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Why Finance Ministers Favor Carbon Taxes, Even if They Do not Take Climate Change into Account

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Summary

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Keywords: Carbon Pricing, Green Paradox, Infrastructure, Optimal Taxation, Strategic Instrument Choice, Supply-Side Dynamics, Tax Competition

JEL Classification: F21, H21, H30, H73, Q38

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Why finance ministers favor carbon taxes, even if they do not take climate change into account*

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Abstract

Fiscal considerations may shift governmental priorities away from environmental concerns: Finance ministers face strong demand for public expenditures such as infrastructure investments but they are constrained by international tax competition. We develop a multi-region model of tax competition and resource extraction to assess the fiscal incentive of imposing a tax on carbon rather than on capital. We explicitly model international capital and resource markets, as well as intertemporal capital accumulation and resource extraction. While fossil resources give rise to scarcity rents, capital does not. With carbon taxes the rents can be captured and invested in infrastructure, which leads to higher welfare than under capital taxation. This result holds even without modeling environmental damages. It is robust under a variation of the behavioral assumptions of resource importers to coordinate their actions, and a resource exporter's ability to counteract carbon policies. Further, no green paradox occurs – instead, the carbon tax constitutes a viable green policy, since it postpones extraction and reduces cumulative emissions.

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1. Introduction

The economic integration of national economies has had beneficial impacts on the world in several ways. Nevertheless, we also observe how the economic forces of globalization constrain democratic governments increasingly. According to Dani Rodrik, the world faces a triangle of impossibility: We cannot have democracy, national sovereignty, and hyperglobalization at the same time (Rodrik, 2011). Hyperglobalization impinges on democratic choices within sovereign nations by giving rise to corporate tax competition, which “restricts a nation’s ability to choose the tax structure that best reflects its needs and preferences” (ibid., p. 193).

When national governments take the unprecedented mobility of capital into account, they find themselves competing for capital through their choice of taxes. Evidence for the resulting race-to-the-bottom in national tax policies is found in declining corporate tax rates (Benassy-Quere et al., 2007; Zodrow, 2010), complemented by a rising share of payroll taxes (Sinn, 2003). Zodrow and Mieszkowski (1986) have conceptualized the underlying economic mechanism in what is often referred to as the workhorse model of tax competition.¹

The race-to-the-bottom constrains a government’s ability to raise sufficient funds, and this has far reaching consequences. Sufficient government funds are required not only for public services such as health care, the pension system, and education, but also for providing productive public capital, in particular public infrastructure stocks. While all spending options matter for public policy, we shall focus only on the latter. In principle, including

¹ Next to the rather empirical survey by Zodrow (2010), the results of this field of research are also summarized in Wilson (1999) in a concise way and Keen and Konrad (2013), who include the perspective of spatial modeling.

any other option would lead to similar results. The main point we need to capture in our model is that public spending enhances productivity. We base our choice to use infrastructure on the fact that its economic impact is relatively well understood. Both theoretical and empirical studies are available. Calderón et al. (2014) use a time series approach with a large cross-country dataset and find that the output elasticity of infrastructure lies between 0.08 and 0.1. In their meta review, Bom and Ligthart (2013) obtain the same numbers. Based on this estimate, the authors compare the marginal user cost with the marginal return on infrastructure investments and conclude that infrastructure stocks are underfinanced. The under-provision of infrastructure is likely to reduce growth, as supported by an emerging consensus in the empirical literature (Romp and de Haan, 2007). This raises the question how governments can reduce their exposure to tax competition and generate sufficient funds to finance essential public goods.

In this study, we identify taxes on the use of carbon resources as a superior alternative to taxes on capital income in terms of fiscal efficiency. Even though fossil resources are also traded on international markets, there is an asymmetry in efficiency between capital and resources as tax base. While ownership of fossil resources gives rise to a scarcity rent, capital does not. Taxes on either input factor cause an interregional reallocation by driving economic activity out of the country with the higher tax rates, and into countries with lower taxes. The carbon tax has the advantage, though, of capturing part of the resource rent which is held initially by resource owners. Governments can use the appropriated rent for infrastructure investments that increase the productivity of the domestic economy, which in turn attracts investments in domestic capital stocks.

A tax reform that substitutes carbon taxation for a capital taxation has

effects beyond improving fiscal efficiency. The supply side dynamics of carbon taxation may have the adverse environmental effect of causing a green paradox². Further, appropriating the resource rents may meet resistance by the rent owners. Thus we explore options for strategic behavior of both, buyers and sellers of carbon resources.

We find that in contrast to Sinn (2008) carbon taxes do not cause a green paradox, but constitute a viable green policy. When the motivation to tax the use of fossil resources is based exclusively on the fiscal needs of a government in a resource importing nation, then a resource exporter reacts by reducing the rate of extraction (a timing effect). Moreover, the amount of fossil resources that are left underground increases, when capital taxes are replaced by carbon taxes (a volume effect). Governments may not take climate externalities fully into account, as modeled in the present paper. In this case, timing and volume effects do not feed back into their decisions about the optimal fiscal policy. Nevertheless, the two effects show that a unilateral tax reform which introduces a carbon tax has both beneficial fiscal and environmental implications.

Finally, we show that both the fiscal and the environmental implications remain beneficial under a variation of the behavioral assumptions of resource importers to coordinate their actions, and a resource exporter to counteract carbon policies.

Our contribution is twofold. To the best of our knowledge, our model is the first combine several key features which allow us to precisely assess the opportunity costs of optimal tax portfolios. It enables us to bridge

² The phrase “green paradox” was introduced by Sinn (2008) to describe a situation in which the implementation of carbon taxes leads to an acceleration of resource extraction by the owners of fossil fuel resources. This would counteract the purpose of the environmental policy. The idea originates in a debate lead by Sinclair (1992, 1994) and Ulph and Ulph (1994).

the gap between the tax competition literature and the economics of exhaustible resources. We implement a decentralized market economy with several representative agents and strategically interacting governments. The tax instruments, which governments use to finance productivity enhancing infrastructure stocks, are determined endogenously for both cooperative and non-cooperative behavior among resource importing nations in the Nash equilibrium. Capital and fossil resources may be traded on explicitly modeled international markets. The use of fossil resources in production is assumed to cause no harmful externality. Finally, we include the intertemporal dynamics of capital accumulation and resource extraction. The savings behavior of households is based on a Ramsey model, and a Hotelling model of the resource exporting sector determines the timing of resource extraction.

Second, we use our model to shed light on the supply side dynamics of fossil resource extraction. So far, most of the research on the conditions under which a green paradox occurs has used partial equilibrium analysis as, for example, in Edenhofer and Kalkuhl (2011), Gerlagh (2011), or van der Ploeg and Withagen (2012). Recently, this strand of research has been extended to general equilibrium models (van der Ploeg and Withagen, 2014; van der Meijden et al., 2014). Now, we are able to go even one step further. Our model allows us to introduce strategic interactions between fossil fuel exporting and importing regions, as well as among the governments of importing countries themselves.³

The idea to study environmental policy in the form of carbon taxes in a dynamic setting and under the assumption of capital mobility has been

³ Irrespective of the literature on the green paradox, it is already known that a cooperating bloc of resource importing countries can appropriate a certain fraction of the exporters' resource rent, as discussed, for example, by Karp (1984), Tahvonen (1995), or Amundsen and Schöb (1999). We are able to reproduce this result and compare it to the outcome under non-cooperative importers.

taken up recently by two publications. First, Withagen and Halsema (2013) find inefficiently strict environmental policy. They assume that capital and demand for environmental quality are complements. Therefore, the race-to-the-bottom in capital taxes translates – via the thusly stimulated higher capital supply – into a race-to-the-top in environmental policy. While the authors also study tax competition in an intertemporal general equilibrium framework, they neglect the dynamics of resource extraction.

