

# Why finance ministers favor carbon taxes, even if they do not take climate change into account<sup>\*†</sup>

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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). National governments find themselves competing for capital through their choice of taxes. Evidence for the resulting race-to-the-bottom<sup>1</sup> in national tax policies is found in declining corporate tax rates (Benassy-Quere et al., 2007; Zodrow, 2010).

The race-to-the-bottom constrains a government’s ability to raise sufficient funds, which has far reaching consequences. Sufficient government funds are required for providing public infrastructure, which is underfinanced in many countries (Bom and Ligthart, 2013) even though it has been shown to increase productivity significantly (see e.g. Romp and de Haan, 2007, or Calderón et al., 2014). 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

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<sup>1</sup> Wilson (1986) and Zodrow and Mieszkowski (1986) have conceptualized the underlying economic mechanism. For an overview of the literature on tax competition see e.g. Zodrow (2010), Wilson (1999), and Keen and Konrad (2013).

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 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 paradox<sup>2</sup>. Further, appropriating the resource rents may meet resistance by the rent owners.

However, we find that financing infrastructure investments optimally does not require the carbon tax to increase at a higher rate than the interest rate, which is known to be a necessary condition for the green paradox to occur (Edenhofer and Kalkuhl, 2011). Carbon taxes thus do not cause a green paradox, but constitute a viable green policy, even if governments' motivation to tax fossil resources is based exclusively on their fiscal needs. Further, we explore options for strategic behavior of both buyers and sellers of carbon resources. We show that both the fiscal and the environmental implications remain beneficial regardless of whether resource importers cooperate or not, and regardless of whether resource exporters can influence the resource price strategically with an export tax.

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

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<sup>2</sup> 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 and an increase of cumulative emissions 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).

production is assumed to cause no harmful externality. Finally, we include the intertemporal dynamics of capital accumulation and resource extraction. Households' savings behavior 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. 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.<sup>3</sup> A novel insight which we derive from opening up the analysis to such interactions is the possibility of a beneficial race-to-the-top in carbon taxes. The conditions under which it occurs in our model are that capital taxes are not available and that the resource exporter strategically increases the resource price with high domestic export taxes.

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 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 – a different mechanism from the one which causes the race-to-the-top in our analysis. While the authors also study tax competition in an intertemporal general equilibrium framework, they neglect the dynamics of resource extraction.

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<sup>3</sup> 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), Amundsen and Schöb (1999), or Liski and Tahvonen (2004). We are able to reproduce this result and compare it to the outcome under non-cooperative importers.

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 from Habla (2014) 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.<sup>4</sup> 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.

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<sup>4</sup>This point is also an example of how we differ from the related literature on the double dividend hypothesis (see e.g. Bovenberg, 1999, and Goulder, 2013, for surveys), in which usually only the income and not the expenditure side of fiscal policy is considered, and which concentrates on flows and not on stocks.

## 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.<sup>5</sup> 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 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

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<sup>5</sup> 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.

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. 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 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 behavior 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  $\delta$ . The household in country  $j$  discounts future utility according to its pure rate of time preference  $\rho$ . 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  $\Pi^F$  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,  $\tau_C$ .

### *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  $\sigma_i$ ,  $i = 1, 2, 3$  differ from each other. The production

function takes the form

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

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

and  $\mathbf{Z}(K_t^d, G_t) = \left[ \alpha_3 (K_t^d)^{s_3} + (1 - \alpha_3) (A_G G_t)^{s_3} \right]^{\frac{1}{s_3}}$ .

The exponents  $s_i$ ,  $i = 1, 2, 3$ , are determined by the respective elasticities of substitution  $\sigma_i$  via  $s_i = \frac{\sigma_i - 1}{\sigma_i}$ . We assume  $\sigma_1 < 1$ ,<sup>6</sup> and for the share parameters it holds that  $\alpha_i \in (0, 1)$ ,  $i = 1, 2, 3$ .  $A_t$  denotes total factor productivity, while  $A_{\zeta,t}$  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 inputs, 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.<sup>7</sup>

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  $\tau_K$ , a payroll tax  $\tau_L$  on the use of labor, or a source based carbon tax  $\tau_R$ , to the government.<sup>8</sup> We have based our choice to model  $\tau_K$  and  $\tau_L$  as ad valorem and  $\tau_R$  as unit tax on reality: The political debate about CO<sub>2</sub> taxes focuses on unit taxes; corporate tax rates, which are approximated by the capital tax, and

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<sup>6</sup> See Appendix A for more details on the calibration and choice of model parameters.

<sup>7</sup> 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.

<sup>8</sup> One could also implement  $\tau_K$  or  $\tau_L$  as a unit tax, or  $\tau_R$  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 (2015).

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 their respective after-tax prices:

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

$$F_L = w(1 + \tau_W) \tag{11}$$

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

#### *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

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

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

$S_0 - S_t$ , as the most accessible resources are depleted first:

$$c_t(S_t, r_t) = r_t \left( 1 + \frac{\chi_2}{\chi_1} ((S_0 - S_t)/S_0)^{\chi_3} \right) \quad (14)$$

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). An overview of the parameter values used can be found in the Appendix in Table 5.

The resource owner's profits in each period are given by

$$\Pi_t^R = (p_t - c_t - \tau_{RO})R_t + \Psi = (p_t - c_t)R_t. \quad (15)$$

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, thus (15) simplifies again. However, the resource owner does not anticipate her influence on  $\Psi$ , but takes it as given, which matters for the first order conditions (see Appendix B). In maximizing her intertemporal stream of profits (16) she discounts profits by the market interest rate net of depreciation  $r_t - \delta$ , which she takes as given. She takes into account the resource constraint (17), the equation of motion for the stock (13), the extraction costs (14), and possibly the unit tax  $\tau_{RO}$  on exports.

$$\max_{R_t} \sum_{t=0}^T \Pi_t^R \left( \frac{1}{1 + r_0 - \delta} \cdot \dots \cdot \frac{1}{1 + r_t - \delta} \right) \quad (16)$$

$$\text{s.t.} \quad \sum_t R_t \leq S_0. \quad (17)$$

### *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 distorting the economy with additional taxes. 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, and how to spend the tax

revenues.

