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ENERGY TAXES, RESOURCE TAXES AND QUANTITY RATIONING FOR CLIMATE PROTECTION

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Abstract

Economic sectors react strategically to climate policy, aiming at a re-distribution of rents. Established analysis suggests a Pigouvian emission tax as efficient instrument, but also recommends factor input or output taxes under specific conditions. However, existing studies leave it open whether output taxes, input taxes or input rationing perform better, and at best only touch their distributional consequences. When emissions correspond to extracted ressources, it is questionable whether taxes are effective at all.

We determine the effectiveness, efficiency and functional income distribution for these instruments in the energy and resource sector, 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 cumulative resource quantity rationing achieve this objective efficiently. Energy taxation is only second best. Mitigation generates a substantial "climate rent" in the resource sector that can be converted to transfer incomes by taxes.

1. Introduction

Climate protection, being a global public good, entails market failure and incentives for free-riding behaviour. The resulting divergence of market and Pareto optimum justifies government intervention, the most prominent being Pigouvian taxes (Pigou, 1932) or markets for emission rights that ration pollution quantities (Dales, 1968). There has been a long discussion about the relative performance of price instruments like taxes and quantity instruments like emission trading schemes. In his seminal paper, Weitzman (1974) analyzed both under uncertainty with respect to damages and costs. He showed that price instruments are superior to quantity instruments if the marginal cost curve is steeper than the marginal damage curve. For climate change as a stock-pollutant problem the original static approach was modified and the Weitzman criteria were confirmed for specific parameterizations (e.g. Hoel and Karp, 2001; Newell and Pizer, 2003). A further asymmetry involves monitoring and transaction costs. When they are substantial, input or output taxes may be better than emission taxes (e.g. Stavins, 1995;

Schmutzler and Goulder, 1997; Vatn, 1998). In our context, input taxes refer to fossil resource as factor in the energy sector, while ouput taxes refer to energy production. Other work considers additional issues as imperfect competition (Sugeta and Matsumoto, 2007), unemployment (Hoel, 1998) and environmental taxation in a second-best setting with government consumption (Sandmo, 1975; Cremer and Gahvari, 2001).

Another argument questions the *effectiveness* of a Pigou tax when—as in the case of climate protection—the supply-side dynamics of fossil resource extraction is considered (cf. Farzin, 1996; Sinn, 2008). Meinshausen et al. (2009) highlights that reaching a climate protection target within the 21st century mainly depends on the amount of cumulative emissions until 2050, while the timing of these emissions is of minor importance. Since carbon emissions are proportional to fossil resource use for thermal power generation by the law of mass conservation, limiting the amount of cumulated emissions is equivalent to limiting the cumulated extraction of fossil resources. However, basic results from resource economics show that non-renewable resources are completely extracted in a competitive economy. If this argument carries over to the regulated context, it has to be expected that cumulative emissions cannot be reduced, whatever tax path is chosen.

Integrated assessment models of climate change consider damages from climate change and thus determine the optimal mix between mitigation costs and damage (e.g. Nordhaus and Boyer, 2000; Hope, 2006), or set an upper temperature limit for global warming, called a mitigation goal, and determine cost-effective strategies to achieve this objective (e.g. Edenhofer et al., 2005). These approaches have in common that they take a social planner perspective that chooses an overall development path to optimize a social welfare function. They are capable of considering very detailed technological options, but mostly neglect strategic interactions, e.g. between government and economic sectors. Understanding the strategic incentives for these actors is yet crucial for evaluating the feasibility and efficiency of policy instruments. This would require to determine prices and distributional effects, being, in general, not possible with a social planner model. Optimal taxes can only be derived in the first-best setting without any markt failures.

The above literature leaves it open which instrument in the direct comparison of output taxation, input taxation and quantitiy rationing in presence of an externality should be preferred based on effectiveness and efficiency grounds. Moreover, most of the models that do not consider the supply-side are static, the effects of the different instruments on income distribution are mostly neglected, and second-best instruments cannot be assessed.

In this paper we develop a flexible integrated policy assessment model. It is used to compare different dynamic price and quantity instruments by their efficiency and functional income distribution. The papers' objective is to demonstrate the general feasibility of the chosen approach, and therefore does not present an empirically calibrated model. It nevertheless shows the possibility of some crucial effects, and it is possible to prove the core results analytically. The model is 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 Stackelber leader, government strives for optimizing household welfare under a mitigation goal, coming as a constraint on cumulated fossil resource extraction over the planning interval. For that purpose it can impose taxes or subsidies on energy or on resource prices and it can limit the amount of resources utilized by the economy (quantity rationing). The government first sets the resource use limit or the time paths of taxes, and the different sectors then play a market game resulting in general equilibrium quantities and prices.