Closer yet to the present study is Habla (2014). The author implements an analytical two-period general equilibrium model of tax competition and resource extraction. The main finding consists in the discovery of an additional channel through which governments, that take environmental damages into account, may counter a green paradox. By raising a positive tax on capital unilaterally, governments can decrease the global interest rate. Through the Hotelling rule, the decrease of the interest rate translates into a lower future price of fossil resources. The price signal, thus, stimulates a shift in demand away from present and towards future resource use.

Our analysis differs in three respects, which highlight the relevance of our results for policy making. First, we assume that the primary motivation for taxation is demand for public infrastructure rather than environmental concern. By focusing on infrastructure as motivation we account for both the income and the expenditure side of fiscal policy. Omitting environmental damages in our analysis accounts for the currently hesitant and incomplete environmental policies to address climate change. Second, we distinguish between a resource seller and resource buyers, opening up the analysis to a richer set of strategic interactions. Finally, the design of our model allows us to quantify the opportunity costs of various tax portfolios under different assumptions. In particular, we can determine the differential impacts of

various assumptions about the strategic behavior of resource importing and exporting countries.

The rest of the paper is structured as follows. After explaining the model in Section 2, we present our results on the comparison of different tax portfolios in Section 3. In Section 4 we assess the impact of different policy choices on the supply side dynamics of resource extraction. In Section 5 we describe how different assumptions about the strategic behavior of the governments change our results. We conclude with Section 6.

2. The model

We implement a differential game based on a Ramsey-type general equilibrium growth model. There are two symmetric countries, each populated by an identical set of economic agents, as well as a group of resource owners who reside outside of the two countries. These resource owners as agents in our model can be thought of as a third country which is endowed with a stock of fossil resources. The economic activity of this third country consists of exporting the resource to the other two countries in exchange for final goods and of consuming these.

The model is calibrated to represent two countries of the developed world which import substantial amounts of fossil resources (see, for example, the U.S. Energy Information Administration's list of the *Top World Oil Net Importers*, EIA, 2014) and which already have in place a relatively high amount of publicly held fixed assets. The initial endowment with infrastructure is extrapolated from US data.⁴ The details of the calibration can be found in the Appendix A.

2.1. International markets

The symmetric importing 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 firm j 's demand for capital $K_{j,t}^d$ and resources $R_{j,t}^d$ at time t , household j 's assets, that is, the capital supply $K_{j,t}^s$ and the exporter's resource supply R_t . Households own only the domestic firms but rent out their accumulated capital to any firm, domestic or abroad. Renting to a firm

⁴ Developing countries usually have a much lower endowment with infrastructure and thus the marginal benefit of additional tax income should be higher than found using our model. Here, we would expect the advantage of the carbon tax to be even higher.

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

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

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

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

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

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

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.

2.2. Agents of the national economy

A large number of households live in each of the two importing countries. Output is produced by a large number of competitive firms which use labor, private capital, and publicly provided infrastructure as well as fossil resources as inputs to produce a homogeneous final consumption good. The two countries are not endowed with any fossil resource, thus the firms have to import them. Fossil resources are extracted by a large number of resource owners who sell them on the international resource market to the firms in the two resource importing countries.

We assume that all households, all the firms producing final goods, and all the resource owners are identical. We thus focus on the aggregated behav-

ior of representative agents. Therefore, each of the two resource importing countries has one representative household and one representative firm, as well as a benevolent government. Resources are extracted and exported to these two countries by one representative resource owner. The governments of the importing 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.

In presenting our results, we make different assumptions about the resource extracting and exporting country. In Section 3 we focus on the comparison between different policy instrument portfolios in the importing countries. Here, we assume that the only control variable of the resource exporting country is the rate of extraction, rendering it a Stackelberg follower. In Section 4, we then introduce a government of the exporting country in addition to the (private) resource owner. We implement this government as a third Stackelberg leader next to the importing countries' governments to analyze the impact of strategic interaction between importers and the exporter.

The following optimization problems characterize the individual economic agents' behavior. Their respective first order conditions can be found in Appendix B.

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 representative household, the representative firm, 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).

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

$$\text{s.t.} \quad C_t(1 + \tau_{C,t}) = r_t K_t^s + w_t L_t - I_t + \Pi_t^F + \Gamma_t \quad (7)$$

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

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 firm Π^F accrue to the household. The government may use tax revenue for lump sum transfers $\Gamma \geq 0$ to the household and it may charge a tax on consumption, τ_C .

The production sector

The representative firm in the importing country j is assumed to be a price taker. Its output is given by a neoclassical production function, which depends on four input factors – capital, infrastructure, labor, and fossil resources, denoted by $Y = F(K^d, G, L, R^d)$. For our calculations we use a nested constant elasticity of substitution (CES) function. On the lowest level, private capital K^d , which the firm may demand on the global capital market, and publicly financed infrastructure G are aggregated to an intermediate input, $\mathbf{Z}(K^d, G)$. This *general capital*, resembling governmental and private fixed assets used to produce output, is then combined with labor on the intermediate level in a further composite input $\mathbf{X}(\mathbf{Z}, L)$. Finally, on the top level, fossil resources R enter in production. We choose this specific structure since the empirically determined values for the substitution elasticities σ_i , $i = 1, 2, 3$ differ from each other. The production function takes the form

$$F(K^d, G, L, R^d) = A [\alpha_1 (A_R R^d)^{s_1} + (1 - \alpha_1) \mathbf{X}(\mathbf{Z}, L)^{s_1}]^{\frac{1}{s_1}}, \quad (9)$$

where $\mathbf{X}(\mathbf{Z}, L) = [\alpha_2 \mathbf{Z}(K^d, G)^{s_2} + (1 - \alpha_2) (A_L L)^{s_2}]^{\frac{1}{s_2}}$.

and $\mathbf{Z}(K^d, G) = [\alpha_3 (K^d)^{s_3} + (1 - \alpha_3) (A_G G)^{s_3}]^{\frac{1}{s_3}}$.

The exponents s_i , $i = 1, 2, 3$, are determined by the respective elasticities of substitution σ_i via $s_i = \frac{\sigma_i - 1}{\sigma_i}$. We assume $\sigma_1 < 1$,⁵ and for the share parameters it holds that $\alpha_i \in (0, 1)$, $i = 1, 2, 3$. A denotes total factor productivity, while A_ζ is the productivity of the factor $\zeta = R, G, L$.

The production technology (9) exhibits constant returns to scale in all four inputs. Since the firm only pays for the three privately provided in-

⁵ See Appendix A for more details on the calibration and choice of model parameters.

puts, profits are non-zero, that is, there are economic rents caused by the unpaid factor. The public input in our analysis is assumed to be of the *firm-augmenting* type.⁶

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 , a payroll tax τ_L on the use of labor, or a source based carbon tax τ_R , to the government.⁷ We have based our choice to model τ_K and τ_L as ad valorem and τ_R as unit tax on reality: The political debate about CO₂ taxes focuses on unit taxes; corporate tax rates, which are approximated by the capital tax, and payroll taxes are usually given in ad valorem terms.

The firm's objective is to choose the amount of capital, labor, and fossil resources it demands in each period which maximizes profit for all points t in time,

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

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

⁶ The alternative assumption that it is of the *factor-augmenting* type, which means that G affects total factor productivity, would imply that the production technology exhibits increasing returns to scale. The solution of the non-linear program then would become technically more challenging. Using the factor-augmenting type would thus complicate matters unnecessarily, since we expect that it would not change our results qualitatively: Matsumoto (1998) addresses the technical difference between the two types in the context of tax competition.