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.<sup>9</sup> 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.<sup>10</sup>

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  $\Gamma_t$  and a fraction  $1 - d_t$  to investments in the infrastructure stock  $I_t^G$ .<sup>11</sup> The infrastructure stock evolves according to the equation of motion

$$G_{t+1} = G_t + I_t^G - \delta G_t. \quad (18)$$

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<sup>9</sup> 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.

<sup>10</sup> Theoretically it would be possible to decouple the income and the expenditure sides: Governments could use positive tax transfers  $\Gamma$  as a buffer to adjust the carbon tax path 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.

<sup>11</sup> We implement the possibility of lump-sum transfers in order to avoid that our results are dominated by unrealistic timing effects due to the optimal timing of infrastructure investments. The average value of the distribution parameter  $d_t$  is 75% (average over time and all possible policy scenarios). Across different policy cases the time average does not vary by more than six percentage points.

The government's problem thus reads

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

and Equations (1), (2), (7) – (13), (17), (18), 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.

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 assume that they can commit to the policies they announce.<sup>12</sup>

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.

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<sup>12</sup> Due 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 Appendix E for more details).

### *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.<sup>13</sup>

At the same time, one country's government also faces the other countries' governments, Stackelberg leaders of the global economy as well.<sup>14</sup> Thus, governments sit at two game tables – here a Stackelberg and there a simultaneous move game. In the former sub-game, the importers' governments have to make decisions about 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 (16). 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 govern-

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<sup>13</sup> 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.

<sup>14</sup> 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.

ments' 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  $\tau_R$ ; payroll tax  $\tau_L$ ; consumption tax  $\tau_C$ ; capital tax  $\tau_K$ . Table 1 shows welfare measured in balanced growth equivalents<sup>15</sup>, and presents the relative difference between the carbon tax on the one hand, and the capital tax, the consumption tax, and the payroll tax on the other.

We find that welfare is highest under the carbon tax, followed by the payroll tax, and then the capital tax. Welfare is lowest under the consumption tax. The carbon tax is the most efficient choice for the government of an importing country.

Further, when the carbon tax is implemented, the net present value<sup>16</sup> of profits

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<sup>15</sup> Balanced growth equivalents (BGE) are a commodity measure of welfare. The BGE of a given welfare level is the value of initial consumption which yields – under a constant annual growth rate – the given level of welfare. It translates the unit-less welfare into more tangible consumption levels in dollars, and thus facilitates comparisons of policy instrument portfolios. It has been introduced by Mirrlees and Stern (1972). Since our model uses discrete time steps, we follow the accordingly modified method of Anthoff and Tol (2009). In calculating the BGE, we assume a constant annual growth rate of 2%.

<sup>16</sup> The net present value of any flow variable  $X_t$  is calculated as the sum over the entire time

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. The consumption tax and the 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.

	BGE [tril. US\$ / year]	Welfare relative to policy case $\tau_R$	$NPV(\pi_R)$ [tril. US\$]
$\tau_R$	24.86	–	84
$\tau_L$	24.30	-2.3 %	119
$\tau_K$	24.28	-2.4 %	151
$\tau_C$	24.13	-3.0 %	124

Table 1: Welfare comparison in balanced growth equivalents (BGE) of policy cases in which importers' governments only use one instrument: Carbon tax  $\tau_R$ , capital tax  $\tau_K$ , payroll tax  $\tau_L$ , or consumption tax  $\tau_C$ . Welfare losses are measured relative to the case in which governments use only carbon taxes. The net present value of the resource owners profits  $NPV(\pi_R)$  is measured in trillion US\$. An extended version of this table showing the impact of different taxes on capital and infrastructure stocks, as well as on interest rate and resource price is included as Table 6 in Appendix D.1.

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.

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horizon, discounted by the interest rate net of depreciation  $r - \delta$ , that is,

$$NPV(X) = \sum_t \frac{X_t}{\Pi_s^t (1 + r_s - \delta)}.$$

### *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 (see e.g. Sinn, 2003, p. 20). 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 \$33 trillion over the period from 2010 to 2065, while the capital tax generates only \$3 trillion over that time horizon.

The outcome confirms our insight from Section 3.1. Because the carbon tax

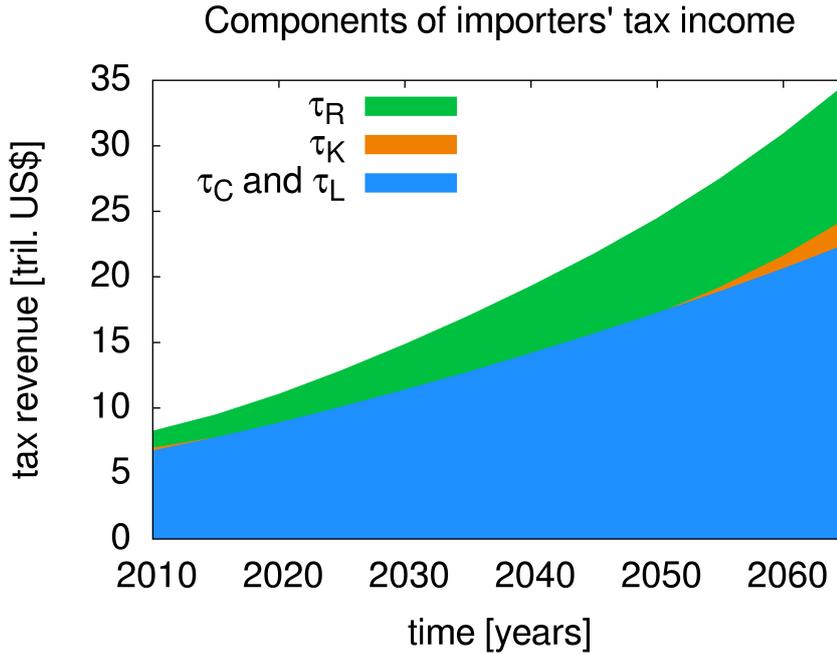


Figure 1: Tax income, decomposed into contributions by the endogenously determined carbon tax  $\tau_R$  and capital tax  $\tau_K$ , as well as the fixed consumption and payroll tax ( $\tau_C = \tau_L = 0.16$ ), respectively. For the underlying data, see the corresponding table in Appendix D.2.

