

Franks, Max; Lessmann, Kai

Conference Paper

Tax competition with asymmetric endowments in fossil resources

Beiträge zur Jahrestagung des Vereins für Socialpolitik 2019: 30 Jahre Mauerfall - Demokratie und Marktwirtschaft - Session: Environmental Economics II, No. A16-V2

Provided in Cooperation with:

Verein für Socialpolitik / German Economic Association

Suggested Citation: Franks, Max; Lessmann, Kai (2019) : Tax competition with asymmetric endowments in fossil resources, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2019: 30 Jahre Mauerfall - Demokratie und Marktwirtschaft - Session: Environmental Economics II, No. A16-V2, ZBW - Leibniz-Informationszentrum Wirtschaft, Kiel, Hamburg

This Version is available at:

<https://hdl.handle.net/10419/203560>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

Tax competition with asymmetric endowments in fossil resources

Max Franks^{*†‡} Kai Lessmann^{*}

February 6, 2019

Abstract

This paper contributes to the theoretical understanding of strategic interactions of governments on global factor markets. We analyze carbon taxes and subsidies and their impact on national welfare in a fiscal federalism setting with international markets for capital and fossil resources, and asymmetric resource endowments. We have four contributions. First, we show that resource poor countries have an incentive to tax the use of fossil fuels to appropriate the resource rent. Resource rich countries subsidize fossil fuel use to attract production factors in order to increase national income. Second, we demonstrate that capital mobility has a taming effect on the incentives to tax and to subsidize resources. When taxing resources not only affects the international resource market, but also the international capital market, taxation is more distortionary and is thus more costly to governments. Third, while other studies of asymmetric tax competition find that small countries in terms of population are winners of tax competition, we show that with asymmetric resource endowments but a symmetric population size, there are no winners. Then, the Nash equilibrium of carbon tax competition is the least desirable outcome in terms of social welfare. A game structure similar to a Prisoner's Dilemma emerges. Fourth, we characterize the option space for Pareto improvements over the Nash equilibrium.

Keywords: Tax competition · capital mobility · strategic instrument choice · carbon pricing · capital tax

JEL Classification: F20 · H23 · Q37 · Q38 · R13

^{*}Potsdam Institute for Climate Impact Research (PIK), Member of the Leibnitz Association, P.O. Box 60 12 03, D-14412 Potsdam, Germany.

[†]Berlin Institute of Technology

[‡]Corresponding author: franks@pik-potsdam.de

1 Introduction

Absent a world government, there is an urgent need for national policies that address global problems such as climate change, stymied growth due to the resource curse, and sustainable development on the national level. Accordingly, the architecture of the Paris Climate Agreement and the Agenda 2030 for Sustainable Development, as well as the conclusions of the 2015 conference in Addis Ababa on finance for sustainable development emphasize the role of national policies. National policies, however, do not leave foreign states unaffected. Low capital taxes may, for example, attract highly mobile capital from abroad triggering foreign policy responses. Asymmetric factor endowments may give rise to beneficial terms-of-trade effects, but also to strategic rent appropriation via carbon taxation. Knowledge about these strategic interactions of governments and their incentives to respond to foreign policies is therefore crucial for sound policy design.

This paper contributes to the theoretical understanding of strategic interactions of governments on global resource- and capital markets. We analyze different tax policies and their impact on national welfare in a fiscal federalism setting with international markets for capital and fossil resources.

Capital mobility has been shown to cause a negative fiscal externality (Zodrow and Mieszkowski, 1986), but also to induce beneficial terms-of-trade effects if country asymmetries are taken into account (Bucovetsky, 1991; Schwerhoff and Edenhofer, 2013). Recently, the standard model of capital mobility and capital tax competition has been extended to include fossil resources as a second mobile factor of production (Franks et al., 2017; Habla, 2016; Ogawa et al., 2016). Even though countries world-wide differ quite strongly in their endowments with fos-

oil resources, only little is known about the implications of such asymmetries for the strategic behavior of governments when capital markets are taken into account. It is well known that resource-importing countries can implement carbon taxes strategically to appropriate a certain fraction of the exporters' resource rent (Karp, 1984; Amundsen and Schöb, 1999; Liski and Tahvonen, 2004). However, in this strand of literature, capital markets have not been taken into account.

We fill the gap by systematically assessing the strategic use of carbon taxes on international capital and resource markets, and the impact of asymmetries in resource and capital endowments. We thus implement a dynamic two-country model similar to Franks et al. (2017). It is based on the workhorse model of Zodrow and Mieszkowski (1986), and combines a Ramsey growth model with the Hotelling model of resource extraction (see also Kalkuhl et al., 2012, for a closed economy version of the model). To isolate the strategic incentives of governments concerned with the medium-run, we abstract from environmental externalities.

In this paper, we make four contributions to the analysis of tax competition on capital and fossil resource markets with asymmetric resource endowments. First, we analyze the strategic incentives to implement carbon taxes and subsidies. Resource rich and resource poor countries have different incentives. Absent any taxation, international factor mobility implies that resources have to flow to the resource poor country and capital has to flow to the resource rich country. This follows from the assumption that there is only one international factor price (interest rate and resource price), which has to equal the marginal product of the respective factor, capital and fossil resources. Given the possibility to tax, there are two channels by which both countries engage in strategic interactions. The first is the price-channel, the second the factor-channel. Using the price-channel,

the resource poor country tries to appropriate the resource rent by taxing domestic resource use. The government of the resource rich country tries to counter this attempt at influencing the resource price by subsidizing domestic use of resources. Using the factor channel, the resource rich country tries to attract more resources and – due to complementarity in production – more capital. An inflow of both factors, compared to the no-tax-case, increases national income, in particular also labor income (assuming that the marginal product of labor increases with increasing capital or resource use). The latter channel can be exploited by the resource rich country, but for the resource poor country it induces a trade-off. By increasing the carbon tax the resource poor country can appropriate more of the resource rent, but at the same time it causes an outflow of mobile factors abroad and hence a reduction of national income, in particular labor income.

Our second contribution is to show what difference it makes when international capital markets and capital taxes are included explicitly. If capital cannot move freely on an international market, the factor channel becomes less important. Then, a resource poor country can tax carbon more heavily and thus appropriate more of the resource rent. It does not have to fear the outflow of capital. The resource rich country can only attract one type of production factor and thus subsidizes domestic resource use more than under capital mobility. Comparing the cases of mobile with fixed capital shows that international integration of capital markets can have a substantial impact on the strategic use of carbon taxes. Going from nationally segmented capital markets to international capital mobility changes average tax rates on an order of magnitude of 10 to 100% in our standard calibration. Moreover, it turns out that this result is robust with respect to the availability of capital taxes.

Our third contribution is the finding that a game structure emerges that stands in contrast to the seminal finding of Bucovetsky (1991). In his model, the population-wise small country is better off under capital tax competition than under a cooperative solution. In that case, small countries will oppose any form of tax harmonization. Including an international market for fossil resources, though, changes the picture. We show that a “small” country – in the sense that it is relatively resource poor instead of having a small population – is worse off under carbon tax competition than under cooperation.

Finally, we show that there are possibilities for Pareto improvements over the Nash equilibrium in carbon taxes.

The remainder of the paper is structured as follows. In Section 2 we describe the model. In Section 3 we describe our results. In Section 4 we discuss the robustness of our results with respect to alternative assumptions about the model structure. We conclude with Section 5.

2 The model

We implement a differential game based on a Ramsey-type general equilibrium growth model. There are two countries, each populated by an identical set of representative economic agents: a household, a final goods producing firm, and a fossil resource extracting firm. We depart from the model in Franks et al. (2017) in two respects. First, we abstract from infrastructure. Taxation is thus used only to strategically distort the market allocation. Second, we allow for asymmetric endowments with fossil resources in situ. As a convention, we will always assume that country 1 is the resource poor country and country 2 is the resource rich

country, whenever endowments are asymmetric.

2.1 International markets

The countries are labeled by the index $j \in \{1, 2\}$. They are linked by the international markets for capital and fossil resources. We distinguish between the final goods producing firms' demand for capital $K_{j,t}^d$ and resources $R_{j,t}^d$ at time t , household's capital assets, that is, the capital supply $K_{j,t}^s$, and the extracting firm's supply of resources $R_{j,t}^s$ and demand for capital $K_{j,t}^R$, which they require to extract the resource. Households own only the domestic firms (final goods and extraction sector) but rent out their accumulated capital and sell the fossil resource to any firm, domestic or abroad. Renting capital to a firm abroad does not afford them any ownership claims abroad, and we assume that capital and resources move around until the prices for each factor are equal in all countries. Thus, the international capital market is described by

$$K_{1,t}^s + K_{2,t}^s = K_{1,t}^d + K_{1,t}^R + K_{2,t}^d + K_{2,t}^R \quad \forall t, \quad (1)$$

$$r_{1,t} = r_{2,t} = r_t \quad \forall t, \quad (2)$$

where r is the interest rate. For the resource market and the price of fossil resources p , we have

$$R_{1,t}^s + R_{2,t}^s = R_{1,t}^d + R_{2,t}^d \quad \forall t, \quad (3)$$

$$p_{1,t} = p_{2,t} = p_t \quad \forall t, \quad (4)$$

Labor is significantly less mobile than capital or fossil resources. Thus, we assume in our model that labor is fixed in supply and may not move across country borders. A further market for final goods is not included as we assume that there is only one final goods producing sector. Firms pay the households and resource owners with their output of the final good.

2.2 Agents of the national economy

A large number of households live in each of the two countries. Output is produced by a large number of competitive firms which use labor, private capital, and fossil resources as inputs to produce a homogeneous final consumption good. The two countries are endowed with differing stocks of fossil resource, thus the firms in the resource poor country have to import them. Fossil resources are extracted in both countries by a large number of resource owners who sell them on the international resource market to the firms in the two countries.

The government of the two countries influence the economy by implementing policy instruments. They are assumed to have perfect knowledge of all agents' objectives and their reactions to the policy instruments, that is, they act as Stackelberg leaders. The following optimization problems characterize the individual economic agents' behavior. Their respective first order conditions can be found in the appendix.

The representative household. The representative household in country j derives instantaneous utility from per capita consumption according to the constant

intertemporal elasticity of substitution (CIES) utility function

$$U(C_{j,t}/L_t) = \frac{(C_{j,t}/L_t)^{1-\eta}}{1-\eta}, \quad (5)$$

where $1/\eta$ is the intertemporal elasticity of substitution, $C_{j,t}$ denotes aggregate consumption in country j at time t , and L_t is labor. The supply of labor is given exogenously and we assume it is equal in the two importing countries.

To improve readability, we will omit the country index j in the description of the household, the firms in the final goods sector and the resource extraction sector, and the government. The household maximizes its welfare W subject to the budget constraint (7) and the equation of motion of the capital it supplies, K^s (8).

$$\max_{C_t/L_t} W = \sum_{t=0}^T U(C_t/L_t) \left(\frac{1}{1+\rho} \right)^t \quad (6)$$

$$\text{s.t.} \quad C_t + I_t = r_t K_t^s + w_t L_t + \Pi_t^F + \Pi_t^R + \Gamma_t \quad (7)$$

$$\text{and} \quad K_{t+1}^s = K_t^s(1-\delta) + I_t. \quad (8)$$

The capital stock depreciates at the annual rate δ . The household in country j discounts future utility according to its pure rate of time preference ρ . It rents out the capital that it supplies, K^s , on the global capital market and earns income according to the world interest rate r . Further, the household receives labor income according the exogenously given time path of labor and the endogenously determined wage rate w . The profits of the final goods firm Π^F and the resource extracting firm Π^R accrue to the household. The government may use tax revenue

for lump sum transfers $\Gamma \geq 0$ to the household.

