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Abstract

By reducing the demand for fossil fuels, climate policy can reduce scarcity rents for fossil resource owners. As mitigation policies ultimately aim to limit emissions, a new scarcity for "space" in the atmosphere to deposit emissions is created. The associated scarcity rent, or climate rent (that is, for example, directly visible in permit prices under an emissions trading scheme) can be higher or lower than the original fossil resource rent. In this paper, we analyze analytically and numerically the impact of mitigation targets, resource availability, backstop costs, discount rates and demand parameters on fossil resource rents and the climate rent. We assess whether and how owners of oil, gas and coal can be compensated by a carbon permit grandfathering rule. One important finding is that reducing (cumulative) fossil resource use could actually increase scarcity rents and benefit fossil resource owners under a permit grandfathering rule. For our standard parameter setting overall scarcity rents under climate policy increase slightly. While low discount rates of resource owners imply higher rent losses due to climate policies, new developments of reserves or energy efficiency improvements could more than double scarcity rents under climate policy. Another important implication is that agents receiving the climate rent (regulating institutions or owners of grandfathered permits) could influence the climate target such that rents are maximized, rather than to limit global warming to a socially desirable level. For our basic parameter setting, rents would be maximized at approximately 650 GtC emissions (50 percent of business-as-usual emissions) implying a virtual certainty of exceeding a 2°C target and a likelihood of 4°C warming.

JEL Codes: Q30, Q38, Q40, Q54

Keywords: global warming, geo rent, Hotelling, carbon budget, fossil resources, renewable energy

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1. Introduction

Greenhouse gas emissions from the combustion of fossil fuels are the leading contribution to anthropogenic climate change, as has been comprehensively summarized in the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007a, p. 25), along with more recent updates (e.g. National Research Council (U.S.), 2010). Perhaps more importantly, signals of a changing climate due to anthropogenic influences are already being observed, and are projected to become more noticeable in the near- to mid-term future (IPCC, 2007b, pp. 36–45;66–74). Since fossil fuels make up 85% of world primary energy consumption (IPCC, 2011, p. 35) and contribute more than 55% of warming potential of anthropogenic greenhouse gases (IPCC, 2007a, p. 28), policies for climate change mitigation concentrate on the decarbonization of the energy system. Given the large amounts of fossil fuels in the earth, decarbonization implies that in the short and medium term either those fossil resources may not be extracted and burned, or that emitted carbon must be effectively captured and permanently sequestered. As the technical and geological potential of carbon capture and sequestration is limited (IPCC, 2005), the starting point of this paper is the necessity of having potential resources remain in the ground to avoid dramatic temperature increases.

We will briefly summarize estimates of the final equilibrium global temperature change that can be tolerated without inducing "dangerous anthropogenic interference with the climate system" (UNFCCC, 1992, Article 2), as well as the fraction of the fossil fuel resource that can be combusted while maintaining consistency with the final tolerable temperature change. After surveying previous related work, we use an analytical model and a slightly extended numerical application of that model to address two main questions: First, given the fact that restricting total future carbon emissions, *i.e.* setting a "carbon budget" for climate mitigation, amounts to creating an artificial scarcity of fossil-fuel resources, what happens to the rents for resource owners under climate policy? Second, depending on the stringency of the climate policy, and therefore on the induced scarcity of fossil fuels, is it possible for resource owners to be compensated for decreased sales of fossil fuels through potentially increasing scarcity rents? We explore the relevant parameter space of carbon budgets, discount rates, backstop technology costs and demand growth rates to determine which are the most crucial determinants for compensation. Our model combines the conventional Hotelling approach of optimal fossil resource extraction with the political-economy dimension of scarcity rents that are associated to finite resources and possibly induced rent-seeking behavior. While the analytical model strengthens the insights in the general dynamics of scarcity rents due to parameter variations, the numerical model application transfers these insights to a more realistic but specific real-world setting.

The focus on the supply-side and on the fossil resource owners is motivated by the green paradox of

Sinn (2008).[1] The intertemporal profit maximizing behavior of fossil resource owners can render climate policy measures ineffective. One critical aspect is the occurrence of so-called supply-side leakage, when unilateral carbon pricing policies induce a re-allocation of fossil resource use via reduced (global) fossil resource prices (Eichner and Pethig, 2011). Without a globally harmonized policy, mitigation is therefore barely feasible or will be very expensive. Sinn (2008) suggests a (theoretically) feasible unilateral policy to subsidize resource stocks *in situ*; nevertheless, he admits that taxpayers will strongly reject a policy that transfers large amounts of money to owners of oil, gas and coal. A similar approach is to develop a market in extraction rights that recognizes the option of foregoing extraction (Harstad, 2010). The starting point for Harstad is the recognition that many countries may not willingly participate in a global scheme to reduce emissions (*e.g.* resource-rich countries), whereas others may be willing to pay for emissions avoidance. Without providing for trade in deposit extraction rights, climate policies enacted by some set of countries have the effect, *ceteris paribus*, of reducing overall demand and therefore prices, potentially stimulating increased consumption by non-participant countries.

As explicit transfers to resource-rich countries may be politically difficult to implement, policies with implicit or hidden transfers might be more successful. Asheim (2011) explicitly considers the implication of climate policy that significant fractions of fossil fuel deposits must necessarily remain in the ground. He concentrates on the distributional issues of different supply-side policy instruments, assuming full participation of all actors. The model framework is a standard approach to optimal extraction of finite resources (Dasgupta and Heal, 1974; Solow, 1974; Stiglitz, 1974), with the assumption that fossil fuel extraction takes place at zero cost, and that there is no backstop technology. He illustrates how different implementations of mitigation policies influence resource owners' pay-off. As we will see in the course of this paper, it is even possible that climate policy results in net benefits for fossil resource owners (compared to a business-as-usual scenario). Hence, not only the distribution of rents may be subject to political considerations, but also the factors that determine the absolute size of rents. This insight could ultimately result in a broader political discussion about the ownership of natural resource rents as they might be a substantial fraction of the global added-value.

Our model is based on the common literature of natural resource economics, starting with Hotelling (1931) and continuing with expanded interest in the 1970s by Dasgupta and Heal (1974) and Solow (1974). We formulate the climate target as a constraint on cumulative fossil resource extraction which serves as proxy for temperature changes, as described below. The carbon budget makes fossil resources abundant (and destroys the associated scarcity rent) and the atmosphere a relatively scarce (and exhaustible) resource which in turn now receives a scarcity rent – a so-called climate rent. If fossil resource owners jointly commit

[1] See also van der Werf and Di Maria (2011) for a survey on the green paradox literature.

to this carbon budget, they will automatically receive this rent. If governments implement an emissions trading scheme, they receive this rent. By grandfathering the permits to resource owners, they can transfer this rent (without transferring money explicitly) which may compensate resource owners. Hence, resource owners might opt for an emissions trading scheme that makes them better-off than without any climate policy in place. We differ from Asheim (2011) in extending the basic Hotelling model by a backstop technology, which truncates the iso-elastic demand function if resources prices reach the backstop price. This backstop price turns out to be a crucial parameter for the possibility to compensate resource owners. Our innovations are to consider explicitly realistic carbon budgets, as introduced below, compared to actual fossil resource data, and to map out the parameter space to determine over which ranges a compensation is possible.

2. Delaying extraction vs. ceasing reserves

There are two different perspectives on fossil fuel use under climate change mitigation: The classical economic view is that fossil resource use should be slowed down and delayed into the far-distant future because (i) climate damages are discounted and (ii) CO_2 is removed from the atmosphere by biosphere and ocean uptake (Hoel and Kverndokk, 1996; Sinn, 2008) on longer time scales. If one of these two conditions holds, it can be efficient to exhaust all fossil resources in infinite time: climate policy is a question of 'timing' of fossil resource use rather than a question of the total amount of usable fossil resources.[2]

The second approach focuses on temperature and concentration targets that are considered to be achievable at moderate economic costs and that avoid the risk of "dangerous anthropogenic interference with the climate system" (UNFCCC, 1992, Article 2) as revealed by the existence of several irreversible tipping points in the Earth system (Lenton et al., 2008). The difficulty in quantifying and normatively evaluating climate damages and their intertemporal development might explain why the public discourse focuses on temperature and concentration targets rather than on the choice of an appropriate damage function.

