbon for our calibration in Section 2.3, which is in line with Nordhaus (2008). The parameters for the numerical exercises are given in Table A.2 in Appendix A.4.

[22] Both, the introduction of a positive tax as compared to $\tau = 0$, and an increase in the carbon tax until the point when $\tau = 12$ entails terms of trade gains for the home country, as can be seen in Figure 2.6.

[23] As the foreign region perceives $G^* = 0$, its "total welfare" consists only of non-green welfare.

[24] 'Possible' or 'feasible' tax rates in the numerical exercises in Figure 2.5 and 2.6 are tax rates which correspond to an equilibrium as delineated in Section 2.2.3, where pollution taxes are not too high and renewable cost is not too low, such that in equilibrium there is supply and demand of both fossil fuels.

Figure 2.5: Home and foreign regions' welfare as function of different carbon tax rates in the home region



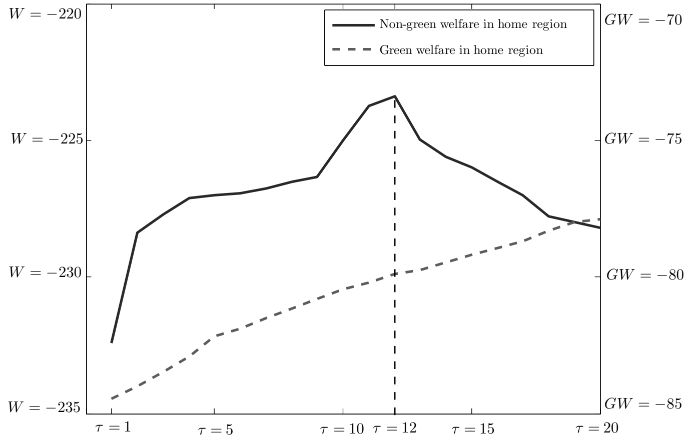
function of different taxation rates.

In this numerical example, the tax rate which maximizes total welfare in Figure 2.5 is at the same time the tax rate maximizing non-green welfare, as can be seen in Figure 2.6. Green welfare is increasing in the tax rate, but it is not always high enough as to make up for the utility loss due to negative terms of trade for the home region in case the tax is too high.

Figures 2.5 and 2.6 are just examples of parameter values where the resulting endogenous tax is higher than the first-best tax, which is equal to the social cost of carbon, i.e., $\tau = 5$ in our example. For other parameter values the resulting endogenous tax can be higher or lower than the first-best tax rate.[25] By varying the stock size, i.e. the relative distribution of stock ownership between the regions, we confirm Eichner and Pethig's (2013) conclusion that the sign and magnitude of optimal (or, in their case, cost effective) carbon taxation depend on the distribution of ownership of the fossil fuel stock between the climate bloc and the rest of the world also in our intertemporal setting: being an importer (exporter) induces the country to levy positive (negative) tax rates which decrease (increase) world

[25]Despite the fact that the Pigouvian tax already is the 'optimal tax' balancing out climate costs and utility losses, optimal endogenous taxes might be lower than the Pigouvian tax rate. The reason is that the Pigouvian tax rate is derived in a Social Planner setting, whereas in the present setting the region maximizes its private welfare containing a terms of trade effect which introduces different trade-offs.

Figure 2.6: Green and non-green welfare components in the home region as function of carbon tax rates



demand and hence decrease (increase) the country's fossil fuel expenses (revenues). Since in our model the foreign region is a fossil fuel exporter and subsequently importer (and *vice versa* for the home region), the terms of trade effect is the accumulated effect of unilateral policies on non-green welfare, i.e., the aggregated gains and losses over the infinite time horizon. Hence, a region's terms of trade gains from higher taxation outweigh the terms of trade losses if its resource stock is relatively small and if the losses are more discounted. Therefore, the home region which is exporting the high cost resource only after the low cost resource is exhausted, is more prone to benefit from carbon taxation than the foreign region.

