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Resource rents: The effects of energy taxes and quantity instruments for climate protection

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HIGHLIGHTS

- ► Resource taxes and quantity rationing (carbon budgets) are efficient.
- ► Carbon budgets increase resource rents, while taxes decrease rents.
- ► Resource owners may support climate protection.
- ► Climate protection introduces a climate rent.

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ABSTRACT

Carbon dioxide emissions correspond to fossil resource use. When considering this supply side of climate protection, crucial questions come to fore. It seems likely that owners of fossil resources would object to emission reductions. Moreover, policy instruments such as taxes may not be effective at all: it seems individually rational to leave no fossil resources unused. In this context, it can be expected that economic sectors will react strategically to climate policy, aiming at a re-distribution of rents.

To address these questions, we investigate the effectiveness, efficiency, and resource rents for energy taxes, resource taxes, and quantity rationing of emissions. The analysis is based on a game theoretic growth model with explicit factor markets and policy instruments. Market equilibrium depends on a government that acts as a Stackelberg leader with a climate protection goal. We find that resource taxes and quantity rationing achieve this objective efficiently, energy taxation is only second-best. The use of quantity rationing to achieve climate protection generates substantial rents for resource owners.

1. Introduction

Climate protection requires a major reduction of carbon emissions, and thus a reduction of fossil fuel use. When considering the supply side of fossil resources, questions of rent-seeking come to fore: Are there gains for resource owners from policies that lead to emission reductions? Which specific policy instruments will they support? This paper compares resource rents for energy taxes, resource taxes, and a carbon budget as instruments for achieving emission reduction targets.

There is substantial evidence that reaching climate protection targets within the 21st century depends mainly on the level of *cumulative* emissions up to 2050 (Meinshausen et al., 2009). This has been used as an argument for proposing internationally binding carbon budgets in a global environmental agreement (WBGU, 2009; Zickfeld et al., 2009). Carbon budgets provide emissions allowances to their holders that can be used at any time within a longer interval, e.g., 50 years. Only cumulative emissions are restricted.

Since carbon emissions from thermal power generation are equivalent to the carbon content of combusted fossil resources, policy targets for limiting (cumulative) emissions thus limit (cumulative) resource extraction. This proposition is central for the paper. Note that it would need to be qualified if, e.g., carbon capture and storage technologies would become available at a large scale (see, e.g., Golombek et al., 2011). It also assumes that the profile of the emission path is of minor importance compared to cumulative emissions (as supported by Meinshausen et al., 2009). It is estimated that the amount of economically recoverable resources is substantially larger than the amount of emissions that do not cause dangerous interference with the climate system (e.g., WBGU, 2009). Goals to mitigate climate change consequently imply that some share of the available resources needs to conserved. However, a mitigation goal needs to be agreed on in international negotiations, and it seems unlikely that resource owners would support policies entailing that they would lose part of their assets that generate rents.

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Investigations into the relationship between resource extraction and stock pollution began in the early 1970s (Schulze, 1974; Hoel, 1978; Forster, 1980). In subsequent research, variations of the seminal models were analyzed (see Balgodere, 2009; Tahvonen, 1997, for an overview). These models consider utility loss from pollution, but not a rationing of pollution (e.g., carbon budgets). Some models contain a backstop technology (e.g., Hoel and Kverndokk, 1996), but only few consider capital as substitute for resource input (with Krautkraemer, 1985, being an exception). Government instruments are discussed, if at all, in terms of Pigouvian taxes in a first-best setting (e.g., Ulph and Ulph, 1994; Sinclair, 1992). Our paper focuses on three instruments. This first is a carbon tax, being equivalent to a resource tax in our setting, and repeatedly proposed in the discourse (e.g., Nordhaus, 2008). Second, quantity rationing is the underlying principle of cap-and-trade systems, being extended to intertemporal trade for carbon budgets (WBGU, 2009). Finally, energy taxes have traditionally been suggested as a means to reduce emissions (see, e.g., Schmutzler and Goulder, 1997; de Mooij, 2000). Some studies examine the path of resource rents in the presence of different policy instruments (Hoel and Kverndokk, 1996; Farzin, 1996; Balgodere, 2009), but their role in garnering political support for a particular policy instrument has not been analyzed yet to our knowledge. We argue that it is likely that such support is crucial if proposed policy instruments should become implemented.

Further, it is not evident that a mitigation goal can be achieved at all. It is textbook knowledge that non-renewable resource deposits are completely extracted in a competitive economy since it is not rational to leave resources unutilized. In his 'green paradox' Sinn (2008) claims that this argument carries over to regulation with a carbon tax, such that the cumulative amount of extraction (equivalent to cumulative emissions) would not change (see also Long and Sinn, 1985). Thus, a policy instrument can only shift emissions between the present and the future, which might be seen as an issue of intergenerational justice, but would be ineffective for climate protection.