⁷ One could also implement τ_K or τ_L as a unit tax, or τ_R as an ad valorem tax. Whether unit, or ad valorem taxes are chosen for the respective input factors has only a relatively weak impact on our results – they are robust with respect to this choice. Determining the differences in detail, though, is a research question that goes beyond the scope of this paper. For a general discussion see Suits and Musgrave (1953). Studies focusing on this question in the light of capital mobility are Lockwood (2004) and Hoffmann and Runkel (2012).

their respective after- tax prices:

$$F_K = r(1 + \tau_K) \quad (10)$$

$$F_L = w(1 + \tau_W) \quad (11)$$

$$F_R = p + \tau_R \quad (12)$$

The fossil resource sector

The representation of the resource extraction sector is based on the classical models of Hotelling (1931) and Dasgupta and Heal (1974). The resource owner depletes the finite stock S of a generic fossil resource according the equation of motion

$$S_{t+1} - S_t = -R_t, \quad S_0 \text{ given}, \quad (13)$$

and sells the quantity R_t in each period on the international resource market at the price p_t . The generic fossil resource can be thought of as coal, oil, and gas. In reality, fossil resources are widely dispersed across the surface of the earth. In particular this holds true for coal. Nevertheless, we abstract from a symmetric endowment with coal among all countries, since our results would not change qualitatively. In general, differentiating between different types of fossil resources would improve model realism, but it would also complicate the analysis substantially and, thus, lies beyond the scope of the present study.

The extraction costs c_t are assumed to increase with cumulative extraction, as the most accessible resources are depleted first. We implement the same cost function used in the model PRIDE (see e.g. Kalkuhl et al., 2012), which is based on the assessment of world hydrocarbon resources by Rogner (1997).⁸

⁸ The detailed formulation of the extraction costs is given in Appendix A.2.

The resource owner makes decisions about the resource extraction path over time in order to maximize the sum of profits in each period $\Pi_t^R = (p_t - c_t)R_t$, discounted by the market interest rate net of depreciation $r_t - \delta$, which she takes as given. More precisely, the cake eating problem reads:

$$\max_{R_t} \sum_{t=0}^T \Pi_t^R \left(\frac{1}{1 + r_0 - \delta} \cdot \dots \cdot \frac{1}{1 + r_t - \delta} \right) \quad (14)$$

$$\text{s.t.} \quad \sum_t R_t \leq S_0. \quad (15)$$

The government

The firms, the resource owner, and the households take all taxes as given. The government of a resource importing country balances the marginal benefits of additional infrastructure investments with the marginal costs of public funds, that is, the policy costs of additional distortionary taxes. In the market equilibrium of the decentralized economy, the government acts as Stackelberg leader and optimizes the representative household's welfare by choosing the tax paths.

Note that the policy instruments – except the payroll tax – are not allocation neutral. Non-zero taxes on capital, and consumption always distort the decisions of the households in our model. On the other hand, a carbon tax path $\{\tilde{\tau}_{R,t}\}_{t \in \{1, \dots, T\}}$ under which the extraction path remains unchanged does exist.⁹ In practice, though, the timing on the income side of governmental fiscal policy does not match the optimal timing on the expenditure side in general: The result of such a path $\{\tilde{\tau}_{R,t}\}_{t \in \{1, \dots, T\}}$ would be inefficient over- and underprovision of infrastructure at different points in time.¹⁰

⁹ In the Hotelling model it is possible to show that the extraction path remains unchanged if the resource price and the unit tax grow at the same rate.

¹⁰ Theoretically it would be possible to decouple the income and the expenditure sides: Governments could use positive tax transfers Γ as a buffer to adjust the carbon tax path

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 a fraction d_t of total tax revenue $\mathcal{T}_t = r_t \tau_{K,t} K_t^d + w_t \tau_{L,t} L + \tau_{C,t} C_t + \tau_{R,t} R_t^d$ to the domestic households as lump sum transfers (Γ_t) and a fraction $(1 - d_t)$ to investments in the infrastructure stock (I_t^G). The infrastructure stock evolves according to the equation of motion

$$G_{t+1} = G_t + I_t^G - \delta G_t. \quad (16)$$

The government's problem thus reads

$$\begin{aligned} \max_{\tau_{K,t}, \tau_{L,t}, \tau_{C,t}, \tau_{R,t}, d} \quad & W = \sum_{t=0}^T L_t U(C_t/L_t) \left(\frac{1}{1 + \rho} \right)^t \\ \text{s.t.} \quad & \Gamma_t = d_t \mathcal{T}_t, \\ & I_t^G = (1 - d_t) \mathcal{T}_t, \end{aligned}$$

and Equations (1), (2), (7) – (13), (15), (16), and (B.1) – (B.6).

2.3. *Equilibria of the economy*

We frame the optimization problem as a non-linear program and solve the economy for the Nash equilibrium using the GAMS software (Brooke et al., 2005). The solution algorithm is described in Appendix C, the program code is contained in the supplementary material.

such that it would be allocation neutral. Any excess in tax revenue that would not be needed for the optimal financing of infrastructure would be transferred to households as lump sum transfers. In practice, though, such an excess revenue will be competed away through a race-to-the-bottom in carbon taxes.

All economic agents take the strategies of the other agents as given. The two governments of the importing countries and the government of the exporting country have an advantage, though, as they are assumed to be Stackelberg leaders and may move first, or, to formulate it in different terms, they anticipate the reactions of firms, households, and the resource owner. We analyze two different solutions: the case of cooperative and non-cooperative importers, by which we mean that welfare is maximized jointly and separately, respectively. This way we can construct a counterfactual to reality in which countries actually do compete for mobile factors. Comparing the two equilibria, we can isolate the effects of harmful tax competition, which disappear when importers cooperate.

Non-cooperative importers

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 external resource owner. This makes the government a Stackelberg leader of the resource owner and firms and households, both domestic *and* foreign.¹¹

At the same time, one country's government also faces the other countries' governments, Stackelberg leaders of the global economy as well.¹² Thus, governments sit at two game tables – here a Stackelberg and there a simul-

¹¹ This assumption is crucial for the present study in order to ensure that governments anticipate how mobile capital will be absorbed by firms abroad. It also seems more realistic than the case in which the domestic government forms no expectations about foreign agents at all. Introducing imperfect knowledge would add further parameters and raise questions which lie beyond the scope of the present study.

¹² Strictly 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.

taneous move game. In the former sub-game, the importers' governments have the objective of financing local infrastructure and they strive to balance the benefits from additional infrastructure with the policy costs of the distortionary taxes. The exporters' government only maximizes profits. 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 governments 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 the resource owner in response to the policy instrument choice.

More formally, the objective of a government of an importing country j is to maximize its payoff, that is, its welfare W_j . The objective of the exporter's government is to maximize the discounted sum of profits given by equation (14). The strategies of the importers' governments are $\{d_t^j, \tau_{\zeta,t}^j\}$ where $t \in \{1, \dots, T\}$ and $\zeta \in \{K, L, C, R\}$. The exporter's government chooses only the path of the export tax $\{\tau_{RO,t}\}$. Each government takes as given the respective other governments' strategies. Note that throughout Section 3 we assume that the exporter's government may not use any taxes, in order to concentrate on the assessment of different tax portfolios in resource importing countries.

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 $\{d_t^j, \tau_{\zeta,t}^j\}$, where $j = 1, 2$, $t \in \{1, \dots, T\}$, and $\zeta \in \{K, L, C, R\}$, that maximize the joint welfare of both importing countries, $W_1 + W_2$.