The reasoning above reveals a mechanism which cannot be captured by the model of Eichner and Pethig (2013): the timing of the switch and discounting. There is a non-green incentive for carbon taxation which stems from the fact that the regions are exporting and importing at different times. The home region discounts its potential revenue losses from a carbon tax more than the gains over the relatively short period. Hence, a positive carbon tax might still be an appealing policy for high discount rates. But even if discount rates are low and X_0 is abundant enough for carbon taxation to always decrease non-green welfare, there might be a purely green rationale for carbon taxation: our direct inclusion of climate damages introduces a trade-off to the welfare optimizaion.[26] Eichner and Pethig

[26]Take the initial stocks $X_0 = 8$ and $Y_0^* = 2$ as an example: for these endowments, we find that taxes

(2013) cannot account for these policy incentives due to the lack of climate damages in their model.

An optimal subsidy can be found numerically in a similar way.[27] The effect of the subsidy on the non-green welfare of the home region is twofold: on the one hand it increases (initial) resource consumption and hence welfare by reducing the consumer price of the resource. Also, the period over which the home region is importing the resource is shortened. On the other hand, with a backstop subsidy, the home region's renewable resource demand is distorted as the costs of financing the backstop are not taken into account in the consumption decision. The subsidy burden reduces the home region's reduce welfare after the switch to renewable energy usage. Disregarding corner solutions, i.e., when the positive (negative) effect of a subsidy is dominating throughout the spectrum of possible subsidy levels, implying that the optimal subsidy should be as high as possible (zero), a possible intermediate welfare path looks similar to the one in Figure 2.6. Also the foreign region's non-green welfare is downward sloping in the subsidy rate: a higher subsidy reduces the low extraction cost resource rent and prolongs the period when the foreign country is importer of the high cost resource.
Climate costs, however, are most likely to rise. Thus, the green welfare in Figure 2.6 would be downward sloping in increasing subsidy levels. Using our Green Paradox definition from Section 2.2.4, we conclude that higher subsidies result in a Strong Green Paradox in our numerical simulations.

It is not easy to answer the question about the choice of the optimal policy instrument from the perspective of the home country as the climate policies have differential effects on the various components of welfare. Whereas taxes unambigously reduce climate costs, backstop subsidies might be more efficient in bringing about favourable terms of trade changes and hence outweigh the negative effects on green welfare. It is not possible to give a definite answer for all potential parameter values. In the calibration of Section 2.3 we will restrict the parameter space and hence the analysis to realistic parameter values, giving us a clue as to which policies are preferable in the real world.

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decrease non-green welfare, i.e., the home region with the more abundant resource stock looses from the tax introduction. Green welfare naturally still increases. The resulting optimal tax rate equals $\tau = 2$ and balances out the losses from non-green welfare and green welfare gains and is thus lower than the Pigouvian tax rate amounting to 5 in our example.

[27] As before, we compute overall and the different components of welfare for different subsidy levels and compare the resulting welfare levels.

2.3 Calibration and Welfare Analysis

2.3.1 Calibration

For the numerical simulations we subsume the OPEC countries as 'the foreign region', whereas the OECD countries together with India and China constitute 'the home region'. This country selection leaves out many important countries such as Russia and Brazil. Yet, as the idea is to include the biggest fossil fuel consumers and the largest fossil fuel producers, we only account for countries whose carbon emissions are most substantial. We use a discrete time version of the model presented above and time intervals of 5 years. The pure rate of time preference ρ is set as high as 10% per decade (Rezai et al., 2012) which corresponds to 4.88% per 5 years (we employ an interest rate of 5% in the calibrations).[28] For simplicity, the exogenous world interest rate is set to the same level, i.e., $\rho = r$. We use isoelastic utilities of the form $U = \frac{(x_c+y_c+z_c)^{1-\gamma}-1}{1-\gamma}$ and set the rate of intertemporal substitution at 1/2, thus $\gamma = 2$ (Rezai et al., 2012).[29] In the calibraton we use scaling parameters to match the real world non-renewable resource demand from the OECD countries together with India and China, and the OPEC countries, respectively.