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.<sup>17</sup> To explore the 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 welfare depends on the elasticity of substitution  $\sigma_1$  between fossil resources and

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<sup>17</sup> 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 composite input  $\mathbf{X}(K, G, L)$ , which combines private and public capital with labor. Then, we perform the same experiment for  $\sigma_3$ , 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.<sup>18</sup> 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 2 summarizes welfare measured as balanced growth equivalents (BGE) in importing countries for the two policy cases. We would like to highlight two observations. First, when the two inputs are assumed to be complementary, that is,  $\sigma_1 < 1$ , the carbon tax always 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).

	$\tau_R$ [tril. US\$]	$\tau_K$ [tril. US\$]	relative difference
0.3	23.03	22.10	4.19 %
0.4	24.17	23.37	3.44 %
<b>0.5</b>	<b>24.96</b>	<b>24.26</b>	<b>2.86 %</b>
0.6	25.52	24.92	2.42 %
0.7	25.95	25.41	2.09 %

Table 2: Comparison of the policy cases in which the importers' governments only determine the carbon tax  $\tau_R$  or only the capital tax  $\tau_K$  endogenously. The numbers give welfare measured as balanced growth equivalents. The column on the right shows the relative difference between the second and the third column.

Second, with a smaller elasticity of substitution, the advantage of the carbon tax over the capital tax increases, as indicated by the increasing difference in welfare between the two policy cases. 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.<sup>19</sup> When demand is relatively inelastic, fossil

<sup>18</sup> The case in which both instruments are optimized does not yield any further insights.

<sup>19</sup> The derivation of the demand functions from a given CES production function can be

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 inputs is still possible – more precisely, infrastructure can be substituted for capital, even when the elasticity  $\sigma_1$  is low. Thus, capital remains relatively more elastic in supply when the elasticity  $\sigma_1$  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  $\sigma_3$ , the elasticity of substitution between private capital and infrastructure, has a rather moderate impact on the model results, when we compare it with the above result on  $\sigma_1$ . In table 3 we present this finding.

Nevertheless we observe a trend in the difference between the two policy cases. The harder it gets to substitute capital for infrastructure, the greater is the difference in welfare losses relative to the benchmark case. In other words, the more inelastic the demand for infrastructure is, the more pronounced becomes the advantage of the carbon tax.

	$\tau_R$ [tril. US\$]	$\tau_K$ [tril. US\$]	relative difference
0.7	24.36	23.59	3.262%
0.9	24.73	24.05	2.864%
<b>1.1</b>	<b>24.96</b>	<b>24.26</b>	<b>2.863%</b>
1.4	25.16	24.48	2.785%
1.7	25.29	24.61	2.734%

Table 3: Comparison of the policy cases in which the importers' governments only determine the carbon tax  $\tau_R$  or only the capital tax  $\tau_K$  endogenously. The numbers give welfare measured as balanced growth equivalents. The column on the right shows the relative difference between the second and the third column.

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found in Allen (1938), p. 369 ff.

## 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.

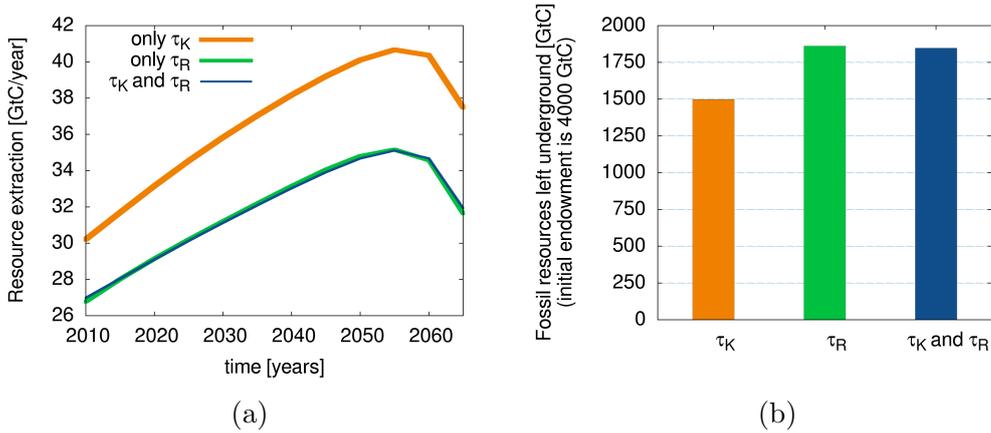


Figure 2: Timing and volume effects of different policy instrument portfolios. Compared to the case in which importing governments only determine the capital tax optimally, portfolios which include an optimally determined carbon tax lead to both a lower rate of extraction and lower cumulative extraction.

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. Note that fossil resources will never be exhausted fully due to the assumption that extraction costs are convex. 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 reason for the above result lies in the time profile of the demand for infrastructure, which determines the time profile of the optimal carbon tax. We find that the annual growth rate of the optimal carbon tax is always less than the interest rate net of depreciation, with which the resource owner discounts her profits (see Table 4). However, a necessary condition for the green paradox to occur is that the annual growth rate of the carbon tax is greater than the discount rate used by the resource owner (see e.g. Edenhofer and Kalkuhl, 2011, Table 1, for an overview over these conditions). Thus, the conditions for a green paradox to occur are not fulfilled.

year	$\tau_R$ [\$/tC]	$\gamma_{\tau_R}$	$r - \delta$
2010	77	0.000	0.039
2020	124	0.049	0.069
2030	194	0.043	0.067
2040	277	0.034	0.063
2050	369	0.028	0.061
2060	483	0.028	0.062

Table 4: Time profile of the optimal carbon tax  $\tau_R$  in dollars per ton of carbon, the annual growth rate of the carbon tax  $\gamma_{\tau_R}$ , and the annual interest rate net of depreciation  $r - \delta$  for the case in which governments optimize only the carbon tax.