Recent papers by Meinshausen et al. (2009) and by Allen et al. (2009) make an important contribution to the discussion linking (cumulative) emissions pathways for the future and probabilities of equilibrium global average temperature change. The first key point of the recent work cited above is that equilibrium temperature changes, as determined by the results from many climate modeling comparisons, are mainly

[2]The first condition is subject to controversial debates on discounting (Stern, 2007; Nordhaus, 2007; Heal, 2009) and the appropriate use of cost-benefit analysis in the presence of high uncertainties (Weitzman, 2011). The second condition is only true for very long time horizons: Archer (2005) estimates that 17-33% of the emitted carbon dioxide remains in the atmosphere within approximately 1,000 years. Solomon et al. (2009) report even higher numbers: After stopping carbon emissions immediately, atmospheric carbon concentration will fall to 40% after 1,000 years. Additionally, the uptake of CO_2 by oceans itself leads to acidification that might seriously damage marine ecosystems (WBGU, 2006).

sensitive to the cumulative amount of carbon emissions, independent of the exact trajectory over time of those emissions. Therefore, one can speak of a carbon budget that corresponds to a future temperature change. A second key point is that, due to the inherent uncertainty of climate models, one must consider probabilities of exceeding a given target for temperature, given a cumulative emission quantity. Thus, the chain of logic is such that "if we emit X tons of carbon dioxide in the future, there is a Y percent chance of exceeding the temperature change target of Z°C". Over the course of the past several years, a political consensus has been emerging that a temperature-change threshold of 2°C with respect to the early 20th century represents a planetary boundary within which it would be advisable to remain (UNFCCC, 2009).[3]

Meinshausen et al. (2009) conclude that cumulative emission of 1440 Gt of CO_2 (392 GtC) between 2000 and 2050 results in a 50% likelihood of exceeding the T = 2°C threshold, and that to reduce the probability to 25%, the total emission budget is reduced to 1000 Gt CO_2 (272 GtC). To gain an idea of just how stringent these limits are, total emissions from 2000-2009 were 315 Gt CO_2 (86 GtC), with 278 Gt CO_2 (76 GtC) from fossil fuel combustion and cement production, and the remainder due to land-use change (Friedlingstein et al., 2010).

Once an agreed-upon carbon budget can be established, there are still many potential energy-system transformation pathways available to satisfy the carbon emissions target. However, any successful strategy for mitigation of climate change must come to terms with the fact that greenhouse gas emissions from fossil fuels must be reduced, and therefore that either those fossil resources may not be extracted and burned, or that emitted carbon must be effectively captured and permanently sequestered (CCS). For example, in its most recent edition of the World Energy Outlook, the International Energy Agency estimates that at least two-thirds of current fossil fuel reserves must remain in the ground if a 2°C target is to be met (IEA, 2012).

Fig. 1 illustrates the enormous amounts of carbon under ground and shows one possible allocation of carbon use among fossil energy types consistent with an ambitious 400 ppm CO_2-eq. mitigation scenario. While integrated assessment models differ in the emission quantities allocated to coal, oil, gas and CCS, they are highly consistent in showing strong reductions of fossil resource consumption (without CCS) to achieve ambitious concentration targets (see IPCC, 2011, p. 804 and Fig. 10.4).

In the remainder of this paper, we will therefore analyze how this carbon budget and the cumulative constraint on fossil resource extraction affects the scarcity rents associated to fossil resources.

[3]It should be noted that, although the link between emissions and temperature change is clear, the exact numerical conversion factor has a fairly large degree of uncertainty, with best estimates giving a range of T = 3°C ± 1.5°C for a doubling of atmospheric carbon dioxide concentration with respect to pre-industrial levels of 285 ppm. The third parameter Y, effectively the risk we are willing to accept in not meeting the temperature goal, is a subjective evaluation of risk willingness. In effect, the current generation of humans living in countries responsible for the majority of emissions will make a risk evaluation for future generations and for those currently vulnerable to impacts visible today.

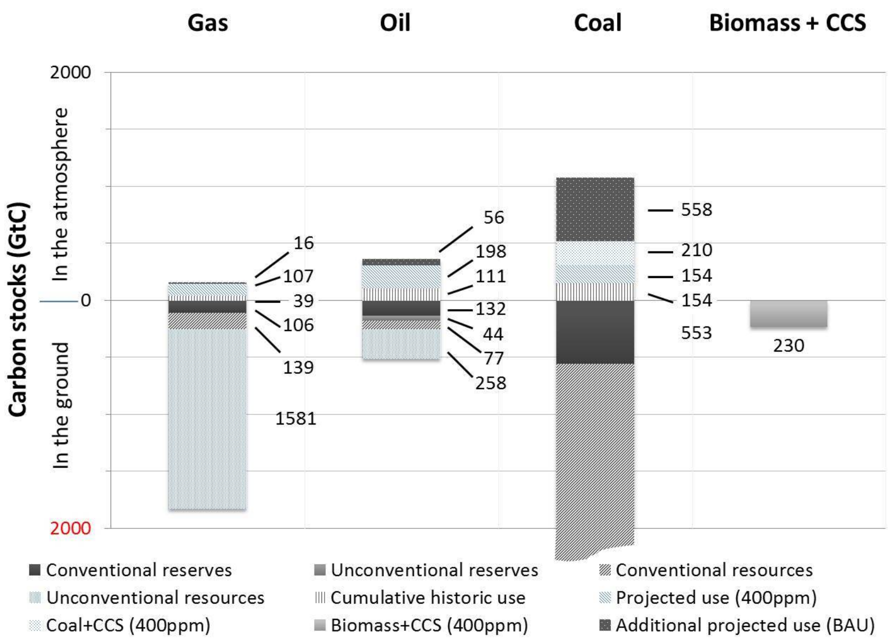

Figure 1: Cumulative historic carbon consumption (1750-2004), estimated carbon stocks in the ground, and estimated future consumption (2005-2100) for business-as-usual (BAU) and an ambitious 400 ppm-CO_2-eq. mitigation scenario. Carbon capture and sequestration technologies (CCS) reduce emissions of coal combustion near zero and lead to negative emissions in combination with biomass combustion (in total 440 GtC are stored underground by CCS which would be emitted additionally in the BAU scenario). Fossil energy stocks are converted to carbon dioxide emissions by using emission factors from IPCC (2006). Sources: Reserves: BGR (2009); historic consumption: Boden et al. (2010); scenarios by the intertemporal optimization model ReMIND, Edenhofer et al. (2010).

3. Theoretical Analysis

3.1. The Basic Model

For our formal analysis we consider a reduced Hotelling (1931) model with isoelastic demand and constant supply costs b of a backstop technology. Thus, the demand function for fossil resources reads:

$$q(p) = \begin{cases} Ae^{\gamma t} p^{-\varepsilon} & \text{if } p < b \\ 0 & \text{if } p > b \end{cases} \tag{1}$$

with $-\varepsilon < 0$ the price elasticity of demand. The exogenous demand growth rate γ results from the product of the income growth rate g and the income elasticity of fossil-fuel demand θ, i.e. $\gamma = g\theta$. For constant unit extraction costs c and discount rate r, the Hotelling resource price evolves according to (see Dasgupta and Heal, 1974, p. 176):

$$p(t) = \lambda_0 e^{rt} + c \tag{2}$$

The initial resource rent (or use cost) component λ_0 is determined from the intertemporal market clearing condition

$$S_0 = \int_0^T q(p(t))\, dt = \int_0^T Ae^{\gamma t} \left(\lambda_0 e^{rt} + c\right)^{-\varepsilon} dt \tag{3}$$

where S_0 is the initial size of the resource base and $T = [\ln(b - c) - \ln(\lambda_0)]/r$ the year when the resource price equals the backstop price, i.e. $p(T) = b$. Hence, λ_0 is exactly the price that leads to a full exhaustion of fossil resources by the time the switch to the backstop technology occurs. The net-present value of resources in the ground (hereafter denoted as *resource rent*) is given by:

$$\pi := \int_0^T (p(t) - c)q(t)e^{-rt}\, dt = \lambda_0 \int_0^T q(t)\, dt = \lambda_0 S_0 \tag{4}$$

3.2. Analytical analysis: zero extraction costs, zero demand growth

To derive some analytical results regarding climate mitigation policies, we assume in this subsection that extraction costs c and demand growth γ are zero. In that case, we can obtain a closed-form solution of λ_0 from solving (3):

$$\lambda_0 = p_0 = \left(b^{-\varepsilon} + \frac{r\varepsilon S_0}{A}\right)^{-1/\varepsilon} = \Theta^{-1/\varepsilon} \tag{5}$$

with $\Theta := b^{-\varepsilon} + \frac{r\varepsilon S_0}{A}$. As there are no extraction costs, the resource price p simply equals the scarcity rent λ.

Change in the resource base. Before studying the case of climate policy, we discuss how a change in S_0 influences the resource rent π. The total derivative is given by $d\pi/dS_0 = S_0\, \partial p_0/\partial S_0 + p_0$. On the one hand, an increase in S_0 leads to higher rents due to a volume effect expressed by the second term: if more resources are in the ground, more may be sold. On the other hand, a higher resource base lowers the resource price as $\partial p_0/\partial S_0 < 0$ (which follows from (5)). To determine which effects dominates we calculate $\pi'(S_0)$ explicitly:

$$\pi'(S_0) = \frac{d\pi}{dS_0} = \left(b^{-\varepsilon} + \frac{r(\varepsilon-1)}{A}S_0\right)p_0^{1+\varepsilon} \tag{6}$$

Eq. 6 reveals the non-monotonic behavior of the resource rents as a function of S_0. Setting $\pi'(S_0^*) = 0$, we calculate the critical resource stock size S_0^* with:

$$S_0^* = \frac{A}{rb^{\varepsilon}(1-\varepsilon)} \tag{7}$$

Hence, S_0^* is the size of the resource base that maximizes the total rent π. If no backstop technology is available and demand is inelastic, i.e. if $b \to \infty$ and $\varepsilon < 1$, S_0^* converges to zero and reducing cumulative demand does always increase scarcity rents. The lower the backstop costs are, the higher is the rent maximizing level of S_0^* and. If $S_0 < S_0^*$, $\pi'(S_0) > 0$. On the other hand, if $S_0 > S_0^*$, the resource rent decreases in the size of the resource stock S_0. It is obvious that for $\varepsilon > 1$, resource rents always decrease in S_0 (as $S_0^* < 0$ and $S_0 > 0$).