3. Optimal tax policies and portfolios

In this section, we assess the performance of different tax instruments in a setting of tax competition. We first consider tax portfolios in which both importing countries may use only one type of instrument, and the government of the exporting country does not implement any taxes. Then, we allow the use of a mixed tax instrument portfolio. Finally, we show how our results depend on the choice of two key parameters. In particular, we vary the substitution elasticity between fossil resources and the composite of all other inputs, as well as the substitution elasticity between capital and infrastructure. .

Throughout this section we assume that the resource exporter does not interact strategically and that the governments of the importing countries do not cooperate.

3.1. *Single instrument portfolio*

We compare the outcome of the Nash game that the two importers' governments play. For exposition, both governments may only use one and the same of the following tax instruments: resource tax τ_R ; payroll tax τ_L ; consumption tax τ_C ; capital tax τ_K . Table 1 shows the net present value of aggregate consumption in an importing country as a measure of their welfare, and the resource exporter's profit, for the four different taxes. The net present value of any flow variable X_t is calculated as the sum over the entire time horizon, discounted by the pure rate of time preference ρ , that is,

$$NPV(X) = \sum_t \frac{X_t}{(1 + \rho)^t}. \quad (17)$$

We find that consumption is highest under the carbon tax, followed by the payroll tax, and then the capital tax. Consumption is lowest under the

consumption tax. Thus the carbon tax is the most efficient choice for the government of an importing country.

Further, when the carbon tax is implemented, the profits of the resource owner are lowest. By implementing the carbon tax, resource importing countries capture part of the resource rent, which they then invest in their local infrastructure. The other tax instruments do not give this advantage to the importing countries. Even though we model labor as fixed in supply and thus the payroll tax does not distort the economy, governments cannot use it to capture the resource rent. Both, consumption and capital tax also lack this advantage. In addition, they distort the households' decisions how much to save or to consume, which is why they are inferior to the payroll tax.

	$NPV(C)$	$NPV(\pi_R)$
τ_R	1346	155
τ_L	1325	248
τ_C	1308	259
τ_K	1299	236

Table 1: Net present value in trillion US\$ of consumption in an importing country, $NPV(C)$, and of the resource owner's profits, $NPV(\pi_R)$, when both governments choose either only the optimal carbon tax τ_R , only the payroll tax τ_L , only the consumption tax τ_C , or only the capital tax τ_K . Consumption is highest, when only τ_R is used. In this case, importers may capture the highest portion of the Hotelling rent and the exporter's profits are lowest.

For the evaluation of the policy instruments the net present value of aggregate consumption is a decisive indicator, but it does not tell us the full story. The timing of the flow of *per capita* consumption matters for social welfare, as defined by equation (5). It depends on the intertemporal elasticity of consumption $1/\eta$. Here, the carbon tax achieves the highest welfare as well as the highest net present value of consumption. Table 2 summarizes the relative difference in balanced growth equivalents¹³ between

¹³ The method of balanced growth equivalents translates the unit-less difference in

	Welfare losses relative to policy case τ_R
τ_L	2.3 %
τ_K	2.4 %
τ_C	3.0 %

Table 2: Average welfare losses in countries 1 and 2 when their governments use only the payroll tax τ_L , only the capital tax τ_K , or only the consumption tax τ_C , relative to the case when they use only the carbon tax τ_R .

the carbon tax on the one hand, and the capital tax, the consumption tax, and the payroll tax on the other. The data reveal that even though the net present value of aggregate consumption under the capital tax is lowest among the four instruments, it ranks third with respect to social welfare.

Thus, when we compare the two internationally mobile factors capital and fossil resources as tax bases, we see a fundamental asymmetry. The endowment with fossil resources gives rise to a scarcity rent (evident in the profits of the resource sector in our model), while private capital does not. Therefore, the carbon tax performs much better in importing countries when their governments have to take into account both the income and the expenditure side of their fiscal policy, as well as the international integration of factor markets.

welfare into the more tangible consumption difference in dollars. It has been introduced by Mirrlees and Stern (1972), but since our model uses discrete time steps, we follow the accordingly modified method of Anthoff and Tol (2009).

3.2. *Mixed tax portfolios*

By allowing the use of only one single tax instrument in the preceding section, we have identified the possibility to capture part of the Hotelling rent with the carbon tax. We now turn to the more realistic case in which governments use a combination of all tax instruments.

In order to focus the role international factor mobility plays for the design of tax portfolios in resource importing countries, we restrict our analysis to those taxes which have mobile factors as tax base, that is, capital and resources. Thus, for the rest of the paper, we make the assumption that the payroll tax and VAT rates are fixed at a specific level, respectively, which is based on data compiled by the World Bank (2014) and the OECD (2014). For more details see Appendix A. Governments may determine only the tax rates on the use of carbon and capital optimally.

A comprehensive discussion including the role of consumption and payroll taxes lies beyond the scope of this paper, because the simultaneous calculation of the optimal time path of four different instruments causes complex tax interaction effects. Further, political economy reasons suggest to focus on carbon and capital taxes. Payroll taxes and VAT are already relatively high and up to now have been used to compensate fiscal losses from lowered corporate income taxes. Our point of departure is thus a situation where governments are much more constrained in their ability to raise payroll taxes or the VAT than to raise environmental taxes.

Figure 1 shows how the tax income of an importing country evolves over time in absolute terms. The revenues from the fixed labor and consumption tax rates are quite high. Further, the amount of income generated with the carbon tax exceeds by far the income from taxing capital. The net present value of tax income generated by the carbon tax in an importing country

amounts to about \$116 trillion over the entire time horizon, while the capital tax generates only \$6 trillion.

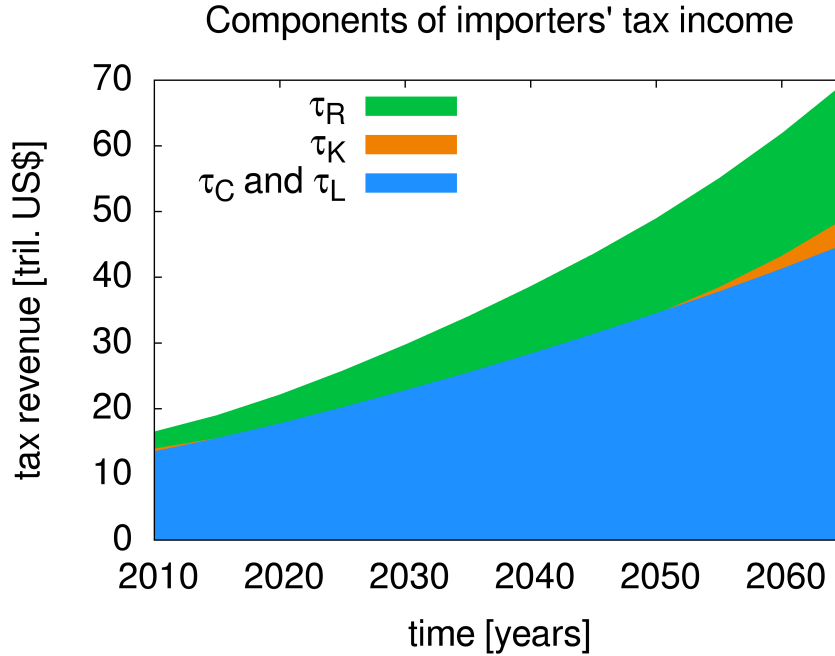


Figure 1: Tax income, decomposed into contributions by the endogenously determined carbon tax τ_R and capital tax τ_K , as well as the fixed consumption and payroll tax ($\tau_C = \tau_L = 0.16$), respectively.

The outcome confirms our insight from Section 3.1. Because the carbon tax can capture part of the Hotelling rent, it plays a decisive role in the unilaterally chosen tax portfolio of an importing nation. Note that this result is robust under the variation of the exogenously fixed rates for the tax on consumption or on labor.