## 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. Further, in Section 5.3, we also identify a special case in which competition among the importing countries leads to a beneficial race-to-the-top in carbon taxes.

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 Nash equilibrium 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, Amundsen and Schöb, 1999, and Liski and Tahvonen, 2004). 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 (this is equivalent to the assumption that resource sellers exercise market power, e.g. as cartel or monopoly). 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.

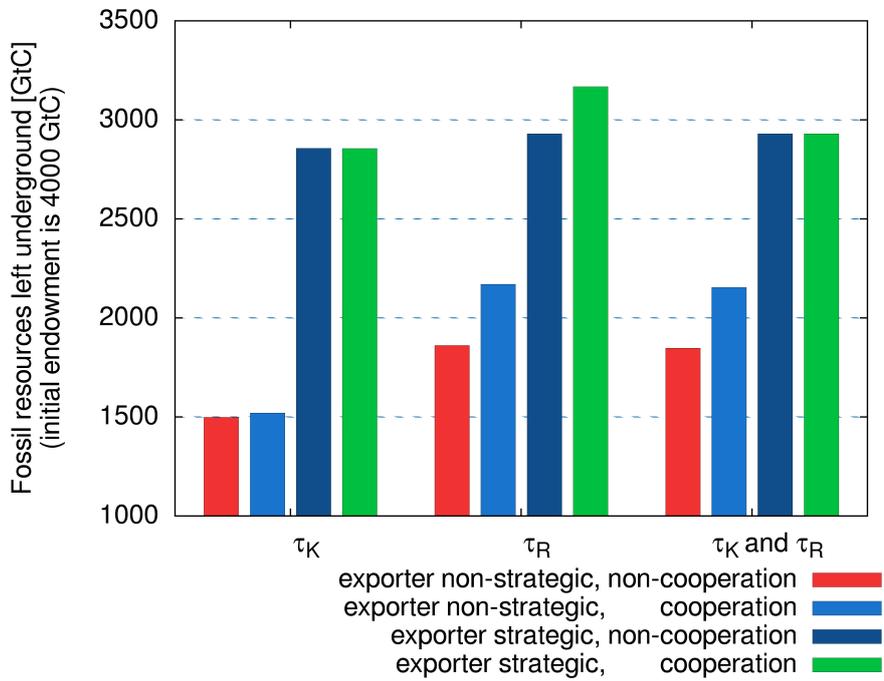


Figure 3: Amount of fossil resources left underground at the end of the time horizon. For the corresponding table, see Appendix D.3, Table 8.

In most cases we see that allowing cooperation among importers leads 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.

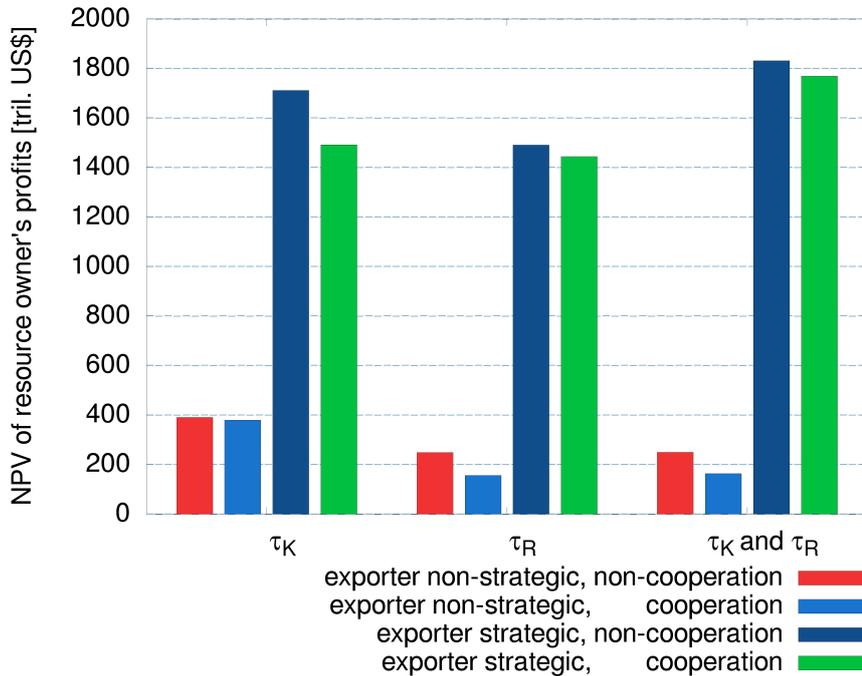


Figure 4: Net present value (NPV) of resource owner’s profits. For the corresponding table, see Appendix D.3, Table 9.

We see that cooperation among importers always reduces the exporter’s prof-

its. 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.<sup>20</sup> When we compare 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 decreases 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.<sup>21</sup>

Further, when the exporter does not interact strategically, the availability of the carbon tax in importing countries unambiguously leads to a reduction of the resource owner's profits. This is the result already obtained above that the carbon tax captures the resource rent. When the exporter interacts strategically, the choice of the policy instrument portfolio has ambiguous impacts on the resource owner's profits. Replacing the capital tax with the carbon tax still has the intuitive effect of reducing the exporters' profits due to rent capturing. However, if the carbon tax is used in addition to the capital tax, the exporter's profits actually increase. The increase occurs because the importers' governments use the carbon tax to subsidize fossil resources to counter the exporter's high price policy. Revenues for financing the subsidies and infrastructure investments are then raised with the capital tax.

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<sup>20</sup> 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.

<sup>21</sup> The exporter's government could theoretically also reduce the price or create fluctuation to increase the dependence of importing economies. However, our model does not capture this possibility since we already assume complementarity between fossil resources and all other input factors, and since we assume that there is no backstop technology available. Both assumption imply a relatively inelastic demand in importing countries.