The final goods production sector. The representative firm is assumed to be a price taker. Its output is given by a neoclassical production function, which depends on three input factors – capital, labor, and fossil resources, denoted by $Y = F(K^d, L, R^d)$. For our calculations we use a nested constant elasticity of substitution (CES) function. On the lower level, private capital K^d , which the firm may demand on the global capital market, is combined with labor. On the upper level, fossil resources R enter in production. The production function takes the form

$$F(K_t^d, L_t, R_t^d) = [\alpha_1(A_{R,t}R_t^d)^{s_1} + (1 - \alpha_1)\mathbf{X}(K_t^d, L_t)^{s_1}]^{\frac{1}{s_1}}, \quad (9)$$

where $\mathbf{X}(K_t^d, L_t) = [\alpha_2(K_t^d)^{s_2} + (1 - \alpha_2)(A_{L,t}L_t)^{s_2}]^{\frac{1}{s_2}}$.

The exponents s_i , $i = 1, 2$, are determined by the respective elasticities of substitution σ_i via $s_i = \frac{\sigma_i - 1}{\sigma_i}$. We assume $\sigma_1 < 1$,¹ and for the share parameters it holds that $\alpha_i \in (0, 1)$, $i = 1, 2, 3$. $A_{\zeta,t}$ is the productivity of the factor $\zeta = R, L$. The production technology (9) exhibits constant returns to scale in all inputs.

The firm produces output with the technology given by (9), rents capital at the market interest rate r_t , pays workers their wage w_t , and pays the price p_t for the fossil resources it uses in each period. In addition, we assume that it may have to pay corporate taxes, which we approximate by an ad valorem tax on capital τ_K , or a source based carbon tax τ_R , to the government. The firm's objective is to

¹See Franks et al. (2017) for more details on the calibration and choice of model parameters.

choose the amount of capital, labor, and fossil resources it demands in each period which maximizes profit for all points t in time,

$$\max_{K^d, L, R^d} \pi^F = F(K^d, G, L, R^d) - r(1 + \tau_K)K^d - wL - (p + \tau_R)R^d.$$

Differentiation with respect to K , L , and R yield the three first order conditions, which equate the marginal product of the private input factors with their respective after-tax prices:

$$F_K = r(1 + \tau_K) \tag{10}$$

$$F_L = w \tag{11}$$

$$F_R = p + \tau_R \tag{12}$$

The fossil resource sector. Each country j is endowed with an exhaustible stock of a fossil resources of S_j gigatons of carbon, owned by a representative extraction firm. The firm extracts the stock at the annual rate of R_t^s using capital K^R . Thus, we have

$$S_{t+1} = S_t - R_t^s \tag{13}$$

$$\text{and } R_t^s = \kappa(S_t)K_t^R \tag{14}$$

where $\kappa(S_t)$ decreases as more of the resource is extracted (we use the same calibration as in Kalkuhl et al., 2012). The firm sells the resource on the international

market to maximize the net present value (NPV) of profits,

$$\max_{R_t^s} \sum_t \pi_t^R \Pi_{s=0}^t (1 + r_s - \delta)^{-1}, \quad (15)$$

$$\text{where} \quad \pi_t^R = p_t R_t^s - K_t^R r_t \quad (16)$$

The government. The firms, the resource owners, and the households take all taxes as given. In the market equilibrium of the decentralized economy, the government acts as Stackelberg leader. It optimizes the representative household's welfare by choosing the tax paths.

The government anticipates the general equilibrium response of the economy. It takes into account all first order conditions, budget constraints, terminal conditions, etc. from the other agents' optimization problems when deciding on the tax paths. The government distributes the tax revenue to the domestic households as lump sum transfers. The government's problem thus reads

$$\begin{aligned} \max_{\tau_K, \tau_R} \quad W &= \sum_{t=0}^T L_t U(C_t/L_t) \left(\frac{1}{1 + \rho} \right)^t \\ \text{s.t.} \quad \Gamma_t &= r_t \tau_{K,t} K_t^d + \tau_{R,t} R_t^d \end{aligned}$$

and Equations (1) - (4), (7), (8), (10) - (13), and (22) - (27).

2.3 Equilibria of the economy

The overall allocation of economic resource for production can be determined either under the assumption of a social planner, or a decentralized market economy. In the latter case, the governments in the two countries can either compete and use

their policy instruments to maximize their domestic household's utility – or, the two governments can cooperate in choosing their policy instruments to maximize the sum of both households utility. In all cases, we frame the optimization problem as a non-linear program and solve the economy using the GAMS software (Brooke et al., 2005). The GAMS code is available from the authors upon request. In the following, we describe each equilibrium concept individually.

Social planner equilibrium. The social planner solves the optimization problem

$$\begin{aligned} \max_{C_{j,t}, I_{j,t}} \quad & W = \sum_{j=1,2} \sum_{t=0}^T L_{j,t} U(C_{j,t}/L_{j,t}) \left(\frac{1}{1+\rho} \right)^t \quad (17) \\ \text{s.t.} \quad & F(K_{j,t}^d, L_{j,t}, R_{j,t}^d) = C_{j,t} + I_{j,t}, \end{aligned}$$

clearing of the international capital and resource markets (1) and (3), the production technologies of final goods and fossil resources (9) and (14), and the equations of motion of the stocks of capital (8) and resources (13).

Nash equilibrium. The solution algorithm is described in the appendix (Section E), the program code is contained in the supplementary material.

All economic agents except the governments take the strategies of the other agents as given. Governments have an advantage, as they are assumed to be Stackelberg leaders and may move first. They anticipate the reactions of the firms in both sectors and households. We assume that governments can commit to the

policies they announce.²

Each country's government faces its local agents and anticipates their reaction, that is, it acts as a Stackelberg leader here. We further assume that the government also anticipates the reactions of each foreign household, firm, and the resource owner. This makes the government a Stackelberg leader of all firms and households, both domestic *and* foreign.

At the same time, one country's government also faces the other country's government, a Stackelberg leader of the global economy as well.³ Thus, governments sit at two game tables – here a Stackelberg and there a simultaneous move game. In the former sub-game, the governments have to make decisions about how to influence the behavior of private actors through influencing prices (rental rate of capital, resource price). In the latter, all governments can interact strategically with each other through the choice of policy instruments.

Each government takes the strategies of the other government as given when choosing its own strategy. In doing so, it anticipates the international movement of capital and fossil resources, but also the behavior of domestic and foreign households, firms, and resource owners in response to the policy instrument choice.

More formally, the objective of the government in country j is to maximize its payoff, that is, its welfare W_j . The strategies of the governments are $\{\tau_{\zeta,t}^j\}$ where $t \in \{1, \dots, T\}$ and $\zeta \in \{K, R\}$. Each government takes as given the other

²Due to the Stackelberg structure of the game, at least in theory time inconsistencies could arise. However, we have checked whether governments have an incentive to deviate from the initially announced tax paths and found no significant deviations (see Franks et al. (2017) for more details).

³Strictly speaking, the national governments are only Stackelberg leaders of the subgame in which they determine their own policy instruments optimally, taking the other governments' policy instruments as given and taking the reactions of all other economic agents into account. In the present study the term Stackelberg leader always refers to this specific meaning.

government's strategies.

The cooperative solution. The Stackelberg game structure described above remains the same, both in the non-cooperative and the cooperative solution. In contrast to non-cooperation, though, we obtain the cooperative solution by calculating those policies $\{\tau_{\zeta,t}^j\}$, where $j = 1, 2$, $t \in \{1, \dots, T\}$, and $\zeta \in \{K, R\}$, that maximize the joint welfare of both importing countries,

$$\begin{aligned} \max_{\{\tau_{\zeta,t}^j\}_{j,\zeta,t}} \quad & W = W_1 + W_2. \\ \text{s.t.} \quad & \Gamma_{j,t} = r_t \tau_{K,t}^j K_{j,t}^d + \tau_{R,t}^j R_{j,t}^d \end{aligned} \tag{18}$$

and Equations (1) - (4), (7), (8), (10) - (13), and (22) - (27).

Social welfare. To evaluate the outcomes of different policy scenarios, we compare each scenario with the social planner's solution. In particular, we follow Kalkuhl et al. (2012) and express the welfare loss of a policy scenario relative to the social optimum in balanced growth equivalents (BGE welfare losses) as introduced by Anthoff and Tol (2009). For an explanation, see the appendix.

3 Results

We present our four main results in the following. We begin by describing the incentives of resource poor and resource rich countries to use carbon taxes and subsidies strategically (Section 3.1). In particular, we also explain the impact of capital mobility on our results by comparing scenarios in which capital is mobile with scenarios without capital mobility. Then, in Section 3.3, we discuss the game structure in terms of payoffs to different strategies and we show the Pareto frontier for the social planner solution and for the decentralized market economy. The latter determines the scope for Pareto improvements over the Nash equilibrium in carbon taxes, which turns out to be the least desirable outcome in terms of social welfare.

3.1 Strategic incentives to use carbon taxes when capital and resources are mobile

Our first result is that the more asymmetric resource endowments are, the more the resource poor country (by our convention country 1) has an incentive to raise a positive carbon tax on domestic production, and the more the resource rich country (country 2) has an incentive to subsidize domestic use of fossil resources (Figure 1).

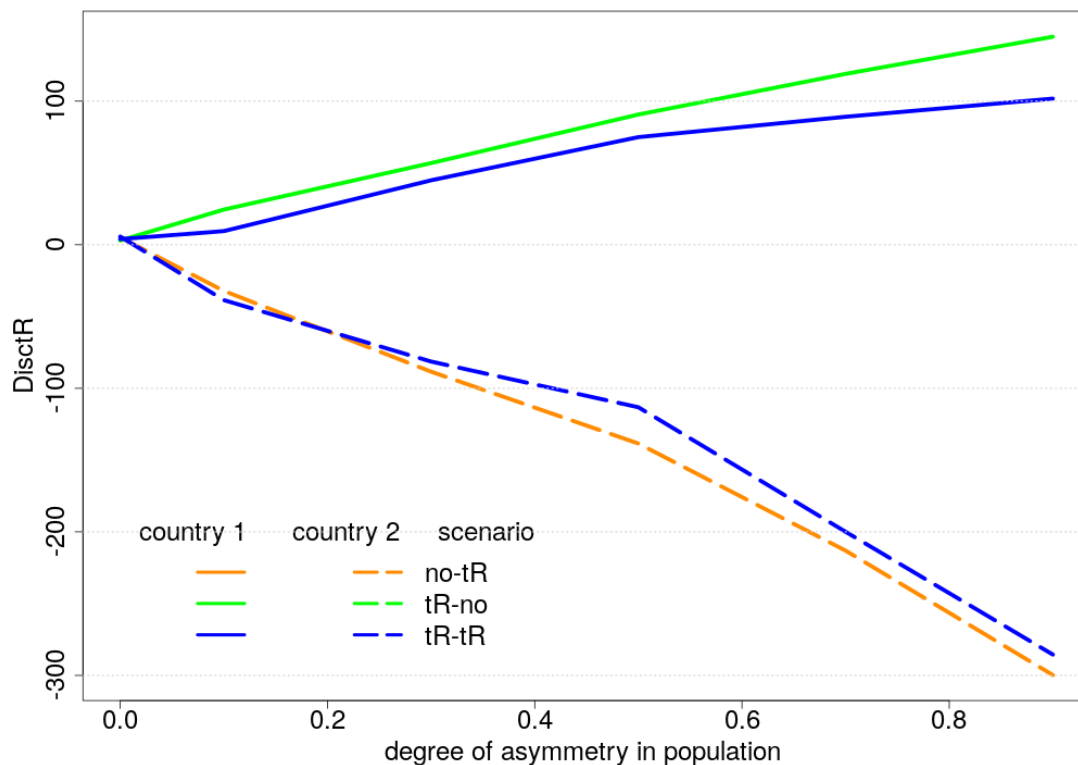


Figure 1: Net present value (NPV) of carbon tax revenues in each country [10^{12} US\$] as function of the degree of asymmetry in resource endowments ϕ : Let total endowments be S_0 , then we vary $\phi \in (0, 1)$ to determine the endowments S_j , $j = 1, 2$, according to $S_j = \frac{S_0}{2} [(1 - \phi) + 2(j - 1)\phi]$. If both countries can use carbon taxes (blue lines), the resource rich country subsidizes resources and the poor country taxes resources. If only the resource rich country may use the carbon tax (red dashed line), it subsidizes even more. Similarly, if only the resource poor country may use the carbon tax, it raises even higher taxes.