The role of climate policy. We consider climate policy as an effective decrease of the usable resource base to the size $\tilde{S}_0 < S_0$. For example, resource owners might be forced by an international agreement to extract only a certain share of their resources. We will elaborate the institutional aspects in more detail below. To begin with, we calculate the rent incidence Γ of climate policy according to:

$$\Gamma := \frac{\pi(\tilde{S}_0)}{\pi(S_0)} = \left(\frac{(Ab^{-\varepsilon} + r\varepsilon S_0)S_0^{-\varepsilon}}{(Ab^{-\varepsilon} + r\varepsilon \tilde{S}_0)\tilde{S}_0^{-\varepsilon}}\right)^{1/\varepsilon} = \frac{\tilde{\Theta}^{-1/\varepsilon}\tilde{S}_0}{\Theta^{-1/\varepsilon}S_0} \tag{8}$$

where the RHS follows from substituting (4–5) and $\tilde{\Theta} := b^{-\varepsilon} + r\varepsilon\tilde{S}_0/A$. If $\Gamma > 1$, capping cumulative fossil resource extraction at $\tilde{S}_0$ increases the total scarcity rent.

Compensation for climate policy. Even if reducing cumulative extraction increases the scarcity rent, this does not necessarily imply that the owners of fossil resources actually benefit from doing so. Whether or not fossil resource owners benefit depends on the design of the policy and the distribution of property rights associated with $\tilde{S}_0$. In the following, we consider the case where a government implements an upstream carbon trading scheme where resource owners need an allowance or permit to to sell one unit of resources.[4]

[4]For an efficient climate policy, permits should be related to the carbon content of different fossil fuels and fossil resources with zero emissions – e.g. due to application of CCS – should be exempted from the trading scheme.

If the government auctions permits for the carbon budget $\tilde{S}_0$, the entire scarcity rent $\pi(\tilde{S}_0)$ belongs to the government (which may transfer it via tax reductions or public spending to various parts of the society). On the other hand, if the government *grandfathers* all carbon permits to the resource owners relative to their share of the resource base, resource owners receive the scarcity rent completely. Obviously, a hybrid approach allows for an arbitrary distribution of scarcity rents if a share β of permits is grandfathered and the remaining share $1-\beta$ auctioned by the government. Using (8), we can calculate the share β of grandfathered permits that exactly compensates resource owners (implying $\beta\pi(\tilde{S}_0) = \pi(S_0)$):

$$\beta = \frac{1}{\Gamma} = \frac{\Theta^{-1/\varepsilon} S_0}{\tilde{\Theta}^{-1/\varepsilon} \tilde{S}_0} \tag{9}$$

In particular, $\Gamma < 1$ implies that more certificates must be grandfathered than available ($\beta > 1$) and governments would therefore have to implement additional transfers to compensate resource owners.

Parameter analysis. In the following, we briefly summarize how changes in parameters influence Γ. By differentiating (8) with respect to b we obtain

$$\frac{d\Gamma}{db} = \Gamma \frac{r\varepsilon(S_0 - \tilde{S}_0)}{Ab^{\varepsilon+1}\Theta\tilde{\Theta}} > 0 \tag{10}$$

This expression shows that higher backstop costs increase the scarcity rent under a climate policy regime. The rationale is that higher backstop costs always lead to higher resource prices (see Eq. 5) and that this price increase is more pronounced for $\tilde{S}_0$ than for S_0.[5] An important implication from this finding is that technological progress, which tends to reduce backstop costs, makes it more difficult to compensate resource owners with grandfathered carbon allowances.

Considering the impact of the discount rate on Γ gives

$$\frac{d\Gamma}{dr} = \Gamma \frac{S_0 - \tilde{S}_0}{Ab^{\varepsilon}\Theta\tilde{\Theta}} > 0 \tag{11}$$

The lower the effective discount rate, *i.e.* the more far-sighted the resource owners are, the smaller is Γ. In contrast to the backstop costs, higher discount rates reduce the resource price according to (5). As this price reduction is now stronger for S_0 than for $\tilde{S}_0$, the overall effect on Γ is positive. Insecure property rights (induced by geo-political instabilities or imperfect legal institutions) increase the effective discount rate used by resource owners by an additional risk-premium mark-up (Sinn, 2008). The absence of futures markets may also lead to higher effective discounting: If futures contracts for resource extraction in five or six decades do not exist, the planning horizon of resource owners is truncated. In both cases, compensation of resource owners becomes easier as Γ increases.

[5] Formally, $\partial\pi(S_0)/\partial b < \partial\pi(\tilde{S}_0)/\partial b$ as $\pi(S_0)/\partial b$ is decreasing in S_0 and $S_0 > \tilde{S}_0$.

Next, we consider the demand scale parameter A. By differentiating Γ with respect to A, we obtain

$$\frac{d\Gamma}{dA} = -\Gamma\frac{r(S_0 - \tilde{S}_0)}{A^2 b^{\varepsilon}\Theta\tilde{\Theta}} < 0 \tag{12}$$

Hence, a higher demand parameter A leads to a lower Γ. From Eq. (5) it follows that A influences the resource price p_0 in the opposite direction as r: A higher demand (large A) increases prices and this price increase is more pronounced for S_0 than for $\tilde{S}_0$. One important implication of this finding is that a positive demand shift (*i.e.* due to economic growth) reduces Γ and thus makes compensation of resources owners more difficult.

As a direct consequence of (6), the change of Γ with respect to S_0 and $\tilde{S}_0$ is also non-monotonic and depends on S_0 and $\tilde{S}_0$, respectively. Assuming $\varepsilon < 1$, we obtain:[6]

$$\frac{d\Gamma}{dS_0} = -\Gamma\frac{r(\varepsilon-1)}{AS_0\Theta}(S_0 - S_0^*) \qquad \begin{cases} < 0 & \text{if } S_0 < S_0^* \\ > 0 & \text{if } S_0 > S_0^* \end{cases} \tag{13}$$

$$\frac{d\Gamma}{d\tilde{S}_0} = \Gamma\frac{r(\varepsilon-1)}{A\tilde{S}_0\tilde{\Theta}}(\tilde{S}_0 - S_0^*) \qquad \begin{cases} > 0 & \text{if } \tilde{S}_0 < S_0^* \\ < 0 & \text{if } \tilde{S}_0 > S_0^* \end{cases} \tag{14}$$

Politically constrained climate target. Usually, temperature or mitigation targets are derived from a cost-benefit analysis or some precautionary principle. Real-world policy makers, however, might be constrained by the fact that the income of fossil resource owners should not be reduced. Although a lump-sum transfer could compensate fossil resource owners even if $\Gamma < 1$, such a transfer might not be politically feasible because voters would likely oppose direct money transfers to resource owners. Hence, given the constraint $\Gamma \geq 1$, what climate targets are possible? Due to the complexity of Eq. 8, it is not possible to explicitly solve the equation analytically for all $\tilde{S}_0$ that lead to $\Gamma \geq 1$. Nevertheless, with the previous findings it is possible to derive some qualitative conclusions.

Fig. 2 shows the present-value rent $\pi(S_0)$ according to Eq. 6 for $\varepsilon < 1$. There is a (unique) maximum rent at S_0^* and S_0 is assumed to be higher than S_0^*. As $\pi(0) = 0$ and $\lim_{S_0\to\infty}\pi(S_0) = 0$, there exists one additional value $S_0' < S_0^* < S_0$ with $\pi(S_0') = \pi(S_0)$. Hence, all climate targets $\tilde{S}_0 \in [S_0', S_0]$ are able to (over)compensate resource owners. In contrast, if the resource base is already below the critical value S_0^*, only $\tilde{S}_0 = S_0$ leads to $\Gamma = 1$ and all more ambitious climate policies (according to Eq. 14) reduce fossil resource rents unless additional direct transfers are established. As we shall demonstrate using resource data, the former case is much more likely to hold.

[6] In case of highly elastic demand, i.e. $\varepsilon > 1$, S_0^* becomes negative and, thus, $S_0, \tilde{S}_0 > S_0^*$. From (13–14) follows that $d\Gamma/dS_0$ is always negative and $d\Gamma/d\tilde{S}_0$ is always positive.