3.3. Substitution elasticities

A sensitivity analysis of the model to assumptions about parameter values showed no particular sensitivity toward any one parameter.¹⁴ To explore the

¹⁴ We have conducted a local sensitivity analysis by varying all parameters one-at-a-time. A parameter variations of $\pm 5\%$ resulted in changes of the net present value of aggregate consumption of the same or smaller order of magnitude. The data can be found

robustness of our findings, we therefore focus on the two parameters which are critical to the characterization of the tax bases of capital tax and carbon tax, namely the parameters governing their factor substitution possibilities. We begin by analyzing how the net present value of aggregate consumption depends on the elasticity of substitution σ_1 between fossil resources and the composite input $\mathbf{X}(K, G, L)$, which combines private and public capital with labor. Then, we perform the same experiment for σ_3 , the elasticity of substitution between private capital and infrastructure. Two policy cases are subject to our comparison, one in which governments determine the capital tax endogenously and do not use the carbon tax, and vice versa. The taxes on consumption and labor remain at their constant level, as discussed in Section 3.2.

Substitution elasticity between fossil resources and composite \mathbf{X}

Table 3 summarizes the net present value of aggregate consumption for the two policy cases. The first two columns show their absolute values.

σ_1	NPV(C), τ_R [tril. US\$]	NPV(C), τ_K [tril. US\$]	absolute difference [tril. US\$]	relative difference [fraction of GDP]
0.3	1208	1148	60	5.5%
0.4	1293	1240	53	4.8%
0.5	1355	1308	47	4.2%
0.6	1401	1360	41	3.6%
0.7	1436	1399	37	3.2%

Table 3: Net present value (NPV) of aggregate consumption in an importing country for the policy cases in which the importers' governments only determine the carbon tax τ_R or only the capital tax τ_K endogenously. The relative difference is given by $\Delta_{rel} = \frac{NPV(C)}{NPV(GDP)} \Big|_{\tau_R} - \frac{NPV(C)}{NPV(GDP)} \Big|_{\tau_K}$. The net present value of the flows of aggregate consumption and output is calculated as defined by equation (17).

We would like to highlight two observations. First, when the two inputs

in the supplementary material.

are assumed to be complementary, that is, $\sigma_1 < 1$, the carbon tax performs better than the capital tax. Our standard value for the elasticity is $\sigma_1 = 0.5$ (for a discussion of the empirical literature see Appendix A).

Second, with a smaller elasticity of substitution, the advantage of the carbon tax over the capital tax increases. The explanation for the latter observation lies in the shape of the demand functions for the input factors. The lower the elasticity of substitution in any CES production function is, the more inelastic demand for the inputs becomes.¹⁵ When demand is relatively inelastic, fossil resources R and the composite input $\mathbf{X}(K, G, L)$ become relatively fixed factors and taxes on these factors distort the market outcome less. Within the composite input, though, substitution between the three inputs is still possible – in particular, labor and infrastructure can be substituted for capital, even when the elasticity σ_1 is low. Thus, capital remains relatively more elastic in supply when the elasticity σ_1 decreases, while fossil resources become a relatively fixed factor and can be taxed at lower costs than capital.

Substitution elasticity between capital and infrastructure

Varying σ_3 , the elasticity of substitution between private capital and infrastructure, has a relatively weak impact on the model results, when we compare it with the above result on σ_1 . In table 4 we present this finding. Nevertheless we observe a subtle trend in the relative difference between the two policy cases. The harder it gets to substitute capital for infrastructure, the greater is the difference in net present value of consumption between the two policy cases in relative terms. In other words, the more inelastic the demand for infrastructure is, the more pronounced becomes the advantage of the carbon

¹⁵ The derivation of the demand functions from a given CES production function can be found in Allen (1938), p. 369 ff.

tax.

σ_3	NPV(C), τ_R [tril. US\$]	NPV(C), τ_K [tril. US\$]	absolute difference [tril. US\$]	relative difference [fraction of GDP]
0.7	1319	1273	46	4.52%
0.9	1342	1300	42	4.46%
1.1	1355	1308	47	4.16%
1.4	1368	1321	47	4.14%
1.7	1376	1330	46	4.07%

Table 4: Net present value (NPV) of aggregate consumption in an importing country for the policy cases in which the importers' governments only determine the carbon tax τ_R or only the capital tax τ_K endogenously. The relative difference is given by $\Delta_{rel} = \frac{NPV(C)}{NPV(GDP)} \Big|_{\tau_R} - \frac{NPV(C)}{NPV(GDP)} \Big|_{\tau_K}$. The net present value of the flows of aggregate consumption and output is calculated as defined by equation (17).

4. Supply side dynamics of resource extraction

In the preceding sections we showed that a carbon tax is superior to capital taxation because the carbon tax has the ability to appropriate part of the resource rent. The argument in favor of carbon taxation was based exclusively on the goal of fiscal efficiency in resource importing countries.

In this section, we consider environmental aspects by identifying the impact of carbon taxation on the supply side dynamics of fossil resource extraction. We compare three tax portfolios. Again, we focus on mobile tax bases, thus the taxes on consumption and labor remain at their fixed level. Governments may either only specify the capital tax, or only the carbon tax, or both the capital and the carbon tax.

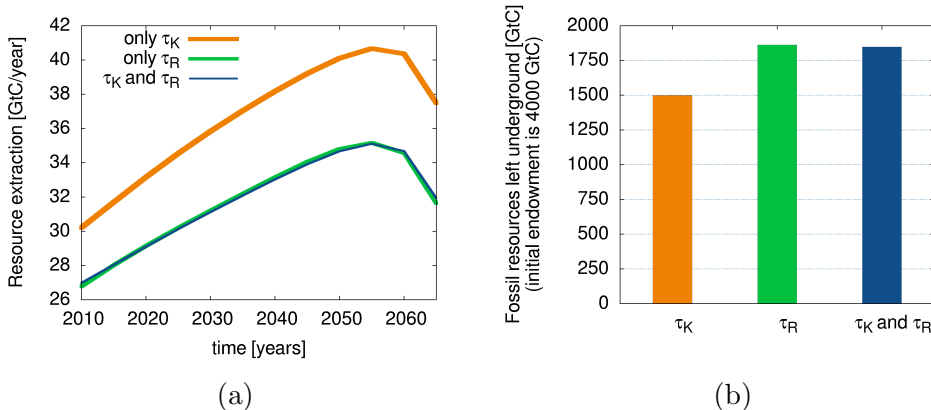


Figure 2: Timing and volume effects of different policy instrument portfolios. Compared to the case in which importing governments only determine the capital tax optimally, portfolios which include an optimally determined carbon tax lead to both a lower rate of extraction and lower cumulative extraction.

Figures 2a and 2b show the time path of resource extraction for the three different policy cases, as well as the amount of fossil resources left underground at the end of the time horizon, respectively. We observe that the use of a carbon tax postpones extraction and also leads to a lower level of cumulative extraction over the entire time horizon, that is, it causes a

conservative volume effect. In other words, the use of carbon taxes to finance infrastructure investments causes no green paradox, but constitutes a viable green policy.

The above result has a straight forward rationale. When an importer's government imposes a tax, it chooses a time profile that balances the marginal benefits of additional infrastructure investments with the marginal costs of public funds, that is, the policy costs of the tax. While capital taxation will always distort the economy, at least theoretically a neutral carbon tax path exists. Since the importers' governments not only have to take into account the income side, but also the expenditure side of their fiscal policy, in general the time profile of a carbon tax will not be allocation neutral: The optimal timing of investments in infrastructure is incongruent with the optimal timing of taxing the use of the fossil resource. Thus, while the capital tax has only an indirect impact on the resource market, the carbon tax increases the consumer price and decreases the producer price. This leads to a significant reduction of the cumulative quantity of resources sold.

