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**Working Paper**

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*Suggested Citation:* Karl Zimmermann (2019) : Public Infrastructure Provision in the Presence of Terms-of-Trade Effects and Tax Competition, ZBW – Leibniz Information Centre for Economics, Kiel, Hamburg

This Version is available at:

<https://hdl.handle.net/10419/193458>

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# Public Infrastructure Provision in the Presence of Terms-of-Trade Effects and Tax Competition

Karl Zimmermann\*

February 28, 2019

## Abstract

This paper analyses and compares the performance of carbon taxes and capital taxes in financing public goods with positive effects on private firm productivity. It is motivated by Franks et al. (2017), who ask whether using carbon taxes could be motivated on fiscal grounds rather than by environmental ones, arguing that the advantage of the carbon tax consists in its potential to reap foreign resource rents. I employ an analytical general equilibrium framework of  $n$  identical countries, where local firms use internationally mobile capital and imported fossil fuel and in production as well as local public infrastructure. The latter is financed solely by either taxing the input of fossil fuels (carbon tax) or capital. The choice of the policy instrument is exogenous to policy makers and symmetric across countries. I find that the effect of policy on the fossil fuel price (terms-of-trade effect) leads to higher public good provision under carbon taxation. However, tax-competition could cause either policy instrument to yield higher provision depending on how strongly either tax base reacts to changes in the tax rate. And finally, I conclude that the ranking of the two policy scenarios is ambiguous when considering tax competition and the terms-of-trade effect simultaneously. A numerical exercise shows cases for higher provision of either policy.

**JEL Classification:** H21 • H54 • Q38

**Keywords:** Tax Competition • Public Infrastructure • Carbon Tax

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# 1 Introduction

Public economists have discussed capital taxation extensively as an instrument to raise public revenue. There are two important aspects in this context. Firstly, capital is internationally mobile and economic agents will therefore invest where they expect the highest returns. Secondly, the domain of capital tax policy is the country- or the subnational level. Due to both aspects, local governments might compete for capital.

Zodrow and Mieszkowski (1986) and Wilson (1986) provide formal arguments for the possibility that interregional mobility of capital yield inefficiently low capital tax rates and public revenues.<sup>1</sup> The rationale behind this finding is, that policy makers will not raise capital taxes to the efficient level since the relocation of capital erodes the tax base, which adds to the cost of revenue raising. In this text, I refer to this effect of capital taxation on business activity as the tax-base-relocation-effect. The occurrence of such detrimental tax competition cannot be completely set aside, even though empirical evidence is mixed.<sup>2</sup> Seemingly, capital taxes are indispensable due to political constraints. Must policy makers thus face the downside of efficiency costs connected to this instrument?

Franks et al. (2017) suggest that carbon taxation could represent an alternative, an instrument, which has been introduced mainly on the basis of environmental arguments.<sup>3</sup> To begin with, it is an instrument, which is fairly similar to capital taxes. There is a lack of international policy coordination and the tax base, fossil fuels, is internationally traded. So, the tax-base-relocation-effect might be observed, just as in the case of capital taxation. In fact, the literature finds evidence for carbon leakage, i.e. the shift of fossil fuel demand to foreign countries in response to elevation of carbon taxes, see Barker et al. (2007), Aichele and Felbermayr (2015) and others. Next to that, carbon taxes might as well lead to a fall in the global price of fossil fuels since the relocation of demand to other jurisdictions leads to a fall in marginal productivity there. This effect is also known from the basic capital tax competition model, see Zodrow and Mieszkowski (1986). Given that many countries are net-importers of fossil fuels,<sup>4</sup> policy makers could use carbon taxes to improve their terms-of-trade to obtain foreign resource rents, i.e. they could depress the price of imported fossil fuels at the expense of foreign resource owners. Bergstrom (1982)

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<sup>1</sup>See Wilson and Wildasin (2004) for a review of capital tax competition literature.

<sup>2</sup>Winner (2005) finds evidence that the increased mobility of capital has put downward pressure on capital tax rates in OECD countries, while Plümper et al. (2009) find that only countries with sufficient budgetary leeway effectively lowered rates. Devereux et al. (2002) and Devereux et al. (2008) find capital tax rates have fallen in the EU and the G7 member countries, while a simultaneous broadening of the tax base led to relatively stable revenues. Finally, Devereux and Loretz (2013) find in a review on empirical literature on tax competition that evidence is found mainly inside the EU and among small open economies.

<sup>3</sup>See Iacobuta et al. (2018).

<sup>4</sup>According to the database global trade of oil provided in OECD, IEA (2016), the largest net-importers of oil and other hydrocarbons during the last two or more decades have been China, the United States, Japan, India, Korea, Germany and France.

as well as Amundsen and Schöb (1999) show that the incidence of taxes levied on fossil fuels falls primarily on countries that export these to the world markets. And Franks et al. (2017) argue that, because of the terms-of-trade-effect, carbon taxes are superior to capital taxes yielding higher public revenue.

The tax-base-relocation-effect as well as the terms-of-trade-effect, as outlined above, arise from the impact of local tax rates on the market equilibrium, to which I refer here as the *tax-rate-channel*. However, the tax competition literature has found that also public expenditures may have their part and a *public-expenditure-channel* could consequently have an impact on the policy choice. The reason is that public spending is of relevance to the productivity of the private sector and to overall economic growth.<sup>5</sup> More precisely, empirical evidence shows that this mainly is the case for public expenditure on infrastructure and education.<sup>6</sup> Such public expenses, henceforth ‘public infrastructure’, may be thought of as a factor in private production, which positively affects other factors’ (marginal) productivity, causing factor prices to rise.<sup>7</sup> Thus, if additional tax revenue, obtained from a rise in the carbon or capital tax rate, is spent on public infrastructure, the tax-base-relocation-effect as well as the effect on the price of the tax base would be dampened through the *public-expenditure-channel*, see Noiset (1995). As a consequence, the potential advantage of carbon taxes arising through the terms-of-trade-effect might be weak or could vanish completely. Moreover, capital taxation might not suffer (too much) from detrimental tax competition.<sup>8</sup>

Therefore, I revisit the research question asked by Franks et al. (2017), i.e. whether carbon taxes yield higher levels of public infrastructure provision than capital taxes, particularly paying attention to the role of the public-expenditure channel. To this end, I compare a world where industrialized fossil-fuel-importing countries use capital taxes to finance local public infrastructure with a world where they use carbon taxes. In the analytical part, the findings indicate that policy makers have a more favorable terms-of-trade-effect under carbon taxation yielding higher infrastructure provision because of the tax-rate-channel. However, tax competition might be stronger in one or the other policy scenario together. Considering the public-expenditure channel does not resolve this ambivalence, but opens up the array of possible outcomes to efficient or inefficiently high infrastructure provision. It is because of this ambivalence, that a carbon tax may not yield higher infrastructure provision despite the terms-of-trade-effect. At the of the text, these results are illustrated by a numerical example.

I derive these results in a one-period tax competition model with several identical, industrialized countries and a non-industrialized region representing the rest of the world.

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<sup>5</sup>See Irmen and Kuehnel (2009) for an overview of the theoretical literature.

<sup>6</sup>See Nijkamp and Poot (2004).

<sup>7</sup>This notion was introduced by Barro (1990).

<sup>8</sup>Noiset (1995) shows that instead of inefficiently low tax rates, there might be inefficiently high tax rates and too much provision of public infrastructure.

In the former, private firms produce a homogeneous consumption good by using the internationally mobile factors fossil fuel and capital as well as the local public infrastructure good. Representative households in these countries inelastically provide capital and fossil fuels to the world markets, receive the local firm's profits and demand the consumption good. The revenues from either capital taxes or carbon taxes serve entirely finance public infrastructure. In the non-industrialized region, the household only (inelastically) provides fossil fuel and uses its income for the foreign-produced consumption good. So, only the industrialized countries conduct fiscal policy, while the non-industrialized region remains passive.

I first focus on the impact of the terms-of-trade effect on the equilibrium policy choice in both scenarios assuming cooperative policy making among industrialized countries. In the carbon taxation scenario, the tax-rate-channel as well as the public-expenditure-channel determine the terms-of-trade effect. If the former dominates the marginal cost of public funds is high since the policy increases the price of imported fossil fuels. Therefore, infrastructure provision will be inefficiently low. In case the tax-rate-channel is dominant, contrary applies, and infrastructure provision is inefficiently high. Under capital taxation, the terms-of-trade effect is only determined by the public-expenditure channel and consequently infrastructure provision is inefficiently low. I also find that equilibria with an inefficient policy choice depress resource rents. However, this is only to the benefit of industrialized countries in case infrastructure provision exceeds the first-best level, which only happens in the carbon taxation scenario. When comparing infrastructure provision levels across both policy scenarios, I find that carbon taxation yields higher levels since only in this scenario the tax-rate-channel is present, which pushes down the marginal costs of public funds.

Then I turn to the tax-base-relocation effect assuming that households in the industrialized countries are endowed with all of the global fossil fuel supply. The tax-base-relocation effect is ambiguous, i.e. fiscal policy could cause an increase or a decrease of firm demand for the tax base, given the simultaneous presence of the public-expenditure and the tax-rate channel. If the tax-base-relocation effect is positive (negative), i.e. firm demand for the tax base rises (falls) in reaction to an increase in local tax rate, marginal costs of public funds are low (high) and infrastructure provision in equilibrium is inefficiently high (low).

Finally, I consider the terms-of-trade and the tax-base-relocation effect simultaneously. If both effects point in the same direction, e.g. a negative tax-base-relocation effect and an unfavorable terms-of-trade effect both indicate inefficiently low provision, the policy equilibrium in each scenario will be as predicted by the separate assessment of each effect. However, if the effects point in different directions, then a policy equilibrium will exhibit inefficiently low (high) infrastructure provision if the tax-base-relocation effect is less (greater) than the terms-of-trade effect. So, given a strongly negative tax-base-relocation

effect, infrastructure provision might be inefficiently low in the carbon taxation scenario despite a favorable terms-of-trade effect. Concerning the comparison of policies, I find that the scenario with the more positive tax-base-relocation effect tends to exhibit higher infrastructure provision, while the terms-of-trade effect distorts this conclusion towards carbon taxation.

I complete this analysis with a numerical example, which shows that the equilibrium policy choice is strongly driven by the degree of net-complementarity<sup>9</sup> between public and private production factors. If public infrastructure is a net-complement to one of the factors and a net-substitute for the other, the former will yield much higher infrastructure provision if chosen as the tax base.

The contribution of this paper is as follows. I enrich the results of Franks et al. (2017) by assessing their research question in an analytical framework. This enables me to show how considering public expenditures as a factor of production alters the incentives for tax policy in the presence of fossil fuel endowment asymmetry. Thereby, this paper contributes to the literature by showing an avenue under which carbon taxation could yield inefficiently high public good provision and inefficiently high tax rates. With respect to capital taxation, I show a channel which leads to inefficiently low equilibrium taxation stemming from an adverse terms-of-trade effect. Finally, I show that despite the terms-of-trade effect, the differing degree of tax competition across these instruments could alter the broader picture - where capital taxation could yield higher provision despite the adverse terms-of-trade effect.

The paper is organized as follows. Section 2 presents the model primitives and derives comparative static effects for both policy scenarios. This is followed by the welfare analysis in Section 3, which explores how policy equilibria compare under the separate and joint consideration of the *terms-of-trade effect* and the presence of *tax competition*. Section 4 presents a numerical example and finally Section 5 concludes.

