Technology Beats Capital —
Sharing the Carbon Price Burden in Federal Europe

C. Roolfs[a,b,*], B. Gaitan[a], O. Edenhofer[a,b,c], K. Lessmann[a]

[a] *Potsdam Institute for Climate Impact Research,*
Postal Address P.O. Box 60 12 03, 14412 Potsdam, Germany
[b] *Technical University of Berlin, Germany*
[c] *Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany*

Abstract

Passing federal environmental policy reform is a challenge as the approval of interest groups such as consumers and state-level governments is often a prerequisite. Among others, the burden sharing's progressivity has a large impact on reform approval. We investigate how carbon tax payments by states to a federal authority are influenced by differences in technological emission intensity and wealth and show how they can turn out to be at the expense of poor states. We show that a uniform federal carbon tax that is endorsed by all states with equal per capita transfers can theoretically put a higher burden on poorer states than richer states. The opposite applies for transfers based on historical emissions (sovereignty transfers) which reduce the burden of emission-intensive states. We test our results numerically in a general equilibrium model with a vertical federalism governance structure calibrated to the European Union. Our simulations show that a federal minimum emissions tax with sovereignty transfers is twice as high as for equal per capita transfers and also has a progressive effect.

JEL classification: H77, H23, Q58, H87, H62

Keywords: Emission Regulation, Federalism, Unanimity, Transfers, Pareto-improving policy, European Union

---

*Corresponding author

Email address: roolfs@mcc-berlin.net

1. Introduction

When French President Macron unveiled his fuel tax reform plans to support the French energy transition in autumn 2018, he triggered one of the fiercest protests France has seen in 50 years. Demonstrators took to the streets fearing the heavy tax burden on workers and the middle class. After months of protests President Macron suspended his reform, conceded that he had failed to sufficiently take into account the burden for low-income earners and promised to improve his reform proposal. The French example is a case in point for the argument to make policies progressive so as to reduce social tensions, avert social resistance, and make their social support more likely (e.g. Sterner and Robinson, 2018; Fullerton, 2016; Chiroleau-Assouline and Fodha, 2014). Much like civil protests at the national level, unanimity rules and veto power of sovereign nations can be an obstacle to new policies in supranational, federal systems such as the European Union (EU). Poland, for example, a country with relatively low income and a carbon intensive energy sector, has vetoed the European Commission's Energy Tax reform proposal several times. Since EU tax matters require unanimous consent of all member states, the EU energy tax reform is pending since 2011.

Studies of the burden and redistribution of carbon pricing and its revenues have so far focused on the single country setting. Within one country, equal per capita revenue recycling make carbon pricing progressive (Burtraw et al., 2009; Klenert and Mattauch, 2016; Boyce and Riddle, 2007; Rausch et al., 2010; Klenert et al., 2018). Less attention has been paid to the carbon price burden from the point of view of a federal system and the implications of inter-jurisdictional heterogeneities (but see Böhringer et al., 2016, 2015). With multiple levels of government, federal policies can interact and conflict with state interests but also provide an additional way for welfare improvements. We ask how uniform carbon pricing and the distribution of its revenues affect acceptance and burden in a federal policy system.

Our research design follows three aspects of the federal structure of EU climate policy: First, EU member states' asymmetries of capital per capita and CO_2 intensity of production technology run contrary to each other (Figure 1). We include both asymmetries to capture their distributional implications. Secondly, many EU policies require unanimity or majority voting. We hence constrain federal choices to Pareto-improving policies. Third, in contrast to the *equal per capita* transfers frequently considered in the single country context, most of the revenue from the EU Emissions Trading Scheme (ETS) is distributed to members on the basis of the *sovereignty* rule, i.e. on the basis