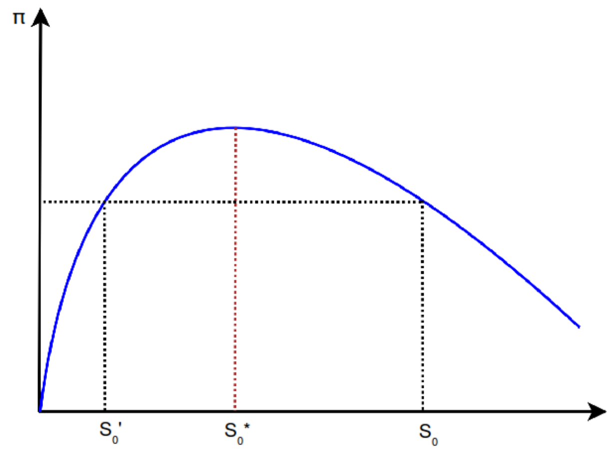

Figure 2: Scarcity rents and fossil resource base when the initial resource stock S_0 is higher than the critical value S_0^*.

Another interesting insight from Fig. 2 is that policy makers may want to determine the amount of fossil resources that maximizes public revenues (due to taxation or auctioning allowances). Similarly, fossil resource owners might influence the regulator to set a carbon budget that maximizes resource rents under a grandfathering rule. The 'optimal' cumulative amount would be $\tilde{S}_0 = S_0^*$, provided that the fossil resource base is higher than the critical value S_0^*. If $S_0 > S_0^*$, the revenue maximizing strategy is to auction resource extraction allowances for all resources available. Hence, even without climate policy, a coordinating resource sector (cartel) or revenue maximizing regulator may limit cumulative fossil resource consumption below the business-as-usual level.

4. Application and Numerical Analysis

4.1. Extended Model: Considering Extraction Costs and Demand Growth

We now turn to a numerical application of our model which gives us a quantitative indication of the impact of climate policy on scarcity rents. We consider three fossil resource types – oil, gas and coal – and constant, positive extraction costs.[7] Thus, we study the effect of higher (constant) extraction costs in a parameter analysis. Furthermore, we allow for exogenously growing demand at the rate γ (induced by GDP growth). As an analytical solution of π is no longer possible, we use numerical calculations with MATLAB

[7] We restrict on constant costs mainly for numerical reasons. Increasing cumulative extraction should lead to higher costs as difficult accessible resource sites have to be used (i.e. Rogner, 1997). However, technological progress may also reduce extraction costs which could out-balance the former cost increase and lead to constant extraction costs (Stürmer and Schwerhoff, 2011).

to solve for λ_0 from the integral (3):

$$S_0 = \int_0^{[\ln(b-c)-\ln(\lambda_0)]/r} Ae^{\gamma t} \left(\lambda_0 e^{rt} + c\right)^{-\varepsilon} \, dt \tag{15}$$

While the analytical model helped to understand the general rent dynamics of climate policy, the numerical model allows a quantitative indication under more realistic real-world conditions. A comprehensive sensitivity analysis generalizes the numerical findings from our standard parametrization to a broad parameter space.

4.2. Data

The parameters chosen for the numerical model are listed in Table 1 and explained in detail in the Appendix. Extraction costs, demand and price elasticities are taken from the literature. The model is calibrated to replicate current demand (at current prices). Backstop costs were estimated according to the costs of non-carbon substitutes in the respective sector from several sources, mainly IEA. Values for the reference resource base (S_0) are chosen to be slightly higher than the total of reserves plus recoverable conventional resources. The overall carbon budget was chosen to achieve a two degree target with 50% likelihood if no CCS were available; allocation to the specific resource types such that 42% of the emissions are attributed to oil, 25% to gas and 33% to coal.

Parameter	Symbol	Oil		Gas		Coal		Total carbon
		value	unit	value	unit	value	unit	[GtC]
Current demand	$\bar{q}$	31.4	Gbbl/yr	0.114	ZJ/yr	4.8	Gtce/yr	9.0
Current price	$\bar{p}$	78	$/bbl	6.5	$/GJ	100	$/tce	
Demand scale factor	A	75		0.29		48		
Demand growth rate	γ	0.024		0.0225		0.03		
Price elasticity of demand	$-\varepsilon$	−0.2		−0.5		−0.5		
Discount rate	r	0.04		0.04		0.04		
Backstop costs	b	250	$/bbl	23	$/GJ	400	$/tce	
Extraction costs	c	50	$/bbl	6	$/GJ	80	$/tce	
Resource base	S_0	2,000	Gbbl	20	ZJ	1,000	Gtce	1290
Carbon budget	$\tilde{S}_0$	1,600	Gbbl	7	ZJ	190	Gtce	434

Table 1: Parameter values for the standard parametrization. These parameters are varied for the extensive sensitivity analysis below. Some relevant conversion factors are: 1 Gbbl oil = 5.7 EJ = 0.114 GtC; 1 ZJ Gas = 15.3 GtC; 1 Gtce = 29.3 EJ = 0.76 GtC (BP, 2012; BGR, 2010).

In the following we present the results for the main variable of interest, Γ, the ratio of total rents with and without climate policy, for various fossil fuels, using our standard parametrization as a starting point. In addition, we then perform a sensitivity analysis of our results for each of the main parameters, using the (*a priori* unknown) size of the resource base as the independent variable.

4.3. Results for the Standard Parameter Setting

For our chosen standard parametrization, results are shown in Table 2 and Table 3, the former showing the results from the reduced analytic model. The results indicate that climate policy (through reducing the effective size of the fossil resource base) increases fossil resource prices remarkably. Note that the scarcity value of fossil resources in the ground, $\pi(S_0)$, is considerable: The value of oil is of the magnitude of the world's total GDP in 2010, the value of gas and coal is approximately 20 % of the world's GDP. These numbers indicate the dimension of the potential distributional conflict climate policy provokes: By assigning an explicit property right to the atmosphere (as carbon deposit), fossil resources in the ground are devalued. Simultaneously, the atmospheric carbon budget $\tilde{S}_0$ becomes a scarce resource that generates a scarcity rent. Table 2 and Table 3 indicate that this rent is of a similar magnitude as the fossil resource rent, although the model specification without demand growth and extraction costs finds higher climate rents and, in all cases, higher Γ's.

The difference between Table 2 and Table 3 arises basically from the consideration of demand growth rather than from extraction costs (see the sensitivity analysis below where extraction costs turn out to be very insensitive for Γ). From the analytical model, we know that a higher demand parameter A reduces Γ. Hence, considering demand growth $\gamma > 0$ has the same effect as it leads to higher demand in the future. While in the basic model the climate rent is always significantly higher than the fossil rent in the BAU scenario, in the extended model this is only clearly the case for gas; however, the other two fossil fuels give essentially the same result (*i.e.* $\Gamma \approx 1$) for climate policy compared to the business-as-usual case. Taking all fossil resources together, the total amount of scarcity rents increases by 3 percent under climate policy. This result illustrates the huge rent transformation effect due to reducing fossil resource use: the creation of the new climate rent is of similar magnitude than the scarcity rents of existing fossil resources that would be nullified. The slightly larger amount of the total climate rent makes full compensation of resource owners possible. An emissions trading scheme with grandfathering would make resource owners even better-off.

Another interesting finding concerns the rent maximizing budget S_0^*. In the basic model without demand growth and extraction costs (Table 2) the S_0^* values are always greater than the respective $\tilde{S}_0$ values in Table 1. Hence, a more ambitious climate policy would even further increase the climate rent and, thus, Γ. In contrast, if demand grows – analogously to a higher A in Eq. 7 – the critical resource size S_0^* increases. Table 3 shows that the rent-maximizing value S_0^* for oil is close to the original resource base S_0. Climate policy will therefore in most cases reduce the scarcity rent associated with oil, although a 20 % reduction of cumulative consumption has almost no effect on Γ. Considering gas, a lower carbon budget $\tilde{S}_0$ could increase the rent. While the cumulative BAU emissions amount to 1290 GtC and the emissions under the 400 ppm CO_2-eq. target amount to 434 GtC, the rent maximizing carbon consumption is 226 GtC (basic model; Table 2) and 646 GtC (extended model; Table 3). Hence, according to the full model results, a

Parameter	Symbol	Oil		Gas		Coal		Total carbon	
		value	unit	value	unit	value	unit	value	unit
No climate policy (BAU)									
Initial rent/price	λ_0, p_0	20.1	\$/bbl	0.4	\$/GJ	4.6	\$/tce		
Rent	$\pi(S_0)$	0.66	GDP_{2010}	0.13	GDP_{2010}	0.07	GDP_{2010}	0.86	GDP_{2010}
Climate policy									
Initial rent/price	$\tilde{\lambda}_0, \tilde{p}_0$	31.3	\$/bbl	2.1	\$/GJ	60.0	\$/tce		
Rent	$\pi(\tilde{S}_0)$	0.80	GDP_{2010}	0.23	GDP_{2010}	0.18	GDP_{2010}	1.21	GDP_{2010}
Rent ratio	Γ	1.20		1.85		2.48			
Rent maximizing budget	S_0^*	777	Gbbl	3.0	ZJ	120	Gtce	226	GtC

Table 2: Results for the basic (analytical) model without extraction costs and demand growth. Parameters are chosen according to Tab. 1. Rent values are calculated as share of the world's nominal GDP in 2010.