## 2 Model

Consider an economy with a fixed amount of fossil fuel, which is extracted at zero cost. Endowments of this resource are distributed between an industrialized world region with  $n$  identical countries, denoted by the indices  $i, j \in \{1, \dots, n\}$ , and a non-industrialized region, denoted by the index  $R$ . In each of the industrialized countries, a representative local firm produces a homogeneous consumption good employing fossil fuel, capital and local public infrastructure and the representative household receives income consisting of returns to capital and fossil fuel rents. In the non-industrialized region, however, there are no production firms and household income only consists of fossil fuel rents. Industrialized

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<sup>9</sup>I refer to the question whether production factors (or composites) are net-substitutes or net-complements.

countries undertake fiscal policy, while the non-industrialized region remains passive. Hence, in what follows, I will mainly make reference to the industrialized countries.

**Local firms.** The production technology is described by the quasi-concave production function  $F(e, k, g)$ , where  $e$  denotes the input of fossil fuels,  $k$  physical capital,  $g$  publicly provided infrastructure. The production function exhibits positive and decreasing returns to scale due to a locally fixed and fully employed production factor such as land or labor. It exhibits the usual characteristics of positive, but decreasing marginal productivity in each single production factor, while all factors are supposed to be imperfect substitutes ( $F_x(\cdot) > 0, F_{xx}(\cdot) < 0, F_{xz}(\cdot) > 0$  with  $x, z \in (e, k, g)$  and  $x \neq z$ ). Thus, public infrastructure exhibits a positive effect on the marginal productivity of the remaining factors. In that I follow Noiset (1995), Bayindir-Upmann (1998) and Dhillon et al. (2007).<sup>10</sup>

The price-taking firms supply the consumption good on the world market at a price normalized to unity and demand private production factors paying the respective factor prices. In addition, they have to pay the local unit tax on either capital or fossil fuel input. In their decision making, firms take the amount of the public good as well as the prevailing tax rate as given. The optimization problem of the firm in country  $i$  formally reads

$$\max_{e_i, k_i} \pi_i = F(e_i, k_i, g_i) - (p + \tau_i^e)e_i - rk_i, \quad (1)$$

in case of carbon taxation and

$$\max_{e_i, k_i} \pi_i = F(e_i, k_i, g_i) - pe_i - (r + \tau_i^k)k_i, \quad (2)$$

in the case of capital taxation, where  $r$  and  $p$  represent the rental rate of capital and the price of fossil fuel,  $\tau_i^k$  and  $\tau_i^e$  denote the unit taxes on capital and fossil fuel input levied in country  $i$ , and  $\pi_i$  is the after-tax profit of the firm in country  $i$ , which is positive due to the decreasing returns to scale of  $F(\cdot)$  in  $e_i, k_i$  and  $g_i$ . In the case of carbon taxation, the firm's first-order conditions are given by

$$F_e(e_i, k_i, g_i^e, \ell_i) = p + \tau_i^e, \quad (3a)$$

$$F_k(e_i, k_i, g_i^e, \ell_i) = r, \quad (3b)$$

while for capital taxation I obtain

$$F_e(e_i, k_i, g_i^k, \ell_i) = p, \quad (4a)$$

$$F_k(e_i, k_i, g_i^k, \ell_i) = r + \tau_i^k, \quad (4b)$$

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<sup>10</sup>To exclude corner solutions I assume that the public good is essential for production, i.e.  $F_g(\cdot) \rightarrow \infty$  for  $g_i \rightarrow 0$ .

where each condition equates marginal productivity of the factor to its respective (gross) price.

**The public sector.** Local policy makers in the industrialized countries conduct fiscal policy, i.e. they raise and spend public funds, in order to maximize welfare. In the present model, I abstract from the availability of lump-sum taxation. If such an option would be available, which in the real world, it is not, public good provision would be efficient and the implication would be that policy makers should fully rely on this type of instrument. In any case, the focus of this study is to investigate how policy makers choose second-best instruments, which could either be the capital tax or the carbon tax, to provide the public infrastructure good.

For simplicity, I assume that policy makers in all countries have only one type of tax available, i.e. the choice of the instrument is exogenous and the same across countries. Hence, either the carbon tax revenue  $\tau_i^e e_i$  or the capital tax revenue  $\tau_i^k k_i$  exclusively serves to finance public expenditure  $g_i$ . Thus, in the case of carbon taxation the budget constraint of the local government is given by

$$g_i^e = \tau_i^e e_i \quad (5a)$$

and in the case of carbon taxation by

$$g_i^k = \tau_i^k k_i. \quad (5b)$$

**Private households.** Each country is assumed to be inhabited by a single, representative household, who provides fossil fuel and capital to the world markets. For capital, I assume symmetric endowments between all industrialized countries,  $\bar{k}_i = \bar{k}_j = \frac{\bar{K}}{n}$  for  $i, j \in \{1, \dots, n\}$ , where  $\bar{k}_i$  and  $\bar{K}$  represent local and world capital supply, respectively. On the contrary, for fossil fuels a share of  $\mu \in (0, 1)$  of  $\bar{E}$ , the global fossil fuel supply, is allocated symmetrically in the industrialized countries and the remainder in region  $R$ , i.e.  $\bar{e}_i = \bar{e}_j = \mu \frac{\bar{E}}{n}$  for  $i, j \in \{1, \dots, n\}$  and  $\bar{e}_R = (1 - \mu)\bar{E}$ , where  $\bar{e}_i$  and  $\bar{e}_R$  represent local fossil fuel supplies. Formally, income of the household in country  $i$  writes

$$y_i = \pi_i + r \cdot \frac{\bar{K}}{n} + p \cdot \mu \frac{\bar{E}}{n}. \quad (6)$$

The representative household in region  $R$  receives  $p \cdot (1 - \mu)\bar{E}$  from fossil fuel export. Owing to the static nature of the model, households in both world regions, industrialized and non-industrialized countries, spend their entire income on consumption. For simplicity, I assume utility to be linear in income, i.e.  $u_i = y_i$ .

**Market clearing.** The model description is completed by the market clearing con-



ditions for the production factors, which read

$$\sum_{i=1}^n k_i = \bar{K}, \quad (7a)$$

$$\sum_{i=1}^n e_i = \bar{E}. \quad (7b)$$

The consumption good market is assumed to clear according to Walras's law.

I proceed with the derivation of the comparative static effects of tax policy to provide the basis for the welfare analysis presented in the subsequent section. The market equilibrium is described by the firm's first-order conditions (3a) and (3b) or (4a) and (4b) depending on the policy scenario, and the market clearing conditions (7a) and (7b). Since industrialized countries are identical, I consider a symmetric choice of tax rates, i.e.  $\tau_i^e = \tau_j^e = \tau^e$  or  $\tau_i^k = \tau_j^k = \tau^k$ , together with a resulting symmetric market equilibrium. The latter implies that firms across countries exhibit identical factor inputs as well as first- and second-order derivatives of their production functions, i.e.  $e_i = e_j = e$ ,  $k_i = k_j = k$ ,  $F_x^i = F_x^j$ ,  $F_{xx}^i = F_{xx}^j$  and  $F_{xz}^i = F_{xz}^j$  for  $x, z \in [e, k, g]$  with  $x \neq z$  and  $i \neq j$ . The effect of tax policy on the market equilibrium will be explained in detail by the example of the carbon tax. The findings carry over to the case of capital taxation due to both instruments' identical design, which is why the results will only be stated briefly at the end of this section. The derivation for both policy cases can be found in Appendix A.

Given each policy maker takes foreign tax rates as given, a unilateral change of the carbon tax rate by country  $i$  yields the following comparative static effects on the market equilibrium

$$\frac{\partial p}{\partial \tau_i^e} = \frac{eF_{eg} - 1}{n} \geq 0 \quad (8)$$

$$\frac{\partial r}{\partial \tau_i^e} = \frac{eF_{kg}}{n} > 0 \quad (9)$$

$$\frac{\partial e_i}{\partial \tau_i^e} = \frac{n-1}{n} \frac{[[1 - eF_{eg}]F_{kk} + eF_{kg}F_{ek}]}{\Omega_e} \geq 0 \quad (10)$$

$$\frac{\partial k_i}{\partial \tau_i^e} = \frac{n-1}{n} \frac{F_{ek}[eF_{eg} - 1] - F_{kg}[eF_{ee} + \tau^e]}{\Omega_e} \geq 0 \quad (11)$$

with  $\Omega_e = [F_{ee} + \tau^e F_{eg}]F_{kk} - [F_{ek} + \tau^e F_{kg}]F_{ek} > 0$ .<sup>11</sup> These state that changing the carbon tax in country  $i$  has an ambiguous effect on fossil fuel and capital demand in

<sup>11</sup> Substituting  $g_i^e$  in  $F(e_i, k_i, g_i^e)$  by (5a) renders  $F(\cdot)$  a function of  $e, k$ , while  $\tau_i^e$  becomes a parameter. Following Dhillon et al. (2007, p. 406f), I assume that marginal productivity of private factors  $e, k$  is decreasing independent of whether a factor serves as the tax base or not, i.e.  $\frac{\partial F_e}{\partial e_i} = F_{ee} + F_{eg}^i \tau^e < 0$  and  $\frac{\partial F_k}{\partial k_i} = F_{kk} < 0$ , which yields  $\Omega_e > 0$ . This rules out virtuous cycles, meaning that more private factor input would result in higher marginal productivity thanks to the public good, which would then result in an increase in demand for factor input and so forth.

that country as well as on the world market price for fossil fuels  $p$ , while the effect on the interest rate  $r$  is positive. As outlined in the introduction, there are two channels through which carbon taxation policy affects the market equilibrium. One is the *tax-rate channel*, which refers to the distortion effect of  $\tau_i^e$  on factor demand. To see its impact, I set  $F_{eg} = F_{kg} = 0$  in (8) - (11), which mutes the effect of public expenditure in the market equilibrium, and obtain  $\frac{\partial e_i}{\partial \tau_i^e} < 0$ ,  $\frac{\partial k_i}{\partial \tau_i^e} < 0$ ,  $\frac{\partial p}{\partial \tau_i^e} < 0$  and  $\frac{\partial r}{\partial \tau_i^e} = 0$ . The reduction of fossil fuel demand by the firm in country  $i$  is due to the increase in the tax rate, which elevates gross factor costs of using fossil fuel for the local firm. The reduction of capital demand can be explained by the complementarity of both factors in production ( $F_{ek} > 0$ ). If the firm rationalizes on fossil fuels it also has to do so for capital to keep up this factor's marginal productivity.

To better explain the impact of the *tax-rate-channel* on  $p$  and  $r$ , I differentiate (3a) and (4a) for countries  $i$  and  $j \neq i$ , sum up over  $m = \{1, \dots, i, j, \dots, n\}$  and use the differentiated factor market clearing conditions to obtain

$$F_{ee} \underbrace{\sum_{m=1}^n de_j}_{=0} + F_{ek} \underbrace{\sum_{m=1}^n dk_m}_{=0} = n \cdot dp + d\tau_i^e = 0 \quad (12)$$

$$F_{ek} \underbrace{\sum_{m=1}^n de_m}_{=0} + F_{kk} \underbrace{\sum_{m=1}^n dk_m}_{=0} = n \cdot dr = 0 \quad (13)$$

Equations (12) and (13) show that the price changes  $dp$  and  $dr$  only depend on changes in the tax wedge in the fossil fuel and the capital market respectively and on the number of countries  $n$ . The fossil fuel price decreases since the tax wedge in country  $i$  increases through  $d\tau_i^e > 0$ . The rental rate  $r$  does not change, since there is no (change in the) tax wedge. Equations (12) and (13) also show how that these findings rest on the assumptions of inelastic factor supply and symmetry.