Incentives of the resource poor country. The resource poor country implements a positive carbon tax in order to appropriate a part of the resource rent that otherwise accrues to the resource rich country. In particular, increasing the carbon tax rate lowers the global net-of-tax price of the fossil resource, and raises the consumer price for the domestic firms in the resource poor country. The carbon

tax drives a wedge between gross and net price. To the extent that the net price is pushed below the initial net price level, the resource poor country appropriates resource rents, which would belong to the resource rich country if the resource poor country would not raise the tax (we explain this in detail in the Appendix using Figure B.1).

However, for the resource poor country, an increase of its carbon tax also implies a shift of capital and resources away from domestic production towards production abroad (Figures B.2 and B.3). Hence, national income decreases, in particular also labor income. The government of the resource poor country chooses the optimal carbon tax rate. It considers the trade-off between appropriating the rent and pushing mobile production factors out of the country.

We illustrate the resource poor country's trade-off associated with small unilateral changes in the carbon tax in Table 1. To obtain the results, we assume that the resource rich country owns 95% of all resource. The table shows data for a scenario in which only the resource poor country may implement taxes and the resource rich country's government does not react. While increasing the tax also increases the resource rent appropriated, at the same time, it drives out production factors, reduces labor income, and ultimately reduces consumption. As benchmark, we use the resource poor country's optimal carbon tax path $\{\tau_{R,t}\}_{t=0,\dots,T}$. Subsequently, we calculate the equilibria for several variations of that optimal carbon tax path. More precisely, we vary the tax path exogenously by multiplying it with one time independent constant ξ , yielding $\{\xi\tau_{R,t}\}_{t=0,\dots,T}$, where we choose $\xi \in [0.5, 2]$. Moreover, the higher the carbon tax, the lower is the fraction of the appropriated rent in total tax revenues, as Figure 2 shows.

ξ	τ_R	π_R	Y^K	Y^L	C	I
0.5	79	17	992	1776	2416	447
0.75	113	16	985	1746	2417	443
1.0	145	16	978	1717	2416	440
1.5	201	15	968	1661	2410	435
2.0	248	14	960	1608	2399	431

Table 1: An exogenous variation of the carbon tax path around the optimum ($\xi = 1$) reveals the trade-off the government in the resource poor country faces. The table shows the net present value (NPV) of the different components of the national budget of the resource poor country: carbon tax revenues, resource sector profits, capital income, labor income on the income side, and consumption and investments on the expenditure side. The NPV of consumption doesn't peak exactly at $\xi = 1$ because the government does not maximize consumption itself, but rather the NPV of utility, which is a non-linear function of consumption.

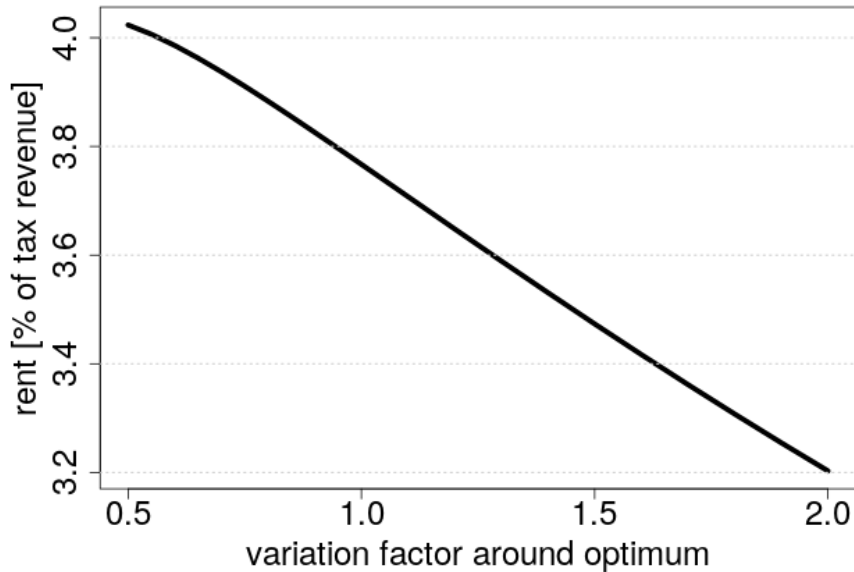


Figure 2: Appropriated rent as fraction of total carbon tax revenue in the resource poor country for a policy scenario in which only the resource poor country implements its optimal carbon tax. Here, we assume that the resource rich country owns 95% of all resource. On the x-axis, we vary the constant factor ξ by which we multiply the optimal carbon tax. For example, in case the resource poor country implements its optimal tax, we have $\xi = 1$ and the appropriated resource rent makes up about 3.7% of total carbon tax revenue.

Incentives of the resource rich country. The resource rich country subsidizes the use of fossil resource in production (cf. Figure 1) to attract production factors on the international factor markets. The inflow of mobile production factors increase labor income due to complementarity. However, it also makes extraction within the resource rich country more attractive. An increase in domestic extraction activity implies that more capital is needed in the resource sector. Accordingly, in the resource rich country, both capital demand by the final goods firm and by the resource extracting firm increase. However, the relative share of capi-

tal employed in the final goods sector decreases, and it increases in the extracting sector. In choosing the optimal subsidy, the government faces a trade-off. It takes into account that increasing the subsidy increases the use of factors in domestic production and hence increases labor income. On the other hand, the subsidies also raise the costs of resource extraction κ , which are a convex function of cumulative extraction – cf. Equations (14) and (21). The government also takes into account that the subsidy distorts the households’ intertemporal savings decisions.

To illustrate the impact a subsidy in the resource rich country has, we exogenously vary the optimal path of the subsidy by a constant factor $\zeta \in [0.5, 2]$.⁴ Table 2 and Figure 3 illustrate the consequences of deviating from the optimal path: Doubling the optimal subsidy rate implies an increase in the net present value of the profits the resource extracting firm makes. While also capital and labor income increase, the increase in total income is not enough to offset the consumption losses associated with the increase of the subsidy. The additional income is not used for consumption, but rather for increased investment necessitated by the increased use of fossil resources. Accordingly, the share of total capital used for resource extraction increases and the share of capital used in the final goods sector decreases (Figure 3).

⁴As benchmark case, we assume that only the resource rich country may implement its optimal subsidy path $\{\tau_{R,t}\}_{t=0,\dots,T}$. Subsequently, we vary the subsidy path exogenously by multiplying it with one time independent constant ζ , yielding $\{\zeta\tau_{R,t}\}_{t=0,\dots,T}$, where we choose $\zeta \in [0.5, 2]$.

ζ	τ_R	π_R	Y^K	Y^L	C	I
0.5	-130	418	1182	1920	2815	575
0.75	-209	449	1211	1962	2821	594
1.0	-298	486	1247	2004	2823	616
1.5	-512	577	1336	2085	2813	673
2.0	-778	696	1453	2157	2781	747

Table 2: An exogenous variation of the optimal subsidy path indicates the trade-off the government in the resource rich country faces. NPV of carbon tax revenues, profits of the resource extracting firm, investments, capital income, labor income and consumption.

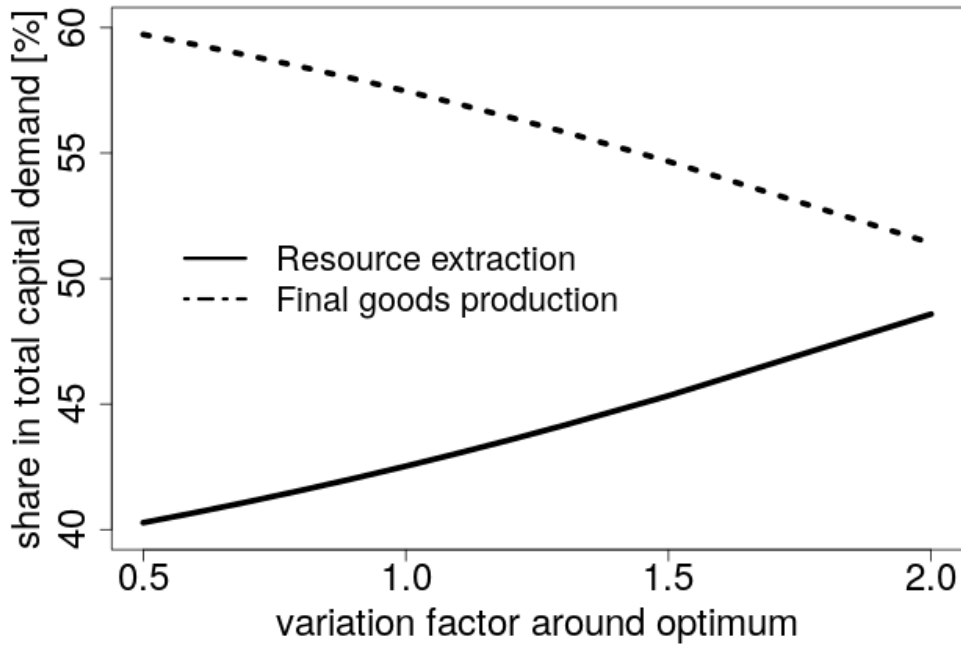


Figure 3: As the resource rich country increases its subsidy, relatively more capital is used for extracting the fossil resource and a smaller share is employed in the production of final goods.

3.2 How do capital mobility influence the strategic use of the carbon tax?

A key contribution of the present paper is to quantify the impact of capital mobility on the optimal carbon tax. Therefore, we compare policy scenarios featuring capital mobility with policy scenarios featuring internationally immobile capital, *ceteris paribus*. Moreover, we also show that the availability of capital taxes only has a minor impact on the optimal carbon tax. In all scenarios considered in the present Section 3.2, we assume that the resource poor country owns 5% of all fossil resources and the resource rich country possesses 95%, as in the preceding section.

Table 3 reports data for scenarios in which only one of the two countries' governments can implement its optimal carbon tax. We observe that capital mobility has a taming effect on the optimal unilateral policies. Without international capital trade, both governments choose higher taxes and subsidies, respectively.