5. Assumptions about strategic behavior

In the two preceding sections we have shown our main results. Resource importing countries prefer to finance their infrastructure by using the carbon tax rather than the capital tax. If they do so, fossil resource extraction is postponed and cumulative emissions are reduced. The aim of the present section is to show that our two main results are robust under a variation of the behavioral assumptions of the resource importers to coordinate their actions, and the resource exporter to counteract carbon policies.

Our premise that resource importing countries compete in their policies for mobile factors is based on the empirical evidence for tax competition

around the world. However, the prospect of valuable resource rents as suggested by our analysis may motivate importers to negotiate coordinated policies. Furthermore, nations are already negotiating about climate policy striving for a coordinated price on carbon emissions, which would have similar implications for resource imports.

Therefore, we ask how the outcome of our modeled economy changes, when the governments of the importing countries could actually cooperate to maximize their joint welfare. It is known from the theoretical literature that a resource buyers' cartel can exercise monopsony power and capture a greater portion of the resource rent, see Karp (1984), Tahvonen (1995), and Amundsen and Schöb (1999). Our analysis confirms the result for the case of an exporter that does not act strategically, and we provide an estimate of the magnitude.

Conversely, resource suppliers may not remain idle when policies are implemented that deprive them of their rent income. One option for the resource exporting country is to use domestic tax instruments to interact strategically on the international resource market. When importers charge a tax for the use of fossil resources, the government of the exporting country has an incentive to tax its exports to prevent the rent from being captured by the importers.

5.1. Volume effects

The first result we would like to highlight concerns the volume effect of a carbon tax. In Figure 3 we present an overview over the three policy cases already considered in Section 4 and all four combinations of assumptions about strategic behavior of the importers' and exporter's governments.

In most cases we see that allowing cooperation among importers leads

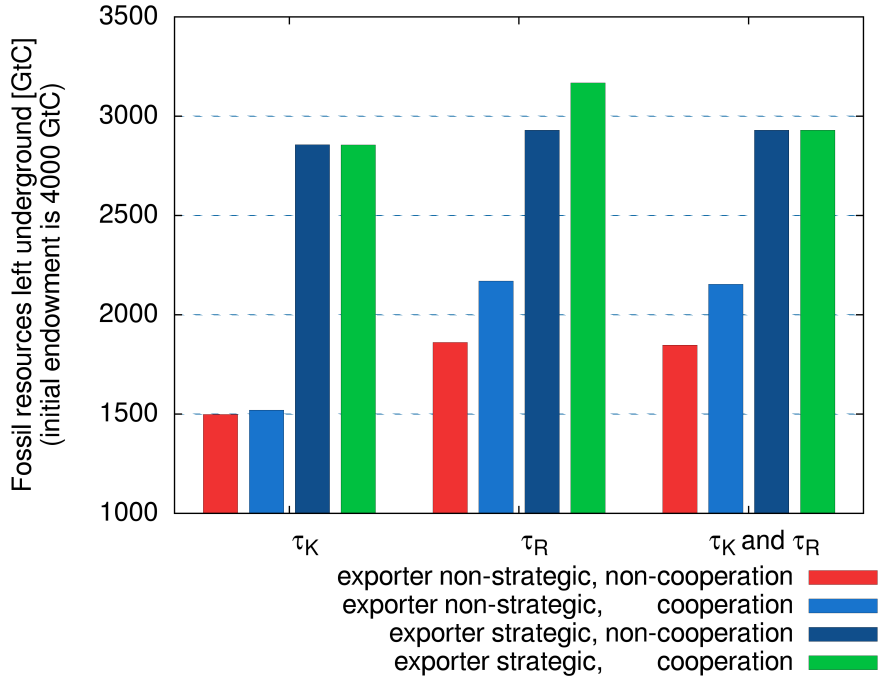


Figure 3: Amount of fossil resources left underground at the end of the time horizon. For the corresponding table, see Appendix D, Table 6.

to an increase of the amount of fossil resources left underground. The assumption about the strategic behavior of the exporter’s government has a much greater impact, though. When the exporter’s government reacts to the importers’ policies by taxing resource exports, we see a strong increase in the amount of resources left underground. The exporter’s government has an incentive to implement very high tax rates in order to retain the resource rent. Thus, the consumer price of fossil resources increases and the quantity sold on the market decreases.

The result from the previous section on the dependence of the volume effect on the policy instrument portfolio is robust under the varying assumptions about strategic behavior of the governments. Importers may cooperate or not, and the exporter may act strategically or not – in all cases we observe that when the importers include a carbon tax in their portfolio to finance their infrastructure, more resources are left underground than if only the

capital tax is used. A green paradox occurs in none of the four cases.

5.2. The resource rent

In Figure 4 we summarize our findings for the dependence of the resource rent on the tax portfolios of the importers and our assumptions about the strategic behavior of the different governments. The graph shows the net present value of the resource owner's profits.

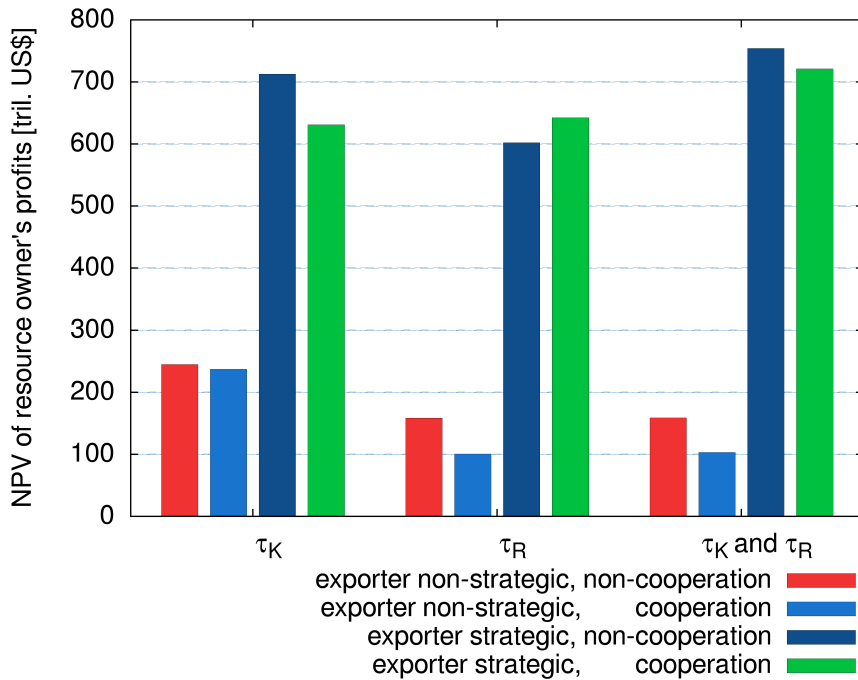


Figure 4: Net present value (NPV) of resource owner's profits. For the corresponding table, see Appendix D, Table 7.

If we first consider those cases in which the exporter may not interact strategically, we see that cooperation among importers always reduces the exporter's profits. When governments cooperate, they design their policies such that the exporter has to accept market conditions that are similar to those which would be caused by monopsony power.¹⁶ When we compare

¹⁶ Since the governments are not identical with the agents who buy the resource, we cannot directly refer to the effect as monopsony. The firms, which are the ones that buy the resource, are assumed to be price takers and have no market power by themselves.

the carbon and capital tax rates, we observe that both increase significantly if the importing countries cooperate. Under cooperation, no harmful tax competition occurs.