Next to that, there is the *public-expenditure channel*, which refers to the effect of changing public expenditure on private factor productivity. Raising the local carbon tax rate in country  $i$  increases revenue  $g_i$ , which ceteris paribus increases the marginal productivity of fossil fuels and capital. This translates into increasing demand for both factors by the local firm in country  $i$  and creates excess demand at the world markets, which in turn translates into upward pressure on  $p$  and  $r$ . In fact, I infer from explanation concerning the *tax-rate-channel* that considering  $F_{eg}, F_{kg} > 0$  in the comparative static effects explains the ambiguity in (8) - (10) and the positive sign in (11). So, the *public-expenditure channel* has a positive effect on comparative static effects.

As outlined above, the findings from the carbon tax carry over to the capital tax. I

find the following comparative static effects of capital taxation:

$$\frac{\partial r}{\partial \tau_i^k} = \frac{kF_{kg} - 1}{n} \begin{matrix} \geq \\ \leq \end{matrix} 0 \quad (14)$$

$$\frac{\partial p}{\partial \tau_i^k} = \frac{kF_{eg}}{n} > 0 \quad (15)$$

$$\frac{\partial k_i}{\partial \tau_i^k} = \frac{n-1}{n} \frac{[[1 - kF_{kg}]F_{ee} + kF_{eg}F_{ek}]}{\Omega_k} \begin{matrix} \geq \\ \leq \end{matrix} 0 \quad (16)$$

$$\frac{\partial e_i}{\partial \tau_i^k} = \frac{n-1}{n} \frac{F_{ek}[kF_{kg} - 1] - F_{eg}[kF_{kk} - \tau^k]}{\Omega_k} \begin{matrix} \geq \\ \leq \end{matrix} 0, \quad (17)$$

with  $\Omega_k = [F_{kk} + \tau^k F_{kg}]F_{ee} - [F_{ek} + \tau^k F_{eg}]F_{ek} > 0$ .<sup>12</sup>

### 3 Welfare Analysis

The aim of this section is to analytically assess the drivers of the policy choices made in the two scenarios and to compare these. I assume throughout that local policy makers maximize welfare consisting of household utility, which is linear in income. Consecutive decisions of public and private agents are modeled as a two-stage, non-cooperative sequential game, if not indicated otherwise. In the first stage local tax rates are set by the policy makers and in the second stage firms decide on factor input.

The benchmark is given by the first-best policy choice consisting of symmetric carbon or capital tax rates, denoted by  $\tau^{e\odot}$  and  $\tau^{k\odot}$  respectively. It is characterized by the Samuelson rule, which formally reads

$$F_g = 1. \quad (18)$$

The symmetry of optimal tax rates across countries yields a symmetric market equilibrium, i.e.  $e_i = e_j = \frac{\bar{E}}{n}$  and  $k_i = k_j = \frac{\bar{K}}{n}$ . Therefore, it follows from (18) that the first-best infrastructure provision level is identical for carbon and capital taxation  $\frac{\bar{E}}{n}\tau^{e\odot} = g^{e\odot} = g^{k\odot} = \frac{\bar{K}}{n}\tau^{k\odot}$ . According to the Samuelson rule, this first-best choice of tax rates equates marginal productivity of public infrastructure to the marginal rate of transformation between the infrastructure and private income. In other words, the social planner increases the tax rate to a level where the marginal tax-dollar just increases private income by exactly one dollar, which balances out the marginal tax payment. If less revenue would be invested into public infrastructure, some of the potential income would be lost, since the marginal benefits of increased output would exceed the unit cost of raising revenue.<sup>13</sup>

<sup>12</sup>For the reasoning of  $\Omega_k > 0$ , see above for  $\Omega_e$ .

<sup>13</sup>By assumption we have  $F_{gg} < 0$ , so that, given symmetry in tax rates and the market equilibrium, for any infrastructure provision level  $g$  with  $g < g^\odot$  it holds that  $F_g > 1$ .

### 3.1 Tax Policy and Fossil-Fuel Import

I now turn to second-best policy, where I first study in isolation the impact of the terms-of-trade effect on the equilibrium in both policy scenarios. Therefore, I suppose that all industrialized countries set their local tax rates cooperatively, i.e. policy makers take into account the repercussions of their policies the income of households in other industrialized countries but not in the non-industrialized region. The policy problem of the government in country  $i$  thus reads

$$\begin{aligned} \max_{\tau_i^e} \quad & y_i + \sum_{j \neq i}^n y_j \\ \text{s.t.} \quad & g_i^e = \tau_i^e e_i \end{aligned} \quad (19)$$

in the case of carbon taxation and

$$\begin{aligned} \max_{\tau_i^k} \quad & y_i + \sum_{j \neq i}^n y_j \\ \text{s.t.} \quad & g_i^k = \tau_i^k k_i \end{aligned} \quad (20)$$

in the case of capital taxation, where household incomes  $y_i$  and  $y_j$  are given by (6). Henceforth, I assume that policy choose identical tax rates, i.e.  $\tau_i^e = \tau_j^e = \tau^e$  or  $\tau_i^k = \tau_j^k = \tau^k$ , yielding a symmetric market equilibrium as outlined in the previous section. The optimality conditions of the problems given by (19) and (20) read

$$F_g = 1 + \frac{\partial p}{\partial \tau_i^e} n \cdot [1 - \mu]. \quad (21)$$

for carbon taxation, and

$$F_g = 1 + \frac{\partial p}{\partial \tau_i^k} \frac{n \bar{E}}{\bar{K}} \cdot [1 - \mu] \quad (22)$$

for capital taxation. See Appendix C for the derivation. I may use (8) and (15) to substitute for  $\frac{\partial p}{\partial \tau_i^e}$  and  $\frac{\partial p}{\partial \tau_i^k}$  since policy cooperation is carried out by the cooperative choice of local tax rates and obtain

**Proposition 1** *Assume that local governments of industrialized countries cooperatively choose local tax rates while  $\mu \in [0, 1)$ . Then, the following statements hold in the respective policy scenarios:*

**Carbon taxation:** *The symmetric equilibrium, where policy makers choose identical tax rates  $\tau^{e\otimes}$ , exhibits*

$$F_g^{e\otimes} \begin{cases} > \\ = \\ < \end{cases} 1 \quad \Leftrightarrow \quad \left. \frac{\partial p}{\partial \tau_i^e} \right|_{\tau_i^e = \tau^{e\otimes}} \begin{cases} > \\ = \\ < \end{cases} 0. \quad (23)$$

where  $F_g^{e\otimes} := F_g(\frac{\bar{E}}{n}, \frac{\bar{K}}{n}, \frac{\bar{E}}{n}\tau^{e\otimes})$ .

**Capital taxation:** *The symmetric equilibrium, where policy makers choose identical tax rates  $\tau^{k\otimes}$ , exhibits*

$$F_g^{k\otimes} > 1. \quad (24)$$

where  $F_g^{k\otimes} := F_g(\frac{\bar{E}}{n}, \frac{\bar{K}}{n}, \frac{\bar{K}}{n}\tau^{k\otimes})$ .

**Proof** Statement (23) is obtained from (21) and (8). Likewise, (24) is derived from (22) and (15).

Proposition 1 states that in the carbon taxation scenario, there could be inefficiently high or low provision of public infrastructure due to the ambiguous effect of policy on the fossil fuel price. However, in the capital taxation scenario infrastructure provision is inefficiently low. These results can be explained by looking at the marginal cost of public funds (MCPF) in each scenario, which is given on the right-hand side in (21) and (22) respectively. If the expenditure channel is dominant, i.e.  $F_{eg} - 1 > 0$  and thus  $\frac{\partial p}{\partial \tau_i^e} > 0$ , there will be inefficiently low tax rates. In other words, if higher expenses for infrastructure strongly push up marginal productivity of (imported) fossil fuels, the consequent deterioration of the terms-of-trade renders revenue raising costly. Therefore, infrastructure expenses are lower than optimal. The contrary holds for a weak impact of infrastructure expenses ( $F_{eg} - 1 < 0$ ). In this case, the tax-rate-channel is dominant and the MCPF is below unity, which yields inefficiently high provision of infrastructure. In the capital taxation scenario, only the expenditure channel affects the terms-of-trade, which is why the equilibrium infrastructure provision is lower than under the social planner's choice.

The argument in favor of carbon taxes raised in the introduction was that it might capture resource rents from the non-industrialized region. To assess this argument, I derive a comparison of the fossil fuel price under the first-best policy and under the policy equilibrium presented in Proposition 1, denoted by  $p^{e\otimes}$  ( $p^{k\otimes}$ ) and  $p^{e\otimes}$  ( $p^{k\otimes}$ ) respectively, see in Appendix C. The results show that in both policy scenarios resource rents are suboptimally low as long as infrastructure provision is inefficient, i.e.  $p^{m\otimes} < p^{m\otimes}$  given  $F_g^{m\otimes} \neq 1$  for  $m = \{e, k\}$ . In case  $F_g^{m\otimes} > 1$ , too low investments in public infrastructure suppress fossil fuels productivity vis-a-vis first-best policy (recall that  $F_{eg} > 0$ ). Therefore, one cannot speak of rent capturing here. An increase of the tax rates in all industrialized countries would improve income there as well as in the non-industrialized countries. However, if  $F_g^{m\otimes} < 1$ , which only applies to carbon taxation, the distortionary effect of the tax-rate channel is dominant and depresses the resource rent. In this case, it is viable to speak of rent capturing, since income in industrialized countries is higher than under first-best policy while the resource rent is lower.

When aiming at the direct comparison between both policy scenarios, it does not become entirely clear from Proposition 1 if a ranking can be established. Whilst I could

not establish a ranking concerning efficiency, I am able to rank both policies with respect to public infrastructure provision levels.

**Proposition 2** *Take the policy equilibrium exhibited in Proposition 1. Comparing the public infrastructure provision levels corresponding to the equilibrium policy choices denoted by  $\tau^{e\otimes}$  and  $\tau^{k\otimes}$  yields*

$$g^{e\otimes} > g^{k\otimes}. \quad (25)$$

**Proof** See Appendix C.

Proposition 2 states that, abstracting from the tax-base-relocation effect, infrastructure provision is higher under carbon taxation than under capital taxation, even if  $g^{e\otimes} < g^{e\circ}$ . This may be explained by the simultaneous impact of the tax-rate- and the expenditure-channel on the terms-of-trade. So, even though the expenditure-channel determines the net-effect of fiscal policy on the terms-of-trade, the tax-rate-channel moderates this net-effect, which is not the case of capital taxation.

### 3.2 Tax Policies in the Presence of Tax Competition

I now turn to the tax-base-relocation effect, which gives rise to tax competition. To analyze its impact on the policy choice, I assume that policy makers maximize only the income of their local household subject to the public budget constraint and ignore fiscal externalities affecting the other industrialized countries and the non-industrialized region. The policy problems for the two scenarios are given by

$$\max_{\tau_i^e} y_i \quad \text{s.t.} \quad g_i^e = \tau_i^e e_i, \quad (26a)$$

$$\max_{\tau_i^k} y_i \quad \text{s.t.} \quad g_i^k = \tau_i^k k_i, \quad (26b)$$

where household income  $y_i$  is again given by (6). After a slight modification, the corresponding first-order conditions read

$$F_g = \frac{(1 - \mu) \frac{\partial p}{\partial \tau_i^e} \frac{e}{e}}{1 + \epsilon_e} + \frac{1}{1 + \epsilon_e}, \quad (27)$$

in the carbon taxation scenario and

$$F_g = \frac{(1 - \mu) \frac{\partial p}{\partial \tau_i^k} \frac{e}{k}}{1 + \epsilon_k} + \frac{1}{1 + \epsilon_k}, \quad (28)$$

in the capital taxation scenario, where  $\epsilon_e = \frac{\partial e_i}{\partial \tau_i^e} \frac{\tau_i^e}{e}$  and  $\epsilon_k = \frac{\partial k_i}{\partial \tau_i^k} \frac{\tau_i^k}{k}$  represent the elasticities of the tax base with respect to the tax rate, see Appendix D for derivation. Again, the

derivatives of market variables with respect to any of the tax rates are given by the comparative statics, see Section 2.