If the 'green paradox argument' holds, resource owners can be expected to prefer a carbon tax over a carbon budget (if their choice is between just these two options): while the ineffective tax would allow for selling the resource stock completely, the budget would require to keep a share *in situ*. This might devaluate the resource stock. These conclusions yet contradict the allocative equivalence of price instruments (such as taxes) and quantity instruments (such as a carbon budget) in the absence of uncertainty and market failure: there must be an efficient price instrument that leads to the same extraction path as a carbon budget with partially non-utilized fossil resources. If a tax is indeed effective, resource owners should not prefer it over a carbon budget in terms of an unused share of the resource stock.

This conclusion basically rests on whether the resource deposits are completely extracted or not. The literature shows mixed results. Cumulative extraction may be complete (e.g., Forster, 1980) or not (e.g., Hoel and Kverndokk, 1996). Both assume the equivalence of resource extraction and emissions, and supplement the model with a stock pollution externality. Complete extraction usually depends on further conditions, in particular the existence of a choke price for resources. If extraction is complete, Sinn (2008) argues that an increasing tax path shifts emissions to the present. This is also shown for an efficient tax path by Ulph and Ulph (1994), at least in the beginning of the time interval, while Sinclair (1992) finds a decreasing tax path. Recently, the green paradox argument has been further evaluated and extended (e.g., Hoel, 2010). Our analysis will assume a mitigation goal that is exogenously set, so we do not require that it balances marginal abatement costs with marginal damage costs, and we can focus on the issue of complete extraction in a clear-cut way. If the mitigation goal can be achieved by a policy instrument, we call it effective. If it does so with maximal welfare, we call it efficient. Against this background, the paper addresses the following questions: Are resource or energy taxes effective and efficient for climate protection by conserving fossil resources? Would resource owners tend to favor taxes or carbon budgets, and would they favor business-as-usual over climate protection?

We develop an intertemporal policy assessment model, formalized as a multi player differential game of economic sectors (in particular the resource sector), households and government, based on an endogenous growth model of a closed economy. As a Stackelber leader, the government strives to optimize household welfare under a mitigation goal, which is a constraint on cumulative fossil resource extraction over the planning interval. To that end, it first imposes a carbon budget or tax path on either energy or resources. The different sectors then play a market game resulting in general equilibrium quantities and prices.

We find that an (increasing) unit tax on fossil resources can achieve the same optimal emission path as a carbon budget. An energy tax, however, is not efficient. Both taxes lead to substantially lower resource rents than the carbon budget. The rents in the latter case are higher than in the business-as-usual scenario with no climate policy. Sensitivity analysis shows that the resource owner's gain from climate protection only decreases when the emission reduction target is quite tight.

We begin the following section with a description of the model structure. Then we provide a set of computations to assess the policy instruments. Some analytical results are shown in the Appendix. We conclude by reflecting on these results.

2. The model

In this section we introduce the sectorally disaggregated intertemporal model to assess price and quantity instruments. We first present the basic structure in a social planner context, that will later serve as a benchmark. Subsequently, we resolve market interactions and government strategies within a differential Stackelberg game. We only present the essential equations here, while the complete model specification is given in Appendix A, and proofs of basic analytical properties are presented in Appendix B.

To determine whether climate policies are effective and how they change resource rents, a limited fossil fuel stock s is crucial for the model. The resource sector employs capital k_R to extract resources at a rate R. A policy instrument effectively achieves a mitigation goal $\underline{s}$, if $s \geq \underline{s}$ forever. This lower constraint represents the amount of carbon that is left *in situ* instead of being emitted to the atmosphere. Extraction generates rents that depend on demand from the energy sector. This sector also employs capital k_E to generate energy E. Energy, capital k_Q and labor L are used as inputs in the production sector with a neoclassical technology. Its output Q is split between investment I and aggregate household consumption C (see Fig. 1 for an overview). Here and in the following, the subscripts Q, E and R indicate the final commodity, energy, and the fossil resource sector, respectively.

2.1. Social planner

The social planner selects consumption, extraction and investment to maximize (utalitarian) intertemporal welfare for a representative household

$$J_H = \int_0^\infty u(C,L)e^{-\rho t}\,dt, \tag{1}$$

with time preference rate ρ, a strictly concave current utility function $u(C,L)$ that is increasing in consumption C and decreasing

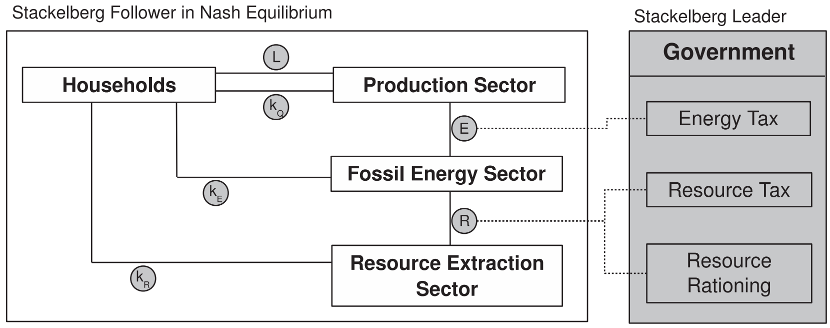

Fig. 1. Model structure.

in labor L. The aggregate capital stock $k = k_Q + k_E + k_R$ changes with investment I and depreciates at rate δ,

$$\dot{k} = I - \delta k. \tag{2}$$

Consumption and investment is provided from production $Q = C + I$.