We find that both a pure tax on fossil resources and quantity rationing achieve optimal emission reductions in the game equlibrium. In contrast, an energy tax is not efficient. The resource tax and quantity rationing generate a scarcity rent. In the former case this leads to substantial transfer incomes. In the latter, transfer incomes vanish and the rent is paid as additional profits from the resource sector.

We begin the following section with a description of the economic and strategic model structure. Based on that we provide a set of numerical experiments to assess the policy instruments and their robustness to some parameter variations. The main results are shown analytically in the Appendix. We conclude by reflecting on these results and the modelling approach in the context of the current debate on climate policy.

2. The model

In this section we introduce the sectorally disaggregated intertemporal model to assess input, output 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

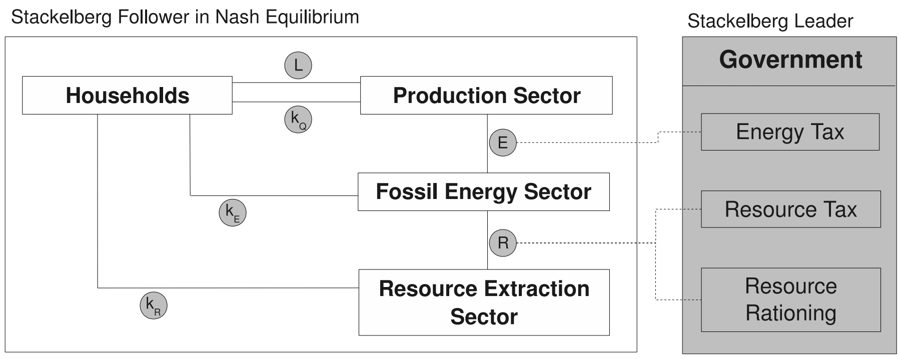

Figure 1: Game structure.

equations here, while the complete model specification is given in Appendix A, and proofs of basic analytical properties are presented in Appendix B.

The model represents households with aggregate consumption C and investment I, both taken from output Q in the production sector. This sector employs capital k_Q, labour L and energy E with a neoclassical technology. Energy is produced in the energy sector with capital k_E and fossil fuel R as input and a neoclassical production function as well. Finally, fossil fuel is extracted from limited stocks s by the resource sector, that employs capital k_R (see Fig. 1 for an overview). Here and in the following, the subscripts Q, E and R indicate the final commodity, energy, and fossil resource sector, respectively. We consider the mitigation goal as an upper limit for cumulated resource extraction. From the formal perspective, this is an equivalent model specification, since cumulated carbon emissions are proportional to cumulated fossil resource use.

2.1. Social planner

The social planner selects labour, consumption, extraction and investment to maximize intertemporal welfare

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

with time preference rate ρ and a strictly concave current utility function $u(C,L)$ that is increasing in consumption C and decreasing in labour L, all being standard assumptions. 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 a usual cost model, where extraction costs depend to the remaining resources. In our specification, capital productivity falls with the decreasing resource stock. We introduce the mitigation goal as a constraint on cumulated resource use

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

In this formulation, $\underline{s}$ 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. The current value Hamiltonian is

$$\begin{aligned} H = {} & u(\tilde{f}(k_Q, k_E, k_R, L, s) - I, L) \\ & + \lambda_Q(I_P - \delta k_Q) + \lambda_E(I_E - \delta k_E) + \lambda_R(I_R - \delta k_R) - \lambda_s h(k_R, s), \end{aligned} \tag{5}$$

with λ_s as shadow price of fossil resources. This formulation considers decomposed investment $I = I_Q + I_E + I_R$ and the aggregated production function

$$\tilde{f}(k_Q, k_E, k_R, L, s) := f(k_Q, L, g(k_E, h(k_R, s))), \tag{6}$$

where output Q is produced with technology $f(k_Q, L, E)$, and energy E with $g(k_E, R)$. First order conditions yield identical shadow prices for all capital types, in the following denoted by $\lambda_k := \lambda_Q \equiv \lambda_E \equiv \lambda_R$, and consumption and labour is determined by

$$u'_C = \lambda_k, \quad u'_L = -\lambda_k \tilde{f}'_L. \tag{7}$$

Here and in the following, 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

$$\hat{\lambda}_s = \rho + h'_s - \frac{\lambda_k}{\lambda_s} \tilde{f}'_s, \tag{8}$$