### Symmetric Allocation of Fossil Fuel Endowments

To show the effect of the tax-base-relocation effect more clearly, I abstract from the terms-of-trade effect by assuming that households in industrialized countries own all of the global fossil fuel supply ( $\mu = 1$ ), i.e. there is no net-import of fossil fuels from the non-industrialized region. Taking this into account in (27) and (28), I obtain

**Proposition 3** *Assume that non-cooperatively acting local governments choose the local tax rate given  $\mu = 1$ . Then, the symmetric policy equilibrium in the carbon taxation as well as in the capital taxation scenario, where policy makers choose identical tax rates  $\tau^{m\ominus}$  for  $m = \{e, k\}$  yielding a symmetric market equilibrium with factor demands  $e_i = e =$  and  $k_i = k$ , exhibits*

$$F_g^m \begin{cases} > \\ = \\ < \end{cases} 1 \Leftrightarrow \epsilon_m^\ominus \begin{cases} < \\ = \\ > \end{cases} 0, \quad (29)$$

where for  $\epsilon_m^\ominus := \frac{\partial m_i}{\partial \tau_i^m} \frac{\tau^{m\ominus}}{m}$  with  $\tau_i^m = \tau^{m\ominus}$  in  $\frac{\partial m_i}{\partial \tau_i^m}$  and  $F_g^m := F_g(e, k, m\tau^m)$ .

**Proof** From (10) and (16) it follows that  $\epsilon_m \gtrless 0$ . Setting  $\mu = 1$  in (27) and (28) respectively gives

$$F_g^m = \frac{1}{1 + \epsilon_m}, \quad (30)$$

from which (29) is derived.

According to Proposition 3, equilibrium infrastructure provision could be inefficiently high, efficient or inefficiently low in either policy scenario. This is so, since the tax-base-relocation effect, which drives the policy makers' decision, could be positive or negative, i.e.  $\epsilon_m \gtrless 0$  for  $m = \{e, k\}$  due to (10) and (16). In case the tax base relocates abroad due to a strong tax-rate channel, the MCPF, given by the right-hand-side of (27) and (28) for carbon and for capital taxation respectively, would exceed the unit cost of converting private income into public revenue. In this case, the tax-base-relocation effect represents an additional cost to the policy maker and therefore, she chooses a level of infrastructure where  $F_g > 1$ . However, if the public-expenditure channel dominates, firm demand for the tax base increases due to a high impact of public expenditure on marginal productivity. Then, the MCPF would be less than unity thanks to  $\epsilon_m > 0$  and the cost providing infrastructure would fall below unity. Consequently, policy makers can justify a level infrastructure provision where  $F_g < 1$ . In this context, Bayindir-Upmann (1998) and Dhillon et al. (2007) show that using standard functional forms, such as the Cobb-Douglas production function, the tax-rate-relocation effect is negative and therefore infrastructure

provision is suboptimally low. However, if non-standard-forms are employed, such as a logistical form, as in Bayindir-Upmann (1998), or a piece-wise defined function, as in Dhillon et al. (2007), equilibria with inefficiently high provision levels could arise.

In any case, the comparison of infrastructure provision across the two policy scenarios depends on which scenario exhibits a higher equilibrium tax-base elasticity. However, this does not necessarily imply greater efficiency since inefficiently high provision has not been ruled out.

**Proposition 4** *Given non-cooperative policy making in industrialized countries with  $\mu = 1$ , it holds for equilibrium public infrastructure provision that*

$$g^{e\ominus} \begin{cases} > \\ = \\ < \end{cases} g^{k\ominus} \Leftrightarrow \epsilon_e^\ominus \begin{cases} > \\ = \\ < \end{cases} \epsilon_k^\ominus. \quad (31)$$

**Proof** See Appendix D.

The characteristics of the production function, such as elasticities of substitution, as well as the number of countries determine the absolute size of the tax base elasticity, either  $\epsilon_e$  or  $\epsilon_k$ , and in consequence the severity of tax competition. In the numerical example below, I concentrate on substitution elasticities to show how parameter choices impact the MCPF and the ranking of equilibrium public good provision across policy scenarios.

### Asymmetric Fossil Fuel Endowments

Finally, I analyze the equilibrium policy choice considering the impact of the tax-base-relocation effect as well as of the terms-of-trade effect on the policy makers' decision. Thus, I assume that industrialized countries are net-importers of fossil fuel, i.e.  $\mu \in [0, 1)$ , and that policy makers maximize only domestic income as stated in the policy problems (26a) and (26b).

**Proposition 5** *Assume that non-cooperatively acting local governments choose the local tax rate given  $\mu \in [0, 1)$ . Then, the following statements hold in the respective policy scenarios:*

**Carbon taxation:** *The symmetric policy equilibrium, where policy makers choose identical tax rates  $\tau^{e*}$  yielding a symmetric market equilibrium with factor demands  $e_i = e$  and  $k_i = k$ , exhibits*

$$F_g^{e*} \begin{cases} > \\ = \\ < \end{cases} 1 \Leftrightarrow \epsilon_e^* \begin{cases} < \\ = \\ > \end{cases} [1 - \mu] \frac{\partial p}{\partial \tau_i^e}, \quad (32)$$



with  $\epsilon_e^* := \frac{\partial e_i}{\partial \tau_i^e} \frac{\tau^{e*}}{e}$ ,  $\tau_i^e = \tau^{e*}$  in  $\frac{\partial e_i}{\partial \tau_i^e}$  and  $F_g^{e*} := F_g(e, k, e\tau^{e*})$ .

**Capital taxation:** The symmetric policy equilibrium, where policy makers choose identical tax rates  $\tau^{k*}$  yielding a symmetric market equilibrium with factor demands  $e_i = e$  and  $k_i = k$ , exhibits

$$F_g^{k*} \begin{cases} > \\ = \\ < \end{cases} 1 \Leftrightarrow \epsilon_k^* \begin{cases} < \\ = \\ > \end{cases} [1 - \mu] \frac{\partial p}{\partial \tau_i^k} \frac{e}{k}, \quad (33)$$

with  $\epsilon_k^* := \frac{\partial k_i}{\partial \tau_i^k} \frac{\tau^{k*}}{k}$ ,  $\tau_i^k = \tau^{k*}$  in  $\frac{\partial k_i}{\partial \tau_i^k}$  and  $F_g^{k*} := F_g(e, k, k\tau^{k*})$ .

**Proof** Given  $\epsilon_e^*, \epsilon_k^* > -1$ , the statement given in (32) directly follows from (27) and, likewise, (33) follows from (28).

Proposition (5) states that equilibrium public infrastructure provision is suboptimally low (high) if the tax-base-location-effect, represented by  $\epsilon_e$  or  $\epsilon_k$ , is less (greater) than the terms-of-trade effect, here  $[1 - \mu] \frac{\partial p}{\partial \tau_i^e}$  and  $[1 - \mu] \frac{\partial p}{\partial \tau_i^k} \frac{e}{k}$  respectively. To better illustrate Proposition (5), it helps to take a look at the constellations of  $\epsilon_e$  ( $\epsilon_k$ ) and  $\frac{\partial p}{\partial \tau_i^e}$  ( $\frac{\partial p}{\partial \tau_i^k}$ ) that cause an inefficient level of infrastructure provision. I hereby concentrate on the case of inefficiently low levels of provision, i.e.  $g^{m*} < g^\circ$  with  $m = \{e, k\}$ , which can be observed,

A: if the tax-base-relocation effect and the terms-of-trade effect are unfavorable, i.e.

$$\epsilon_m^* < 0; \frac{\partial p}{\partial \tau_i^m} > 0, \text{ or}$$

B: despite a favorable tax-base-relocation effect, i.e.  $\epsilon_m^* > 0$ ;  $\frac{\partial p}{\partial \tau_i^m} > 0$ ,

see (32) and (33). In the carbon taxation scenario the case where  $g^{e*} < g^\circ$  could occur also

C: despite a favorable terms-of-trade effect, i.e.  $\epsilon_e^* < 0$ ;  $\frac{\partial p}{\partial \tau_i^e} < 0$ ,

due to the ambiguous sign of  $\frac{\partial p}{\partial \tau_i^e}$ , see (8). Case A comes at no surprise, see Propositions 1 and 3. Since  $\epsilon_m > 0$  requires rather non-standard functional forms, as outlined in the text above, Case B may be discarded. So, I am left with case A and C. The numerical example presented in the subsequent section shows that for carbon taxation case C applies, while for capital taxation it is case A.<sup>14</sup>

Comparing the equilibrium infrastructure provision levels across the two policy scenarios, I obtain

<sup>14</sup>See Figures 7 and 8 in Appendix E, where this is shown for parameter setting 1, while the same pattern is also found in the other parameter settings. The author will kindly provide findings upon request.

**Proposition 6** *Given non-cooperative policy making in industrialized countries with  $\mu \in [0, 1)$ , it holds for equilibrium public infrastructure provision that*

$$g^{e*} \begin{cases} > \\ = \\ < \end{cases} g^{k*} \Leftrightarrow \frac{[1 - \mu][F_{eg}^e e - 1] + n}{[1 - \mu]F_{eg}^k e + n} \begin{cases} > \\ = \\ < \end{cases} \frac{1 + \epsilon_e^*}{1 + \epsilon_k^*}, \quad (34)$$

where  $F_{eg}^e := F_{eg}(e, k, e\tau^e)$ ,  $F_{eg}^k := F_{eg}(e, k, k\tau^k)$ ,  $g^{e*} = e\tau^{e*}$  and  $g^{k*} = k\tau^{k*}$ . Given  $F_{eg}^e = F_{eg}^k =: F_{eg}$ , statement (34) simplifies to

$$g^{e*} \begin{cases} > \\ = \\ < \end{cases} g^{k*} \Leftrightarrow 1 - \chi \begin{cases} > \\ = \\ < \end{cases} \frac{1 + \epsilon_e^*}{1 + \epsilon_k^*}, \quad (35)$$

with  $\chi = \frac{1 - \mu}{[1 - \mu]F_{eg}e + n} > 0$ .

**Proof** See Appendix D.

Relations (34) and (35) show that carbon taxation might deliver higher public infrastructure provision in equilibrium, i.e.  $g^{e*} > g^{k*}$ , despite a lower tax base elasticity, i.e.  $\epsilon_e^* < \epsilon_k^*$ , which is owed to the terms-of-trade-effect, see Proposition 4. In that respect, Proposition 6 is a synthesis of Propositions 2 and 4. However, it is also possible that the tax base elasticity under carbon taxation is much lower than under capital taxation ( $\epsilon_e^* \ll \epsilon_k^*$ ), so that, despite the favorable terms-of-trade effect, the equilibrium provision level of the former scenario is less than the equilibrium provision under capital taxation policy. Since the analytical model remains fairly general in Proposition 6, in the next section I specify functional forms to show a numerical example.