Fossil fuel is extracted from a limited set of deposits with initial stock $s_0 > 0$ according to

$$\dot{s} = -R = -h(k_R, s), \tag{3}$$

with a production function h that is linear in k_R, and increasing in the resource stock s. This is an equivalent formulation to the usual cost model, in which extraction costs depend on the remaining resources. In our specification, capital productivity falls with the decreasing resource stock. We introduce the mitigation goal as a constraint on cumulative resource use

$$s \geq \underline{s}, \tag{4}$$

i.e. $\underline{s}$ represents the part of the resource stock that should not be extracted. If there is no climate policy, we simply set $\underline{s} = 0$, i.e. any amount of total resource extraction complies with constraint (4).

The social planner's problem can be solved with Pontryagin's maximum principle. From the costate equations a modified Ramsey rule can be derived (see Appendix B): the marginal utility of consumption equals the value of capital. Marginal disutility of labor is balanced with its marginal productivity. On the optimal path, the capital stocks k_Q and k_E have identical marginal productivities, while the marginal productivity of k_R has to be corrected by the influence of increasing extraction costs and the resource scarcity due to the mitigation goal. This determines the optimal growth rate of consumption.

2.2. The Stackelberg game

We now introduce markets, prices, taxes, and the government as an additional actor. The following options are at the government's disposal. Price instruments are represented by charging unit taxes τ_E, τ_R on energy and resource quantities, or setting the quantity constraint $\underline{s}$ (corresponding to a carbon budget). The government (as the Stackelberg leader) sets taxes or a quantity constraint, while individual economic agents such as firms and households (as Stackelberg followers) are assumed to be price takers in a competitive economy and take government decisions as given. Hence, the remainder of the economy determines equilibrium prices and quantities in reaction to the policy path under the assumption that the government cannot be induced to modify its decision. Although sometimes not labeled explicitly, this is a common approach to modeling the game between regulator and economy in public finance and monetary policy analysis (e.g., Lucas and Stokey, 1983; Chamley, 1986). Nevertheless, Stackelberg games have rarely been applied to complex and dynamic environmental regulation problems (see Batabyal, 1996, for an exception).

Households are assumed to dispose of capital k intertemporally, and labor L is exogenously given by population growth. Capital generates an interest rate r. Labor is compensated at the wage rate w. Therefore, households make decisions subject to the budget constraint

$$C = wL + rk + \Gamma - I + \pi, \tag{5}$$

where Γ represents lump-sum transfer incomes or payments to or from the government, and total profits from firms $\pi = \pi_Q + \pi_E + \pi_R$ augment the households' budgets. We assume that there is a representative household dynasty that maximizes present value utility Eq. (1) for given paths of w, r, π and Γ (depending on the government policy). Households' decision problem can be solved by Pontryagin's maximum principle (see Appendix B), yielding, inter alia, the following modified Ramsey rule:

$$r - \delta = \rho + \eta \hat{C}, \tag{6}$$

where η denotes the elasticity of the marginal utility of consumption, and $\hat{C}$ the growth rate of consumption.

Production firms select the inputs capital k_Q, labor L, and energy E to maximize profits as price takers with respect to given factor prices $r, w, \overline{p}_E$, the latter denoting the net market prices for energy after taxation (energy is taxed on the demand side). This yields the standard results that marginal factor productivities equal marginal (net) factor prices.

Similarly, the energy sector selects capital k_E and fossil resources R to maximize profits for a given net resource price $\overline{p}_R$ and gross energy price p_E, such that marginal factor productivities equal marginal (net) factor prices as well.

The resource sector faces an intertemporal decision due to a limited resource stock s. It takes the gross resource price p_R as given and determines the input k_R to maximize

$$J_R = \int_0^\infty \pi_R(t) e^{\int_0^t (-r(\xi)+\delta)\, d\xi}\, dt,$$

with

$$\pi_R = p_R h(k_R, s) - r k_R, \tag{7}$$

being the profits at time t. Solving this problem (see Appendix B) leads to a modified Hotelling rule

$$r - \delta = \frac{\dot{p}_R - \frac{\dot{r}}{h'_{k_R}}}{p_R - \frac{r}{h'_{k_R}}}. \tag{8}$$

The equation simplifies to the original formulation (Hotelling, 1931) when extraction costs vanish (i.e. when we discard the term rk_R in Eq. (7)).

To consider quantity rationing for the resource sector as a policy instrument, we introduce the parameter s_c, defining the

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constraint

$s \geq s_c,$

for the resource sector. A minimal amount of the resource that should not be extracted is *imposed* on the resource sector by setting $s_c = \underline{s} > 0$. If $s_c = 0$ the resource sector can extract the entire resource stock if it is profitable. Quantity rationing is anticipated by the resource sector and requires the appropriate transversality condition *for the resource sector* (see Appendix B). This means the announcement of a credible regulation by the government to forbid any extraction below s_c, e.g., by introducing a carbon budget.