Scenario		$\tau_{R,1}$ (NPV)	$\tau_{R,2}$ (NPV)	$\tau_{R,1}$ (rate)	$\tau_{R,2}$ (rate)
τ_R - no	capital mobile	145	0	396	0
	capital immobile	157	0	542	0
no - τ_R	capital mobile	0	-294	0	-526
	capital immobile	0	-425	0	-827

Table 3: Net present value of carbon tax revenues [tril. US\$] and average carbon tax rate [\$/tC] for different policy scenarios under the assumption that the resource poor country (Country 1) owns 5% of all resources and the resource rich country (Country 2) owns 95%.

If capital is mobile internationally, then a marginal increase in the carbon tax rate in the resource poor country induces a certain amount of resources to relocate abroad (recall Figure B.2), and, due to complementarity, also capital. This negative effect associated with carbon taxation limits the resource poor country's

ability to appropriate resource rents. When capital cannot be traded internationally, the negative effect is less pronounced. Resources may relocate, but carbon taxes do not cause an outflow of capital, and thus the resource poor country's optimal carbon tax rate increases.

While capital mobility limits the resource poor country's ability to appropriate resource rents, its overall effect for that country is beneficial, as Figure 4 of the “ τ_R - no” scenario illustrates. The figure shows the difference in income shares between the cases of immobile and mobile capital. The most notable impact of opening the borders to capital trade is the shift of capital income from the resource rich to the resource poor country. Opening the borders to capital trade allows the relatively abundant capital from the resource poor country to flow into the resource rich country, where it may earn a higher interest rate. Without capital mobility, interest rates in both countries differ, that is $r_{1,t} < r_{2,t}, \forall t$. Once we allow capital mobility, in the new equilibrium the international interest rate \tilde{r}_t lies between the two national interest rates of the scenario without capital mobility, thus $r_{1,t} < \tilde{r}_t < r_{2,t}, \forall t$. The increase (decrease) in the interest rate for the households in the resource poor (rich) country coincides with an increase (decrease) in capital income and an increase (decrease) in investment. In the “no - τ_R ” scenario, we observe the same qualitative impact on capital income, interest rates, and investments, as in the “ τ_R - no” scenario (see Figure 5).

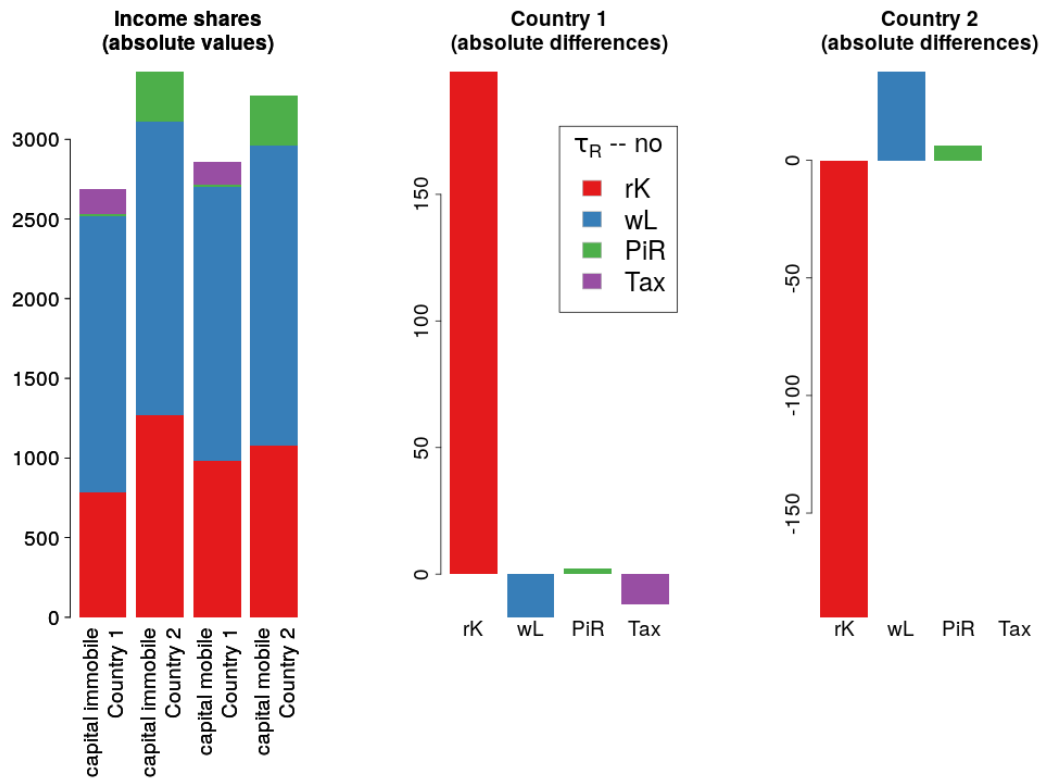


Figure 4: Comparing the NPV of national income for “ τ_R - no” scenarios with and without capital mobility. Resources may be traded in both scenarios. The resource poor country (Country 1) implements its optimal carbon tax. National income is disaggregated into the shares of capital and labor, and the profits in the resource sector. The resource rich country (Country 2) owns 95% of all resources. If capital is mobile, the resource poor country implements lower taxes than if capital is fixed. With capital mobility, households in the resource poor country can invest their relatively abundant capital abroad where it is more scarce and hence more productive.

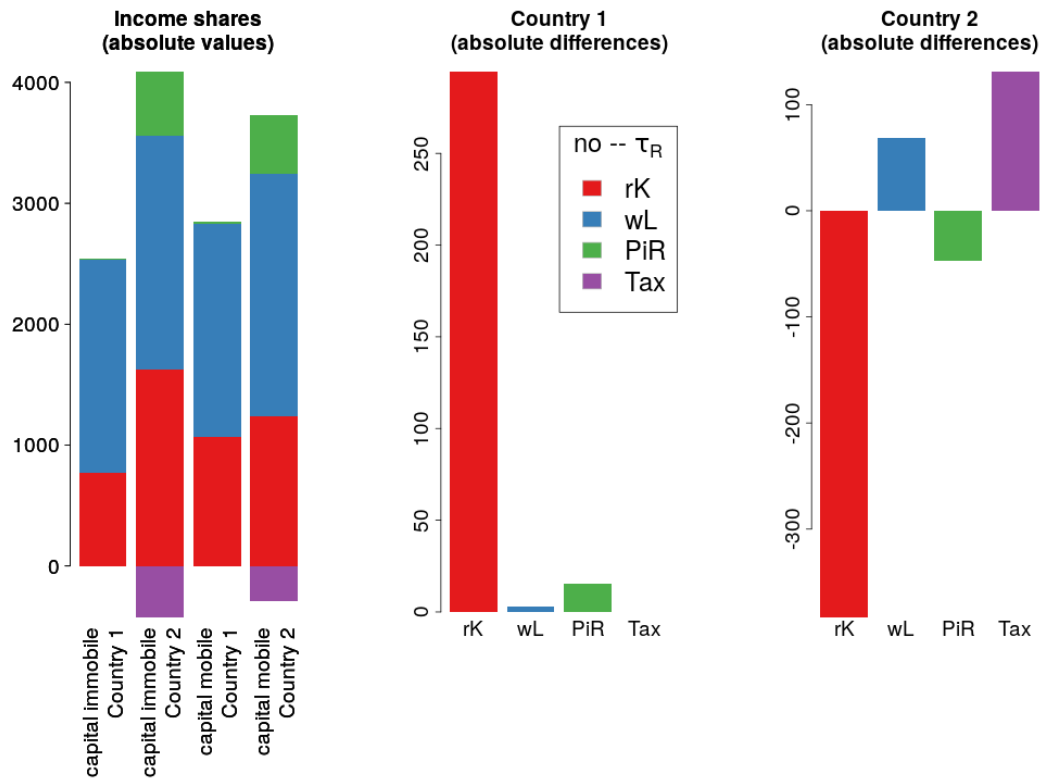


Figure 5: Comparison of “no - τ_R ” scenarios with and without capital mobility, when the resource rich country (Country 2) implements its optimal subsidy on fossil resources and the resource poor country’s government (Country 1) remains passive.

3.3 Winners and losers of factor mobility and tax competition

In this section, we discuss who winners and losers of factor mobility and tax competition are, when both capital and fossil resources can be traded on international markets and either one or the other, or both countries implement carbon taxes or subsidies. We also consider the impact of the availability of capital taxes. In Section 3.3.1 we describe the model outcomes in terms of welfare for an economy with asymmetric resource endowments, assuming that 95% of all resources are owned by Country 2. Then, in Section 3.3.2, we discuss our observations.

3.3.1 Model data

We begin with an overview of the feasible allocations. In Figure 6, we show the allocations that a social planner can implement in the space of utility of the two countries.⁵ The green curve delineates the Pareto frontier of the social planner economy. Given the utilitarian social welfare function (17) that simply adds up utility in both countries, the indifference curve is given by the straight gray line. The social optimum is marked in the figure. It is the point at which the indifference curve is tangent to the Pareto frontier. If, instead of a social planner, the two governments would implement carbon taxes in both countries to maximize the sum of their social welfare (cf. Equation (18)), the Pareto frontier would be the one delineated by the blue curve. Note that we do not allow for direct cash transfers in these cooperative equilibria.

If additional instruments are available to the two governments, the outcomes

⁵Utility is measured relative to the socially optimal value in BGE consumption losses. See Appendix A.

under cooperation can be improved. If direct cash transfers are available, cooperating governments can move closer to the first best optimum, which the social planner implements. However, even if there are no direct cash transfers available, but both government implement optimal capital taxes in addition to carbon taxes, the Pareto frontier under cooperation moves closer to the Pareto frontier of the social planner. We illustrate this in the appendix, Figure B.4.

Finally, assume that all three instruments, capital- and carbon taxes as well as direct cash transfers, are available the two cooperating governments. Even in that case they would not achieve the first-best optimum because there are convex extraction costs and – in contrast to the social planner – they have to take the behavior of the private extraction sector into account. However, if extraction costs are zero, the first best solution can be achieved with only the carbon tax.⁶ Cooperating government are more constrained with respect to the timing of the resource extraction than the social planner. Hence, to achieve the first best solution in a world with positive extraction costs, cooperating governments would need an instrument that gives them perfect control over the resource extraction path. This could be achieved, e.g., by expropriation of the resource extracting firms. Indeed, if we assume in our model that the resource extracting sector is under control of the government, the social planner solution and the cooperative decentralized solution coincide (not shown).

⁶In the appendix, in Figure C.5 we show how decentral cooperative and centralized planner solution differ in terms of the two countries welfare levels for a variation of extraction costs from zero to our standard calibration.