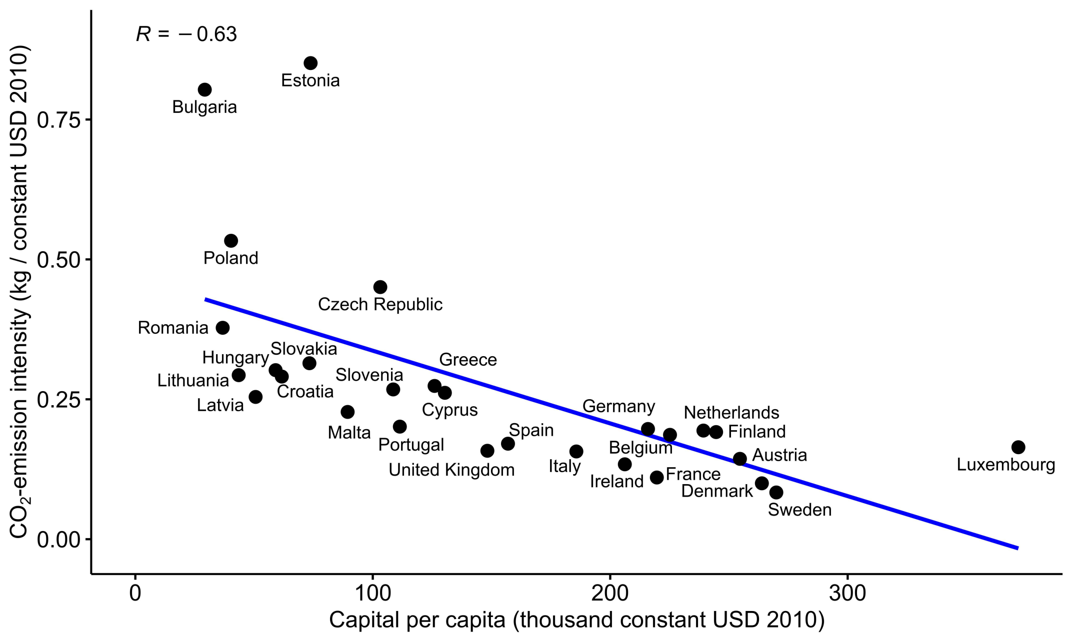

Figure 1: Capital per capita and CO_2-emission intensities in EU member states for the year 2014. The correlation line and coefficient (R) show that capital-poor countries tend to have greater emission intensities. Data based on World Development Indicators (WDI) and Berlemann and Wesselhöft (2017, 2014). See detailed description in Section 4.1.

of the historical emission levels. We include both distribution rules in our analysis of the federal carbon price burden.[1]

The first part of our analysis develops an intuition how the burden of a uniform federal CO_2 price is affected by technological emission intensity and wealth differences in closed form. The implications of the differences across member states are intuitive: We show how a large capital stock but also a large emission intensity result in a higher federal tax burden and prove that high emission-intensity in production causes high emission level, if gross complementarity of production inputs is strong and cost shares of capital and labor are high. The opposite is true with low cost shares for capital and labor and better substitution possibilities. The intuition is that since low wealth is associated with high emission intensities for many EU member states, a uniform federal carbon price absent of revenue recycling threatens to place a greater tax burden

[1] See on these rules also Kverndokk (2018); Kverndokk and Rose (2008); Cazorla and Toman (2001). In particular, the sovereignty rule immediately raises the question of justice and historical accountability of large historical emitters and has been discussed extensively elsewhere in the literature. We refer the interested reader to Ju et al. (2019); Kverndokk and Rose (2008); Cazorla and Toman (2001); Grubb et al. (1992) to mention at least some. Zhou and Wang (2016) gives an overview of the allocation rules that have been studied for many analyses of multinational emission reductions.

on poorer states. We investigate federal tax burden adjustments by the redistribution of federal tax revenues. We find that an equal per capita redistribution makes the federal carbon tax regressive. Mobile capital reinforces the regressive effect. In contrast, the sovereignty transfer relieves emission-intensive states from their federal tax burden and hence the federal emission tax becomes progressive.

In the second part our analysis, we use numerical simulations to solve the full multi-level equilibrium of the model with strategic state policies and differences in labor and population size heterogeneities in addition to capital and technological differences. The properties of three distinct groups among the European member states are decisive for our numerical results, namely being *rich* in terms of capital per capita while (1) being *large* in population size or (2) *small* in population size, or (3) being *poor* in capital per capita and *small* in population size. We find that in terms of CO_2-intensity, groups 1 ("rich and large") and 2 ("rich and small") fall below the average EU country, whereas the "small and poor" group countries have a higher emission intensity than the EU average.