Together with the initial resource stock s_0, a given set of tax paths and given quantity rationing s_c, the above conditions completely determine the joint intertemporal market response of all economic sectors. Government as the Stackelberg leader sets these parameters in order to optimize its objective functional subject to the mitigation goal. Net prices are $\overline{p}_E = p_E + \tau_E$ and $\overline{p}_R = p_R + \tau_R$. Quantity rationing is implemented by selecting $s_c > 0$. The mitigation goal $\underline{s}$ is formulated as a constraint Eq. (4). Under these conditions, the government seeks to maximize the same objective as households Eq. (1), subject to a balanced government budget

$-\Gamma = \tau_E E + \tau_R R.$

The Stackelberg leader takes into account the budget constraints, equations of motion, production technology and implicit reaction functions of the followers. Together with the above reactions of the followers, this completely determines the Stackelberg equilibrium.

2.3. Model calibration

Completely solving the game analytically would distract attention due to its complexity, although some results can be derived analytically (see Appendix B). For most parts of the quantitative analysis, a numerical version of the model was implemented and calibrated (as NLP in GAMS, GAMS Development Corporation, 2012). The discrete maximum principle is used to determine the first-order and transversality conditions of the followers that serve as implicit reaction functions. The optimal strategy of the Stackelberg leader is computed by numerical optimization with the first-order and transversality conditions of the followers (and the usual marginal conditions for market demand and supply Eqs. (B.2) and (B.3)) as analytical constraints. Production functions are of the CES-type and extraction costs are convexly increasing with the amount of extracted resources (cf. Nordhaus and Boyer, 2000). See Appendix D for the complete specification.

Parameters are calibrated along the medium growth baseline scenario of the ADAM model comparison project (Edenhofer et al., 2010). This generates similar projections for emissions and GDP as the IPCC's high-growth A1F1 scenario (Nakićenović et al., 2000). GDP increases with exogenous labor productivity growth to 430 trillion USD, the population approaches 9.5 billion people, and total energy consumption increases up to 1800 EJ at the end of the 21st century. Annual emissions grow continuously and reach 32 GtC in 2100. The resulting energy price ranges from 4 ct/kWh (2010) to 12 ct/kWh (2100) due to increasing extraction costs and the scarcity of fossil fuels. The fossil resource base S_0 is set to 4000 GtC and parameterization of the Rogner curve yields extraction costs increasing from 80 USD/tC in 2010 to 800 USD/tC in 2100. Converted to the carbon content of oil, this implies an extraction cost increase from 12 USD/bbl oil to 120 USD/bbl. Thus, we assume a world of significant economic growth that is driven mainly by the increasing use of fossil resources.

3. Evaluation of policy instruments

This section analyzes the capability of the following instruments to achieve a mitigation goal (effectiveness) in a socially optimal way (efficiency), and determine their influence on resource rents π_R: (1) a carbon budget for cumulative resource extraction; (2) a unit resource tax; and (3) a unit energy tax. We evaluate by comparing the *business as usual* scenario (BAU) of the social optimum with $s_c = \underline{s} = 0$, and the *reduction* scenario (RED) with a mitigation goal $\underline{s} > 0$ corresponding to cumulative emissions of 450 GtC. This is an ambituous mitigation goal with a strong likelihood to achieve the 2 °C policy goal (Meinshausen et al., 2009). Efficiency is determined by comparing the market with the social planner results. The distortions of second-best instruments are measured by their relative loss of discounted household welfare. Before comparing results and conducting some sensitivity analyses, we first discuss the three instruments separately.

A carbon budget restricts cumulative resource extraction by setting $s_c = \underline{s} > 0$ for the extraction sector. This means that the restriction defines the the transversality condition Eq. (B.6). In other words, the extraction sector anticipates from the beginning that less resources can be extracted. All taxes are set to zero. Obviously, the resulting extraction path is effective, i.e. it complies with the mitigation goal, since this is formally required. It is also efficient since there are no further market distortions. The resource price rises by a factor of 8.63 in the beginning of the century (compared to the BAU case). The resource price further increases by a factor of 37.88 during the 21st century. This large effect is due to the tight carbon budget of 450 GtC and the relatively inelastic resource demand in the model. The resource price signal propagates to the energy market, such that the production sector substitutes energy input in the appropriate way.

For a resource tax, and in the absence of quantity rationing, resource extractors do not anticipate the mitigation goal directly. This requires to set $s_c = 0$ in the transversality condition Eq. (B.6), such that the resource would be completely extracted if there were no tax. Instead, the unit tax on the resource price drives a wedge between selling price p_R of the extraction sector and purchase price $\overline{p}_R$ of the energy sector. In contrast to the possible objections laid out in the introduction, the resource tax in the game equilibrium is effective in the model runs. Moreover, the tax path set by the government is also efficient. Consequently, the taxed purchase price $\overline{p}_R$ equals exactly the resource price in the case of a carbon budget, such that the unit tax is increasing in time.