Following Rezai et al. (2012), we assume that there are 1000 parts per million by volume of CO_2 (ppmv) *in situ*, stemming from carbon-based energy sources which are cheap to extract, hence $Y_0^* = 1000$ ppmv. This amount is equivalent to 2130 gigaton carbon (GtC) as 2.13 GtC are equivalent to 1 ppmv. It is hard to estimate stocks of carbon-based energy sources. While Rezai et al. (2012) assume an initial carbon stock of 2000 ppmv, Van der Ploeg (2013) estimates the current fossil fuel reserves to be 3 trillion tons of carbon which correspond to 1408.45 ppmv of CO_2. We find a middle ground and assume the total initial stock of carbon to be 1500 ppmv. Thus, the home region disposes of $X_0 = 500$ ppmv.

In the calibration we interpret both the low and the high cost resource as oil. While the fossil fuels differ in extraction costs, their emission factors hence are equal. Similar to Rezai et al. (2012) we calibrate the low extraction costs to give 5 $ per barrel for onshore oil, initially. A barrel of oil is taken to be equivalent to 1/10 ton of carbon.[30] We express prices in $ trillion per ppmv (Rezai et al., 2012). Thus, we calculate the extraction costs of the

[28] The calibration parameters are summarized in Table A.3 in Appendix A.4.

[29] The functional form of the utility is depicted in equation (A.47) in Appendix A.4. A positive change in γ results in higher resource consumption and thus in faster exhaustion of the non-renewable resource. Yet, numerical analyses suggest that the equilibrium properties, such as the order of switching, do not change with γ, given that an equilibrium with two switching points for both countries exists.

[30] We take an oil density of 0.85 g/cm^3; thus, a barrel (159 liters) corresponds to 135 kg of oil. Hence, a barrel contains 118 kg of carbon at the higher end, less for thin and 'good' crude oil.

low-cost resource at $c_y^* = 0.1065$ \$ trillion per ppmv. According to the IEA (2008) the cost of oil depletion will quadruple if another 500 ppmv are extracted. Since we consider only constant marginal extraction costs in our paper, this cost increase is taken up by the higher extraction costs in the home region. Thus, after the depletion of the 1000 ppmv of the low-cost resource, we assume an octuple increase in extraction costs for the last 500 ppmv, i.e., $c_x = 0.852$ \$ trillion per ppmv.

In the estimation of the production price of renewables we follow Van der Ploeg (2013) and suppose that the renewables' cost is 1.5 times the extraction cost of the high cost resource.[31] Hence, we set $b = 1.278$ \$ trillion per unit of renewable energy that corresponds to 1 unit of ppmv with respect to its energy content. Given that our renewable energy production cost depends on our estimate of the extraction cost of the high cost non-renewable resource, and in reality is prone to decrease over time (due to e.g. technological improvements), this estimate of the renewable resource production cost is very crude. Yet, as argued before, this simplification can be defended for the purposes of this paper. We reasoned above that the production cost of the backstop technology is higher in the foreign region. Hence, we set $b^* = 1.6614$, which corresponds to 30% higher costs than in the home region. Expressed in dollars per kilowatt per hour (kWh), the price of the backstop in the climate coalition would equal 0.284 \$/kWh, and in the OPEC countries 0.37 \$/kWh.[32] The assumption that $b < b^*$ is debatable as one could argue that the OPEC countries have more favorable conditions with respect to solar energy, for instance. Yet, we think that the OPEC countries lack the technology and expertise to exploit their favorable conditions. It seems reasonable to assume that the 'climate coalition' is more developed with respect to other renewables such as hydro, wind and biomass, regarding its technological possibilities, and also with respect to intangible factors such as knowledge accumulation, human capital and learning by doing. This makes $b < b^*$ a reasonable assumption.[33]

For the climate costs we refer to Nordhaus (2008) who estimates the SCC to be approximately 30 \$ per ton of carbon for his standard set of assumptions. Thus, for 1 ppmv of CO_2, this amounts to a social cost of carbon of $2\nu\left(\frac{\alpha}{\rho} + \frac{1-\alpha}{\rho+\delta}\right) = 0.0639$ \$ trillion.[34] Nordhaus'

[31]In Van der Ploeg (2013) the renewables cost was assumed to be 1.5 times the current market price of fossil fuels.