### 5.3. Welfare

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

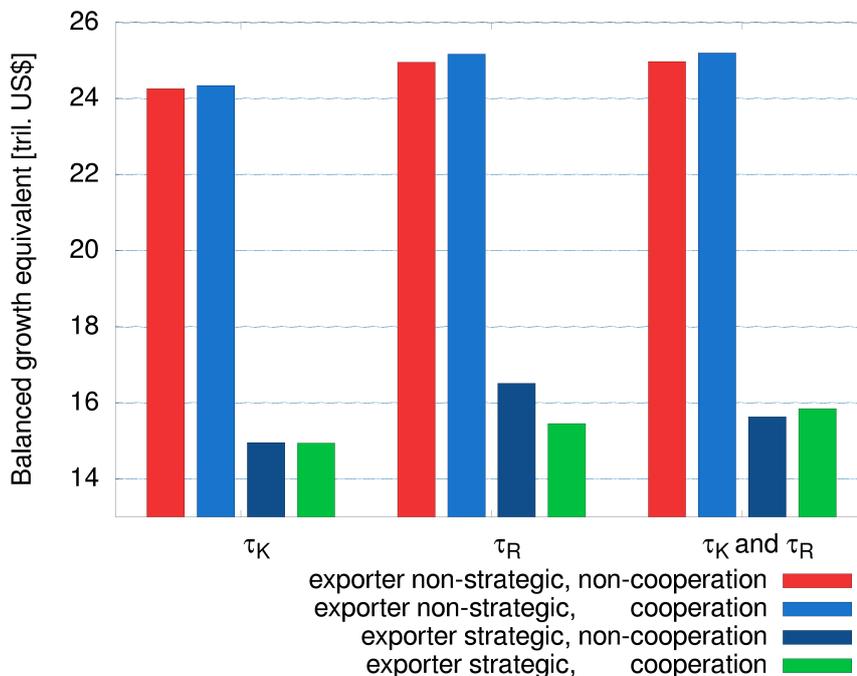


Figure 5: Social welfare in importing countries, measured as balanced growth equivalent. For the corresponding table, see Appendix D.3, Table 10.

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

However, when only the carbon tax is available and exporters may interact strategically, cooperation decreases welfare in the importing countries significantly. When importers do not cooperate, but instead compete against each other, the average carbon tax rate increases by approximately 20 percent relative to the case of cooperation. One rationale behind the low carbon tax rate in case of cooperation is the incentive to try to keep the carbon price at the lowest level possible, since it is already driven up very high due to the strategic actions of the exporter. Further, the presence of productivity enhancing infrastructure gives

importers which do not cooperate an additional incentive to engage in a race-to-the-top in carbon tax rates. Greater infrastructure stocks make the domestic economy more attractive for capital investments. Accordingly, the net present value of infrastructure investments is one and a half times higher if importers do not cooperate relative to the case of cooperation. Thus when only the carbon tax is optimized and the exporter interacts strategically, importers are better off if they do not cooperate.

Strategic behavior of the exporter's government has a much stronger impact on welfare in the importing countries than cooperation among importers. When we allow for an export tax to be levied, welfare in an importing country decreases by around 60%, independent of the assumptions about cooperation and the policy instrument portfolio.

Most importantly, regardless of the assumptions about strategic behavior the use of a carbon tax increases welfare relative to a tax portfolio which only uses a capital tax, *ceteris paribus*. This confirms the results we have presented in Section 3: The carbon tax gives governments the possibility of capturing the resource rent and thus increases the potential to raise revenue for infrastructure investments. Resource importing countries prefer to tax carbon instead of capital.

## 6. Conclusion

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. The reason is that 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, regardless of 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 or not.

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. This is because financing infrastructure investments optimally does not require the carbon tax to increase at a higher rate than the interest rate, which is known to be a necessary condition for the green paradox to occur (Edenhofer and Kalkuhl, 2011). A carbon tax thus constitutes a viable green policy option.

Before drawing final conclusions we discuss applicability and scope of our model. First note that it applies to the short to medium run. In the long run we expect that carbon pricing has effects which our model does not capture. First, carbon pricing will increase the substitution elasticity between fossil resources and other inputs, e.g. through the availability of clean backstop technologies. Further, unilaterally implemented carbon taxes constitute a good entry point for climate policy and render an international agreement on climate change mitigation more feasible. Both long run effects reduce demand for fossil resources, and would consequently reduce the value of resource rents.

Further, 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. Similarly, the interactions of several optimally determined tax instruments (i.e. not only the capital and the carbon taxes, but also the VAT and in particular the payroll tax) implies a high degree of complexity. A characterization of the additional effects lies beyond the scope of the present paper. Incorporating at least a subset of these effects, however, could be an avenue for future research.

Another interesting possibility to extend our model would be to include distributional effects of carbon taxes. This could be done, e.g. by differentiating between a 'clean' and an energy-intensive final goods sector and by allowing for competition on the market for these goods. In such a model it would also be possible to trace more precisely the relative strength of the so-called 'tax interaction effect', through which higher prices of carbon intensive products reduce factor returns. De Mooij and Bovenberg (1994) identified the tax interaction effect to be the main obstacle to the existence of a strong double dividend<sup>22</sup>. In our model a strong double dividend does occur.<sup>23</sup> Two reasons for its occurrence, which Goulder (2013) for instance highlights, are that the carbon tax captures rents (also found by Bento and Jacobsen, 2007) and the initial tax system (in which only the capital tax is optimized) is inefficient due to the intertemporal and interregional mobility of capital. Therefore, the strong double dividend might still

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<sup>22</sup> There is an extensive strand of literature discussing the so-called (strong) double dividend hypothesis: Environmental policy may not only benefit the environment (the first dividend), but the revenues it generates may be used to reduce other distortionary taxes and thus to reduce the gross costs of environmental policy (see e.g. Tullock, 1967, Goulder, 1995, Bovenberg, 1999).