## 4 Numerical Example

The numerical application shown below rests on the work of Franks et al. (2017), who employ a twice nested CES production function, formally given by

$$F^i(k_i, g_i, e_i, \ell_i) = ((1 - a_1)X(g_i, k_i, \ell_i)^{s_1} + a_1 e_i^{s_1})^{1/s_1} \\ \text{with } X(g_i, k_i, \ell_i) = \left( a_2 \left( ((1 - a_3)g_i^{s_3} + a_3 k_i^{s_3})^{1/s_3} \right)^{s_2} + (1 - a_2)\ell_i^{s_2} \right)^{1/s_2}, \quad (36)$$

where  $s_m = \frac{\sigma_m - 1}{\sigma_m}$  for  $m = \{1, 2, 3\}$ . Thereby  $\sigma_m$  denotes the elasticity of substitution between two factors or a factor and a composite.<sup>15</sup> I implement four scenarios with

<sup>15</sup>Labor, denoted by  $\ell$ , is assumed to be locally fixed by Franks et al. (2017). This type of production factors was omitted in the analytical part of the text.

differing degrees of net-substitutability between capital  $k$  and the public good  $g$  ( $\sigma_3$ ) as well as between the capital – public-infrastructure – labor composite  $k/g/\ell$  and fossil fuel  $e$  ( $\sigma_1$ ). The parameter settings suppose net-substitutabilities as stipulated in Table 1, while  $\mu = 0$  and  $n = 2$ . See Table 2 for the remaining parameter values.<sup>16</sup>

Setting	$k$ and $g$	$k/g/\ell$ and $e$
1	substitutes	complements
2	complements	substitutes
3	complements	complements
4	substitutes	substitutes

Table 1: Net-complementarity of production factors

	Setting 1	Setting 2	Setting 3	Setting 4
$\sigma_1$	.5	1.1	.5	1.1
$\sigma_2$	.7	.7	.7	.7
$\sigma_3$	1.1	.9	.9	1.1
$a_1$			.05	
$a_2$			.42	
$a_3$			.7	
$k = e = \ell$			1	

Table 2: Parameter Values

Numerical solutions are represented in Figures 1 - 4, where the solid lines represent the marginal productivity of the public good and the dotted and dashed lines the MCPF under carbon taxation and capital taxation respectively supposing symmetric levels of tax rates.

The findings reveal that the MCPF rises much quicker with the level of tax rates when the tax base is a net-substitute to the public good. With rising public revenues, firms reduce their demand for the tax base much stronger than if it were a complement to  $g$ . This in turn leads to a strong tax-base-relocation-effect and causes the steep inclination of the MCPF curve. Consequently, when one factor is highly complementary to public infrastructure, its choice to be the tax base pays off in higher provision and efficiency, see carbon taxation in Setting 1 and capital taxation in Setting 2. In case both, fossil fuels and capital, are net-complements to  $g$  (Setting 3) both scenarios exhibit almost identical provision levels, while in case both are net-substitutes to  $g$  (Setting 4) carbon taxation yields more provision and higher efficiency than capital taxation. The impact of the terms-of-trade effect is thereby significant.<sup>17</sup> In its absence, carbon taxation would

<sup>16</sup>The parameter values for  $k$ ,  $e$  and  $\ell$  have been chosen arbitrarily. Nevertheless, the results qualitatively carry over to other calibrations for these parameters.

<sup>17</sup>See Figures 5 and 6 in Appendix E for policy equilibria in the absence of the terms-of-trade effect.

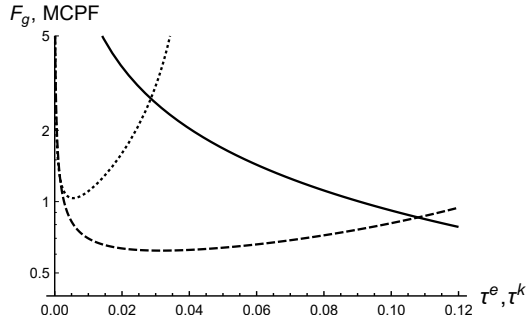


Figure 1: Setting 1

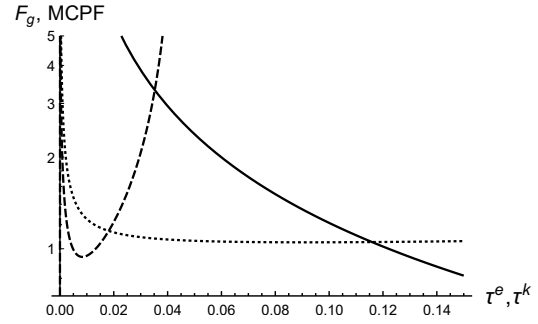


Figure 2: Setting 2

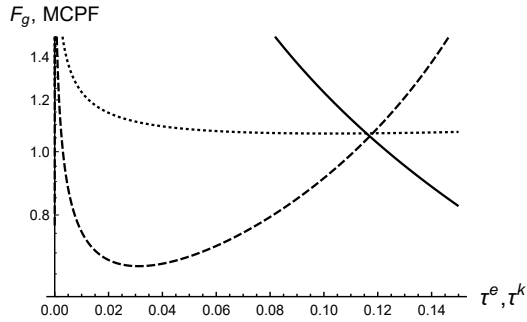


Figure 3: Setting 3

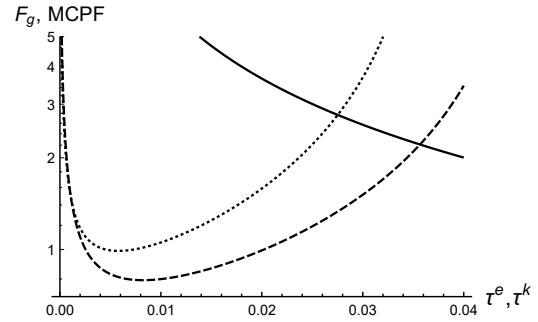


Figure 4: Setting 4

—  $F_g$     - - - - -  $MCPF \tau^e$     .....  $MCPF \tau^k$

Legend

yield far less infrastructure provision than capital taxation policy in Setting 3, instead of higher provision as shown in Figure 3. And in Setting 4, the advantage attached to carbon taxation, i.e. higher provision levels than under carbon taxation, would be much smaller.

Thus, this numerical exercise shows that results are highly sensitive to assumptions regarding factor substitutability. Baier and Glomm (2001) draw a similar conclusion. On the contrary, Franks et al. (2017) state that their results are robust against a particularly wide range of parameter values. Their analysis incorporates dynamics so that comparability to the model incorporated here is limited. Still, the present findings point into a different direction as suggested by Franks et al. (2017).

In the literature, estimates for the substitution elasticity of private and public capital give support to both notions, net-substitutes or net-complements, see Coenen et al. (2012) and Otto and Voss (1998). For the natural resource, estimations of Kemfert and Welsch (2000) suggest a weakly complementary relationship of energy (in coal-equivalent units) with the composite of capital and labor for Germany. More generally, Koetse et al. (2008) find a complementary relationship of energy and capital for the short and medium run (substitution elasticities of .64 and .89 respectively) and a weak net-substitutional effect in the long run (substitution elasticity of 1.21). Since dynamic effects are left out in the present model and factor supply is assumed to be inelastic, it rather applies to the

short run. Thus, parameter settings 1 and 3 may be most relevant, since these show the difference concerning the substitution elasticity between private and public capital.

## 5 Conclusion

This paper investigates under which conditions a carbon tax might be superior to a capital tax when it comes to the provision of public infrastructure. The analysis abstracts from environmental degradation as a motivation for choosing one or the other policy instrument. It rather follows Franks et al. (2017) in assessing whether, on pure fiscal grounds, a carbon tax could be advantageous in the sense that it yields higher provision levels of public infrastructure. I find that the policy choice in each scenario (carbon taxation or capital taxation), and thus the ranking between the two scenarios, is driven by two effects. First, there is the ‘terms-of-trade effect’, which hinges on the possibility that the policy instruments in question have an impact on the price of imported fossil fuels, which affects income of the domestic household. Second, there is the ‘tax-base-relocation-effect’, which makes reference an to interregional shift of the market allocation of production factors in response to local tax changes. This could lead to tax competition where policy makers set local tax rates in order to attract the internationally mobile tax base yielding an inefficient policy choice. Both effects are altered when considering the impact of public spending on firm productivity, which I refer to as the public-expenditure channel.

There are three major findings. First, the terms-of-trade effect leads to higher public infrastructure provision under carbon taxation, since the distorting effect of this tax instrument on the price of the imported fossil fuels lowers the costs of raising public revenues. At the same time, the public-expenditure channel helps to explain why the terms-of-trade effect in the carbon taxation scenario might be negative, leading to inefficiently low public infrastructure provision. Capital taxes have a disadvantage here, since in the present model this instrument does not distort the fossil fuel price while, just as in the carbon taxation scenario, the public-expenditure channel renders fossil fuels costlier. Second, carbon taxation policy yields higher provision levels only if the tax-base-relocation-effect is greater (less negative) than in the case of the capital taxation. The public-expenditure channel here explains, why the tax-base-relocation effect might be positive, i.e. the tax base relocates inwards instead of outwards in response to higher local taxes and the resulting increase in public expenditure. Considering both, the terms-of-trade effect and the tax-base-relocation effect, simultaneously, I find that carbon taxation policy may yield higher provision levels than capital taxation even if its tax-base-relocation-effect is more negative. However, the numerical example reveals that the results are highly sensitive to the tax-base-relocation effect, which is strongly driven by the complementarity in production between public infrastructure and the tax base.

Since empirical evidence is inconclusive with regard to the complementarities, the ranking of carbon and capital taxation has to remain inconclusive.

Looking beyond this analytical exercise, this paper clearly makes the case, that neither of the policy options discussed here is generally superior to the other, not even if this only refers to provision levels leaving aside questions of efficiency. The results indicate that a policy maker must make a thorough assessment of the context. One aspect would be the presence or absence of policy coordination between jurisdictions. A country might be in a different situation compared to a state in a federal system, where fiscal equalization schemes might considerably reduce tax competition. It is then the question, whether this applies to environmental policy instruments the same way as to capital taxation. Furthermore, expenditure policy could make a difference too, i.e. the type of publicly financed good being provided. Taking the example of fossil fuels, complementarity may be high if the infrastructure consists of road networks and airports, but it may be low in the case of public transport. And finally, the policy maker must address the question, whether a country is in state of reaping foreign resource rents via the terms-of-trade effect when taxing fossil fuels. Thus, she must answer the question whether the impact of domestic demand on the world market prices is significant.