[32]The backstop price in the climate coalition approximately equals the estimated total system levelized costs of solar thermal and wind offshore energy generation in the U.S. in 2018 (EIA, 2013).

[33]A scenario where $b^* < b$ would not alter the Green Paradox results of the previous section as it has no effect on the first switching point. The welfare analysis, however, would likely be affected. We do not conduct a welfare analysis for the scenario $b^* < b$ because we focus on the more realistic case of $b < b^*$ in our calibration, as explicated above.

[34]The costs of 1 ppmv are $10^9 * 2.13 * 30$\$. Furthermore, we assume $\psi = \psi^* = 1$.

estimates are located at the lower range of the social cost estimates in the literature. Thus, our SCC estimate is rather conservative.
We calibrate the model in order to obtain 110395 million tons of carbon which correspond to the amount of carbon emitted by the OECD countries, India, China and the OPEC countries during the 5 year period 2006-2010. OPEC's emissions are calibrated to equal 8095 million tons of carbon, whereas the emissions of the OECD countries together with India and China account for 102300 million tons of carbon (IEA, 2008). Thus, $y_c^*(0) = 3.8$ ppmv and $y_c(0) = 48.028$ ppmv. In the next section we denote the home region as 'climate coalition'.

2.3.2 Unilateral Pigouvian Taxation and Backstop Subsidy

We start our analysis by investigating the effects of a carbon tax introduction in the climate coalition relative to the baseline of no climate policies at all. With no climate policies in place, the switching points are $T_1 = T_1^* = 120$, $T_2 = 205$ and $T_2^* = 270$. Thus, in the case of no regulation the home region switches to using the backstop technology in the year 2211, whereas the foreign region does so only by the year 2276.[35] This is a late transition to renewable energy as compared to Rezai and van der Ploeg (2014), for instance, who estimate that the world switches to renewables in the year 2120 in their no-policy scenario. There are two main reasons for our long fossil fuel usage phase: Firstly, contrary to Rezai and van der Ploeg (2014), there is no possibility of economic exhaustion in our model, i.e., all the fossil fuel which is in the crust of the earth is extracted eventually.[36] Secondly, although the global primary energy consumption is expected to increase, we assume stationary demand.[37] We do this for simplicity as our aim is not primarily to accurately predict the world's switching time to renewable energy usage, but to focus on the occurrence of the Green Paradox and the region's incentive structure for climate policies.

Let us suppose that the countries in the climate coalition agree to introduce the Pigouvian tax rate of $\tau = 2\nu\left(\frac{\alpha}{\rho} + \frac{1-\alpha}{\rho+\delta}\right) = 0.0639$ \$ trillion per ppmv. This unilateral policy change

[35]We calibrate our model's parameters to the cumulative emissions of the years 2006-2010; thus, we take 2006 as our starting year.

[36]In contrast to the 1500 ppmv of fossil fuel which are extracted in our calibration, Rezai and van der Ploeg (2014) consider an initial stock of fossil fuel equal to 1878 ppmv, whereas only 1178 ppmv are extracted in their no-policy scenario.

[37]BP estimates in its Energy Outlook 2030 that the "World primary energy consumption is projected to grow by 1.6% p.a. from 2011 to 2030, adding 36% to global consumption by 2030" (BP, 2013).