(with hats $\hat{x} := \frac{\dot{x}}{x}$ denoting change rates), and—by equalizing the shadow prices—the modified Ramsey rule

$$\tilde{f}'_{k_Q} = \tilde{f}'_{k_E} = \tilde{f}'_{k_R} - \frac{\lambda_s}{\lambda_k} h'_{k_R} = \rho + \delta + \eta \hat{C}, \tag{9}$$

where the last equation follows by substituting Eq. (7) and its derivative with respect to time in the costate equations and defining the elasticity of the marginal utility of consumption $\eta := -\frac{u''_C}{u'_C} C$. As expected, the marginal utility of consumption equals the value of capital. Marginal disutility of labour is balanced with its marginal productivity. On the optimal path, the capital stocks k_Q, 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 additional actor. The government (as Stackelberg leader) sets taxes or a quantity constraint, while individual economic agents like firms and households (as Stackelberg followers) are assumed to be price takers in a competetive economy and take government decisions as given. Hence, the remainder of the economy determines equilibrium prices and quantities as reaction to the policy path under the assumption that the government cannot be induced to modify its decision. Though sometimes not labeled explicitly, this is a common approach to model the game between regulator and economy in public finance and monetary policy analysis (e.g. Kydland and Prescott, 1977; Calvo, 1978; Lucas and Stokey, 1983; Chamley, 1986). Nevertheless, Stackelberg games have rarely been applied to complex and dynamic environmental regulation problems (see Batabyal, 1996a,b, for an exception). This is, of course, a specific and idealized structural modeling assumption, that assumes government to be very powerful. In different settings, other game theoretic assumptions might be adequate.

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

$$C = wL + rk + \Gamma - I + \pi, \tag{10}$$

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 budget. Although households own the entire economy, they delegate the administration of firms to managers who maximize firms' pay-off. Hence, households cannot influence the production decisions of firms directly—they only provide labor and capital at market prices and recieve profits and rents. Beeing price takers, the households maximize welfare Eq. (1) (assumed to be identical with that of the social planner) for given paths for w, r, π and Γ, depending on government policies.

Households' decision problem can be solved by Pontryagin's maximum principle (see Appendix B), yielding i.a. the following modified Ramsey rule

$$r - \delta = \rho + \eta \hat{C}, \tag{11}$$

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, labour L and energy E to maximize profits as price taker with respect to given factor prices $r, w, \bar{p}_E$, 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.

Similarily, the energy sector selects capital k_E and fossil resources R to maximize profits for a given net resource price $\bar{p}_R$ 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

$$J_R = \int_0^\infty \pi_R(t) e^{\int_0^t (-r(\xi)+\delta) d\xi} dt, \tag{12}$$

with

$$\pi_R = p_R h(k_R, s) - r k_R, \tag{13}$$

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

$$r - \delta = \frac{\dot{p}_R - \frac{\dot{r}}{h'_{k_R}}}{p_R - \frac{r}{h'_{k_R}}}. \tag{14}$$

The equation simplifies to the original formulation (Hotelling, 1931) when extraction costs vanish (i.e. when we discard the term rk_R in Eq. 13).

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

$$s \geq s_c, \tag{15}$$

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 transversality condition

$$0 = \lim_{t \to \infty} \lambda_R (s - s_c) e^{\int_0^t (-r+\delta) d\xi}, \tag{16}$$

where λ_R is the shadow price of the resource (see Appendix B). This means the announcement of a credible regulation by government to forbid any extraction below s_c. This may be achieved by a volume of pollution certificates that is determined by international agreements. It should be noted that the model in its current version implies that such certificates are given to the extraction sector for free.

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 Stackelberg leader sets these parameters to optimize its objective functional subject to the mitigation goal. The following options are at the government's disposal. Price instruments are represented by charging ad-valorem taxes τ_E, τ_R on energy and resource prices, such that $\bar{p}_E = p_E(1+\tau_E)$, and $\bar{p}_R = p_R(1 + \tau_R)$. Quantity rationing is implemented by selecting $s_c > 0$. The mitigation goal $\underline{s}$ is formulated as constraint Eq. (4). Under these conditions, the government seeks to maximize the same objective as housholds Eq. (1), subject to a balanced government budget

$$-\Gamma = \tau_E p_E E + \tau_R p_R R. \tag{17}$$

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.

The model contains all ingredients that are necessary for the policy questions laid out in the introduction. There are sperate markets for Q, E and R to represent both energy and resource taxes. Resource extraction is formulated as an intertemporal decision to consider the supply-side of carbon. All prices are explicitly modeled to consider strategic interactions, to keep analysis open to second-best results, and to decompose household budgets to labour, capital, rent and transfer incomes. The latter is crucial for determining distributional effects. Completely solving the game analytically would distract attention due to its complexity. There are, however, some strong results that can be derived analytically. Those that are needed for later proofs in this paper are provided in Appendix B. Core results can accessibly be presented by means of quantitative experiments, and we will do so in the following. For that, a numerical version of the model was implemented (see Appendix C for the parameterization). The optimal strategy of the Stackelberg leader is computed by numerical optimization with the first-order and transversality conditions of the followers as analytical contraints. When testing the robustness of the model, several sensitivity analyses where made, of which some examples will be presented below. The model is, however, not calibrated to real-world data. It is meant to illustrate the analytical results and to show that the modelling approach can effectively and flexibly be used for climate policy assessment.