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## A Comparative Statics

### Carbon Taxation:

The equilibrium conditions in this policy scenario are given by (3a) and (3b), as well as (7a) and (7b). These are first totally differentiated supposing that country  $i$  changes its tax rate while in all other countries' tax rates remain unchanged, i.e.  $d\tau_i^e \neq 0$  and  $d\tau_j^e = 0$  with  $i \neq j$ , and then divided by  $d\tau_i^e$ . The change in public expenditure is substituted by the differentiated budget constraint (5a), which writes  $\frac{\partial g_i}{\partial \tau_i^e} = e_i + \tau_i^e \frac{\partial e_i}{\partial \tau_i^e}$  for country  $i$  and  $\frac{\partial g_j}{\partial \tau_i^e} = \tau_j^e \frac{\partial e_j}{\partial \tau_i^e}$  for country  $j$ . I then obtain

$$F_{ee}^i \frac{\partial e_i}{\partial \tau_i^e} + F_{ek}^i \frac{\partial k_i}{\partial \tau_i^e} + F_{eg}^i \left[ \tau_i^e \cdot \frac{\partial e_i}{\partial \tau_i^e} + e_i \right] = \frac{\partial p}{\partial \tau_i^e} + 1, \quad (37)$$

$$F_{ee}^j \frac{\partial e_j}{\partial \tau_i^e} + F_{ek}^j \frac{\partial k_j}{\partial \tau_i^e} + F_{eg}^j \tau_j^e \cdot \frac{\partial e_j}{\partial \tau_i^e} = \frac{\partial p}{\partial \tau_i^e}, \quad (38)$$

$$F_{ek}^i \frac{\partial e_i}{\partial \tau_i^e} + F_{kk}^i \frac{\partial k_i}{\partial \tau_i^e} + F_{kg}^i \left[ \tau_i^e \cdot \frac{\partial e_i}{\partial \tau_i^e} + e_i \right] = \frac{\partial r}{\partial \tau_i^e}, \quad (39)$$

$$F_{ek}^j \frac{\partial e_j}{\partial \tau_i^e} + F_{kk}^j \frac{\partial k_j}{\partial \tau_i^e} + F_{kg}^j \tau_j^e \cdot \frac{\partial e_j}{\partial \tau_i^e} = \frac{\partial r}{\partial \tau_i^e}, \quad (40)$$

$$\frac{\partial e_i}{\partial \tau_i^e} + \sum_{j \neq i} \frac{\partial e_j}{\partial \tau_i^e} = 0, \quad (41)$$

$$\frac{\partial k_i}{\partial \tau_i^e} + \sum_{j \neq i} \frac{\partial k_j}{\partial \tau_i^e} = 0. \quad (42)$$

I proceed by summing up (37) and (38) as well as (39) and (40) over all countries  $i$  and  $j$  using the symmetry assumption, i.e.  $\tau_i^e = \tau_j^e = \tau^e$ ,  $e_i = e_j = e$  and  $k_i = k_j = k$ , as well as  $F_x^i = F_x^j = F_x$ ,  $F_{xx}^i = F_{xx}^j = F_{xx}$  and  $F_{xz}^i = F_{xz}^j = F_{xz}$  for  $x, z \in \{e, k, g\}$  with  $x \neq z$ ,



and get

$$\begin{aligned}
n \frac{\partial p}{\partial \tau_i^e} + 1 &= F_{ee} \left[ \frac{\partial e_i}{\partial \tau_i^e} + \sum_{j \neq i} \frac{\partial e_j}{\partial \tau_i^e} \right] \\
&\quad + F_{ek} \left[ \frac{\partial k_i}{\partial \tau_i^e} + \sum_{j \neq i} \frac{\partial k_j}{\partial \tau_i^e} \right] + F_{eg} \left[ \tau^e \left[ \frac{\partial e_i}{\partial \tau_i^e} + \sum_{j \neq i} \frac{\partial e_j}{\partial \tau_i^e} \right] + e \right], \\
n \frac{\partial r}{\partial \tau_i^e} &= F_{ek} \left[ \frac{\partial e_i}{\partial \tau_i^e} + \sum_{j \neq i} \frac{\partial e_j}{\partial \tau_i^e} \right] + F_{kk} \left[ \frac{\partial k_i}{\partial \tau_i^e} + \sum_{j \neq i} \frac{\partial k_j}{\partial \tau_i^e} \right] + F_{kg} \left[ \tau^e \left[ \frac{\partial e_i}{\partial \tau_i^e} + \sum_{j \neq i} \frac{\partial e_j}{\partial \tau_i^e} \right] + e \right].
\end{aligned}$$

I then use (41) and (42) to simplify rearrange for  $\frac{\partial p}{\partial \tau_i^e}$  and  $\frac{\partial r}{\partial \tau_i^e}$  and obtain

$$\frac{\partial p}{\partial \tau_i^e} = \frac{F_{eg}e - 1}{n} \begin{matrix} \geq \\ \leq \end{matrix} 0, \quad (43)$$

$$\frac{\partial r}{\partial \tau_i^e} = \frac{F_{kg}e}{n} > 0. \quad (44)$$

Finally, I take (37) and (39) as a system of equations to solve for  $\frac{\partial e_i}{\partial \tau_i^e}$  and  $\frac{\partial k_i}{\partial \tau_i^e}$  using (43) and (44). By rearrangement and substitution I obtain

$$\frac{\partial e_i}{\partial \tau^e} = \frac{n-1}{n} \frac{[1 - eF_{eg}]F_{kk} + eF_{kg}F_{ek}}{[F_{ee} + \tau^e F_{eg}]F_{kk} - [F_{ek} + \tau^e F_{kg}]F_{ek}} \begin{matrix} \geq \\ \leq \end{matrix} 0, \quad (45)$$

$$\frac{\partial k_i}{\partial \tau_i^e} = \frac{n-1}{n} \frac{F_{ek}[eF_{eg} - 1] - F_{kg}[eF_{ee} + \tau^e]}{[F_{ee} + \tau^e F_{eg}]F_{kk} - [F_{ek} + \tau^e F_{kg}]F_{ek}} \begin{matrix} \geq \\ \leq \end{matrix} 0. \quad (46)$$

### Capital Taxation:

The equilibrium conditions in this policy scenario are given by (4a) and (4b) as well as (7a) and (7b). The procedure is the same as for the derivation of comparative static effects under carbon taxation, only that the budget constraint is given by (5b). For the first step I obtain

$$F_{ee}^i \frac{\partial e_i}{\partial \tau_i^k} + F_{ek}^i \frac{\partial k_i}{\partial \tau_i^k} + F_{eg}^i \left[ \tau_i^k \cdot \frac{\partial k_i}{\partial \tau_i^k} + k_i \right] = \frac{\partial p}{\partial \tau_i^k}, \quad (47)$$

$$F_{ee}^j \frac{\partial e_j}{\partial \tau_i^k} + F_{ek}^j \frac{\partial k_j}{\partial \tau_i^k} + F_{eg}^j \tau_j^k \cdot \frac{\partial k_j}{\partial \tau_i^k} = \frac{\partial p}{\partial \tau_i^k}, \quad (48)$$

$$F_{ek}^i \frac{\partial e_i}{\partial \tau_i^k} + F_{kk}^i \frac{\partial k_i}{\partial \tau_i^k} + F_{kg}^i \left[ \tau_i^k \cdot \frac{\partial k_i}{\partial \tau_i^k} + k_i \right] = \frac{\partial r}{\partial \tau_i^k} + 1, \quad (49)$$

$$F_{ek}^j \frac{\partial e_j}{\partial \tau_i^k} + F_{kk}^j \frac{\partial k_j}{\partial \tau_i^k} + F_{kg}^j \tau_j^k \cdot \frac{\partial k_j}{\partial \tau_i^k} = \frac{\partial r}{\partial \tau_i^k}, \quad (50)$$

while the differentiated market clearing conditions are identical to the carbon taxation

case, see (41) and (42). For the price changes I receive

$$\frac{\partial p}{\partial \tau_i^k} = \frac{F_{eg}k}{n} > 0, \quad (51)$$

$$\frac{\partial r}{\partial \tau_i^k} = \frac{F_{kg}k - 1}{n} \begin{matrix} \geq \\ < \end{matrix} 0. \quad (52)$$

And finally, I obtain the following expressions for the changes of factor demand in country  $i$

$$\frac{\partial k_i}{\partial \tau_i^k} = \frac{n-1}{n} \frac{[[1 - kF_{kg}]F_{ee} + kF_{eg}F_{ek}]}{[F_{kk} + \tau^k F_{kg}]F_{ee} - [F_{ek} + \tau^k F_{eg}]F_{ek}} \begin{matrix} \geq \\ < \end{matrix} 0, \quad (53)$$

$$\frac{\partial e_i}{\partial \tau_i^k} = \frac{n-1}{n} \frac{F_{ek}[kF_{kg} - 1] - F_{eg}[kF_{kk} + \tau^k]}{[F_{kk} + \tau^k F_{kg}]F_{ee} - [F_{ek} + \tau^k F_{eg}]F_{ek}} \begin{matrix} \geq \\ < \end{matrix} 0. \quad (54)$$

## B First Best Policy

By assumption, the social planner chooses the local tax rates in industrialized countries to maximize the sum all countries' welfare. For industrialized countries  $i, j$  welfare is given by equation (6), where  $\pi_i$  ( $\pi_j$ ) is given by (1) and  $g_i$  ( $g_j$ ) by (5a), and for the non-industrialized region by  $y_R = [1 - \mu]\bar{E}$ . The policy problem formally reads

$$\max_{\tau_i^e} y_i + \sum_{j \neq i} y_j + y_R \quad (55)$$

and the first-order condition is given by

$$\frac{\partial y_i}{\partial \tau_i^e} + [n-1] \cdot \frac{\partial y_j}{\partial \tau_i^e} + \frac{\partial y_R}{\partial \tau_i^e} = 0 \quad (56)$$

for the case of carbon taxation, which serves for the derivation of first-best policy choice. At the end of this Appendix, the optimal choice for capital taxation is derived. In order to obtain the single derivatives in (56), I differentiate (6) for countries  $i, j$ , where  $j \neq i$ , as well as  $y_R$  with respect to  $\tau_i^e$  considering (43) – (46). I simplify by using (3a), (3b), and the symmetry assumption ( $\tau_i^e = \tau_j^e = \tau^e$ ,  $e_i = e_j = e = \frac{\bar{E}}{n}$ ,  $k_i = k_j = k = \frac{\bar{K}}{n}$ ,

$F_x(e_i, k_i, g_i) = F_x(e_j, k_j, g_j) = F_x$  for  $x = \{e, k, g\}$ ) and obtain

$$\begin{aligned} \frac{\partial y_i}{\partial \tau_i^e} &= \underbrace{[F_e - p - \tau^e]}_{=0} \frac{\partial e_i}{\partial \tau_i} + \underbrace{[F_k - r]}_{=0} \frac{\partial k_i}{\partial \tau_i} + F_g \left[ e + \frac{\partial e_i}{\partial \tau_i^e} \tau^e \right] \\ &\quad - \left[ \frac{\partial p}{\partial \tau_i} + 1 \right] e - \frac{\partial r}{\partial \tau_i} k + \frac{\partial p}{\partial \tau_i} \mu \frac{\bar{E}}{n} + \frac{\partial r}{\partial \tau_i} \frac{\bar{K}}{n} \\ &= F_g \left[ e + \frac{\partial e_i}{\partial \tau_i^e} \tau^e \right] - e + [\mu - 1] \frac{\bar{E}}{n} \frac{\partial p}{\partial \tau_i^e}, \end{aligned} \quad (57)$$

$$\begin{aligned} \frac{\partial y_j}{\partial \tau_i^e} &= \underbrace{[F_e - p - \tau^e]}_{=0} \frac{\partial e_j}{\partial \tau_i} + \underbrace{[F_k - r]}_{=0} \frac{\partial k_j}{\partial \tau_i} + F_g \frac{\partial e_j}{\partial \tau_i^e} \tau^e - \frac{\partial p}{\partial \tau_i} e - \frac{\partial r}{\partial \tau_i} k + \frac{\partial p}{\partial \tau_i} \mu \frac{\bar{E}}{n} + \frac{\partial r}{\partial \tau_i} \frac{\bar{K}}{n} \\ &= F_g \frac{\partial e_j}{\partial \tau_i^e} \tau^e + [\mu - 1] \frac{\bar{E}}{n} \frac{\partial p}{\partial \tau_i^e}, \end{aligned} \quad (58)$$

$$\frac{\partial y_R}{\partial \tau_i^e} = [1 - \mu] \bar{E} \frac{\partial p}{\partial \tau_i^e}. \quad (59)$$