results in a flattening out of the resource extraction paths; the new switching points are now $T_1 = 130$, $T_2 = 210$ and $T_2^* = 295$. As can be seen in Figure 2.7, no Green Paradox occurs. The tax clearly benefits the climate: in our calibration, the discounted present value of climate costs decreases from 46.9 $ trillion to 44.89 $ trillion.[38] Yet, the prevented cost of climate damages of about 2 $ trillion seems small compared to the climate coalition's gains in their terms of trade equalling 46.95 $ trillion. Our welfare analysis hence shows that the climate coalition has incentives to introduce a tax *even in the absence of climate concerns*. A carbon tax increases its non-green welfare as it reduces the coalition's very costly non-renewable resource demand in the low cost resource extraction phase, where its resource consumption is satisfied by imports from the OPEC countries. Furthermore, the climate coalition largely benefits from the long resource exporting phase to the OPEC countries, after having switched to the backstop technology itself. Hence the name 'climate coalition': the implementation of climate policies is in this coalition's interest as both truly welfare improving and as 'green' alternative to staying unregulated. Moreover, the climate coalition has an incentive to raise the carbon tax above the Pigouvian level: its non-green welfare is increasing in the carbon tax, even after surpassing its Pigouvian level. On the other hand, OPEC's welfare shrinks by the considerable amount of about 25.8 $ trillion as its revenues from exporting the non-renewable resource decrease.

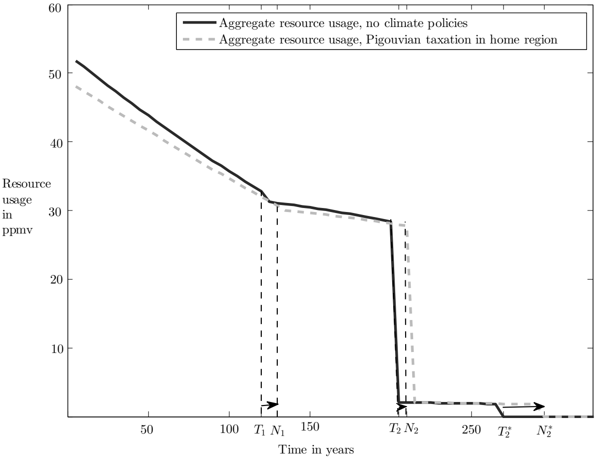
Given the climate coalition's unilateral climate policy, does OPEC have an incentive to also employ climate policies on its part?[39] Introducing a non-zero carbon tax in the OPEC countries additionally to employing a tax in the climate coalition results in a further decrease of total climate costs.[40] Moreover, the climate coalition profits from the tax increase in the OPEC countries as it decreases the coalition's consumer price for oil. Yet, the chances for a global carbon taxation scheme to be set in place are very slim in case the OPEC countries do not have direct climate concerns. The adoption of a carbon tax by OPEC leaves its non-green welfare almost unaffected. Though OPEC profits from higher resource prices during its exporting phase, the overall welfare increase is within the margin of error. There is hence no significant incentive for OPEC to introduce a Pigouvian carbon

[38] Climate costs are defined as before as $G + G^*$ in equation (2.33) with constant marginal damages $C' = C^{*\prime} = v$.

[39] In the sequel we are not solving for the Nash equilibrium of a climate policy game; this would be beyond the scope of this paper. However, we elucidate incentives that are very likely to be crucial when solving for Nash equilibrium strategies.

[40] Establishing a non-zero carbon tax in the climate coalition is, however, more effective than a tax in the OPEC countries. The decrease in total climate costs naturally is higher for the same tax because the total consumption of fossil fuels in the climate coalition exceeds the total consumption in the OPEC countries multiple times.

Figure 2.7: Total resource usage in the case of no climate policies and in the case of a Pigouvian tax in the home country, N and N^* denoting the new switching points after the policy change

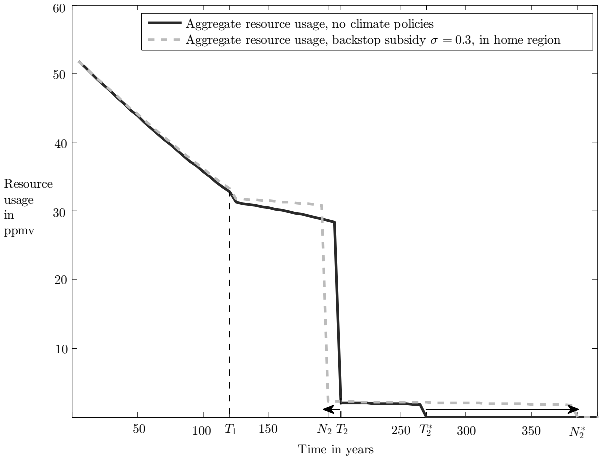


tax. The introduction of a backstop subsidy in the OPEC countries is also not a viable alternative, although it in fact considerably shortens their dependence on the high cost resource imports from the climate coalition. Yet, this is not enough to offset the losses in the resource rent and to increase OPEC's welfare.