The effect of the assumption whether importers cooperate is much smaller, though, than the impact of allowing the government of the exporting country to interact strategically. When we allow it to tax resource exports, it is quite successful in retaining more of the resource rent. As we have seen above, the quantity sold is reduced significantly, but the increase in the resource price caused by the export tax overcompensates the reduction in quantity. It comes as no surprise that opening up the policy space for the exporter's government should increase the resource owner's payoff.

Further, when the exporter interacts strategically, the assumptions about cooperation and the choice of the policy instrument portfolio have ambiguous impacts on the resource owner's profits. The ambiguity results from the complex interplay of a multitude of strategic and general equilibrium effects. A complete characterization of all these effects lies beyond the scope of the present paper. However, one additional known effect is that the importers now face a relatively high resource price due to the exporter's policy. Thus, in some cases the importers set their carbon tax rates lower than when the exporter does not interact strategically. If both capital and carbon taxes are available, for instance, the importers' governments use the carbon tax to subsidize fossil resources while revenues are generated with the capital tax.

5.3. Consumption and welfare

To complete the assessment of the impact of different assumptions about strategic behavior and tax portfolios, we present an overview of the net present value of consumption in an importing country in Figure 5.

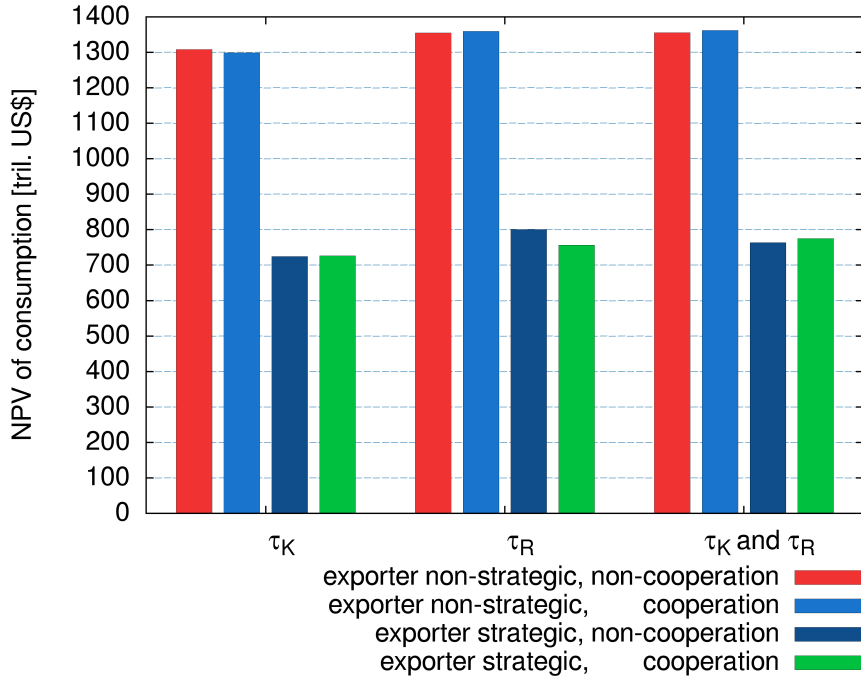


Figure 5: Net present value (NPV) of consumption in an importing country. For the corresponding table, see Appendix D, Table 8.

In most cases, cooperation among importers and strategic behavior of the exporter result in the outcomes we would expect intuitively. When importers cooperate, they are able to increase their consumption slightly.

When only the capital tax is available and exporters do not interact strategically, we see that cooperation has a negative effect on consumption. However, Figure 6 reveals that social welfare in the importing countries actually increases under cooperation, which restores our intuition, that without cooperation harmful capital tax competition occurs. Figure 6 shows that except for the latter case, the welfare ordering and the ordering of consumption are identical.

When only the carbon tax is available and exporters may interact strategically, cooperation not only decreases consumption but also social welfare in the importing countries. Under cooperation the average carbon tax rate is decreased by approximately ten percent relative to the case of non-cooperation.

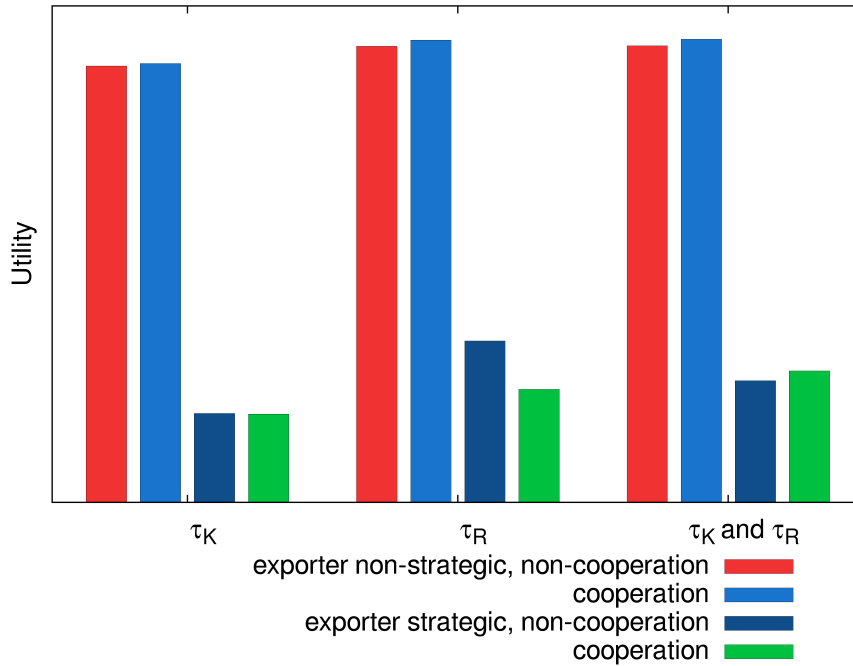


Figure 6: Social welfare in importing countries. For the corresponding table, see Appendix D, Table 9.

We conjecture that the rationale behind the reduction is the incentive to try to reduce the carbon price, which is driven up by the strategic actions of the exporter.

Strategic behavior of the exporter's government has a much stronger impact on aggregate consumption in the importing countries than cooperation among importers. When we allow for an export tax to be levied, the net present value of consumption in an importing country decreases by around 50%, independently of the assumptions about cooperation and the policy instrument portfolio.

Most importantly, the use of a carbon tax increases the net present value of consumption relative to a tax portfolio which only uses a capital tax. This confirms the results we have presented in Section 3: Resource importing countries prefer to tax carbon instead of capital.

6. Conclusion

In our analysis, we have used an intertemporal numerical general equilibrium model to calculate the opportunity costs of implementing different tax portfolios to finance productive infrastructure investments.

We have two main results. First, we find that the carbon tax is superior to the capital tax with respect to social welfare in the resource importing countries. This is because the costs of public funds are lower when governments include the carbon tax in their portfolios. Using the carbon tax has the advantage for governments of resource importing countries that they may capture part of the rents of fossil resource owners. Here lies the difference between capital and fossil resources as a tax base. While the ownership of fossil resources gives rise to a scarcity rent, capital does not. Thus, the former can be taxed more efficiently than the latter. This efficiency result is also robust under different assumptions about the strategic behavior of the different governments. The carbon tax is the superior tax, no matter whether the governments of the importing countries cooperate or not, or whether the government in the exporting country may interact strategically on the resource market.

Second, the unilateral implementation of carbon taxes does not cause a green paradox. Quite the contrary, under all assumptions about the strategic behavior of governments listed above, unilaterally imposing a carbon tax postpones extraction and reduces the amount of cumulative emissions. A carbon tax constitutes a viable green policy option.