Parameter	Symbol	Oil		Gas		Coal		Total carbon	
		value	unit	value	unit	value	unit	value	unit
No climate policy									
Resource use	S_0	2000	Gbbl	20	ZJ	1000	Gtce	1290	GtC
Initial rent	λ_0	37.1	\$/bbl	0.6	\$/GJ	15.0	\$/tce		
Initial price	p_0	87.1	\$/bbl	6.6	\$/GJ	95.0	\$/tce		
Rent	$\pi(S_0)$	1.18	GDP_{2010}	0.20	GDP_{2010}	0.24	GDP_{2010}	1.62	GDP_{2010}
Climate policy									
Carbon budget	$\tilde{S}_0$	1,600	Gbbl	7	ZJ	190	Gtce	434	GtC
Initial rent	$\tilde{\lambda}_0$	46.2	\$/bbl	2.4	\$/GJ	77.1	\$/tce		
Initial price	$\tilde{p}_0$	96.2	\$/bbl	8.4	\$/GJ	157.1	\$/tce		
Rent	$\pi(\tilde{S}_0)$	1.17	GDP_{2010}	0.27	GDP_{2010}	0.23	GDP_{2010}	1.67	GDP_{2010}
Rent ratio	Γ	0.99		1.32		0.98		1.03	
Rent maximizing budget	S_0^*	1940	Gbbl	5.6	ZJ	448	Gtce	646	GtC

Table 3: Results for the extended model with extraction costs and demand growth. Parameters are chosen according to Table 1. Rent values are calculated as share of the world's nominal GDP in 2010.

revenue maximizing regulator or a rent maximizing fossil resource monopolist would extract considerable less resources than the (competitive) business-as-usual economy; this could also lead to quite ambitious emission reductions (approximately 50 percent of BAU emissions) that are, however, still 50 percent higher than the desired carbon budget to meet a 2°C target.

4.4. Sensitivity analysis

As there is a great deal of uncertainty in many of the parameters used in the analysis above, it is also important to have an idea of the sensitivity of the result to the assumptions we have made. Figs. 3–4 show how different parameters influence Γ for oil, and coal, respectively.[8] In each figure, the six parameters explored are: (i) backstop technology cost (b); (ii) extraction costs (c); (iii) size of the climate policy carbon budget ($\tilde{S_0}$); (iv) growth rate in demand (γ); (v) discount rate (r); and (vi) demand elasticity (ε). In each case the size of the total resource base (S_0) is taken as the independent variable.

We begin by noting that for most parameters, higher resource endowments would increase Γ substantially. Furthermore, the non-monotonic behavior of Γ in S_0 or $\tilde{S}_0$ with respect to the critical value S_0^* according to Eqs. (13–14) is reproduced. For coal, gas and oil, and for nearly all values of b, c, $\tilde{S_0}$, and ε, compensation is possible even under stringent climate mitigation policies. Although backstop and extraction costs have a considerable impact on the magnitude of both, $\pi(S_0)$ and $\pi(\tilde{S}_0)$, the rent ratio Γ is very insensitive as the rent changes nearly cancel each other out.[9] The analytical finding regarding the impact of the backstop costs b on Γ in Eq. (10) holds also in the extended numerical model. Regarding the role of the price elasticity of demand $-\varepsilon$, a more elastic demand leads to a higher Γ. Technological progress and the possibility of fuel switch between oil, gas, and coal could lead to a higher elasticity than reported by the empirical studies – at least in the long-term.

The two parameters that the show greatest sensitivity for the possibility of compensation are the discount rate and the demand growth rate for the fossil fuel. For increasing demand growth of oil and gas, Γ decreases – as one would expect from the change of Γ in A in Eq. (12). This increase is nearly independent of the actual size of the resource base; however, one would have to assume growth rates well above historical norms of the past few decades to reach a regime in which $\Gamma < 1$. Coal shows the same qualitative sensitivity to demand growth rates, but the boundary $\Gamma = 1$ lies much closer to our baseline parameter. In fact, for two decades at the end of the 20th century, coal consumption increased at less than 1%/year. Since 2000, demand has grown at approximately 5% per year, making compensation for coal resource rent losses very difficult. Once again, this result shows very little sensitivity to the actual size of the coal resource. When demand for fossil resources in emerging economies saturates, the income elasticity θ should decrease implying a lower γ.

As Eq. (11) suggests, sensitivity to the discount rate is such that a smaller value of r leads to a lower value of Γ. Note that the relevant discount rate to consider here is not necessarily the social discount rate on consumption (interest rate), but rather the effective discount rate of the resource owners because the question of compensation depends on the resource owners' intertemporal preferences and allocation possibilities and not on that of society as a whole. Insecure property rights, incomplete futures markets

[8]We omit the figures for gas as they are qualitatively similar to those of oil and coal. They can be found in the Supplementary Material to this article

[9]See the Supplementary Material for the change of oil rents $\pi(S_0)$.

and impatience may lead to considerably higher discount rates than those a social planner would use for long-term project evaluation. Interestingly, here we see that for discount rates of 3 - 4%, compensation for owners of all fossil fuel resources rapidly becomes more favorable. Thus, if a resource owner has a long-term planning horizon, it will be much more difficult for a compensation scheme to work without additional transfers. These results are also relatively insensitive to the total resource amount, especially if those resources tend to be larger than our assumed baseline cases.

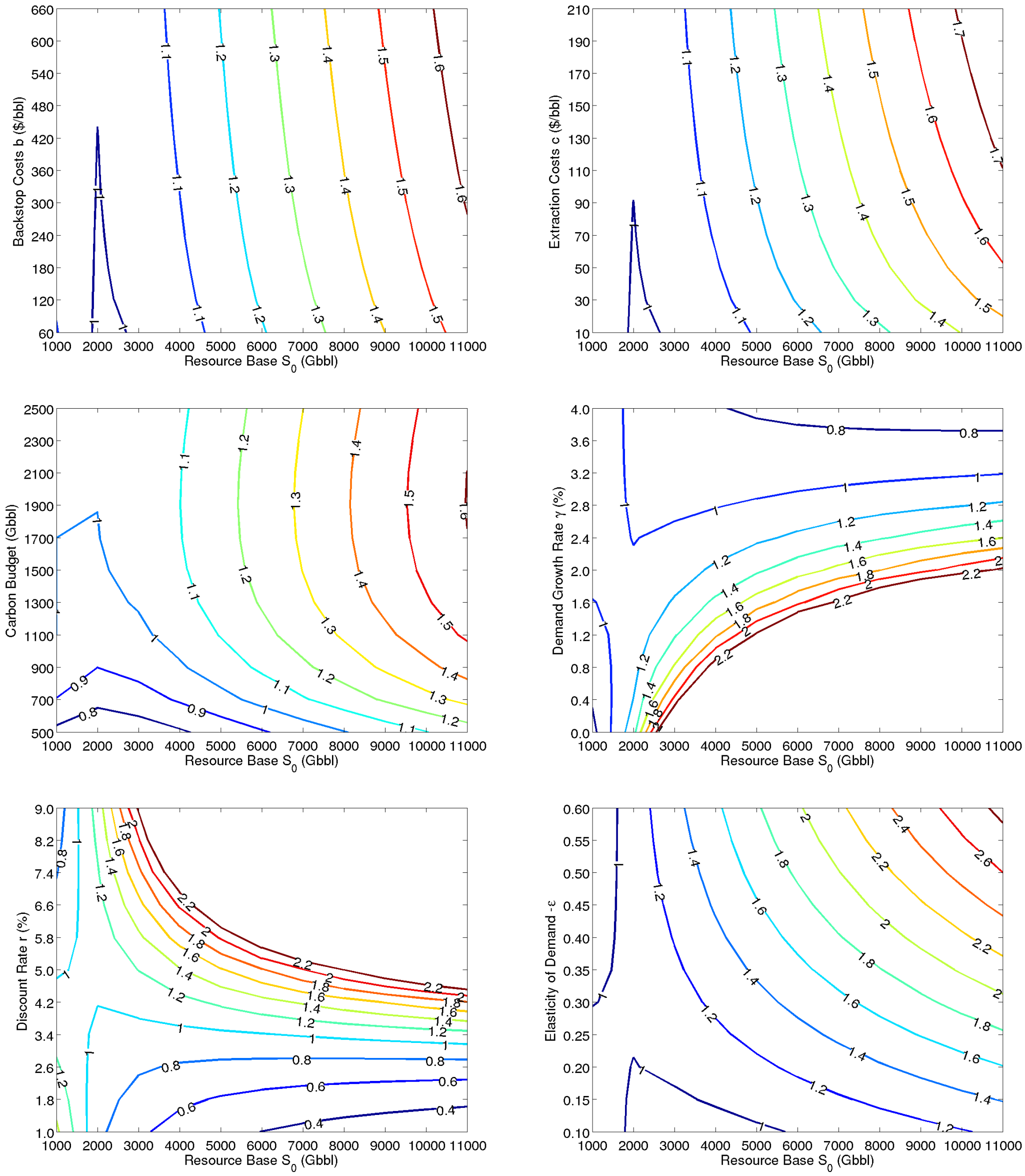

Figure 3: Effect of climate policy on oil rents: Γ for several parameter variations.