Efficiency is due to the allocative equivalence of the optimal resource tax and the carbon budget in the game equilibrium (see Appendix C for a proof). The resource industry voluntarily leaves a fraction of the resource unused. Although increasing taxes are anticipated, that fraction is not shifted to earlier use. This result supports the equivalence of price and quantity instruments against the green paradox arbitrage argument. The government, as Stackelberg leader, anticipates the resource sector's reaction, and sets the tax path in a way that there is no incentive for the resource industry to deviate from the optimal extraction plan.

The energy tax changes the purchase price of energy for the production sector to $\overline{p}_E$. This instrument is effective, i.e. it achieves the mitigation goal in the model runs. The tax increases from 0.09 \$/kWh to 2.74 \$/kWh during the 21st century. Since energy and resource markets are linked through the energy sector, the energy tax might be effective as a corollary of the effectiveness of a resource tax. Yet, the energy tax path in the game equilibrium leads to an inefficient factor allocation. An energy tax reduces energy demand E, and consequently demand

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for the inputs R and K_E in the energy sector as well. But the ratio K_E/R remains unchanged due to the CES energy production technology. An energy tax has a volume effect, but no substitution effect. It is only capable of achieving a mitigation goal by reducing overall energy consumption.

We now compare the resource rents that are generated if one of the three policy instruments is applied (see Fig. 2). Since they all lead to less fossil fuel sold on the market (compared to the BAU), it might be expected that profits in the resource sector decrease. For an energy or resource tax, the profits in the resource sector indeed strongly fall in comparison to the BAU case. The inefficiency of the energy tax decreases the resource rents even more. Yet with a carbon budget, profits in the resource sector rise. This is due to the politically created scarcity of carbon that increases the resource price and over-compensates the loss from unused resources. This shows that (1) resource owners should prefer a carbon budget over taxes and (2) they can profit from effective climate protection, although they lose a part of their assets.

This conclusion is robust when carbon budgets change (see Fig. 3). The costs of climate protection (measured in GDP or consumption loss in comparison to the BAU) obviously increase with more ambitious mitigation goals. Interestingly, in the case of a carbon budget resource rents also increase with tighter goals until a maximum is reached. The rent-maximizing mitigation goal is very low in our computations. There are two opposing effects in place here. First, resource prices increase due to policy-induced scarcity. Second, the volume of resource sales decreases. As long as the first effect dominates, it is beneficial for the resource sector to support a carbon budget. Voluntarily reducing the available resource stock would not work in an unregulated market, since there would be an incentive for each firm to deviate from that path by extracting more. If leaving a share of the resources unused is obligatory by regulation, instead, such a deviation is not possible.

We conclude with some observations from further sensitivity analyses that vary substitution elasticities. Most of the aforementioned effects do not change in principle. They confirm the expectation that for lower substitutability of resources in the energy sector, welfare losses from an energy tax are higher. There is a stronger need for consumption reduction to achieve the mitigation goal. The same holds for the elasticity of substitution of energy in the production sector. For a low elasticity of substitution in the energy and production sector, the resource rent increases. In all model runs, however, the resource rents are greater than in the BAU case, even if elasticities are near one.

4. Conclusions

We have investigated three different policy instruments that could be used to achieve a climate protection goal. We have compared them for their effectiveness, their efficiency, and their contribution to resource rents. The analysis is based on a combined Stackelberg-Nash differential game that regards government and the fossil resource sector as strategic actors. In contrast to a standard social planner model, this allows us to explicitly compute prices, tax paths, and sectoral profits for

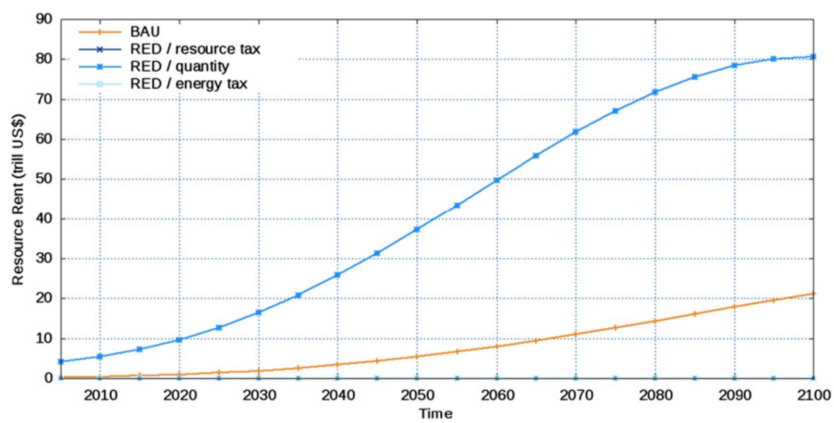

Fig. 2. Resource rents for different instruments.