Its weak form is widely accepted to hold, i.e. efficiency gains may be attained when the use of revenues from environmental policy is shifted away from lump-sum transfers to households towards reductions in other distortionary taxes.

Our approach goes beyond the standard assumptions of the double dividend literature in several ways: Instead of distortionary labor taxes, we consider capital taxes; we do not include environmental quality in households' utility; we model environmental policy to capture resource rents; we do not limit ourselves to revenue neutral tax reforms but consider instead endogenously determined optimal infrastructure investments.

<sup>23</sup> To see this, compare the case in which only the capital tax is optimized with the case in which in addition also the carbon tax is available and set optimally. Then, with the carbon tax overall (non-environmental) welfare increases and carbon emissions are reduced through both a timing and a volume effect.

hold, even if final goods sectors were differentiated, and additional trade-offs for the use of tax revenues were considered.

Going 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 PRIDE<sup>24</sup>, 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 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  $\alpha_i$ ,  $i = 1, 2, 3$  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.

The variation of  $\sigma_1$ , 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  $\sigma_1$ . Therefore, we have calibrated the CES production function to a specific baseline point (Klump and Saam, 2008). As standard

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<sup>24</sup> 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.

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,  $\sigma_3$ , 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  $\sigma_3$ , cf. Section 3.3.

Description	symbol	value	range	sources
Intertemporal elasticity of substitution	$\eta$	1.1		
Pure rate of time preference	$\rho$	0.03		
Annual depreciation rate of capital	$\delta$	0.025		
Share parameter of fossil resource	$\alpha_1$	0.05		Edenhofer et al. (2005)
Elasticity of substitution between $\mathbf{X}$ and $R$	$\sigma_1$	0.5	0.25 – 0.92	Hogan and Manne (1979)
				Kemfert and Welsch (2000)
				Burniaux et al. (1992)
				Markandya and Pedroso-Galinato (2007)
				Caselli and Feyrer (2007)
Share parameter of general capital $\mathbf{Z}$	$\alpha_2$	0.42		
Elasticity of substitution between $\mathbf{Z}(K, G)$ and $L$	$\sigma_2$	0.7		
Share parameter of private capital $K$	$\alpha_3$	0.7		
Elasticity of substitution between $K$ and $G$	$\sigma_3$	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]	$T$	2085		
Time step [years]	$\Delta$	5		
Scaling parameter	$\chi_1$	20		
Scaling parameter	$\chi_2$	700		
Slope of Rogner's curve	$\chi_3$	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).

*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  $\zeta = L, R$ .

## 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  $\Pi^F$  and governmental transfers  $\Gamma$  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  $\lambda$  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 (16) taking into account the resource constraint (17), the equation of motion for the stock (13), and possibly a unit tax  $\tau_{RO}$  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  $\Psi$ , 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  $\lambda^R$  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. Additional data

### D.1. Extension of Table 1

	Welfare relative to policy case $\tau_R$	$NPV(\pi_R)$ [tril. US\$]	$\overline{K^d}$ [tril. US\$]	$\overline{G}$ [tril. US\$]	$\bar{r} - \delta$ [1/a]	$\bar{p}$ [\$/tC]
$\tau_R$	0%	84	137.1	122	0.063	517
$\tau_L$	-2.3 %	119	136.9	123	0.067	714
$\tau_K$	-2.4 %	151	124.4	100	0.066	757
$\tau_C$	-3.0 %	124	151.0	126	0.061	675

Table 6: Extended version of Table 1. Comparison of policy cases in which importers' governments only use one tax instrument. Impact of carbon tax  $\tau_R$ , capital tax  $\tau_K$ , payroll tax  $\tau_L$ , and consumption tax  $\tau_C$  on welfare (measured relative to the case in which governments use only the carbon tax), the net present value of the resource owners profits  $NPV(\pi_R)$ , the stocks of capital  $\overline{K^d}$  and infrastructure  $\overline{G}$ , the average annual interest rate net of depreciation  $\bar{r} - \delta$ , and the average resource price  $\bar{p}$ .

### D.2. Data table corresponding to Figure 1

year	$r$	$\tau_K$	$K^d$ [tril. US\$]	$r\tau_K K^d$ [tril. US\$]	$\tau_R$ [\$/tC]	$R^d$ [GtC]	$\tau_R R^d$ [tril. US\$]
2010	0.060	0.068	83	0.34	74	13.1	1.0
2020	0.094	0.002	75	0.01	124	14.0	1.7
2030	0.093	-0.020	100	-0.19	198	15.1	3.0
2040	0.089	-0.024	131	-0.28	283	16.0	4.5
2050	0.086	-0.016	162	-0.23	374	17.0	6.3
2060	0.087	0.021	184	0.33	472	17.6	8.3

Table 7: Underlying data for Figure 1. Interest rate  $r$ , capital tax rate  $\tau_K$ , capital demand  $K^d$ , capital tax revenue  $r\tau_K K^d$ , carbon tax rate  $\tau_R$ , resource demand  $R^d$ , and carbon tax revenue  $\tau_R R^d$ . Data for consumption tax  $\tau_C$  and payroll tax  $\tau_L$  are omitted since they are fixed exogenously.

D.3. Data tables corresponding to Figures 3 to 5

	non-strategic exporter		strategic exporter	
	no cooperation	cooperation	no cooperation	cooperation
$\tau_K$	1498	1521	2857	2856
$\tau_R$	1862	2171	2931	3169
$\tau_K$ and $\tau_R$	1848	2155	2931	2931

Table 8: 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
$\tau_K$	391	380	1712	1492
$\tau_R$	249	157	1491	1444
$\tau_K$ and $\tau_R$	250	164	1832	1769

Table 9: 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
$\tau_K$	24.26	24.35	14.96	14.94
$\tau_R$	24.96	25.17	16.52	15.46
$\tau_K$ and $\tau_R$	24.97	25.21	15.64	15.85

Table 10: Social welfare in an importing country measured as balanced growth equivalent (corresponds to Figure 5).