Then I plug in these into (56), differentiate (7b) with respect to  $\tau_i^e$ , which I use together with (41) to simplify, and obtain

$$\begin{aligned} \frac{\partial y_i}{\partial \tau_i^e} + [n - 1] \cdot \frac{\partial y_j}{\partial \tau_i^e} + \frac{\partial y_R}{\partial \tau_i^e} &= F_g \cdot e + F_g \tau^e \underbrace{\left[ \frac{\partial e_i}{\partial \tau_i^e} + [n - 1] \frac{\partial e_j}{\partial \tau_i^e} \right]}_{=0} \\ &\quad - e + [\mu - 1] \frac{n \bar{E}}{n} \frac{\partial p}{\partial \tau_i^e} - [\mu - 1] \bar{E} \frac{\partial p}{\partial \tau_i^e} = 0 \\ \Rightarrow F_g &= 1. \end{aligned}$$

The first-best choice of the capital tax must satisfy the same condition, from which follows

$$F_g(e, k, e\tau^{e\odot}) = F_g(e, k, k\tau^{k\odot}) = 1. \quad (60)$$

## C Cooperative Policy

### Carbon Taxation:

Take the policy problem given by (19) and plug in (6) for country  $i$  as well as for countries  $j \neq i$  by simply adapting country indices. Firm profits  $\pi_i$  (and again  $\pi_j$ ) are given by (1). The policy problem then reads

$$\begin{aligned} \max_{\tau_i^e} y_i + \sum_{j \neq i}^n y_j &= F(e_i, k_i, g_i^e) - (p + \tau_i^e) e_i - r \cdot k_i \\ &\quad + \sum_{j \neq i}^n \left[ F(e_j, k_j, g_j^e) - [p + \tau_j^e] e_j - r \cdot k_j \right] + p \cdot \mu \bar{E} + r \bar{K}. \end{aligned}$$

Deriving with respect to  $\tau_i^e$  and equating to zero gives the first-order condition to the policy problem. To simplify, I use (3a) and (3b), differentiate (5a) for  $i, j$  with respect to  $\tau_i^e$  to substitute for  $\frac{\partial g_i}{\partial \tau_i^e}$  and  $\frac{\partial g_j}{\partial \tau_i^e}$  respectively, employ (41) differentiated with respect to  $\tau_i^e$  and apply the symmetry assumption as stated in Appendix B to obtain

$$\begin{aligned}
\frac{\partial Y_i}{\partial \tau_i^e} + \sum_{j \neq i}^n \frac{\partial Y_j}{\partial \tau_i^e} &= F_g \frac{\partial g_i}{\partial \tau_i^e} - \left[ \frac{\partial p}{\partial \tau_i^e} + 1 \right] e - \frac{\partial r}{\partial \tau_i^e} k \\
&+ \sum_{j \neq i}^n \left[ F_g \frac{\partial g_j}{\partial \tau_i^e} - \frac{\partial p}{\partial \tau_i^e} e - \frac{\partial r}{\partial \tau_i^e} k \right] + \mu \bar{E} \frac{\partial p}{\partial \tau_i^e} + \bar{K} \frac{\partial r}{\partial \tau_i^e} = 0 \\
&= F_g \left[ \tau^e \underbrace{\left[ \frac{\partial e_i}{\partial \tau_i^e} + \sum_{j \neq i}^n \frac{\partial e_j}{\partial \tau_i^e} \right]}_{=0} + \underbrace{e}_{=\frac{\bar{E}}{n}} \right] - \frac{\bar{E}}{n} + \frac{\partial p}{\partial \tau_i^e} \bar{E} [\mu - 1] = 0 \\
\Rightarrow F_g &= 1 + \frac{\partial p}{\partial \tau_i^e} n \cdot [1 - \mu].
\end{aligned} \tag{61}$$

Since  $\frac{\partial p}{\partial \tau_i^e} \geq 0$ , see equation (43), it follows that  $F_g \geq 1$ .

### Capital Taxation:

Following the steps outlined above for the case of carbon taxation, the policy problem in this scenario, given by (20), reads

$$\begin{aligned}
\max_{\tau_i^k} \quad & y_i + \sum_{j \neq i}^n y_j = F(e_i, k_i, g_i^e) - (r + \tau_i^k) k_i - p \cdot e_i \\
& + \sum_{j \neq i}^n \left[ F(e_j, k_j, g_j^e) - [r + \tau_j^k] k_j - p \cdot e_j \right] + p \cdot \mu \bar{E} + r \bar{K}.
\end{aligned}$$

Applying the same procedure as above gives the following optimality condition

$$\begin{aligned}
\frac{\partial y_i}{\partial \tau_i^k} + \sum_{j \neq i}^n \frac{\partial y_j}{\partial \tau_i^k} &= F_g \frac{\partial g_i}{\partial \tau_i^k} - \left[ \frac{\partial r}{\partial \tau_i^k} + 1 \right] k - \frac{\partial p}{\partial \tau_i^k} e \\
&+ \sum_{j \neq i}^n \left[ F_g \frac{\partial g_j}{\partial \tau_i^k} - \frac{\partial p}{\partial \tau_i^k} e - \frac{\partial r}{\partial \tau_i^k} k \right] + \mu \bar{E} \frac{\partial p}{\partial \tau_i^k} + \bar{K} \frac{\partial r}{\partial \tau_i^k} = 0 \\
0 &= F_g \left[ \tau^k \underbrace{\left[ \frac{\partial k_i}{\partial \tau_i^k} + \sum_{j \neq i}^n \frac{\partial k_j}{\partial \tau_i^k} \right]}_{=0} + \underbrace{k}_{=\frac{\bar{K}}{n}} \right] - \frac{\bar{K}}{n} + \frac{\partial p}{\partial \tau_i^k} \bar{E} [\mu - 1] \\
\Rightarrow F_g &= 1 + \frac{\partial p}{\partial \tau_i^k} \frac{n \bar{E}}{\bar{K}} \cdot [1 - \mu].
\end{aligned} \tag{62}$$

Since  $\frac{\partial p}{\partial \tau_i^k} > 0$ , see equation (51), it follows that  $F_g > 1$ .

### Fossil Fuel Price under Second-Best Policy (Carbon Taxation Scenario):

Take (3a) with  $\tau_i^e = \tau^{e\odot}$ , as well as  $e_i = \frac{\bar{E}}{n}$  and  $k_i = \frac{\bar{K}}{n}$ , and differentiate with respect to the symmetric tax rate, i.e.  $d\tau_i^e = d\tau_j^e = d\tau^{e\odot}$  for  $i \neq j$ , which implies  $\frac{\partial e_i}{\partial \tau_i^e} = 0$  and

$\frac{\partial k_i}{\partial \tau_i^e} = 0$ , and which gives

$$\begin{aligned} F_e \left( \frac{\bar{E}}{n}, \frac{\bar{K}}{n}, \tau^e \frac{\bar{E}}{n} \right) &= p^\circ + \tau^{e\circ} \\ F_{eg} d\tau^e &= dp + d\tau^e \\ F_{eg} - 1 &= \frac{\partial p}{\partial \tau^e}. \end{aligned} \quad (63)$$

Furthermore, assume that for any symmetric level of tax rates  $\tau^e \leq \tau^{e\circ}$  it holds that  $F_g \geq 1 + \frac{\partial p}{\partial \tau_i^e}$ . Then the choice of  $\tau^{e\circ}$ , which satisfies  $F_g = 1 + \frac{\partial p}{\partial \tau_i^e}$ , represents is the unique stable policy equilibrium. So,  $\tau^{e\circ} \geq \tau^{e\circ}$  implies .

$$F_g^\circ \geq 1 + \frac{\partial p}{\partial \tau_i^e} \Big|_{\tau_i^e = \tau^{e\circ}} \quad (64)$$

Suppose  $\tau^{e\circ} > \tau^{e\circ}$  ( $\tau^{e\circ} < \tau^{e\circ}$ ). It then follows from (64) that  $\frac{\partial p}{\partial \tau_i^e} \Big|_{\tau_i^e = \tau^{e\circ}} < 0$  ( $> 0$ ), so that  $F_{eg} < 1$  ( $> 1$ ) for  $\tau = [\tau^{e\circ}, \tau^{e\circ}]$  ( $\tau = [\tau^{e\circ}, \tau^{e\circ}]$ ). From there and from (63) it follows that

$$p^{e\circ} > p^{e\circ}, \quad (65)$$

### Fossil Fuel Price under Second-Best Policy (Capital Taxation Scenario):

Take (4a) with  $\tau_i^e = \tau^{e\circ}$ , which implies a symmetric market equilibrium with  $e_i = \frac{\bar{E}}{n}$  and  $k_i = \frac{\bar{K}}{n}$ , and differentiate with respect to the symmetric tax rate, i.e.  $d\tau_i^k = d\tau_j^k = d\tau^{k\circ}$  for  $i \neq j$ , which implies  $\frac{\partial e_i}{\partial \tau_i^k} = 0$  and  $\frac{\partial k_i}{\partial \tau_i^k} = 0$ , and which gives

$$\begin{aligned} F_e \left( \frac{\bar{E}}{n}, \frac{\bar{K}}{n}, \tau^{k\circ} \frac{\bar{E}}{n} \right) &= p^\circ \\ F_{eg} d\tau^e &= dp + d\tau^e \\ F_{eg} &= \frac{\partial p}{\partial \tau^k}. \end{aligned} \quad (66)$$

From (18) and (24), for which symmetry holds, i.e.  $e_i = \frac{\bar{E}}{n}$  and  $k_i = \frac{\bar{K}}{n}$ , it follows  $\tau^{k\circ} < \tau^{k\circ}$ . From there and from (66) follows

$$p^{k\circ} < p^{k\circ}. \quad (67)$$

### Proof of Proposition 2:

**Proof** This proof begins by showing that  $y_i$  is a single-peaked function in symmetric tax levels  $\tau^e$  or  $\tau^k$ . Suppose  $n = 1$ , so that  $d\tau_i^e$  or  $d\tau_i^k$  represent global changes of the tax level and comparative statics, given by (8) - (17), follow this notion. Take the capital

taxation scenario for example. Using (5b), (7a) and (7b) in (6) gives

$$y = F(\bar{E}, \bar{K}, \tau^k \bar{K}) - p\bar{E} - [r + \tau^k]\bar{K} + \mu p\bar{E} + r\bar{K}, \quad (68)$$

where the country index has been dropped for convenience. Then, deriving (68) with respect to  $\tau^k$  and using (15) to substitute for  $\frac{\partial p}{\partial \tau^k}$  gives

$$\begin{aligned} \frac{\partial y}{\partial \tau^k} &= F_g \bar{K} - \frac{\partial p}{\partial \tau^k} \bar{E} - \left[ \frac{\partial r}{\partial \tau^k} + 1 \right] \bar{K} + \mu \frac{\partial p}{\partial \tau^k} \bar{E} - \frac{\partial r}{\partial \tau^k} \bar{K} \\ &= \bar{K} [F_g - F_{eg} \bar{E} [1 - \mu] - 1] \geq 0. \end{aligned} \quad (69)$$

Assuming  $\lim_{\tau^k \rightarrow 0} \{F_g, F_{eg}e\} \rightarrow \infty$ ,  $\lim_{\tau^k \rightarrow \infty} \{F_g, F_{eg}e\} \rightarrow 0$  as well as  $F_g - F_{eg}e > 0$  gives

$$\lim_{\tau^k \rightarrow 0} \frac{\partial y}{\partial \tau^k} > 0, \quad \lim_{\tau^k \rightarrow \infty} \frac{\partial y}{\partial \tau^k} \rightarrow -1. \quad (70)$$

Finally, assuming  $F_{egg} < 0$ ,

$$\frac{\partial^2 y}{\partial (\tau^k)^2} = \bar{K} [F_{gg} - F_{egg} \bar{E} [1 - \mu]] < 0 \quad (71)$$

is obtained from (68). From (69), (70) and (71) it follows that  $y$  is single-peaked in  $\tau^k$  and of inverted u-shape.