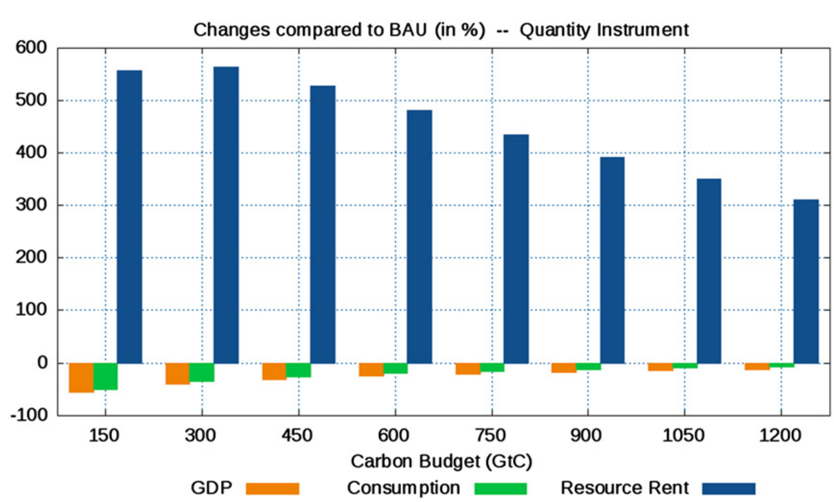

Fig. 3. Results for total production, consumption and resource rents for different carbon budgets.

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instruments that are not *prima facie* first-best. In the case of an instrument that is capable of achieving the mitigation goal, the model determines the optimal policy path automatically. Our results are the following.

The mitigation goal is achieved with a resource tax, an energy tax, and also with a carbon budget. Differences between the instruments exist in terms of their efficiency and the rents they generate. Resource instruments (taxes and carbon budgets) are efficient, and thus preferable to inefficient energy taxes, in particular if there are good substitution possibilities for resource input in the energy sector. An energy tax only causes a volume effect on the energy output side, resulting in welfare losses. A carbon budget increases resource rents in comparison to the business-as-usual scenario, while the opposite holds for taxes. This is the case even for very strict climate protection targets.

We can thus conclude (1) that there is a strong case for fossil resource owners to support a stringent climate policy, (2) that their support will depend on the use of an instrument that leaves some of the policy-induced scarcity rents with the resource industry, and (3) that considering the supply-side dynamics of fossil resource extraction does not render climate policy ineffective.

This contradicts parts of the green paradox argument of Sinn (2008), who claimed that climate policies may have adverse impacts on climate protection. He suggests that the resource sector anticipates increasing resource taxes. Even if such taxes are meant to reduce emissions, they have the opposite effect: in order to safeguard resource rents, the resource sector increases current extraction and therefore emissions. Thus, taxes would not contribute to climate protection, and may even raise issues of intergenerational justice. However, our analysis shows that this is not necessarily the case, and that an effective and efficient resource tax increases in time.

In our numerical estimates the resource owners' loss from unused fossil fuel is more than compensated by an increase in net resource prices. Resource owners would thus support even very ambitious climate protection targets. This result has yet to be taken with caution. The model determines very high resource taxes. The main reason is that there is currently no backstop technology in the model. Changing this is will decrease resource rents. Working with a more detailed energy system model would thus refine the results.

The increasing resource rents in a climate protection regime can be best understood by considering the carbon budget. Holding parts of that fixed supply of allowances generates rents. Our model assumed that the carbon budget was given to the resource sector for free. So this rent replaces the usual resource rent. If, alternatively, taxes are used as an instrument to achieve equivalent emission reductions, this rent is appropriated by the government. We might also think of, e.g., allocating carbon budgets through auctions, leading to another distributional effect. Yet, changing distribution of the additional rents with different budget allocation mechanism does not alter the effectiveness and efficiency of the instruments. These additional rents from climate protection may be called the "climate rent". Its appropriation is a matter of instrument choice. This provides an additional degree of freedom for international agreements on climate protection, since the climate rent can be re-distributed without market distortions. On the other hand, this indicates conflict potential due to rent-seeking behavior.

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Appendix A. Complete model specification

A.1. Social planner

The social planner maximizes $J_H = \int_0^\infty u(C,L)e^{-\rho t}\,dt$, with the aggregated capital stock $k = k_Q + k_E + k_R$ subject to $\dot{k} = I - \delta k$. Output $Q = C + I$ is produced with technology $f(k_Q,L,E)$. Energy E is generated via the production function $g(k_E,R)$, and fossil fuel R is extracted from the resource stock s according to $\dot{s} = -R = -h(k_R,s)$ with production function h. The mitigation goal is a constraint $s \geq \underline{s}$. The solution of the social planner's problem considers decomposed investment $I = I_Q + I_E + I_R$ and the aggregated production function

$$\tilde{f}(k_Q,k_E,k_R,L,s) := f(k_Q,L,g(k_E,h(k_R,s))). \tag{A.1}$$

The current value Hamiltonian is

$$H = u(\tilde{f}(k_Q,k_E,k_R,L,s) - I,L) + \lambda_Q(I_P - \delta k_Q) + \lambda_E(I_E - \delta k_E) + \lambda_R(I_R - \delta k_R) - \lambda_s h(k_R,s),$$