Whereas a positive carbon tax never seems favourable for the OPEC countries, they do have an incentive to employ a *negative* tax rate. Introducing a carbon *subsidy* in the OPEC countries increases their welfare, whereas the climate coalition's welfare falls. The subsidy increases OPEC's demand and hence the scarcity rent: OPEC producers profit from the higher fuel price more than OPEC suffers when it turns into a non-renewables importer itself. The effects on the climate are unambigously negative: the overall non-renewable resource usage time is shortened and climate costs increase.

Let us suppose now that carbon taxation is infeasible for the climate coalition for political reasons. A backstop subsidy might seem to be a viable alternative from a policy maker's point of view, although it always results in a Green Paradox, as our analysis has shown. In our calibration, however, the introduction of a backstop subsidy in the climate coalition

Figure 2.8: Aggregate resource usage in the case of $\sigma_2 = 0.3$ and in the case of no climate policies



does not have large Green Paradox effects.[41] The low extraction cost resource period is hardly shortened as can be seen in Figure 2.8. In the figure, the first switching point is still at $T_1 = 120$, whereas the climate coalition switches now at $T_2 = 195$, and the OPEC countries as late as at $T_2^* = 385$ to using the backstop technology. Though the increase in initial emissions is very small, a Strong Green Paradox occurs: the total climate costs increase slightly from 46.9 \$ trillion to 47.04 \$ trillion as a result of the subsidy.

The introduction of a subsidy benefits the coalition in terms of their utility from resource consumption, but only slightly so. In contrast, the terms of trade of the coalition worsen: although the coalition benefits from the lower resource price while importing the non-renewable resource, its resource rent has to fall more than OPEC's resource rent as a consequence of the subsidy. This lower price impairs its terms of trade position when the climate coalition is exporting its resources, after having switched to the renewable resource themselves.

What might be the appropriate answer of the OPEC countries to the climate coalition's policy? Neither a positive tax nor a subsidy significantly improve OPEC's welfare.

Do the OPEC countries have the same incentives as the climate coalition to unilaterally introduce a positive backstop subsidy in the first place if they do not perceive the climate

[41]We employ a subsidy of $\sigma = 0.3$ which amounts a subsidy of 24.5% of the original backstop production cost of $b = 1.278$, but neither higher nor lower subsidies have significantly different effects.

costs? Our calibration exercise negates this. Employing $\sigma^* > 0$ when $\sigma = 0$ results in lower welfare for OPEC, whereas the welfare level of the climate coalition increases.

Our calibration exercise has shown that it is beneficial for the largest fossil fuel using regions to form a 'climate coalition' and to unilaterally introduce climate policies, even in the absence of real climate concerns. The results of such climate policies are large gains in the terms of trade position of the coalition with respect to the non-renewable energy producers, the OPEC countries, and, in the case of a carbon tax, a significant reduction of climate costs. Yet, as further analysis reveals, the first-best climate policy, i.e., a world-wide carbon tax, does not seem attainable as the OPEC countries have little incentives to follow the climate coalition in introducing a carbon tax.

The assumptions underlying the calibration are clearly simplifications. For a 'climate coalition' to exist the OECD countries together with India and China needed to form not only a political (with respect to climate policies), but also, as prerequisite for common climate policies, an economic coalition. Alternatively, the different impacts of this coalition's unilateral climate policies on the coalition's member countries would need to be offset by transfer payments within the coalition. This kind of coordination in international climate agreements has so far not been proven to be successful. Accounting for the difficulties to form a real world international climate coalition, we conduct the same analysis with only the OECD countries entering the 'climate coalition', and India and China being part of a non-policy bloc. Also for this smaller 'climate coalition' we find positive welfare effects of introducing a carbon tax.