Our analysis of the assumptions about the strategic behavior of the importers and the exporter of fossil resources has shown that the interaction of the economic agents can become quite complex. A full characterization of

all involved effects lies beyond the scope of the present paper, but could be a promising avenue for future research.

Thus, when we go beyond our model and its non-environmental scope, we can draw an important conclusion from our results. Even when governments do not intend to address the climate externality in any way, they have a strong incentive to implement a carbon tax to improve the efficiency of their fiscal policy. When only fiscal aspects are considered, the introduction of a carbon tax nevertheless contributes to the effort of mitigating the adverse effects of climate change.

Our results suggest to rethink the role of carbon taxes. We conclude that not only the environmental ministers are the ones who should favor carbon taxes, but also the ministers of finance.

Appendix

A. Calibration and implementation of model

We assume that resource importing countries are characterized by the same economic parameters. The model should apply to countries with comparable endowments and production technologies, which compete on international capital markets. These could be member states of the EU, or China and the USA. Each resource importing country's initial endowment of public and private capital is given by the same share of the initial global endowment. Table 5 summarizes the parameters used in the model. If not otherwise indicated, we have chosen their values in accordance with the closely related model PRIDE¹⁷, as introduced in Kalkuhl et al. (2012), and the model comparison exercise referenced therein, Edenhofer et al. (2010).

We estimate the initial global level of infrastructure G_0 according to the ratio of public to private fixed assets from US data published by the Bureau of Economic Analysis (BEA, 2013). The tax rate on consumption of 16 % is calculated as weighted average over all countries of 2013 rates taken from data of the OECD (2014), where the respective countries are weighted according to their GDP. The average payroll tax rate of 16 % is taken from the World Banks' world development index on labor tax and contributions (World Bank, 2014).

The parameters of the production function are calibrated according to the empirical literature. We insert the elasticities of substitution between the respective factors directly. The share parameters α_i , $i = 1, 2, 3$ are chosen such that the observed output elasticities reported in Calderón et al. (2014), Bom and Ligthart (2013), and Caselli and Feyrer (2007) are matched.

¹⁷ Both 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.

The variation of σ_1 , the elasticity of substitution between the fossil resource R and general capital \mathbf{Z} , is a key method to generate part of our results. In particular, results are relatively sensitive to variations of σ_1 . Therefore, we have calibrated the CES production function to a specific baseline point (Klump and Saam, 2008). As standard value, we choose $\sigma_1 = 0.5$, which is in line with the literature on CGE models (see for example Burniaux et al., 1992; Babiker, 2001; Burniaux and Truong, 2002; Paltsev et al., 2005; Edenhofer et al., 2010).

As the benchmark case for the elasticity of substitution between public and private capital, σ_3 , we have implemented a value of 1.1. The empirical literature gives mixed evidence about the substitutability between public and private capital and identifies both cases of relatively high and low substitutability between the two factors. It turns out that the results presented in this paper are quite robust under variation of σ_3 , cf. Section 3.3.

A.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:

$$\begin{aligned}\gamma_{\zeta,t} &= \gamma_{\zeta,0} e^{-d_{\zeta}t} \\ A_{\zeta,t+1} &= A_{\zeta,t} \left(1 + \left(\frac{\gamma_{\zeta,t}}{1 - \gamma_{\zeta,t}} \right) \right), \quad A_{\zeta,0} \text{ given,}\end{aligned}$$

where $\zeta = L, R$.

A.2. Extraction costs

The calibration of extraction costs c_t is based on Rogner (1997). Costs depend on the size of the resource stock S_t and on the cost of capital, that is, the interest

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 $\mathbf{Z}(K, G)$ and L	σ_2	0.7		
Share parameter of private capital K	α_3	0.7		
Elasticity of substitution between K and G	σ_3	1.1	0.5 – 4	Baier and Glomm (2001)
				Coenen et al. (2012)
				Otto and Voss (1998)
Total factor productivity	A	1		
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_L	0.001		“
Productivity of infrastructure	A_G	2		“
Initial world capital [tril. US\$]	K_0	165		
Initial world infrastructure [tril. US\$]	G_0	50		
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] [years]	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 5: List of model parameters. If source not indicated otherwise, values are chosen in accordance with Kalkuhl et al. (2012) and Edenhofer et al. (2010).

rate r_t . The costs are given by

$$c_t(S_t, r_t) = r_t \left(1 + \frac{\chi_2}{\chi_1} ((S_0 - S_t)/S_0)^{\chi_3} \right).$$

B. 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 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

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

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

$$\frac{L_t^{\eta-1}}{C_t^\eta} = \lambda_t(1 + \tau_{C,t}), \quad (\text{B.1})$$

$$\lambda_{t-1}(1 + \rho) = \lambda_t(1 + r_t - \delta), \quad (\text{B.2})$$

$$(I_T - (1 - \delta)K_T^s) \lambda_T = 0. \quad (\text{B.3})$$

Resource extraction sector

The resource owner maximizes her intertemporal stream of profits (14) taking into account the resource constraint (15), the equation of motion for the stock (13), and possibly a unit tax τ_{RO} on exports. We assume that the government of the resource exporting country recycles the tax revenue $\tau_{RO,t}R_t =: \Psi_t$ as lump-sum transfer to the resource owner. The resource owner does not anticipate its influence on Ψ , but takes it as given. The Hamiltonian then reads

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

and thus the first order and terminal conditions for the control and costate variables

R and λ^R are

$$\lambda_t^R = p_t(1 - \tau_{RO,t}) - \frac{r_t}{\kappa_t}, \quad (\text{B.4})$$

$$\lambda_t^R - \lambda_{t-1}^R(1 + r_t - \delta) = -\frac{r_t R_t \chi_2 \chi_3}{\chi_1 S_0} \left(\frac{S_0 - S_t}{S_0} \right)^{\chi_3 - 1}, \quad (\text{B.5})$$

$$\lambda_{T-1}^R S_T = 0. \quad (\text{B.6})$$

C. Solution algorithm

We solve the model in four phases:

Phase 1: Find good initial values.

Phase 2: Find symmetric policy variables with Nash algorithm.

Phase 3: Solve model with fixed policy variables to find good lower bound for investment in last period.

Phase 4: Find symmetric policy variables with Nash algorithm and fixed lower bound for last-period investment.

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

```

D. Data tables corresponding to Figures 3 to 6

	non-strategic exporter		strategic exporter	
	no cooperation	cooperation	no cooperation	cooperation
τ_K	1498	1521	2857	2856
τ_R	1862	2171	2931	3169
τ_K and τ_R	1848	2155	2931	2931

Table 6: Amount of fossil resources left underground at the end of the time horizon in gigatons of carbon, GtC (corresponds to Figure 3).

	non-strategic exporter		strategic exporter	
	no cooperation	cooperation	no cooperation	cooperation
τ_K	245	237	713	631
τ_R	158	101	602	642
τ_K and τ_R	159	103	754	721

Table 7: Net present value of of resource owner's profits in trillion US\$ (corresponds to Figure 4).

	non-strategic exporter		strategic exporter	
	no cooperation	cooperation	no cooperation	cooperation
τ_K	1308	1299	725	726
τ_R	1355	1359	801	757
τ_K and τ_R	1356	1362	764	775

Table 8: Net present value of consumption in an importing country in trillion US\$ (corresponds to Figure 5).

	non-strategic exporter		strategic exporter	
	no cooperation	cooperation	no cooperation	cooperation
τ_K	-254.1733	-254.0850	-266.7709	-266.7949
τ_R	-253.4569	-253.2387	-264.1391	-265.8970
τ_K and τ_R	-253.4401	-253.2067	-265.5877	-265.2286

Table 9: Unitless social welfare in an importing country (corresponds to Figure 6).

Conflict of interest

The authors declare that they have no conflict of interest.

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