3. Evaluation of policy instruments

This section analyzes the capability of the following instruments to achieve a mitigation goal, and evaluates them with respect to social optimality and functional income distribution: (1) Quantity rationing of cumulative resource extraction; (2) a pure input tax on the resource; (3) a pure output tax on energy. We evaluate them relative to two scenarios: 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 $\underline{s} > 0$.

Efficiency is evaluated by comparing with the social planner results. First-best instruments produce the same quantity paths. Overall distortions of second-best instruments are measured by their relative loss of discounted household welfare Eq. (1). In the BAU scenario the social planner solution is equivalent to the market solution when all taxes vanish. This is due to the absence of any externalities and the reasonable convexity properties of the model.

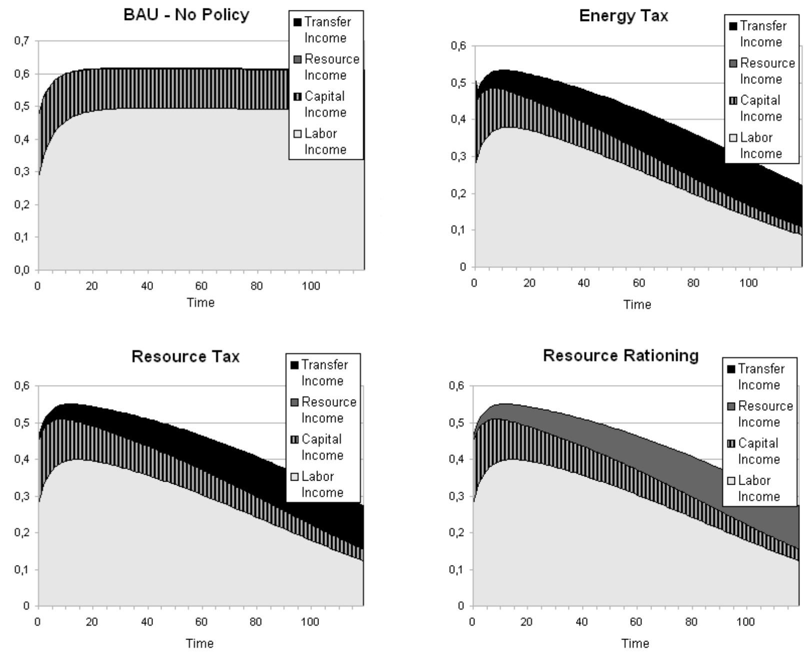

Figure 2: Functional income distribution

Distributional consequences are determined along the concept of functional income (e.g. Bronfenbrenner, 1971). The budget constraint of households Eq. (10) is decomposed to income from labour wL, income from capital rK, income from the resource sector's rent π_R, and (positive or negative) transfer incomes Γ (note that $\pi_Q \equiv \pi_E \equiv 0$ due to constant returns to scale in the production and energy sector). The share of these incomes may differ between policy instruments.

3.1. The effect of emission reductions

In contrast to the BAU scenario, the RED scenarios show consumption falling rapidly after a short period of economic growth (see Fig. 2). The entire economy crucially depends on fossil resources. With limited substitution possibilities, the mitigation goal is mainly achieved by consumption reduction.

3.2. Quantity rationing

Quantity rationing restricts cumulated resource extraction by setting $s_c = \underline{s} > 0$ for the extraction sector in the transversality condition Eq. (16). The extraction sector then anticipates the mitigation goal. All taxes are set to zero. Obviously, the resulting extraction path complies with the mitigation goal since this is formally required. Numerical experiments indicate that the solution is also efficient. Quantity rationing raises resource prices, that propagate to the energy market, such that the production sector substitues energy input in the appropriate way. It can be proven analytically that quantity rationing is always efficent(see Appendix D).

When less fossil fuel can be sold on the market, it might be expected that profits in the resource sector decrease. However, compared to the BAU scenario, profits in the resource sector rise in the numerical simulation (see Fig. 2). The is due to the politically created scarcity that increases the resource price. It is discussed below how the sign of the overall effect on resource rents depends on further conditions.

Since there is no government income due to the absence of taxes or auctioning of permits, the scarcity rents are appropriated by the extraction sector. For later reference, we label the socially optimal values for quantity rationing with an asterisk, p_R^*, p_E^*, s^*, etc.