Our calibration exercise has shown that unilateral climate action, such as the introduction of carbon taxation, can be desirable for a self-interested coalition, composed of the biggest fossil fuel emitters or a smaller subcoalition thereof, and also preferable from an environmental perspective. This result emphasizes the importance of the energy market channel of intertemporal leakage. In the partial equilibrium setting, carbon leakage is induced by the market channel (Van der Werf and Di Maria, 2012) and incentivized by a 'terms of trade channel'. Usually a terms of trade channel of carbon leakage relates to the change in relative prices for non-energy goods if climate policies are introduced (Van der Werf and Di Maria, 2012). Considering a global resource market with resources that are spatially separated and differ in extraction costs, terms of trade issues arise also in the energy market itself. The antecedent analysis highlights the incentives stemming from energy market changes induced by climate policy and resulting in welfare changes. This angle reveals which policies are 'desirable', i.e., compatible with the coalitions' self-interest, and thus have a chance of being implemented in the first place.

Hence, to answer the initial question about which climate policies to prefer in the real world, we state that, both from a coalition's self-interested non-green and from a global environmental point of view, unilateral carbon taxation in the countries of the climate coalition seems to be the preferential policy choice.

2.4 Concluding Remarks

In this paper we highlight the importance of the effects of unilateral climate policies in a world with heterogeneous regions, which differ in important characteristics: their non-renewable resource extraction costs, emission factors and backstop production costs. Using a two-region partial equilibrium framework of resource extraction, we show that the introduction of carbon taxation in one region rarely results in a Weak Green Paradox, whereas a higher subsidy does. In a numerical analysis of optimal carbon taxation and backstop subsidy we assess the differential impacts of these climate policies on green and non-green welfare in both regions. We show that, in some cases, the policies are set to maximize only non-green welfare and thus do not necessarily coincide with the first-best policy levels.

We calibrate the model and differentiate between a 'climate coalition' formed by the world's largest fossil fuel users, and the OPEC countries. We find that the climate coalition has non-green incentives to introduce carbon taxation as this improves its terms of trade position. Furthermore, climate costs are significantly reduced. A global carbon taxation scheme, however, is not very probable as the OPEC countries have little incentive to implement (unilateral) climate policies. Nevertheless, the welfare and climate cost analysis indicates that unilateral carbon taxation by the climate coalition is the best feasible course of climate action.

The study at hand has some limitations which stem from the simplifying assumptions made in order to solve analytically for the direction of change of our Green Paradox variables of interest. Differing constant marginal non-renewables' extraction costs constitute a novel addition to the framework in Hoel (2011), but they also have the most severe implications for the analysis: the possibility of economic exhaustion of the non-renewable resource is ruled out in the presence of constant marginal renewables production costs, and the resource producers in *both* regions are affected by changes in climate policies. Although full exhaustion of fossil fuel reserves is rather unrealistic, we think that it is important to also account for how the policy affects the high cost resource producers. Hence, we believe that we are able to distill the basic mechanisms of how unilateral policy changes affect the global emissions path in the presence of different resource pools and different regions, to illustrate a full solution of the model by providing numerical examples, and to discuss the global impacts of unilateral policies in the real world. After unraveling the basic mechanisms at work in this simple framework, possible extensions of the model encompass the introduction of stock-dependent extraction costs, which might differ spatially in their levels or the speed at which they increase. The constancy of the production costs of the backstop technology could be abandoned like in Fischer and Salant (2014), and the backstop production costs could be endogenized. A next step would be a general equilibrium model in a heterogeneous regions setting. Another exciting direction of research is to concentrate on the (non-green) incentive structure of the regions. Studying the incentives for the use of climate policies by different coalitions in a game theoretic setting might provide us with a more complete picture of the climate and welfare effects of 'climate' policies, taking into account the players' interests and market power.