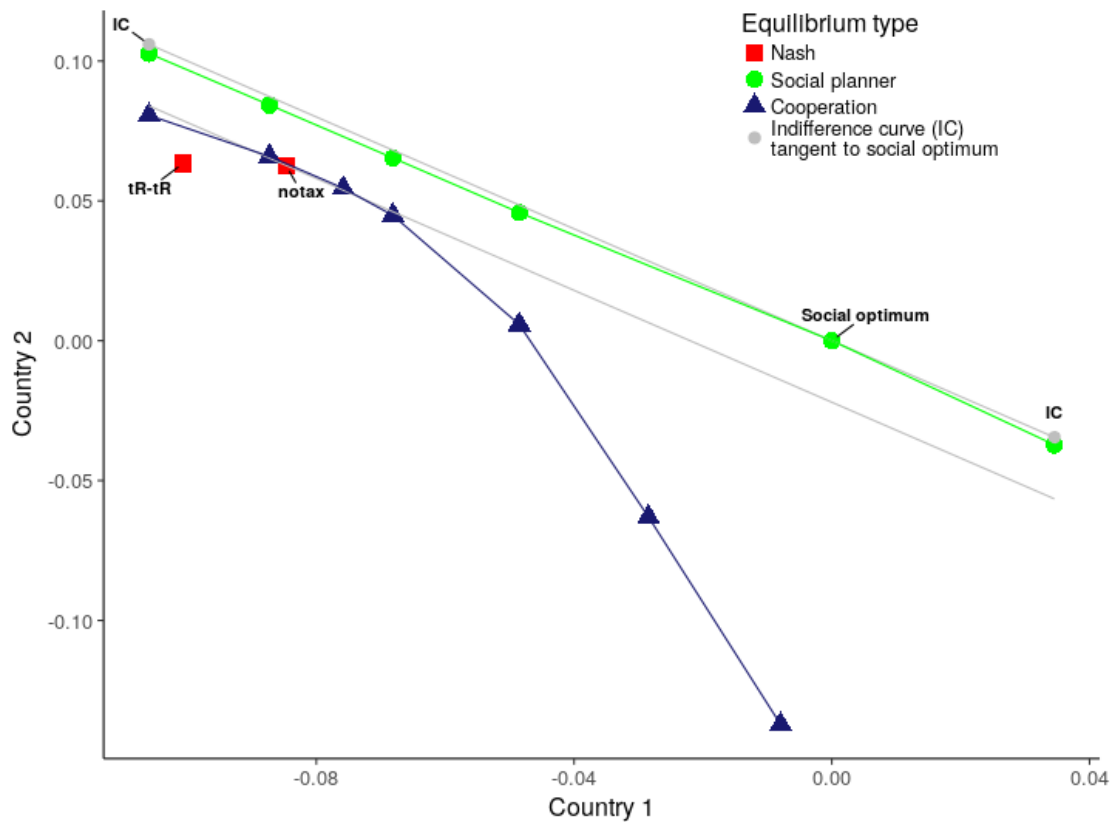


Figure 6: Welfare (relative to the social optimum) in Country 1 (resource poor) and Country 2 (resource rich) for different allocations a social planner can achieve, and for different allocations attainable by implementing carbon taxes in both countries cooperatively.

In Figure 7 we show the outcomes for different policy scenarios, along with the indifference curve associated with social welfare tangent to the social optimum (connecting the grey dots labeled IC), and two indifference curves with lower welfare levels. The social optimum that a social planner implements is outside of the bounds of this figure. We observe that the policy scenarios involving non-cooperation induce a game situation for the two countries that is similar to a Prisoner's Dilemma. To see this, consider for simplicity only two possible strategies: to either implement a carbon tax/subsidy, or to leave the tax rate at zero.

The socially desirable combination of strategies for the two governments would be to leave tax rates at zero. As can be seen in Figure 7, this would result in a payoff vector lying on the highest possible indifference curve of the social planner. The Nash equilibrium in this game would be for both countries to implement their unilaterally optimal tax/subsidy. The Nash equilibrium is the least desirable outcome from the perspective of social welfare. The only difference to the Prisoner's Dilemma is that the resource rich country is about as well off in the Nash equilibrium as in the social optimum. In our standard calibration the resource rich country has a BGE welfare loss of a mere 0,006% when moving from the Nash equilibrium ("tR-tR") to the socially desirable outcome ("notax").

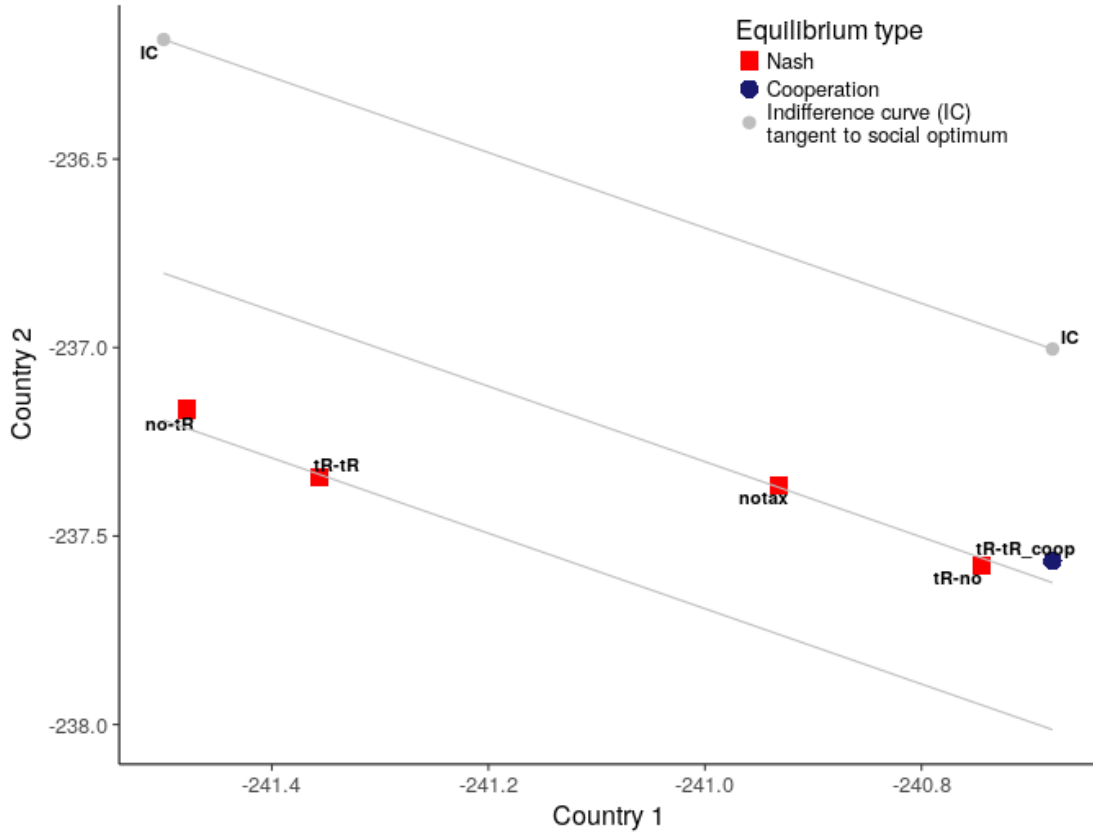


Figure 7: Welfare in country 1 (resource poor) and country 2 (resource rich) for different types of equilibria and different combinations of policy instruments.

3.3.2 Discussion

When countries are symmetric, tax competition causes the well know race to the bottom. In that case, tax harmonization is mutually beneficial. Countries should therefore in principle be able to agree on a tax harmonization (although negotiations may of course be more difficult with many countries). Relaxing the assumption of symmetry implies that gains and losses are distributed according to the asymmetries, that is, there are winners and losers. Winners may then have no incentive to agree to harmonization.

We are interested in policy options that improve welfare over the level achieved

in the Nash equilibrium in carbon taxes identified in Figure 7. Due to the game structure that emerges in our model of asymmetric tax competition, the “small” country, that is the resource poor country, loses relative to the socially desirable *notax* scenario. Also, the resource rich country does not gain much in the Nash equilibrium relative to the *notax* scenario. The game structure that we find in our model with two mobile factors stands in contrast to the seminal finding of Bucovetsky (1991). Bucovetsky finds that small countries are better off in the decentral Nash equilibrium than under a cooperative solution with harmonized tax rates. Of course, in the model considered in Bucovetsky (1991), “smallness” refers to the size of the population of the two regions.

We can show in our model how cooperation creates possibilities for Pareto-improvements. Similar to symmetric tax competition, negotiations could produce a Pareto improvement by agreeing on any point in the quadrant upwards and to the right of the tR - tR point in Figure 8. When restricted to harmonization of carbon taxes (that is, other instruments like direct transfers or other taxes are not available), the intersection of this quadrant with the Pareto frontier of the cooperative solution defines the possible Pareto-improvements (blue line). Other solutions with possibly higher social welfare would require compensation payments.

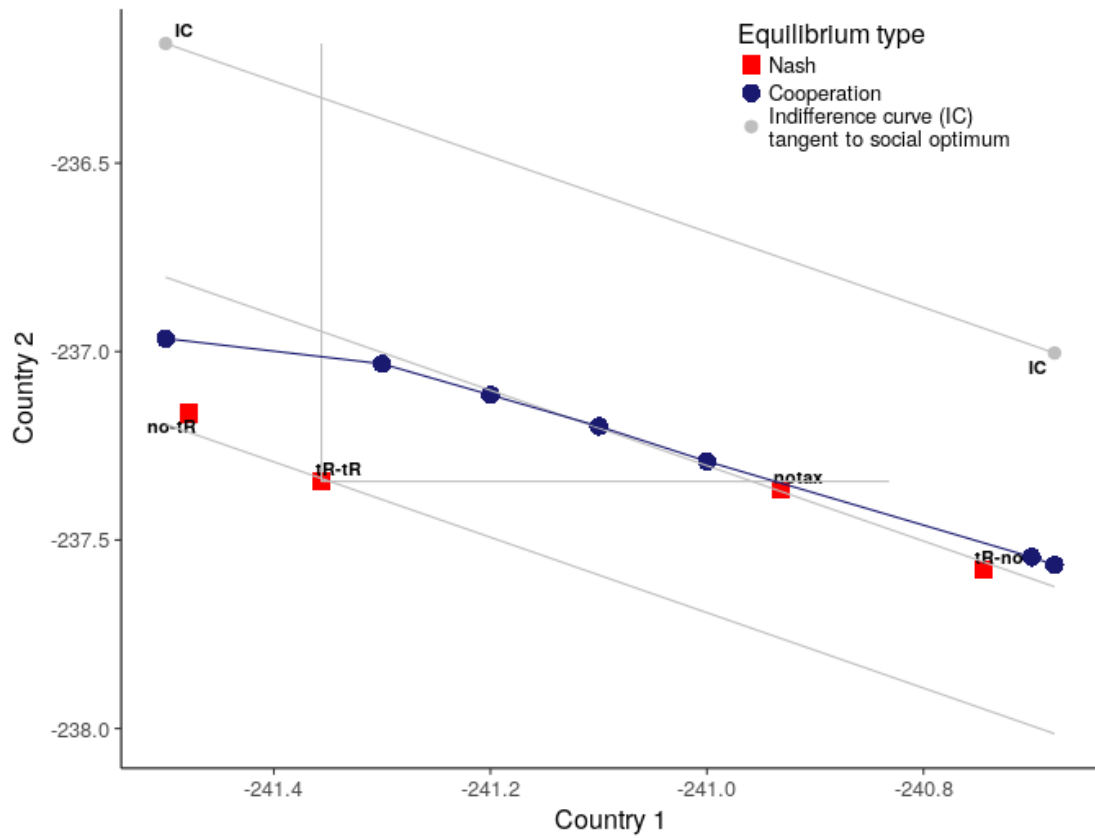


Figure 8: The Pareto frontier for cooperative implementations of the carbon tax in both countries is shown in green.