## E. Time consistency

To check whether governments have an incentive to deviate from the tax paths they have announced at the beginning of the first period, we have performed the following experiments. First, we calculate the tax paths of two standard benchmark cases in which the governments may only use the carbon tax or only the capital to finance the infrastructure investments,  $\{\tau_R\}_t$  and  $\{\tau_K\}_t$ , respectively. Then, we run the model again, but fixate the respective tax rate in the first  $n$  time periods to the value we have found in the benchmark case. Now, we compare the benchmark tax paths with the newly found ones  $\{\widetilde{\tau}_R\}_t$  and  $\{\widetilde{\tau}_K\}_t$ , respectively.

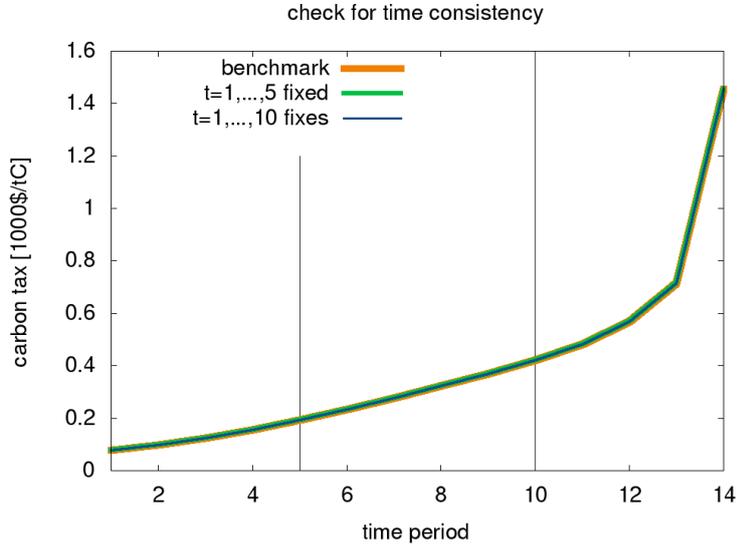


Figure 6: Governments have no incentive to deviate from the initially announced carbon tax path.

For the carbon tax it turns out that governments do not deviate at all from the announced tax path (Figure 6). For the capital tax we observe minor unsystematic deviations (Figure 7). Measured in tax revenues, we find that on average this difference is less than 0.01 percentage points if  $n = 5$  and less than 0.26 percentage points if  $n = 10$ . Here, we express the relative difference in fractions of GDP. More precisely, for each period  $t$  we calculate the difference as

$$\Delta = \frac{\tau_K r K^d}{GDP} - \frac{\widetilde{\tau}_K \widetilde{r} \widetilde{K}^d}{\widetilde{GDP}}.$$

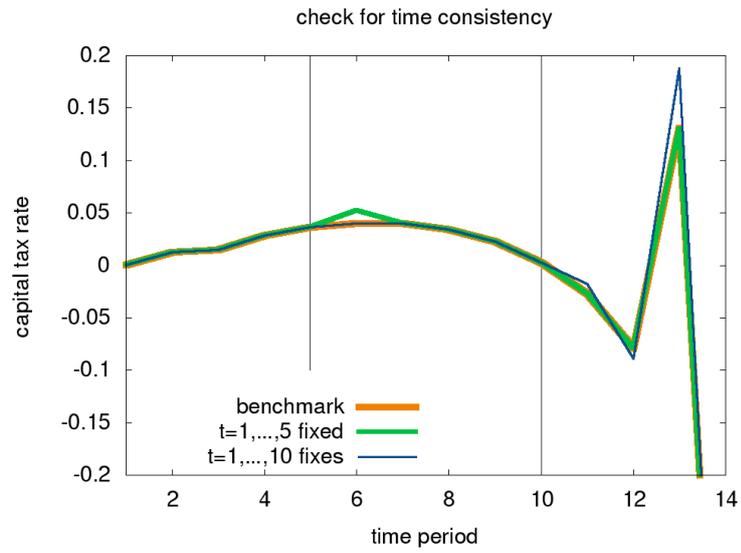


Figure 7: Governments deviate only to an insignificant extent from the initially announced capital tax path.

## Conflict of interest

The authors declare that they have no conflict of interest.

## References

- Allen, R., 1938. *Mathematical analysis for economists*. Macmillan and Co.
- 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.
- Babiker, M.H., 2001. Subglobal climate-change actions and carbon leakage: the implication of international capital flows. *Energy Economics* 23, 121–139.
- Baier, S.L., Glomm, G., 2001. Long-run growth and welfare effects of public policies with distortionary taxation. *Journal of Economic Dynamics and Control* 25, 2007–2042.
- BEA, 2013. U.S. Bureau of Economic Analysis, "Fixed Assets Accounts Tables". <http://www.bea.gov/iTable/iTable.cfm?ReqID=10&step=1#reqid=10&step=1&isuri=1>. Accessed: 2013-11-04.
- Benassy-Quere, A., Goyalraja, N., Trannoy, A., 2007. Tax and public input competition. *Economic Policy* 22, 385–430.
- Bento, A.M., Jacobsen, M., 2007. Ricardian rents, environmental policy and the 'double-dividend' hypothesis. *Journal of Environmental Economics and Management* 53, 17–31.
- Bom, P., Ligthart, J., 2013. What have we learned from three decades of research on the productivity of public capital? *Journal of Economic Surveys* 00, 1–28.
- Bovenberg, A.L., 1999. Green tax reforms and the double dividend: an updated reader's guide. *International Tax and Public Finance* 6, 421–443.
- Brooke, A., Kendrick, D., Meeraus, A., Raman, R., Rosenthal, R., 2005. *GAMS – A Users Guide*. GAMS Development Corporation.