with λ_s as shadow price of fossil resources. First order conditions yield identical shadow prices for all capital types $\lambda_k := \lambda_Q \equiv \lambda_E \equiv \lambda_R$. Consumption is determined by

$$u'_C = \lambda_k, \quad u'_L = -\lambda_k \tilde{f}'_L. \tag{A.2}$$

Here, f'_x, f''_x denote partial derivatives of a function f with respect to its argument x. The transversality condition for the resource stock is $\lim e^{-\rho t}\lambda_s(s - \underline{s}) = 0$. The costate equations yield $\hat{\lambda}_s = \rho + h'_s - (\lambda_k/\lambda_s)\tilde{f}'_s$, (with hats $\hat{x} := \dot{x}/x$ denoting change rates). By equalizing the shadow prices—the modified Ramsey rule

$$\tilde{f}'_{k_Q} = \tilde{f}'_{k_E} = \tilde{f}'_{k_R} - \frac{\lambda_s}{\lambda_k} h'_{k_R} = \rho + \delta + \eta \hat{C}, \tag{A.3}$$

holds. The last equation follows by substituting Eq. (A.2) and its derivative with respect to time in the costate equations and defining the elasticity of the marginal utility of consumption $\eta := -(u''_C/u'_C)C$.

A.2. Stackelberg game

Aggregate households maximize Eq. (1) subject to the budget constraint $C = wL + rk + \Gamma - I + \pi$ with total profits $\pi = \pi_Q + \pi_E + \pi_R$ and with given price and tax paths.

Taking Q as numéraire, the production sector maximizes profit $\pi_Q = f(k_Q,L,E) - rk_Q - wL - \overline{p}_E E$, and the energy sector $\pi_E = p_E g(k_E,R) - \overline{p}_R R - rk_E$.

The resource sector maximizes $J_R = \int_0^\infty \pi_R(t) e^{\int_0^t (-r(\xi)+\delta)\,d\xi}\,dt$ with $\pi_R = p_R h(k_R,s) - rk_R$. Quantity rationing is introduced by the constraint $s \geq s_c$ that is anticipated by the resource sector.

Government – as Stackelberg leader – sets taxes and s_c to maximize Eq. (1), subject to a balanced government budget $-\Gamma = \tau_E E + \tau_R R$, and subject to the reaction functions of the followers as determined by their first order conditions (next section).

Appendix B. Some analytical properties of the Stackelberg equilibrium

Households' current value Hamiltonian is $H_H = u(C,L) + \lambda_H(wL + rk + \Gamma - C - \delta k + \pi)$. The first order conditions are

$$u'_C = \lambda_H, \quad u'_L = -\lambda_H w, \quad \dot{\lambda}_H = \lambda_H(\rho + \delta - r). \tag{B.1}$$

This is sufficient for optimality due to the strict concavity of u and the concavity of Eq. (2). Using Eq. (B.1), the transversality condition $\lim_{t\to\infty} \lambda_H k e^{-\rho t} = 0$ is equivalent to $\lim_{t\to\infty} \lambda_H(0) k e^{\int_0^t (\delta - r(\xi))\,d\xi} = 0$. The Ramsey rule Eq. (6) is derived in analogy to the social planner case Eq. (A.3) by equating shadow prices.

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Factor demand in the production and the energy sector is given by the standard conditions

$$f'_{k_Q} = r, \quad f'_L = w, \quad f'_E = \overline{p}_E, \tag{B.2}$$

$$g'_R = \frac{\overline{p}_R}{p_E}, \quad g'_{k_E} = \frac{r}{p_E}. \tag{B.3}$$

The current value Hamiltonian of the resource sector is $H_R = p_R h(k_R,s) - rk_R + \lambda_R \dot{s}$, such that the first order conditions evaluate to

$$r = (p_R - \lambda_R) h'_{k_R}, \tag{B.4}$$

$$\dot{\lambda}_R = (r-\delta)\lambda_R - (p_R - \lambda_R) h'_s. \tag{B.5}$$

By substituting Eq. (B.4) and its derivative with respect to time into Eq. (B.5), one obtains the modified Hotelling rule Eq. (8). Due to possible quantity rationing, the transversality condition is

$$0 = \lim_{t\to\infty} \lambda_R (s - s_c) e^{\int_0^t (-r+\delta)\, d\xi}. \tag{B.6}$$

In the Stackelberg equilibrium capital is allocated as follows. Due to Eqs. (B.2) and (B.3),

$$f'_{k_Q} = (f'_E - \tau_E) g'_{k_E}. \tag{B.7}$$

Capital in the production and the energy sector yield the same marginal profits. By further considering Eqs. (B.4) and (B.3), we see that

$$f'_{k_Q} = h'_{k_R}((f'_E - \tau_E) g'_R - \tau_R - \lambda_R). \tag{B.8}$$

Marginal profits from capital in the resource sector differ due to the resource scarcity expressed by λ_R.