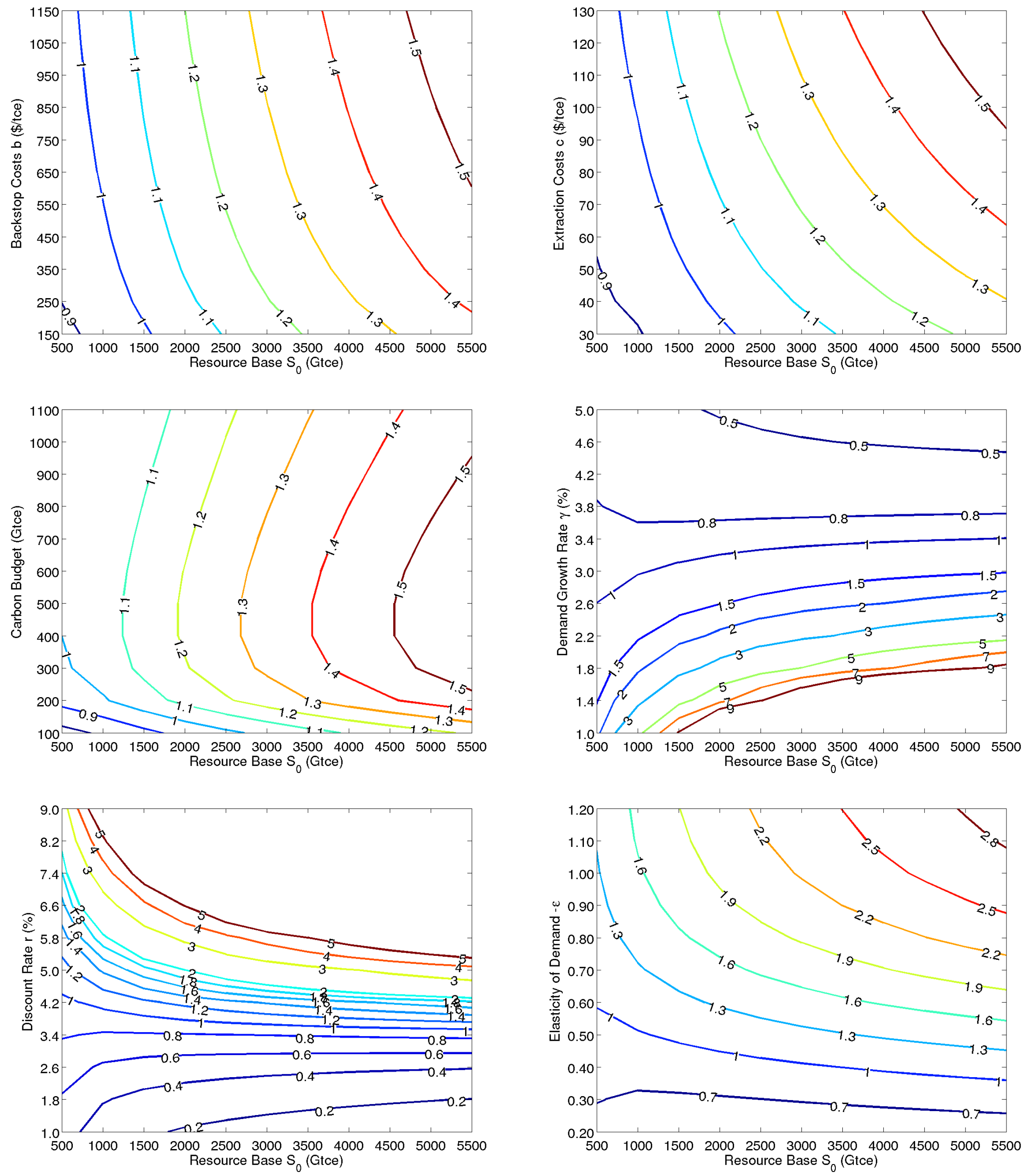

Figure 4: Effect of climate policy on coal rents: Γ for several parameter variations.

The qualitative pattern of rent dynamics does not differ between the three resource types as they all use the same model with only the parameter values being varied. However, the parameters that lead to higher ($\Gamma > 1$) or lower ($\Gamma < 1$) resource rents differ. Oil rents show (Fig. 3–B.5) a slightly different pattern in the sensitivity analysis as the rent-maximizing carbon budget lies within the interval of the resource base we consider. In contrast, gas and coal resource estimates are much higher and are always greater than the rent-maximizing carbon budget. Therefore, for oil there is a structural break in the parameter space (to the left in Fig. 3; resource base below the rent maximizing budget of 1,940 Gbbl), a pattern that is absent in the gas and coal figures.

4.5. Discussion of results and model limits

The analytical model as well as the numerical results depend on a basic model setting that incorporates intertemporal optimization of resource owners, demand growth and backstop technologies in a stylized manner. Although the model makes a number of simplifying assumptions like competitive markets, existence of complete futures markets and separability of oil, gas and coal markets, it gives some useful information about the qualitative dynamics of scarcity rents and the possible magnitude of rent transformations due to mitigation.

Nevertheless, market power is currently an important issue characterizing oil and gas markets, while less so for coal. Technological progress in drilling technologies (shale gas, oil sands, hydraulic fracturing) is likely to reduce market power. The substitutability between energy types can be ignored if the chosen resource-specific emission caps represent an optimal allocation (which they are at least within the integrated assessment model we used for the parametrization of the caps as it is an intertemporal optimization model). Nevertheless, the sensitivity analysis captures other possibilities for allocating an overall carbon budget to individual resource-specific budgets.

Exploration activities are not considered explicitly but can be subsumed under changes in the extraction cost parameter and the size of the reserve. Likewise, technological progress in extraction and backstop costs has been neglected to keep the number of parameters under consideration manageable. Changes in (static) extraction and backstop costs give at least a rough idea about the impacts of technological progress.

5. Conclusions

Climate policies consistent with a given physical target will invariably imply the combustion of only a fraction of the earth's total fossil fuel resource. In contrast to a hypothetical situation in which the fossil resource becomes scarce in an absolute sense, leading to, *ceteris paribus*, increased rents for resource owners, we concentrate here on scarcity rents associated with a politically mandated carbon budget. A carbon budget effectively makes the fossil resource in the ground abundant, whereas space in the atmosphere for absorbing carbon emissions is relatively scarce.

Because there is in either case a relative scarcity of resource availability with respect to potential demand, total rents to the owners of these exhaustible resources are not necessarily reduced, even in the case of ambitious reductions in fossil-fuel consumption that would be consistent with climate-change mitigation targets. In fact, for many portions of the parameter space explored here, scarcity rents are substantially increased. This increase is more pronounced when backstop costs, extraction costs, the discount rate and the elasticity of demand are high, and when the demand growth rate is low. While backstop and extraction costs are fairly insensitive parameters, the demand growth rate – evolving from GDP growth and income elasticity – has a strong impact on the magnitude of the scarcity rents.

The potential for an increase in rents allows, in principle, for the compensation of resource owners for the effects of climate policy that requires them to leave resources in the ground. Such a compensation could be implemented by grandfathering a sufficient fraction of carbon permits to resource owners proportional to the size of their reserves. For those areas of the parameter space in which total rents are reduced under climate policy, additional transfers would be required as compensation. Such transfers would likely be difficult to implement; however, an analogy can be made to currently existing climate change mitigation programs such as REDD (Reducing Emissions from Deforestation and Degradation). Similar to compensation payments for conserving forests, owners of fossil resources could be compensated for not extracting all resources (Sinn, 2008; Harstad, 2010). Whether and to what extent fossil resource owners are compensated, however, depends also on the relative power of resource owners, tax-paying citizens and political entities. The interplay of these actors will decide the effective ownership on the atmosphere (which could also be assigned to all citizens on an equal-per-capita basis).

In addition to the question of compensation, our analysis indicates how rent-seeking aspects may influence the climate target. A revenue-maximizing regulator or a rent-maximizing fossil-resource cartel can benefit from a cumulative shortage of fossil resource supply independently from a climate protection motive. In the first case, the regulator is like a monopolist who maximizes intertemporal revenues by anticipating the reaction function of the economy. But instead of manipulating the time path of extracting all available resources as in the classic monopolistic extraction setting, the regulator chooses the budget only *ex-ante*. This setting is more relevant for climate policy as government institutions may lack the capacity to determine the rent-maximizing time path. Instead, they might prefer to auction the entire budget at the initial time to competitive bidders. After the auction an intertemporally efficient permit price (subject to the budget) evolves due to the competitive intertemporal allowance market. Likewise, if a resource cartel influences the regulator to set a budget to a revenue-maximizing level, the resource owners can increase revenues without forming a stable cartel for the entire extraction period. Permanent coordination among resource owners to establish a cartel that influences the extraction path in each period is generally unstable due to free-rider effects. Hence, a rent-maximizing carbon budget might be easier to enforce as coordination is only necessary in the initial period . After the budget was set, a competitive market resource market prevails where no coordination is necessary and the budget is enforced by the regulator.