3.3. Resource tax

In absence of quantity rationing, resource extractors do not anticipate the mitigation goal directly. Instead, the ad-valorem tax on the resource price drives a wedge between selling price p_R of the extraction sector and purchase price $\bar{p}_R$ of the energy sector. To comply with the mitigation goal in an efficient way, this has to result in the same allocative effect as quantity rationing. It is not obvious that such an allocation can indeed be achieved. If it is rational to extract the complete resource stock, the price path can only determine the timing, but not the cumulative resource supply, such that the mitigation goal is not achieved by a resource tax.

In contrast to this expectation, the resource tax is effective in the numerical experiments, and even without welfare losses. The resource tax increases in time, and the profits in the resource sector fall in comparison to the BAU case. Yet when resource demand is inelastic with respect to price changes, a very high tax rate is necessary. It is obeserved that the taxed purchase price $\bar{p}_R$ equals exactly the resource price p_R^* for quantity rationing: the resource tax gives the same price signals to the energy sector.

That the resource tax can achieve the mitigation goal in an efficient way can be shown analytically (see Appendix E). The socially optimal tax is determined by

$$1 + \tau_R = \frac{p_R^*}{\frac{r^*}{h'^*_{K_R}} + \lambda_R}. \tag{18}$$

Recall that λ_R is the shadow price of the resource, that in turn depends on the game equilibrium (see Appendix B).

3.4. Energy tax

The energy tax changes the purchase price of energy for the production sector to $\bar{p}_E$. This instrument reaches the mitigation goal in the numerical experiments. After having discussed the effectiveness of the resource tax above, the question is whether the energy tax is efficient. Since energy and resource markets are linked through the energy sector, it may play no role where a tax is imposed.

The computed energy tax is increasing in time, but yet leads to an inefficient factor allocation. The ratio of resource and capital input in the energy sector remains the same as in the BAU scenario, while for the (optimal) resource tax and quantity rationing, resource input is substituted by capital. The following partial equilibrium analysis indicates the inefficiency of the pure energy tax. Demand for energy E depends on energy price p_E and energy tax τ_E. To reach the mitigation goal the resource path R has to be changed by decreasing demand via taxes on p_E or p_R. With a CES technology in the energy sector, the ratio of factor inputs is characterized by

$$\frac{K_E}{R} = \left(\frac{\bar{p}_R}{r} \frac{a}{(1-a)}\right)^b, \tag{19}$$

with the elasticity of subsitution $b = \frac{1}{1-\sigma}$ (Arrow et al., 1961). That is, the ratio of factor inputs depends only on prices r and $\bar{p}_R$. An energy tax reduces energy demand E, and consequently demand for the inputs R and K_E in the energy sector as well. But the ratio of K_E/R remains unchanged because no changes in the prices r and p_R occur. Only for a diminishing elasticity of substitution b, the mis-allocation of the energy tax converges to zero because factor shares become independent from prices (see Fig. 3). In short, an energy tax has a volume effect, but no substitution effect in the

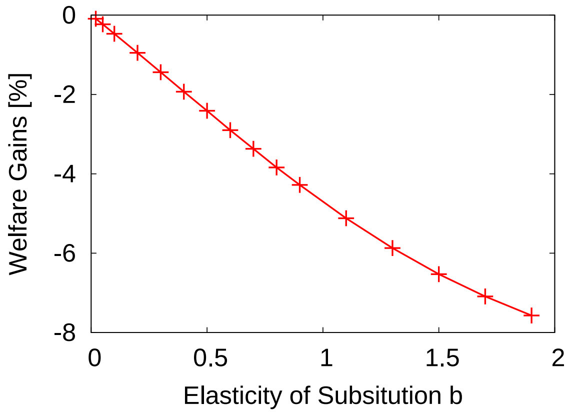

Figure 3: Welfare losses of energy tax relative to the social optimum.

energy sector. It is only capable of achieving a mitigation goal by reducing overall energy consumption. Profits in the resource sector are lower than for a resource tax since the economy grows at a lower pace and the volume effect reduces resource demand. On the other hand, additional transfer incomes are generated.

3.5. Sensitivity analysis

Most of the above effects do not change in principle when model parameters are changed. We performed further sensitivity analyses by varying substitution elasticities, the resource stock and the mitigation goal. Additional sensitivity analyses below investigate the volume of the additional rents generated by climate protection.

They confirm the expectation that for lower substitutability of resources in the energy sector, welfare losses 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 scarcity rent (for quantity rationing) and the transfer incomes (for taxes) increase.