Appendix C. Efficiency proof for resource tax

It needs to be shown that a resource tax exists that leads to a social optimal Stackelberg equilibrium. Let variables with an asterix $\cdot^*$ denote the time paths of the solution with quantity rationing. We claim that assuming

$$w := w^*, \quad r := r^*, \quad p_E := p_E^*, \quad \overline{p}_R := p_R^*, \quad \lambda_H := \lambda_H^*, \tag{C.1}$$

$$\tau_R := \lambda_R^* - \lambda_R, \tag{C.2}$$

determines (i) the same allocation as quantity rationing and (ii) that it is the Stackelberg equilibrium. Optimality is a corollary of (i), since we already know that quantity rationing is optimal. The last assumption allows for explicitly determining the resource tax for every instant t.

Ad (i): since all prices except the resource price are identical to the quantity rationing solution, it only needs to be checked whether the same extraction path is produced. By the definition of $\overline{p}_R$ and τ_R, it holds that $p_R - \lambda_R = \overline{p}_R - \tau_R - \lambda_R = p_R^* - \lambda_R^*$. Since extraction is determined by Eq. (B.4) it follows from the assumptions that $h'^*_{k_R} = h'_{k_R}$: both rationing and the tax generate the same extraction path.

Ad (ii): the path represents an optimal reaction of the households, since Eq. (B.1) is obviously fulfilled. It is also an optimal reaction of the resource sector, since Eq. (B.5) is fulfilled as well. Since the government has the same objective function as households, that path is also optimal for the government. We therefore have a game equilibrium.

Appendix D. Numerical implementation

For the numerical calculations, production is expressed by a nested CES-technology

$$f(k_Q, L, E) = (a_1 z^{\sigma_1} + (1-a_1) E^{\sigma_1})^{(1/\sigma_1)},$$
$$z(k_Q, L) = (a_2 k_Y^{\sigma_2} + (1-a_2) A_L L^{\sigma_2})^{(1/\sigma_2)}, \tag{D.1}$$

with z being a composite of capital and labor (cf. van der Werf, 2007) and $\sigma_1, \sigma_2 < 0$. For numerical convenience, we use the common assumption of technological progress being Harrod-neutral (labor-augmenting, see e.g., Barro and i Martin, 1999). Labor productivity A_L increases due to technological change

$$A_{L,t+1} = \frac{A_{L,t}}{1 - \gamma_A^1 e^{-\gamma_A^2 t}}.$$

Labor supply is assumed to be inelastic and evolves according to the logistic population growth equation

$$L_t = L_0(1-q_t) + q_t L^{max},$$
$$q_t = \frac{e^{\gamma_L t} - 1}{e^{\gamma_L t}}.$$

The logistic growth formula allows a simple closed-form description that approximates existing UN population growth scenarios (see, e.g., Nordhaus, 2008). Energy is produced by a CES technology with $\sigma < 0$,

$$g(k_E, R) = (a k_E^{\sigma} + (1-a) R^{\sigma})^{(1/\sigma)}.$$

We assume a low substitution elasticity, as electricity output is roughly equivalent to primary energy input. The technical efficiency of power plants improves only slowly with more advanced generation technology (e.g., Flosdorff and Hilgarth, 2005).

Resource extraction uses capital as input with a rising capital intensity at diminishing reserves (cf. Edenhofer et al., 2005; Nordhaus and Boyer, 2000)

$$h(k_R, s) = c(s) k_R, \quad c(s) = \frac{\chi_1}{\chi_1 + \chi_2 \left(\frac{s_0 - s}{\chi_3}\right)^{\chi_4}}.$$

Household and government utility are defined with isoelastic marginal utility of per capita consumption

$$u(C, L) = (1-\eta)^{-1}((C/L)^{1-\eta} - 1).$$

We approximate the infinite horizon problem by a finite one. To identify equilibrium paths, single model runs with very long time horizons were computed first. Due to discounting, these paths and the values of the objective functions are almost identical to those with a 150 years time horizon if analysis is restricted to the first 120 years (after that dissaving effects occur). These assumptions were taken for the evaluation of the policy instruments (i.e. discounted welfare effects).

ρ	Pure time preference rate	0.03
η	Marginal utility elasticity	1
$\underline{s}$	Final resource stock under carbon budget (GtC)	3550
s_0	Fossil resource base (GtC)	4000
k_0	Initial capital stock (trill US$)	165
s_1	Elasticity of substitution (Z-E)	0.5
s_2	Elasticity of substitution (K-L)	0.7
s	Elasticity of substitution (K-R)	0.15
a_1	Share parameter in final good production	0.95
a_2	Share parameter in intermediate input production	0.3
a	Share parameter in energy production	0.8
δ	Capital depreciation rate (all sectors)	0.03
L_0	Initial population (10^9)	6.5

L_{max}	Population capacity (10^9)	9.5
γ_L	Population growth parameter	0.04
$A_{L,0}$	Initial labor productivity	6.0
γ_A^1	Productivity growth parameter	0.026
γ_A^2	Productivity growth parameter	0.006
χ_1	Scaling parameter	20
χ_2	Scaling parameter	400
χ_3	Resource base (GtC)	4000
χ_4	Slope of Rogner's curve	2

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