If the budget were set to maximize rents it will not be time consistent – after time has passed, or the announced budget is depleted, it becomes beneficial for the monopolist to start extracting further amounts.[10] As rational market agents anticipate this, the announced budget is not credible. A time-consistent feed-back strategy, however, would require coordination among resource owners in every period, which is difficult due to the internal instability of cartels. If, in contrast, the budget were set according to a socially agreed-upon temperature target, climate policy can serve as a commitment device to reduce cumulative resource supply in order to increase rents. This commitment device will be stronger in a better institutional setting that can guarantee the budget over time. The proposal of creating an independent Atmospheric Carbon Trust by Barnes et al. (2008) would, for example, creates a strong institution to enforce the carbon budget. While fossil-resource owners might support ambitious carbon budgets in the beginning, they might revise their support after time has passed and a relaxation of the budget becomes attractive. Hence, the existence of a strong institution (or internally stable international agreement) enforcing emission cuts is a prerequisite for successful emission reductions in the long-term.

Whether a global agreement to reduce emissions is achievable and stable is an important question that goes beyond the scope of this paper. Our aim is to emphasize that climate policy leads to a huge transformation of rents that is susceptible to extensive rent-seeking not only affecting the distribution of the rent but also the amount of fossil resource use. Our analysis indicates that carbon-related scarcity rents might even increase under climate policy and benefit fossil resource owners.

[10] A regulator would accordingly sell additional allowances.

Appendix A. Parameters and data sources

Oil. Data on proved reserves are relatively consistent across sources. BGR (2010) quantifies conventional oil reserves with 1,182 Gbbl and unconventional reserves with 489 Gbbl. A further amount of 3,012 Gbbl oil resources is expected to be accessible, although economic costs are uncertain and existence and technological feasibility is not always proven. Extraction costs of oil are in the range of 10-100 $/bbl, transport amounts to additional 9 $/bbl per 8,000 km shipping (BGR, 2009). We thus employ an average number of 50 $/bbl as extraction costs. With respect to oil, we consider the life-time cost of an electric car as illustrative case of a backstop technology (numbers from IEA, 2011). With 15 ct/kWh consumer electricity price, an electric car becomes competitive to a conventional internal combustion engine technology if fuel prices are 250 $/bbl.

Gas. Conventional gas reserves are 7 ZJ and conventional and unconventional gas resources are further 44 ZJ (BGR, 2010). Additionally, BGR (2010) estimates 68 ZJ of (speculative) resources in aquifers and gas hydrates. BGR (2009) quantifies extraction costs from 0.4–2.4 $/GJ with transportation costs via shipping or pipeline of 0.9–1.6 $/GJ. In contrast, IEA (2009) uses 4.7 $/GJ as extraction cost in its base scenario; maximum extraction costs for unconventional gas are 8.5 $/GJ. We use as default 6 $/GJ as extraction costs as we employ a relatively high resource base for gas (where large amounts of unconventional gas resources are integrated). Based on IEA (2010a) data on levelized costs of electricity for gas power plants, a gas price of 23 $/GJ would results in an electricity price of 9 ct/kWh. As many renewable energy technologies can compete at this price (IEA, 2010b), we chose 23 $/GJ as a backstop price.

Coal. BGR (2010) quantifies coal reserves at 721 Gtce and estimates additional resources at the amount of 16,233 Gtce. The extraction costs for coal range currently from 15 $/tce (Indonesia) to 80 $/tce (USA) (BGR, 2009). As easily extractable resources have often to be shipped over the ocean to consuming countries[11] and extraction costs are likely to increase further, we consider 80 $/tce as extraction costs for coal. We chose a backstop price for coal of 400 $/tce. Similarly to the calculation of the gas backstop price, such a coal price would result in an electricity price of 9 ct/kWh with IEA (2010b) data.

Demand parameters. The world income elasticity of demand for fossil fuels is 0.7 (IEA, 2009). For specific fuels, however, this number changes: Several studies estimate income elasticities of demand for oil or gasoline ranging from 0.09 to 1.54 (Dahl and Sterner, 1991; Krichene, 2002; IEA, 2006) and for gas from 0.78 to 1.6 (Krichene, 2002; IEA, 2009)). We use an average value for the income elasticity of 0.8 for oil,

[11] Shipping costs are approximately 50 $/tce (IEA, 2009, 2010b).

0.75 for gas, and 1.0 for coal. With an assumed modest GDP growth rate of 3%, the resulting demand growth rates γ for consumption of oil, gas and coal are 2.4, 2.25, and 3.0, respectively.

Similarly, price elasticities of demand differ due to different estimation techniques and time horizons considered: For oil or gasoline, they range from -0.01 to -0.8 (Dahl and Sterner, 1991; Krichene, 2002; IEA, 2006) and for natural gas from 0.04 (short-term) to -1.1 (long-term). We thus employ price elasticities for oil and gas of -0.2 and -0.5. As we did not find any numbers for coal, we use the same elasticity as for gas (as both are similarly used to a certain extend). Due to the high aggregation in our model, ongoing technological progress and structural shift in economies, the employed elasticities are highly uncertain. Current worldwide consumption levels of fossil fuels is found in the BP Statistical Review, as are prices in the recent past. We calculate A according to $A = \bar{p}^{-\varepsilon}\bar{q}$ where $\bar{p}$ and $\bar{q}$ denotes current prices and current demand, respectively. We assume as well a discount rate of 4%.

Carbon budget. The carbon budget for a given climate change mitigation target can be estimated (Allen et al., 2009; Meinshausen et al., 2009); we choose the 2° target, to be exceeded with a likelihood of no more than 50%, as our reference, implying a total of approximately 450 GtC for the period 2010-2100. Within that target for mitigation, however, there are many pathways that might be followed depending on the allocation between fossil energy carriers oil, gas and coal and the use of carbon capture and sequestration (CCS). We start with budgets for individual resources consistent with results from integrated assessment models (IAMs) taking part in a model comparison project (Edenhofer et al., 2010).[12] Our purpose here is simply to use one resource-resolved scenario that meets the overall budget as a starting point, from which we will then also perform a sensitivity analysis; IAMs, depending on structure and input assumptions, give a range of results (see Edenhofer et al. (2010)). For a 400 ppm CO_2-eq. stabilization scenario, approximately 1600 Gbbl oil, 7 ZJ gas and 190 Gtce coal (without CCS) are extracted by 2100.[13] With respect to the carbon content of these resources, 430 GtC (1600 Gt CO_2) are emitted over the entire time horizon.

Appendix B. Supplementary Figures

Appendix B.1. Change in Gas Rents

Appendix B.2. Value of Oil Rents

[12] Integrated assessment models combine the science of climate change with socio-economic and technological aspects about energy use and mitigation options to calculate the costs of mitigation targets and the deployment of different technologies.

[13] Our model implicitly allows consideration of CCS as an increase in the amount of extractable fossil resources $\tilde{S}_0$ that is consistent with a specific climate target.