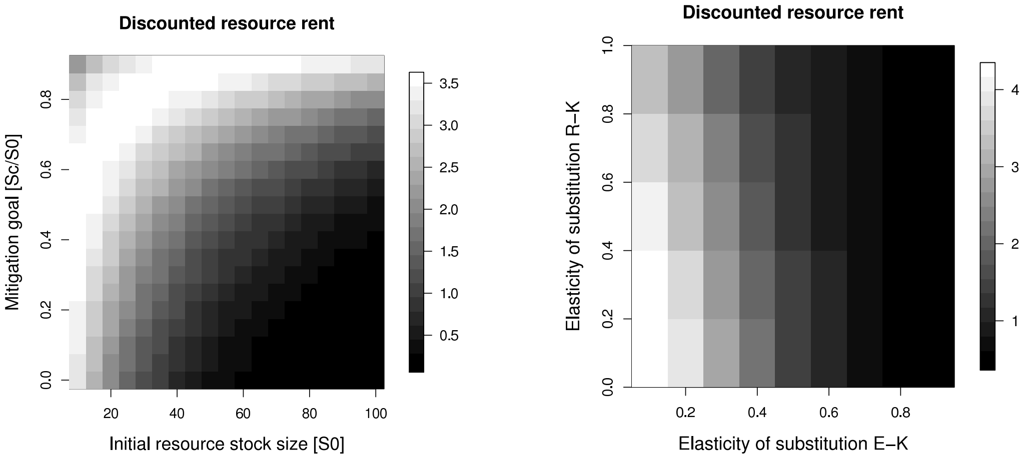

Figure 4: Resource rent with quantity rationing depending on (a) the initial resource stock and the mitigation goal (relative to the initial stock size) and (b) on the elasticieties of substitution for resources and energy.

4. Discussion

4.1. Robustness of the "climate rent"

We have seen that quantity rationing generates an additional resource scarcity rent—caused by a reduced resource stock available for extraction—that is paid as profits from the resource sector. If, alternatively, taxes are used as instrument, this rent is replaced by transfer incomes (see Fig. 2). Although the mitigation goal generally reduces welfare compared to the BAU case (note that there are no damages from climate change included in the model), there are some income types that benefit from climate protection. We therefore call this additional rent from climate protection the "climate rent". Its appropriation is a matter of instrument choice.

The volume of the climate rent substantially exceeds the resource rents in the BAU scenario for most numerical experiments. To assess whether this is more than a trivial consequence of a politically introduced scarcity, we performed a sensitivity analysis with different resource stocks and mitigation goals. Fig. 4a shows that with increasingly ambitous mitigation goals the resource rent increases up to a maximum, where it begins to decline sharply. Thus, in addition to scarcity, further effects have to be considered. When the amount of extractable resources is limited quite strongly, this has general equilibrium effects on growth. Reduced production can therefore lower resource demand and over-compensate the scarcity effect.

For better substition possibilities of fossil resources and energy with capital, the climate rent is smaller (Fig. 4b). In all model runs, however, the climate rent is greater than the resource rent in the BAU case, even if elasticities are near one.

4.2. Further policy instruments

4.2.1. Energy tax revisited

Seeing the inefficiency of a pure energy tax due to its missing substitution effect, it is interesting to know whether this can be corrected by combining it with a specific capital tax in the energy sector. This requires only straightforward modifications of the model: distinguishing net and gross interest rate in the energy sector, and introducing a new strategic variable for the government. This indeed leads to the socially optimal trajectory in our experiments. Capital in the energy sector is strongly subsidized but functional income distribution does not change. Given the optimal pure resource tax τ_R^*, the specific capital tax $\tau_{K_E}^*$ that leads to the same factor share K_E/R can be computed from Eq. (19), yielding $\tau_{K_E}^* = (1+\tau_R^*)^{-1} - 1$. Since $\tau_R^* > 0$, the tax $\tau_{K_E}^*$ has to be negative, and for high values of τ_R^* the capital tax converges to a 100% subsidy. The capital subsidy reduces the energy price, such that the energy tax has to compensate this effect.

4.2.2. Capital and labor taxes

If the energy tax combined with a specific capital subsidy can have a correcting effect, we may ask whether general capital and/or labor taxes without energy and resource charges can achieve this. This question provides a link to the established literature on taxation of capital and labour (e.g. Chamley, 1986; Judd, 1985). To keep the answer short, numerical experiments with simple modifications on the model show that neither a general capital tax nor a capital tax combined with a labour tax can achieve the mitigation goal in an efficient way. The combined tax leads to significant lower consumption and higher leisure. The mitigation goal can only be achieved at the cost of high welfare losses because these taxes fail to reallocate factor shares in an optimal way due to their unspecific nature.