4 Robustness of results

In the following, we demonstrate to what extent the results we've presented above are robust with respect to different changes in the assumptions underlying our modeling approach. We begin with a sensitivity analysis of central parameters in Section 4.1. Then, in Section 4.2, we illustrate the implications of including capital taxes in the analysis. It turns out that making capital taxes available to the governments does not change the basic insights we've gained from the above analysis in which we've abstracted from capital taxation.

4.1 Sensitivity to parameters

We have conducted one-at-a-time variations of all model parameters. Here, we describe only those variations of parameters to which our model is sensitive. Variations of the parameters that we have left out here do not change our results qualitatively nor quantitatively to a significant extent.

4.1.1 Elasticity of substitution

4.2 Availability of capital taxes

In the following, we discuss how the above results change, when in addition to carbon taxes, the two governments can optimize capital taxes as well. By and large, the above results still hold qualitatively and the changes are quantitatively rather small.

For example, Table 4 shows that closing borders to capital movements has a far greater impact than allowing both countries to optimize capital taxes.

Scenario		$\tau_{R,1}$ (NPV)	$\tau_{R,2}$ (NPV)	$\tau_{R,1}$ (rate)	$\tau_{R,2}$ (rate)
τ_R - no	capital mobile	145	0	396	0
τ_R - no	capital immobile	157	0	542	0
$(\tau_K, \tau_R) - \tau_K$	capital mobile	145	0	396	0
no - τ_R	capital mobile	0	-294	0	-526
no - τ_R	capital immobile	0	-425	0	-827
$\tau_K - (\tau_K, \tau_R)$	capital mobile	0	-298	0	-523

Table 4: Net present value of carbon tax revenues [tril. US\$] and average carbon tax rate [\$/tC] for different policy scenarios under the assumption that the resource poor country (Country 1) owns 5% of all resources and the resource rich country (Country 2) owns 95%.

Moreover, when governments have access not only to carbon taxes, but may also tax capital, we observe quantitatively small effects that do not change the game Prisoner's Dilemma game structure as shown in Figure 7. In Figure 9 we show how the game structure depicted above changes. Deviations from the equilibria without availability of capital taxes are minor.

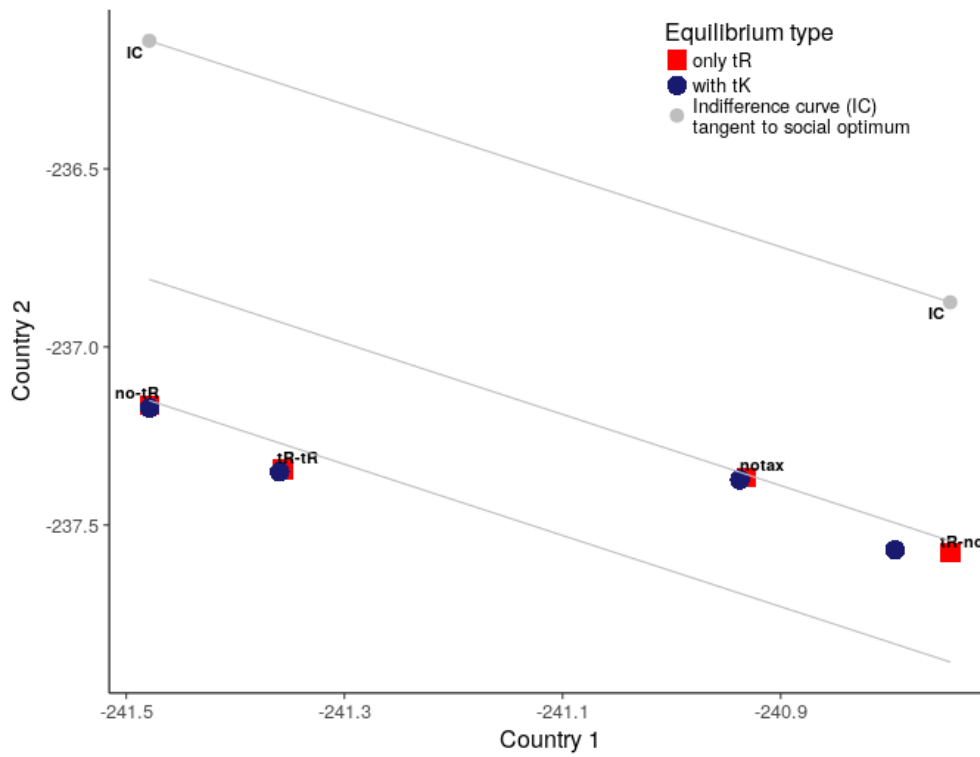


Figure 9: Nash equilibria for different policy instrument portfolios.

5 Conclusion

We have discussed the strategic incentives of countries with asymmetric resource endowments, in particular with respect to implementing carbon taxes, when fossil resources and capital are internationally mobile, but labor is not. Our results show that resource poor countries have a tendency to try to appropriate resource rents via the price-channel. Its government will use the carbon tax to depress the produce price, which reduces the foreign resource sector's profits, but increases domestic tax revenues. Resource rich countries have the tendency to try to stop the outflow of fossil resources via the factor channel. By subsidizing the use of fossil fuels, they attract foreign capital and thus aim at increasing their national income, in particular labor income. Capital mobility has a dampening effect on the incentives of both resource rich and poor countries. Both carbon taxes and subsidies are lower if capital is mobile, compared to scenarios without capital mobility. Finally, we have shown that including internationally tradable fossil resources changes the game structure found by Bucovetsky (1991) for tax competition with asymmetric countries.

It is standard in the tax competition literature is to consider tax financed public goods and infrastructure. Moreover, typical studies of carbon taxation are concerned with the Pigouvian motive to tax. We have omitted these features in the present paper to focus exclusively on the strategic incentives involved in the revenue raising side of fiscal policy. A promising avenue for future research would be to include both motives and discuss the differential impact on the outcomes.

The architecture of the Paris Climate Agreement 2015 underlines that global climate policy is and will be deeply rooted in unilateral action. The political

process of complying with the agreement via nationally determined contributions (the NDCs) makes it clear that strategic considerations are central to individual countries' decisions. This paper contributes to the understanding of some of these strategic considerations.

References

- Amundsen, E.S., Schöb, R., 1999. Environmental taxes on exhaustible resources. *European Journal of Political Economy* 15, 311–329.
- Anthoff, D., Tol, R., 2009. The impact of climate change on the balanced growth equivalent: An application of FUND. *Environmental and Resource Economics* 34, 351–367.
- Brooke, A., Kendrick, D., Meeraus, A., Raman, R., Rosenthal, R., 2005. GAMS – A Users Guide. GAMS Development Corporation.
- Bucovetsky, S., 1991. Asymmetric tax competition. *Journal of Urban Economics* 30, 167–181. DOI: 10.1016/0094-1190(91)90034-5.
- Burniaux, J.M., Martin, J.P., Nicoletti, G., Martin, J.O., 1992. GREEN a Multi-Sector, Multi-Region General Equilibrium Model for Quantifying the Costs of Curbing CO₂ Emissions: A Technical Manual. OECD Economics Department Working Papers.
- Caselli, F., Feyrer, J., 2007. The marginal product of capital. *The Quarterly Journal of Economics* 122, 535–568.
- Coenen, G., Straub, R., Trabandt, M., 2012. Fiscal policy and the great recession in the euro area. *American Economic Review* 102, 71–76.
- Edenhofer, O., Bauer, N., Kriegler, E., 2005. The impact of technological change on climate protection and welfare: Insights from the model MIND. *Ecological Economics* 54, 277–292.

- Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magne, B., Scricciu, S., Turton, H., van Vuuren, D., 2010. The economics of low stabilization: model comparison of mitigation strategies and costs. *The Energy Journal* 31, 11–48.
- Feichtinger, G., Hartl, R.F., 1986. *Optimale Kontrolle ökonomischer Prozesse*. de Gruyter.
- Franks, M., Edenhofer, O., Lessmann, K., 2017. Why Finance Ministers Favor Carbon Taxes, Even If They Do Not Take Climate Change into Account. *Environmental and Resource Economics* 68, 445–472. DOI: 10.1007/s10640-015-9982-1.
- Habla, W., 2016. *The Green Paradox and Interjurisdictional Competition across Space and Time*. Working Papers in Economics 668, University of Gothenburg, Department of Economics. .
- Hogan, W.W., Manne, A.S., 1979. Energy-economy interactions: the fable of the elephant and the rabbit?, in: Pindyck, R. (Ed.), *Advances in the Economics of Energy and Resources*. JAI Press, Greenwich, CT. volume 1.
- Kalkuhl, M., Edenhofer, O., Lessmann, K., 2012. Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics* 34, 1–23.
- Karp, L., 1984. Optimality and consistency in a differential game with non-renewable resources. *Journal of Economic Dynamics and Control* 8, 73 – 97.

- Kemfert, C., Welsch, H., 2000. Energy-Capital-Labor Substitution and the Economic Effects of CO2 Abatement: Evidence for Germany. *Journal of Policy Modeling* 22, 641–660.
- Liski, M., Tahvonen, O., 2004. Can carbon tax eat OPEC's rents? *Journal of Environmental Economics and Management* 47, 1–12.
- Markandya, A., Pedroso-Galinato, S., 2007. How substitutable is natural capital? *Environmental Resource Economics* 37, 297–312.
- Ogawa, H., Oshiro, J., Sato, Y., 2016. Capital Mobility—Resource Gains or Losses? How, When, and for Whom? *Journal of Public Economic Theory* 18, 417–450. DOI: 10.1111/jpet.12145.
- Otto, G.D., Voss, G.M., 1998. Is public capital provision efficient? *Journal of Monetary Economics* 42, 47–66.
- Rogner, H.H., 1997. An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment* 22, 217–262.
- Schwerhoff, G., Edenhofer, O., 2013. Is Capital Mobility Good for Public Good Provision. CESifo Working Paper Series 4420.
- Zodrow, G.R., Mieszkowski, P., 1986. Pigou, Tiebout, Property Taxation, and the Underprovision of Local Public Goods. *Journal of Urban Economics* 19, 356–370.

A Calculation of balanced growth equivalents (BGE)

Given the welfare levels achieved in the policy scenario W_{pol} and the social optimum W_{so} , we calculate the BGE welfare loss by comparing those consumption time paths that differ in initial consumption levels C_{pol} and C_{so} , but share a common growth rate γ such that they yield the respective welfare levels W_{pol} and W_{so} :

$$W_{pol} = \sum_t^T U(C_{pol}(1 + \gamma)^t / L_t) \quad (19)$$

$$W_{so} = \sum_t^T U(C_{so}(1 + \gamma)^t / L_t). \quad (20)$$

Then, the BGE welfare loss is defined as $1 - \frac{C_{pol}}{C_{so}}$. It specifies the once-and-forall loss of consumption that is caused by changing from the socially optimal path to a policy path.