Now consider a policy choice  $\hat{\tau}^k$ , which satisfies  $\bar{K} \hat{\tau}^k = \bar{E} \tau^{e\otimes}$ . Using  $F_g(\cdot, \bar{K} \hat{\tau}^k) = F_g(\cdot, \bar{E} \tau^{e\otimes})$  and  $F_{eg}(\cdot, \bar{K} \hat{\tau}^k) = F_{eg}(\cdot, \bar{E} \tau^{e\otimes})$  in (69) and substituting  $F_g(\cdot, \bar{E} \tau^{e\otimes})$  by (61) and (8) with  $k = \bar{K}$  gives

$$\left. \frac{\partial y_i}{\partial \tau^k} \right|_{\tau^k = \hat{\tau}^k} = \bar{K} [\mu - 1] < 0. \quad (72)$$

From (72), given  $y$  is single-peaked in  $\tau_k$ , and since  $\tau^{k\otimes}$  satisfies (69) with equality, see (22), it follows that  $\tau^{k\otimes} < \hat{\tau}^k$ , and therefore it also  $g^{k\otimes} = k\tau^{k\otimes} < k\hat{\tau}^k = e\tau^{e\otimes} = g^{e\otimes}$  holds.

## D Non-cooperative Tax Policy

### Carbon Taxation:

I use (1) and (6) in the non-cooperative policy problem, given by (26a). Deriving with respect to  $\tau_i^e$  and equating to zero gives the first-order condition. Then, I replace  $\frac{\partial g_i}{\partial \tau_i^e}$  by the differentiated budget constraint (5a), simplify further by using (3a) and (3b) and

apply the symmetry assumption as outlined in Appendix B to obtain

$$\begin{aligned}
\frac{\partial y_i}{\partial \tau_i^e} &= F_g \left[ \tau_i^e \frac{\partial e_i}{\partial \tau_i^e} + e \right] - \left[ \frac{\partial p}{\partial \tau_i^e} + 1 \right] e - \frac{\partial r}{\partial \tau_i^e} k + \frac{\mu \bar{E}}{n} \frac{\partial p}{\partial \tau_i^e} + \frac{\bar{K}}{n} \frac{\partial r}{\partial \tau_i^e} = 0 \\
\Rightarrow 0 &= F_g \left[ \tau_i^e \frac{\partial e_i}{\partial \tau_i^e} + e \right] - e + \frac{\partial p}{\partial \tau_i^e} [\mu - 1] e \\
\Leftrightarrow F_g &= \frac{(1 - \mu) \frac{\partial p}{\partial \tau_i^e}}{1 + \epsilon_e} + \frac{1}{1 + \epsilon_e}, \tag{73}
\end{aligned}$$

with  $\epsilon_e = \frac{\partial e_i}{\partial \tau_i^e} \frac{\tau_i^e}{e} \gtrless 0$  due to the ambiguous sign of  $\frac{\partial e_i}{\partial \tau_i^e}$ , see (10). Also the sign of  $\frac{\partial p}{\partial \tau_i^e}$  is ambiguous, see (8), so that  $F_g \gtrless 1$ .

### Capital Taxation:

The derivation procedure for capital taxation directly carries over from that of carbon taxation just above here. The policy maker's first-order condition reads

$$\frac{\partial y_i}{\partial \tau_i^k} = F_g \left[ \tau_i^k \frac{\partial k_i}{\partial \tau_i^k} + k \right] - \left[ \frac{\partial r}{\partial \tau_i^k} + 1 \right] k - \frac{\partial p}{\partial \tau_i^k} e + \frac{\mu \bar{E}}{n} \frac{\partial p}{\partial \tau_i^k} + \frac{\bar{K}}{n} \frac{\partial r}{\partial \tau_i^k} = 0,$$

where the differentiated budget constraint (5b) as well as (4a) and (4b) have been used to simplify. Then, I use the symmetry assumption as stated above to rearrange, which gives

$$\begin{aligned}
0 &= F_g \left[ \tau_i^k \frac{\partial k_i}{\partial \tau_i^k} + k \right] - k + \frac{\partial p}{\partial \tau_i^k} [\mu - 1] e \\
\Leftrightarrow F_g &= \frac{(1 - \mu) \frac{\partial p}{\partial \tau_i^k} \frac{e}{k}}{1 + \epsilon_k} + \frac{1}{1 + \epsilon_k}, \tag{74}
\end{aligned}$$

with  $\epsilon_k = \frac{\partial k_i}{\partial \tau_i^k} \frac{\tau_i^k}{k} \gtrless 0$  due to the ambiguous sign of  $\frac{\partial k_i}{\partial \tau_i^k}$ , see (10), so that  $F_g \gtrless 1$ .

### Proof of Proposition 4:

**Proof** Take the policy equilibria for carbon and capital taxation exhibited in Proposition 3, which yield a symmetric market equilibrium, i. e.  $e_i = e_j = e$  and  $k_i = k_j = k$ . So, it can be stated that

$$F_g^e \left\{ \begin{array}{l} < \\ = \\ > \end{array} \right\} F_g^k \Leftrightarrow g^e \left\{ \begin{array}{l} > \\ = \\ < \end{array} \right\} g^k, \tag{75}$$

where  $F_g^e := F_g(e, k, e\tau^e)$ ,  $F_g^k := F_g(e, k, k\tau^k)$ ,  $g^e = e\tau^e$  and  $g^k = k\tau^k$ . Then reformulate

the relation  $F_g^e \gtrless F_g^k$  with the help of (30), which gives

$$\begin{aligned}
& F_g^e \gtrless F_g^k \\
\Leftrightarrow & \frac{1}{1 + \epsilon_e^\ominus} \gtrless \frac{1}{1 + \epsilon_k^\ominus} \\
\Leftrightarrow & \epsilon_e^\ominus \gtrless \epsilon_k^\ominus.
\end{aligned} \tag{76}$$

The statements (75) and (76) imply (31), which completes the proof.

### Proof of Proposition 6:

**Proof** Denote  $F_{(e)g}(e, k, e\tau^e)$  by  $F_{(e)g}^e$  and  $F_{(e)g}(e, k, k\tau^k)$  by  $F_{(e)g}^k$ , and take (27) and (28) to reformulate the relation  $F_g^e \gtrless F_g^k$ , making use of (8) and (15), which gives

$$\begin{aligned}
& F_g^e < F_g^k \\
\Leftrightarrow & \frac{(1 - \mu) \frac{\partial p}{\partial \tau_i^e} + 1}{1 + \epsilon_e^*} \gtrless \frac{(1 - \mu) \frac{\partial p}{\partial \tau_i^k} \frac{e}{k} + 1}{1 + \epsilon_k^*} \\
\Leftrightarrow & \left[ (1 - \mu) \frac{\partial p}{\partial \tau_i^e} + 1 \right] [1 + \epsilon_k^*] \gtrless \left[ (1 - \mu) \frac{\partial p}{\partial \tau_i^k} \frac{e}{k} + 1 \right] [1 + \epsilon_e^*] \\
\Leftrightarrow & \frac{[1 - \mu][F_{eg}^e e - 1] + n}{[1 - \mu]F_{eg}^k e + n} \gtrless \frac{1 + \epsilon_e^*}{1 + \epsilon_k^*}.
\end{aligned} \tag{77}$$

The statements (75), which carries over from the proof of Proposition 4, and (77) imply (34), which completes this proof.

## E Numerical Example

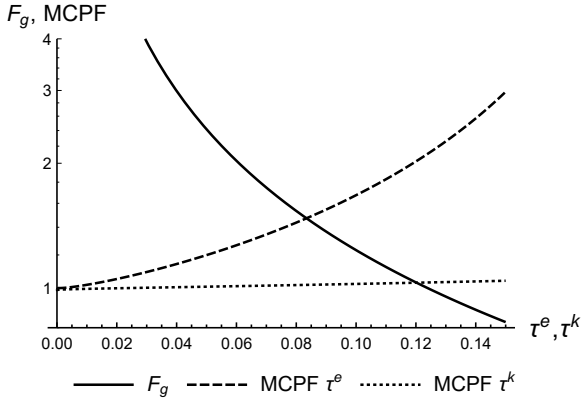


Figure 5: Setting 3 ( $\mu = 1$ )

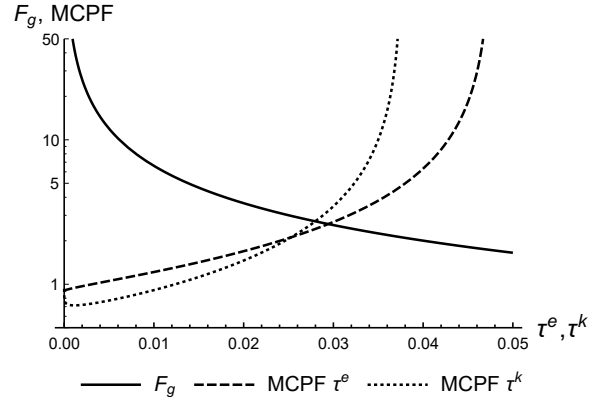


Figure 6: Setting 4 ( $\mu = 1$ )



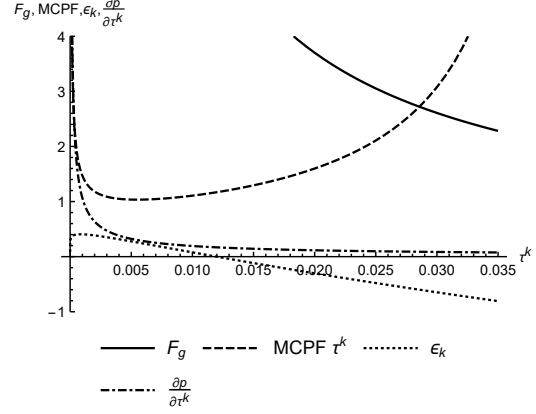
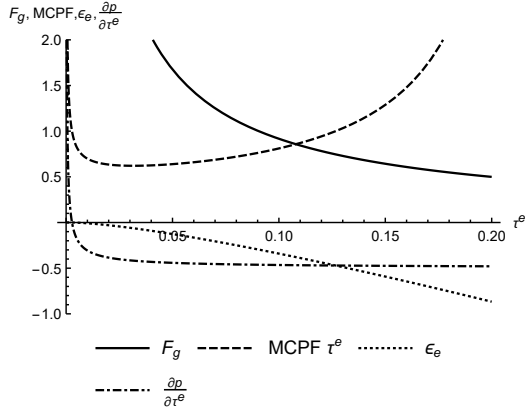


Figure 7: Carbon Taxation: Terms-of-Trade-Effect vs. Tax-Base-Relocation-Effect (Parameter Setting 1)

Figure 8: Carbon Taxation: Terms-of-Trade-Effect vs. Tax-Base-Relocation-Effect (Parameter Setting 1)

Setting	$\tau^{e\ominus}$	$\tau^{e*}$	$\tau^{k\ominus}$	$\tau^{k*}$
1	0.070	0.108	0.029	0.029
2	1.836	1.892	0.119	0.116
3	0.083	0.117	0.120	0.116
4	0.029	0.036	0.028	0.028
Setting	$F_g^{e\ominus}$	$F_g^{e*}$	$F_g^{k\ominus}$	$F_g^{k*}$
1	1.257	0.857	2.661	2.720
2	0.064	0.062	1.028	1.052
3	1.472	1.056	1.028	1.067
4	2.611	2.212	2.726	2.766

Table 3: Numerical equilibrium values for tax rates and marginal productivity of public infrastructure