4.3. Supply-side dynamics and the "green paradox"

When the supply-side dynamics of fossil resource extraction is considered, Sinn (2008) shows that climate policies may have adverse impacts on climate protection, coined as the “green paradox”. He suggests that increasing resource taxes, Pigouvian taxes and demand reducing policies are neither efficient nor effective. Since increasing taxes are anticipated by the resource sector, its intertemporal arbitrage condition is altered. Since the cumulative amount of resources extracted remains independent from the increasing tax, it would therefore accelerate the depletion of the resource stock—and thus global warming.

This work shows the importance of integrating the intertemporal incentive structure of resource supply into the policy analysis. It nevertheless contradicts our results, where a resouce tax is first-best. This is possible since the tax drives the shadow price of the resource to zero in the long run. Numerical calculations show that the supply-side dynamics is very sensitive to parameters like interest rates and tax growth rates. Increasing taxes do not always accelerate global warming(Kalkuhl and Edenhofer, 2009). A main difference to Sinn (2008) is that our model explicitly considers strategic interactions. The government as Stackelberg leader accounts for the reactions of the resource sector when the equilibrium tax path is determined.

5. Conclusions

We have investigated three different policy instruments to achieve a climate protection goal. The analysis was based on a combined Stackelberg-Nash differential game of different economic sectors that portrays government as a strategic actor. In a novel hybrid approach, algebraic reaction functions of the followers were combined with a numerical algorithm for the leader to efficiently compute optimal instruments. In contrast to a standard social planner model, this allows for explicitly computing prices, tax paths and changes in functional income distribution for instruments that are not *prima facie* first-best, and that depend on the strategic policy situation. In the case of an instrument that is capabable of achieving the mitigation goal, the model determines the optimal policy path automatically. We have shown, in particular, the following results.

The mitigation goal is achieved by a resource tax, an energy tax and by quantity rationing as well. Thus, in contrast to basic resource economic considerations, considering the supply-side dynamics of fossil resource extraction does not render climate policy ineffective. Differences between the instuments are in terms of their efficiency and their functional income distibution.

Resource instruments (taxes and rationing) are preferable to energy taxes, in particular if there are good substitution possibilities for resource input in the energy sector. To be efficient, the factor allocation needs to be optimal, as achieved by a resource tax and by resource rationing. In contrast, an energy tax only cause a volume effect on the output side, resulting in welfare losses.

The advantage of resource rationing over a resource tax—both being efficient—is its simplicity and less need for government interventions. The substantial informational requirements for an optimal resource tax are illustrated by Eq. (18). Differences to other instruments occur in the distribution of the "climate rent" that is induced by the mitigation goal.

For quantity rationing, the climate rent is paid as income from the resource sector. In contrast, price instruments collect the climate rent for re-distribution as transfer income. It is thus basically a matter of instrument choice which income types increase, leaving an additional degree of freedom. As this can be made without market distortions, there are many possibilities to compensate for welfare losses or to reduce existing taxes. This may open up new negotation paths for international agreements for climate protection. On the other hand, this indicates conflict potential due to rent seeking behaviour.

We think that a game theoretic analysis as presented in this paper will provide further novel insights for climate policy as it addresses the strategic and incentive structure of economic actors. The integrated policy assessment model provides a consistent framework to determine optimal and second-best policy instruments.

Appendix A. Complete model specification

Appendix 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

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

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

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 $-\Gamma = \tau_E p_E E + \tau_R p_R R$, 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 model solution

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). By 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. (11) is derived in analogy to the social planner case Eq. (9) by equating shadow prices.

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

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

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

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. (14). Due to possible quantity rationing, the transversality condition is $0 = \lim_{t\to\infty} \lambda_R(s - s_c)e^{\int_0^t(-r+\delta)d\xi}$.

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

$$f'_{k_Q} = (1 + \tau_E)f'_E g'_{k_E}. \tag{B.6}$$

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

$$f'_{k_Q} = h'_{k_R}\big(\frac{f'_E g'_R}{(1 + \tau_E)(1 + \tau_R)} - \lambda_R\big). \tag{B.7}$$

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

Appendix C. Numerical implementation

The time-continuous differential Stackelberg game is transformed to a discrete one with finite time horizon. The discrete maximum principle is used to determine 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 as analytical contraints.

Production is expressed by a nested CES-technology

$$f(k_Q, L, E) = (a_1 z^{\sigma_1} + (1 - a_1)E^{\sigma_1})^{(1/\sigma_1)}, \tag{C.1}$$

$$z(k_Q, L) = (a_2 k_Y^{\sigma_2} + (1 - a_2)L^{\sigma_2})^{(1/\sigma_2)} \tag{C.2}$$

with z being a composite of capital and labor (cf. van der Werf, 2007) and $\sigma_1, \sigma_2 < 0$, such that production factors are essential. Energy is produced by a CES technology with $\sigma < 0$ (cf. Edenhofer et al., 2005),

$$g(k_E, R) = (ak_E^{\sigma} + (1 - a)R^{\sigma})^{(1/\sigma)}, \tag{C.3}$$

i.e. capital and fossil resources are essential factors as well. As these are constant returns-to-scale technologies, profits π_P, π_E vanish.