B Additional material

B.1 Rent appropriation

In Figure B.1 we compare average prices and quantities on the market for fossil resources to explain how we understand the appropriation of resource rents referred to in Section 3.1. Here, we only consider the quantity of resources sold to the firm in the resource poor country. The numbers are based on our standard calibration. The red squares show the quantity R_1 sold in the scenario without any government intervention, resulting in price p_0 . The yellow triangles indicate quantity and prices

for the scenario in which the resource poor country can implement a carbon tax and the resource rich country's government does not implement any policy instrument. In the latter scenario, the net-of-tax price on the international market is reduced to \tilde{p} . The firm in the resource poor country, however, has to pay the gross price $\tilde{p} + \tau_R$ and thus demands the quantity \tilde{R}_1 . Since both the net-of-tax price and the quantity sold are reduced under the carbon tax, profits of the resource owners are reduced (note, however, that extraction costs are not displayed in the diagram). The resource rent that the resource exporting country can retain is thus reduced. By taxing the use of resources, the government in the resource poor country can appropriate part of the resource rent. The portion of the resource rent appropriated corresponds to the small vertically hatched rectangle in the diagram. While total tax revenues in the resource poor country are made up of both the vertically and the horizontally hatched rectangles, the latter corresponds simply to the consumer surplus of the resource buying firm.

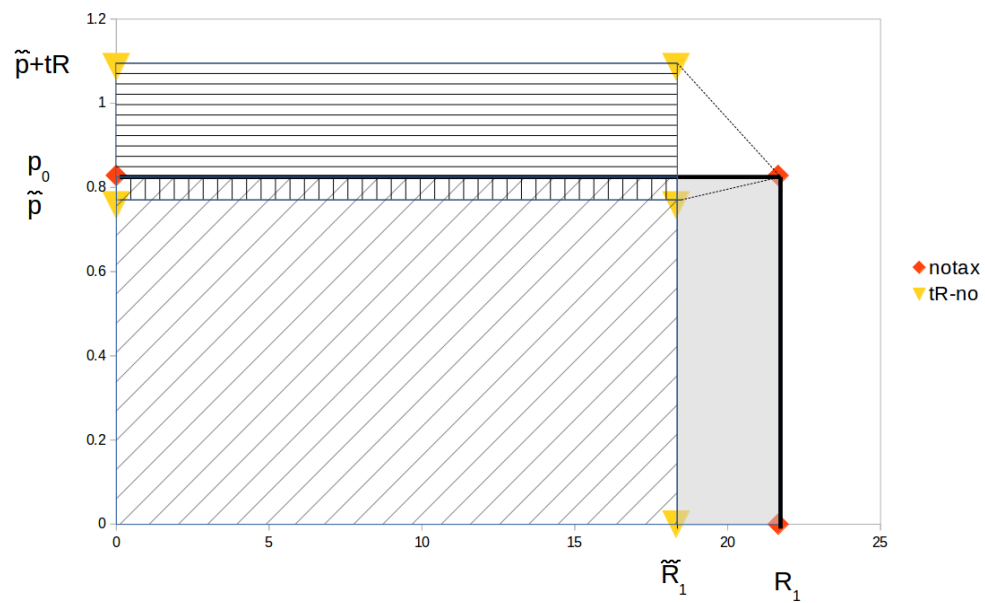


Figure B.1: Comparison of prices and quantities in the scenarios with a) no taxes, and b) the Nash equilibrium with only the resource poor country implementing its optimal carbon tax.

B.2 Movement of production factors with varying carbon tax

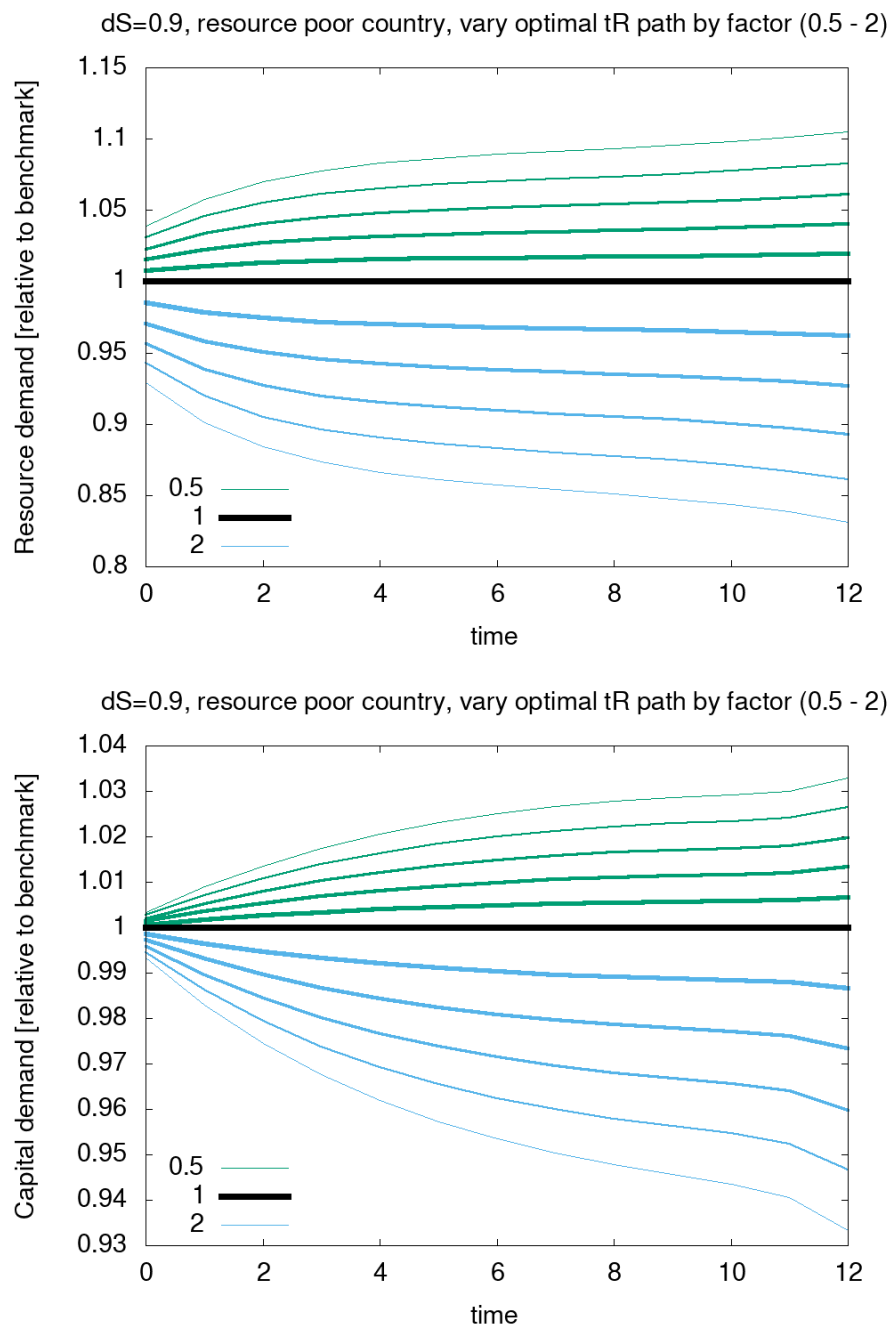


Figure B.2: Exogenous variation of the optimal carbon tax path the resource poor country chooses if the resource rich country does not use any taxes: We show the impact on the demand for capital and resources in the resource poor country (cf. Section 3.1).

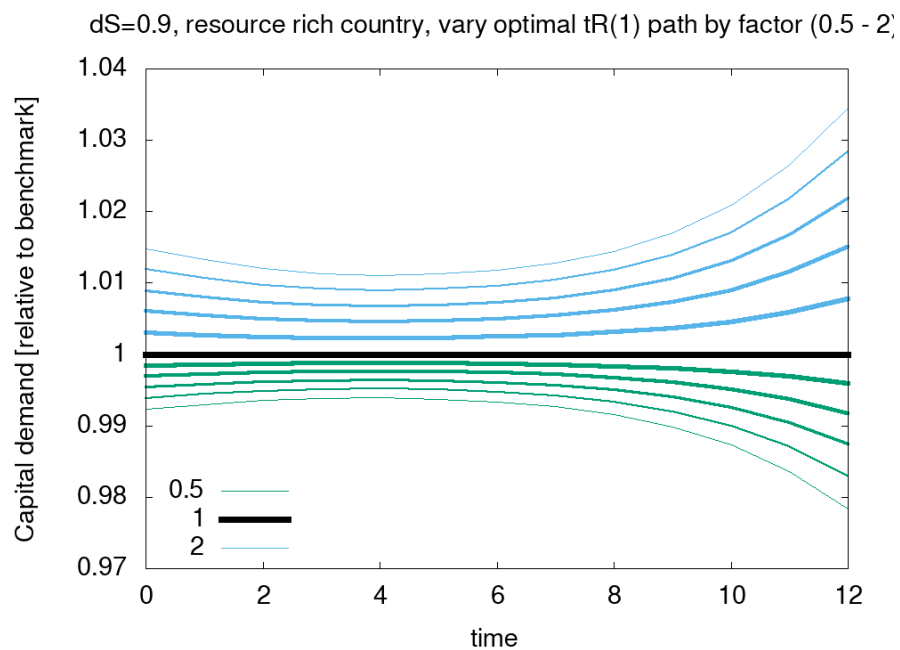
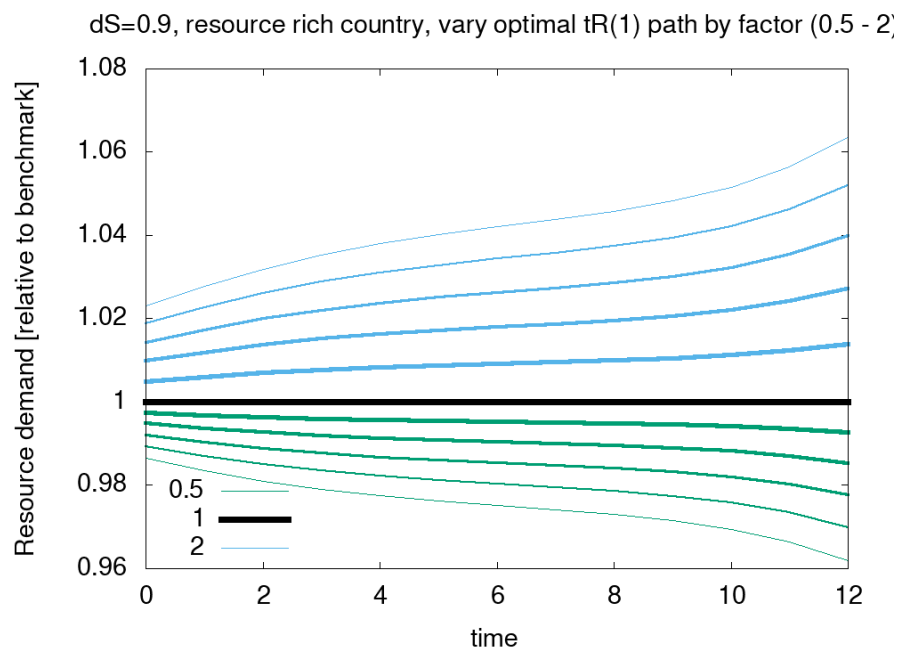


Figure B.3: For the same scenarios as in Figure B.2, the plots demonstrate the inflow in the resource rich country if the resource poor country increases its carbon tax (cf. Section 3.1).