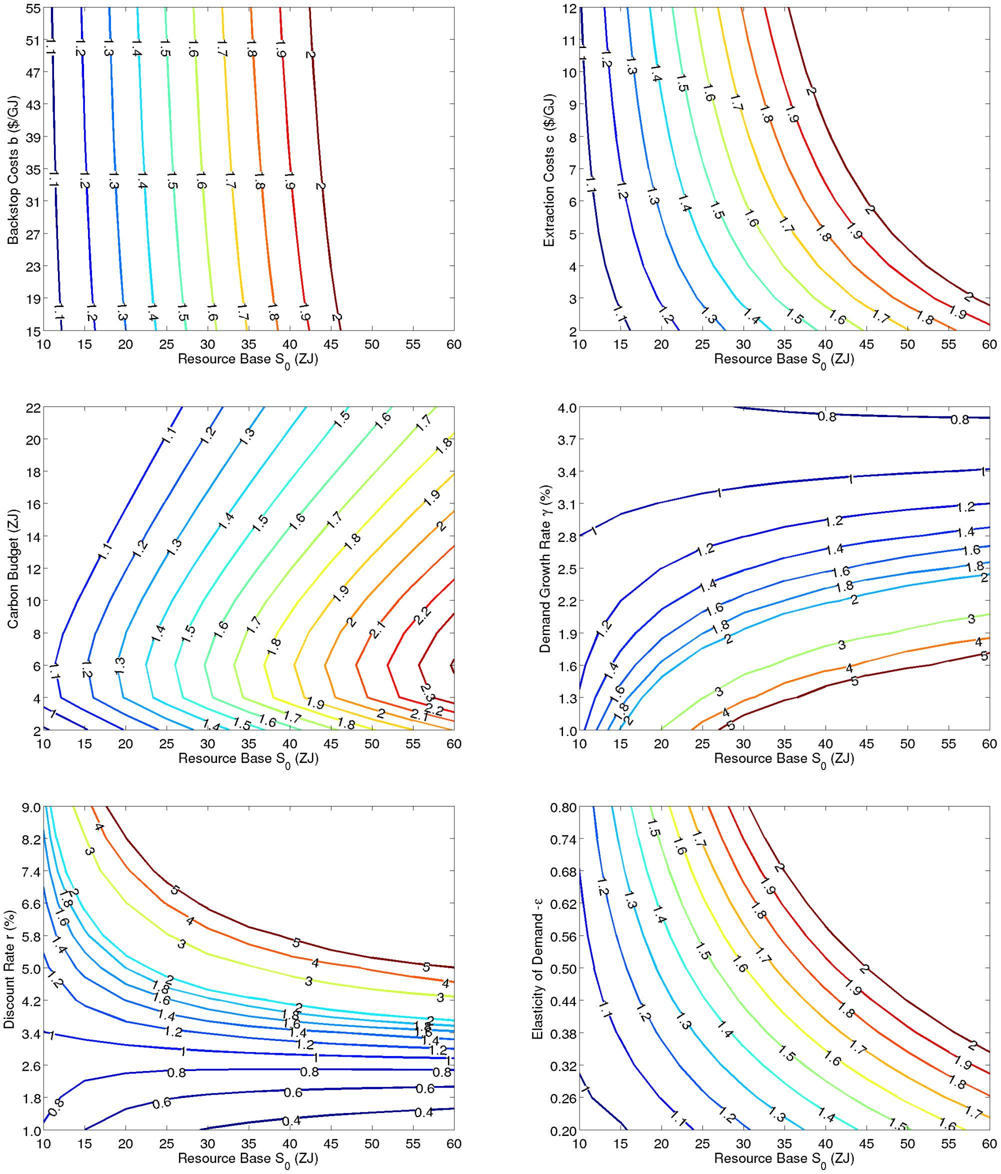

Figure B.5: Effect of climate policy on gas rents: Γ for several parameter variations.

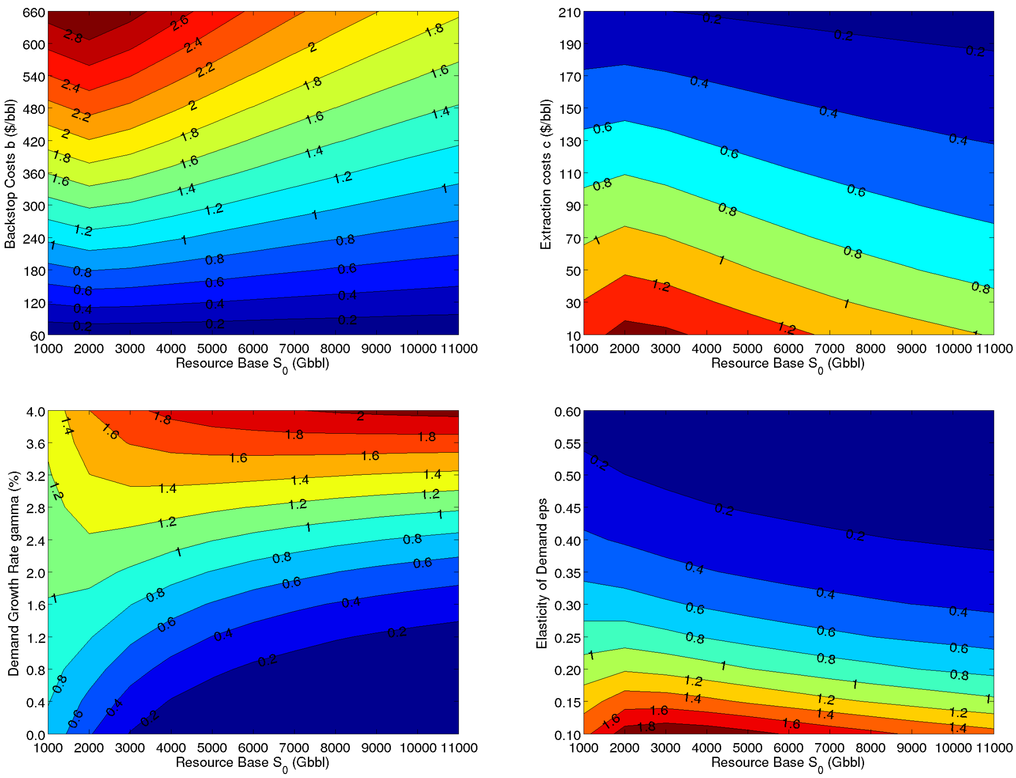

Figure B.6: Discounted oil rents without climate policy (i.e. *in situ* value of oil) as share of world's GDP in 2010.

References

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature 458*, 1163–1166.

Archer, D. (2005). Fate of fossil fuel CO2 in geologic time. *J. Geophys. Res. 110*(C9), C09S05.

Asheim, G. (2011). A distributional argument for supply-side climate policies. *International Forum on Global Agreements on Environmental Protection and Sustainability*.

Barnes, P., R. Costanza, P. Hawken, D. Orr, E. Ostrom, A. Umaña, and O. Young (2008). Creating an earth atmospheric trust. *Science 319*(5864), 724b.

BGR (2009). Energierohstoffe 2009. Reserven, Ressourcen, Verfügbarkeit. Technical report, Bundesamt für Geowissenschaften und Rohstoffe, Hannover, Germany.

BGR (2010). Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen. Technical report, Bundesamt für Geowissenschaften und Rohstoffe, Hannover, Germany.

Boden, T., G. Marland, and R. Andres (2010). Global, regional, and national fossil-fuel CO2 emissions. Technical report, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

BP (2012). Statistical review of world energy. Technical report, BP.

Dahl, C. and T. Sterner (1991). Analysing gasoline demand elasticities: a survey. *Energy economics 13*(3), 203–210.

Dasgupta, P. and G. Heal (1974). The optimal depletion of exhaustible resources. *Review of Economic Studies*, 3–28.

Edenhofer, O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos, M. Leimbach, K. Lessmann, B. Magne, S. Scrieciu, H. Turton, and D. P. van Vuuren (2010). The economics of low stabilization: Model comparison of mitigation strategies and costs. *The Energy Journal 31*(Special Issue), 11–48.

Eichner, T. and R. Pethig (2011). Carbon leakage, the green paradox, and perfect future markets. *International Economic Review 52*(3), 767–805.

Friedlingstein, P., R. Houghton, G. Marland, J. Hackler, T. Boden, T. Conway, J. Canadell, M. Raupach, P. Ciais, and C. Le Quéré (2010). Update on CO2 emissions. *Nature Geoscience 3*(12), 811–812.

Harstad, B. (2010). Buy coal? deposit markets prevent carbon leakage. Working Paper 16119, National Bureau of Economic Research.

Heal, G. (2009). Climate economics: A meta-review and some suggestions for future research. *Review of Environmental Economics and Policy 3*(1), 4–21.

Hoel, M. and S. Kverndokk (1996, June). Depletion of fossil fuels and the impacts of global warming. *Resource and Energy Economics 18*(2), 115–136.

Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy 39*(2), 137–175.

IEA (2006). *World Energy Outlook 2006.* Paris: Organization for Economic Cooperation and Development.

IEA (2009). *World Energy Outlook 2009.* Paris: Organization for Economic Cooperation and Development.

IEA (2010a). *Projected Costs of Generating Electricity*. International Energy Agency, Paris, France.

IEA (2010b). *World Energy Outlook 2010.* Paris: Organization for Economic Cooperation and Development.

IEA (2011). *Technology Roadmap. Electric and plug-in hybrid electric vehicles*.

IEA (2012). *World Energy Outlook 2012.* IEA International Energy Agency OECD.

IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

IPCC (2006). *IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 1 Energy. Hyama, Japan: Institute for Global Environmental Strategies.

IPCC (2007a). *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

IPCC (2007b). *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

IPCC (2011). *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Krichene, N. (2002). World crude oil and natural gas: a demand and supply model. *Energy Economics 24*(6), 557–576.

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber (2008). Tipping elements in the earth's climate system. *Proceedings of the National Academy of Sciences 105*(6), 1786–1793.

Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen (2009, April). Greenhouse-gas emission targets for limiting global warming to 2°c. *Nature 458*(7242), 1158–1162.

National Research Council (U.S.) (2010). *Advancing the science of climate change*. Washington D.C.: National Academies Press.

Nordhaus, W. D. (2007). A review of the stern review on the economics of climate change. *Journal of Economic Literature 45*(3), 686–702.

Rogner, H.-H. (1997). An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment 22*(1), 217–262.

Sinn, H.-W. (2008). Public policies against global warming: a supply side approach. *International Tax and Public Finance 15*, 360–394.

Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences 106*(6), 1704–1709.

Solow, R. (1974). Intergenerational equity and exhaustible resources. *Review of Economic Studies*, 29–45.

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

Stiglitz, J. (1974). Growth with exhaustible natural resources: Efficient and optimal growth paths. *Review of Economic Studies 41*, 123–137.

Stürmer, M. and G. Schwerhoff (2011). Non-renewable but inexhaustible – resources in an endogenous growth model. *Working Paper*. University of Bonn, Germany.

UNFCCC (1992). *United Nations Framework Convention on Climate Change*.

UNFCCC (2009). *Copenhagen Accord*.

van der Werf, E. and C. Di Maria (2011). Unintended detrimental effects of environmental policy: The green paradox and beyond. *CESifo Working Paper* (3466).

WBGU (2006). *The Future Oceans - Warming up, Rising High, Turning Sour*. German Advisory Council on Global Change.

Weitzman, M. (2011). Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy 5*(2), 275–292.