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

$$h(k_R, s) = c(s)k_R, \quad c(s) = \frac{\chi_1}{\chi_1 + \chi_2 \left(\frac{s_0 - s}{\chi_3}\right)^{\chi_4}}. \tag{C.4}$$

Household and government utility are defined by

$$u(C, L) = ln(C) + ln(L_{max} - L), \tag{C.5}$$

where L_{max} is total available labor.

The time horizon for numerical calculation is set to 150 years. In order to avoid distraction of our analysis by dissaving effects at the end of the time horizon, we restrict our analysis to the first 120 years. Substitution elasticities are in typical ranges used in the literature (see van der Werf, 2007; Edenhofer et al., 2005) and are partially varied for sensitivity studies. The time preference rate is set to 3% per annum. Capital intensity for resource extraction is parameterized such that it falls from 1 to 0.65 when $\underline{s} = 0$. Compared to cumulative resource extraction in this case, the initial resource stock is set to 100 units, and the mitigation goal is set to 25% of the cumulative resource extraction in the case without any instruments (except for sensitivity analyses).

Appendix D. Efficiency proof of resource rationing

It has to be shown that the market solution for quantity rationing meets the first-order conditions of the social planner solution. We (i) show that certain *assumed* shadow prices from the market model with quantity rationing imply efficient paths for the decision variables. It can then (ii) be seen, that the assumed shadow prices actually follow the costate equations. First assume that the social shadow price of the resource $\lambda_s \equiv \lambda_H \lambda_R$ (the right-hand side from the market model), and that the social shadow price of capital $\lambda_k \equiv \lambda_H$. It is obvious from Eq. (7) and Eq. (B.1) that this indeed leads to the same values for C and L. Capital allocation is also identical in the market and the social planner model (note that $\tau_E = \tau_R = 0$ for quantity rationing): For the market, by the definition of $\tilde{f}$ Eq. (6), it follows from Eq. (B.6) that

$$\tilde{f}'_{k_Q} = f'_{k_Q} = f'_E g'_{k_E} = \tilde{f}'_{k_E}, \tag{D.1}$$

and from Eq. (B.7) that

$$\tilde{f}'_{k_Q} = f'_E g'_{k_E} h'_{k_R} - \lambda_R h'_{k_R} = \tilde{f}'_{k_R} - \frac{\lambda_s}{\lambda_k} h'_{k_R}. \tag{D.2}$$

Hence, the social planner condition Eq. (9) holds. The transversality conditions are identical by substitution as well. The resource stock develops equally in both cases because the extraction path is solely determined by the identical allocation of k_R. Therefore, the shadow prices assumed for the social planner model produce the same time path as the market model. It remains to show that these shadow prices actually obey the costate equations of the social planner model. Showing that indeed $\hat{\lambda}_H + \hat{\lambda}_R \equiv \hat{\lambda}_s$ can be confirmed as follows. By the costate equations of the market model Eq. (B.5), Eq. (B.1) and the price equations Eq. (B.2), Eq. (B.3), it holds that

$$\hat{\lambda}_H + \hat{\lambda}_R = \rho + h'_s - \frac{p_R}{\lambda_R} h'_s = \rho + h'_s - \frac{\lambda_H}{\lambda_s} f'_E g'_R h'_s = \rho + h'_s - \frac{\lambda_k}{\lambda_s} \tilde{f}'_s, \tag{D.3}$$

where the last equation is true by definition of $\tilde{f}$ in Eq. (6). Due to Eq. (8), this expression is identical to $\hat{\lambda}_s$. Consequently, quantity rationing yields an efficient allocation in the presence of a mitigation goal.

Appendix E. Efficiency proof of resource tax

The resource tax is socially optimal if all system variables equal those of the socially optimal quantity rationing, except for p_R and λ_R. Substituting the values of quantity rationing in Eq. (B.4) yields $r^* = (p_R - \lambda_R) h'^*_{k_R}$. By Eq. (B.3) this transforms to

$$1 + \tau_R = \frac{p^*_R}{\frac{r^*}{h'^*_{K_R}} + \lambda_R}. \tag{E.1}$$

Given the solution for λ_R from Eq. (B.5) and Eq. (16), the resource tax is determined explicitly for every instant t. This is sufficient to reach the social optimum of the RED scenario as all other variables and first-order conditions equal those of quantity rationing.

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