B.3 Pareto frontier

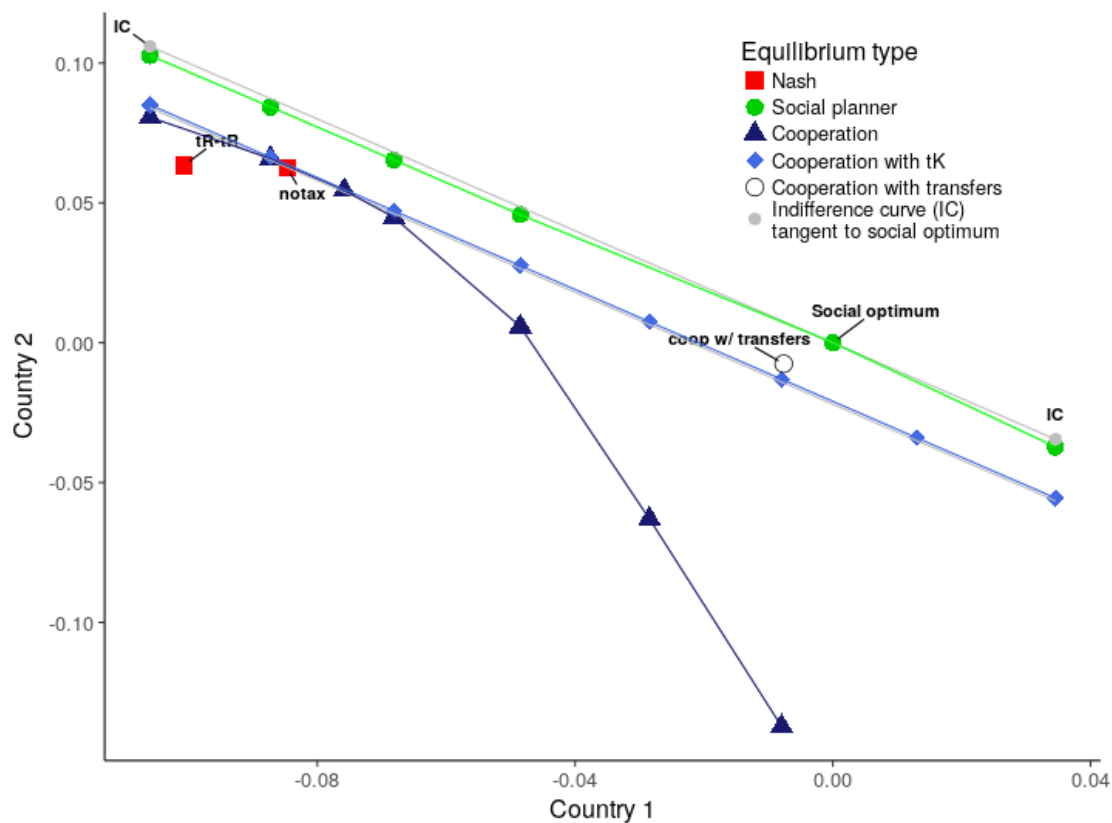


Figure B.4: Welfare in Country 1 (resource poor) and Country 2 (resource rich) for different allocations a social planner can achieve, and for different allocations attainable by governments implementing policy instruments in both countries cooperatively. Policy instrument portfolios analyzed here are a) carbon taxes (dark blue triangles), b) carbon taxes and capital taxes (light blue diamonds), c) carbon taxes and direct cash transfers (empty circle).

C Calibration and implementation of model

Table C.1 summarizes the parameters used in the model. If not otherwise indicated, we have chosen their values in accordance with the closely related model

PRIDE⁷, as introduced in Kalkuhl et al. (2012), and the model comparison exercise referenced therein, Edenhofer et al. (2010). The parameters of the production function are calibrated according to the empirical literature. We insert the elasticities of substitution between the respective factors directly.

Description	symbol	value	range	sources
Intertemporal elasticity of substitution	η	1.1		
Pure rate of time preference	ρ	0.03		
Annual depreciation rate of capital	δ	0.025		
Share parameter of fossil resource	α_1	0.05		Edenhofer et al. (2005)
Elasticity of substitution between Z and R	σ_1	0.5	0.25 – 0.92	Hogan and Manne (1979) Kemfert and Welsch (2000) Burniaux et al. (1992) Markandya and Pedroso-Galinato (2007)
Share parameter of general capital \mathbf{Z}	α_2	0.42		Caselli and Feyrer (2007)
Elasticity of substitution between K and L	σ_2	0.7		Coenen et al. (2012) Otto and Voss (1998)
Initial labor productivity	$A_{L,0}$	6		
Initial growth rate of A_L	$\gamma_{L,0}$	0.026		
Decline rate of labor productivity	d_L	0.006		
Initial resource use productivity	$A_{R,0}$	1		authors' calibration
Initial growth rate of A_R	$\gamma_{R,0}$	0.005		“
Decline rate of resource use productivity	d_R	0.001		“
Initial world capital [tril. US\$]	K_0	165		
Initial world resource stock [GtC]	S_0	4000		
Initial world population [bill.]	L_0	6.5		
Population maximum [bill.]	L_{max}	9.5		
First period [year]	t_0	2010		
Last period [year]	T	2085		
Time step [years]	Δ	5		
Scaling parameter	χ_1	20		
Scaling parameter	χ_2	700		
Slope of Rogner's curve	χ_3	2		

Table C.1: List of model parameters. If source not indicated otherwise, values are chosen in accordance with Kalkuhl et al. (2012) and Edenhofer et al. (2010).

⁷Both our model and PRIDE are capable of calculating 2nd best solutions in a decentralized economy with several different economic actors. Both models are formulated as non-linear programs which are implemented with the GAMS software (Brooke et al., 2005). While PRIDE involves a more detailed energy sector and a broader set of policy instruments, it does not represent multiple countries, but only one global closed economy.

C.1 Exogenously given growth rates

The productivity of labor A_L and fossil resources A_R are assumed to increase over time due to exogenous technological change. The parameters are chosen in accordance with empirically observed output and consumption growth rates:

$$\gamma_{\zeta,t} = \gamma_{\zeta,0} e^{-d_{\zeta}t}$$

$$A_{\zeta,t+1} = A_{\zeta,t} \left(1 + \left(\frac{\gamma_{\zeta,t}}{1 - \gamma_{\zeta,t}} \right) \right), \quad A_{\zeta,0} \text{ given,}$$

where $\zeta = L, R$.

C.2 Extraction costs

The calibration of extraction costs is based on Rogner (1997). We assume that resources with the lowest extraction costs are extracted first. The productivity κ is hence assumed to decline with increasing cumulative extraction.

$$\kappa_t = \frac{\chi_1}{\chi_1 + \chi_2 \left(\frac{S_0 - S_t}{S_0} \right)^{\chi_3}} \quad (21)$$

D First order conditions of representative agents

To determine the first order conditions, we use a maximum principle for discrete time steps as given in Feichtinger and Hartl (1986). We use their concept of the *discrete Hamiltonian* which is more convenient than the equivalent formulation of

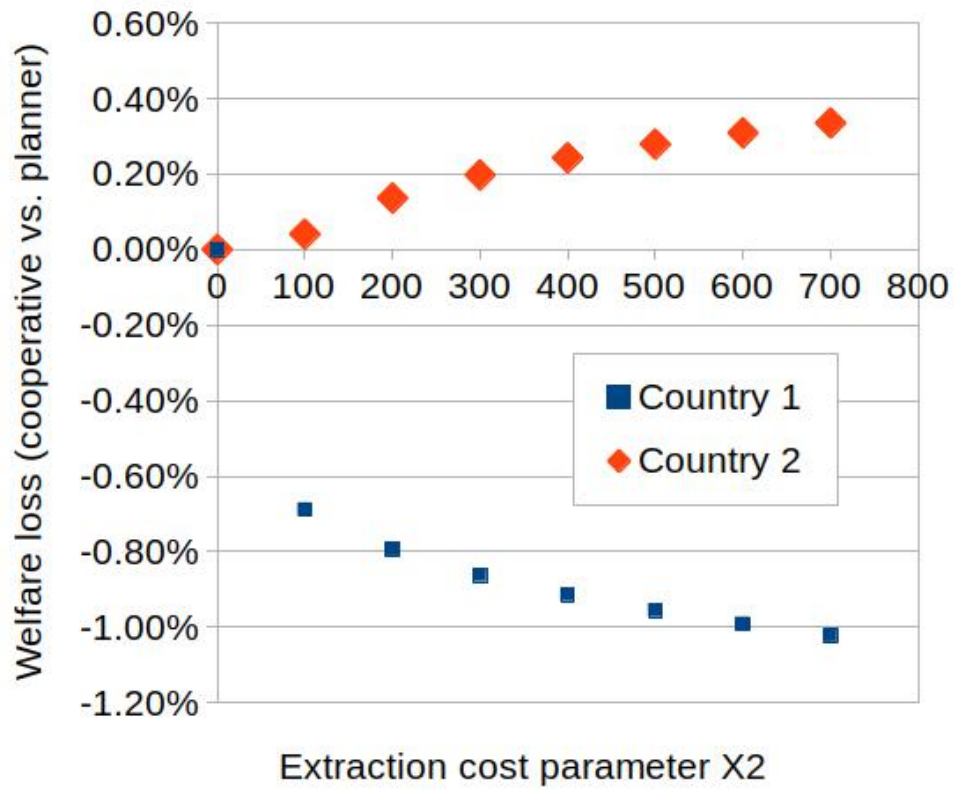


Figure C.5: If extraction costs are zero, i.e. $\chi_2 = 0$, the (decentral) cooperative solution and the (centralized) social planner solution coincide. As extraction costs increase to our standard calibration, $\chi_2 = 700$, the two cooperating governments are less and less able to achieve the first best outcome.

the optimization problems with Lagrangians. In the following we shall use the term *Hamiltonian* in this sense.

Household. The household maximizes its intertemporal welfare (6) taking into account the budget constraint (7) and the equation of motion for his assets (8). Since the economic impact of a single household on the total of all profits is small, the representative household takes Π^F and governmental transfers Γ as given. The Hamiltonian is given by

$$\mathcal{H}_t^{HH} = U(C_t/L_t) + \lambda_t [(1 + (r_t - \delta)) K_t^s + w_t L_t + \Pi_t^F + \Gamma_t - C_t],$$

and thus the first order and terminal conditions for the control and costate variables C and λ are

$$\frac{L_t^{\eta-1}}{C_t^\eta} = \lambda_t, \tag{22}$$

$$\lambda_{t-1}(1 + \rho) = \lambda_t(1 + r_t - \delta), \tag{23}$$

$$(I_T - (1 - \delta)K_T^s) \lambda_T = 0. \tag{24}$$

Resource extraction sector. The representative firms in the resource extracting sector maximizes its intertemporal stream of profits (15) taking into account the resource constraint (14), the equation of motion for the stock (13). The Hamil-

tonian then reads

$$\mathcal{H}_t^R = \left(p_t - \frac{r_t}{\kappa_t(S_t)} \right) R_t + \lambda_t^R (S_t - R_t^s),$$

and thus the first order and terminal conditions for the control and costate variables R and λ^R are

$$\lambda_t^R = p_t - \frac{r_t}{\kappa_t}, \quad (25)$$

$$\lambda_t^R - \lambda_{t-1}^R (1 + r_t - \delta) = - \frac{r_t R_t \chi_2 \chi_3}{\chi_1 S_0} \left(\frac{S_0 - S_t}{S_0} \right)^{\chi_3 - 1}, \quad (26)$$

$$\lambda_{T-1}^R S_T = 0. \quad (27)$$

E Solution algorithm

To find a Nash equilibrium, we use the following algorithm:

```

until policy instruments converge
  repeat for each player j:
    unfix policy variables
    optimize player j's payoff/welfare
    fix player j's newly found policy variables

```