- 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 CO<sub>2</sub> Emissions: A Technical Manual. OECD Economics Department Working Papers.
- Burniaux, J.M., Truong, P.T., 2002. GTAP-E: An Energy-Environmental Version of the GTAP Model. GTAP Technical Paper No. 16. Purdue University.
- Calderón, C., Moral-Benito, E., Servén, L., 2014. Is Infrastructure Capital Productive? A Dynamic Heterogeneous Approach. *Journal of Applied Econometrics* .
- 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.
- Dasgupta, P., Heal, G., 1974. The optimal depletion of exhaustible resources. *The Review of Economic Studies* 41, 3–28.
- De Mooij, R.A., Bovenberg, A.L., 1994. Environmental levies and distortionary taxation. *American economic review* 84, 1085–1089.
- 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., Kalkuhl, M., 2011. When do increasing carbon taxes accelerate global warming? A note on the green paradox. *Energy Policy* 38, 2208–2212.
- 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.
- EIA, 2014. Tax Database. <http://www.eia.gov/countries/index.cfm?topL=imp>. Accessed: 2014-09-29.
- Feichtinger, G., Hartl, R.F., 1986. Optimale Kontrolle ökonomischer Prozesse. de Gruyter.

- Gerlagh, R., 2011. Too Much Oil. CESIFO Economic Studies 57, 79–102.
- Goulder, L.H., 1995. Environmental Taxation and the Double Dividend: A Reader's Guide. *International Tax and Public Finance* 2, 157–183.
- Goulder, L.H., 2013. Climate change policy's interactions with the tax system. *Energy Economics* 40, S3–S11.
- Habla, W., 2014. Non-Renewable Resource Extraction and Interjurisdictional Competition across Space and Time. Technical Report. University of Munich.
- Hoffmann, M., Runkel, M., 2015. A welfare comparison of ad valorem and unit tax regimes. *International Tax and Public Finance* , 1–18.
- 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.
- Hotelling, H., 1931. The Economics of Exhaustible Resources. *Journal of Political Economy* 39, 137–175.
- 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.
- Keen, M., Konrad, K.A., 2013. Chapter 5 - The Theory of International Tax Competition and Coordination, in: Alan J. Auerbach, Raj Chetty, M.F., Saez, E. (Eds.), *handbook of public economics*, vol. 5. Elsevier. volume 5 of *Handbook of Public Economics*, pp. 257 – 328.
- 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.
- Klump, R., Saam, M., 2008. Calibration of normalised CES production functions in dynamic models. *Economic Letters* 99, 256–259.

- Liski, M., Tahvonen, O., 2004. Can carbon tax eat OPEC's rents? *Journal of Environmental Economics and Management* 47, 1–12.
- Lockwood, B., 2004. Competition in Unit vs. Ad Valorem Taxes. *International Tax and Public Finance* 11, 763–772.
- Markandya, A., Pedroso-Galinato, S., 2007. How substitutable is natural capital? *Environmental Resource Economics* 37, 297–312.
- Matsumoto, M., 1998. A note on tax competition and public input provision. *Regional Science and Urban Economics* 28, 465–473.
- van der Meijden, G., van der Ploeg, F., Withagen, C., 2014. International Capital markets, Oil Producers and the Green Paradox. Technical Report. Oxford Centre for the Analysis of Resource Rich Economies.
- Mirrlees, J.A., Stern, N., 1972. Fairly good plans. *Journal of Economic Theory* 4, 268–288.
- OECD, 2014. Tax Database. <http://www.oecd.org/tax/tax-policy/tax-database.htm#vat>. Accessed: 2014-08-27.
- Otto, G.D., Voss, G.M., 1998. Is public capital provision efficient? *Journal of Monetary Economics* 42, 47–66.
- Paltsev, S., Reilly, J.M., Jacoby, Henry D., E.R.S., McFarland, J., Sarofim, M., Asadoorian, M., Babiker, M., 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. Report No. 125. Massachusetts Institute of Technology.
- van der Ploeg, F., Withagen, C., 2012. Is there really a green paradox? *Journal of Environmental Economics and Management* 64, 342–363.
- van der Ploeg, F., Withagen, C., 2014. Growth, Renewables, and the optimal carbon tax. *International Economic Review* 55, 283–311.
- Rodrik, D., 2011. *The Globalization Paradox*. Oxford University Press.
- Rogner, H.H., 1997. An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment* 22, 217–262.

- Romp, W., de Haan, J., 2007. Public capital and economic growth: A critical survey. *Perspektiven der Wirtschaftspolitik* 8, 6–52.
- Sinclair, P.J.N., 1992. High does nothing and rising is worse: Carbon taxes should keep declining to cut harmful emissions. *The Manchester School* 60, 41–52.
- Sinclair, P.J.N., 1994. On the Optimum Trend of Fossil Fuel Taxation. *Oxford Economic Papers* 46, 869–877.
- Sinn, H.W., 2003. *The New Systems Competition*. Wiley-Blackwell.
- Sinn, H.W., 2008. Public policies against global warming: a supply side approach. *International Tax and Public Finance* 15, 360–394.
- Suits, D.B., Musgrave, R.A., 1953. Ad Valorem and Unit Taxes Compared. *The Quarterly Journal of Economics* 67, 598–604.
- Tullock, G., 1967. Excess benefit. *Water Resources Research* 3, 643–644.
- Ulph, A., Ulph, D., 1994. The optimal time path of a carbon tax. *Oxford Economic Papers* 46, 857–868.
- Wilson, J.D., 1986. A Theory of Interregional Tax Competition. *Journal of Urban Economics* 19, 296–315.
- Wilson, J.D., 1999. Theories of Tax Competition. *National Tax Journal* 52, 269–304.
- Withagen, C., Halsema, A., 2013. Tax competition leading to strict environmental policy. *International Tax and Public Finance* 20, 434–449.
- World Bank, 2014. World Development Indicators, Labor tax and contributions. <http://data.worldbank.org/indicator/IC.TAX.LABR.CP.ZS>. Accessed: 2014-08-27.
- Zodrow, G.R., 2010. Capital Mobility and Capital Tax Competition. *National Tax Journal* 63, 865–902.
- Zodrow, G.R., Mieszkowski, P., 1986. Pigou, Tiebout, Property Taxation, and the Underprovision of Local Public Goods. *Journal of Urban Economics* 19, 356–370.