We find that the net burden of a uniform federal emission tax given equal per capita transfers largely falls on the group of "rich and small" countries and several "poor and small"countries while "rich and large"countries may even face a net benefit. Thus the policy package is regressive. In contrast, sovereignty transfers achieve more progressiveness as the net burden is by and large carried by consumers of countries belonging to group "rich and large". The sovereignty transfers rule also facilitates a Pareto-improving minimum federal tax level double that of the equal per capital transfers rule.

The remainder of the paper is structured as follows. In Section 2, we relate our paper's contribution to the existing literature on progressive environmental policy design and fiscal federalism. In Section 3 we describe the structure of the federal general equilibrium model. Subsection 3.2 conveys the reasoning behind the results that we produce with our more complex numerical model for the EU. Subsection 3.3 expands the model set-up to the federal multilevel policy architecture. Section 4 contains the numerical simulation. We conclude in Section 5.

2. Literature

The design of progressive environmental policy from a multinational (and fiscal federalism) perspective explores the intersection of environmental taxation and fiscal federalism. This section reviews relevant contributions from the respective strands of literature in turn.

Previous literature on the distributional implications of environmental taxes and transfer design has frequently focused on the single country context exploring different income groups within an economy and policies choices of a single national government. A literature overview is provided by Klenert et al. (2018). Many empirical studies find carbon pricing (absent of revenue redistribution) to be regressive for OECD countries (Dorband et al., 2019). When revenue recycling schemes are considered, the literature is ambiguous about the progressive impact of such policies, as Klenert and Mattauch (2016) point out, except for equal per capita revenue recycling, which tends to make carbon pricing progressive (Boyce and Riddle, 2007; Burtraw et al., 2009; Rausch et al., 2010; Klenert and Mattauch, 2016; Klenert et al., 2018).

But even with a clear understanding of welfare and distributional implications, national environmental policies are restricted by concerns about their effect on mobile tax bases and transboundary spillovers (e.g. Musgrave, 1959; Oates, 1972, 2000)[2]. The fiscal federalism literature hence argues that, in general, relief of poor households and provision of public goods with spillover effects across states, as it is the case for mitigating CO_2-emissions, should be carried out by the federal authority. The EU in particular, however, may not be very well equipped to relieve poor households, as it does not have sufficient power and budget for redistribution (Oates, 2000). So while an EU carbon pricing scheme exists by means of the EU ETS, the adoption of mainly sovereignty based revenue recycling to member states suggests that little or no redistribution was intended or was simply not feasible. For a literature overview of the related environmental fiscal federalism we refer to Oates (2001); Böhringer et al. (2016).

Strategic interaction of federal and state-level environmental policies are addressed in a recent line of literature observing that federal environmental policy is often counteracted or overruled by state policies (see e.g. Williams, 2012; Lutsey and Sperling, 2008; Knopf et al., 2014; Böhringer et al., 2016). In this line, Williams (2012) uses an analytical framework to compare the efficiency of emission policies when strategic federal and state policies regulate emissions simultaneously. He finds the superiority of a federal emission tax over federal quantity controls. A decisive prerequisite for this result is the availability of optimal revenue recycling by means of optimal transfers to the states. Our modeling approach builds on a federal-state policy structure similar to Williams

[2]In fact, there are several narratives for state's inefficiency regarding transboundary spillovers: one is that state governments simply ignore or cannot measure their spillover impact on other states (Oates, 2001). Another one is that states would engage in a 'race to the bottom' in their environmental policy to attract mobile factors (Zodrow and Mieszkowski, 1986).

(2012) but extends the analysis by constraining federal regulation to Pareto-improving policy packages. The focus on Pareto-improvements connects our research to the literature on voluntary public good provision and the analytical model of Bergstrom and Blume, L., Varian, H. (1986). They show that rich individuals would voluntarily donate more to public good provision than poor individuals. We use a model with a strategic multilevel policy structure which has been developed in a simpler version and absent of technological, and labor size differences in Roolfs et al. (2018a). Their method identifies a range of possible voluntary (unanimity-ensuring) federal uniform carbon prices, consisting of a minimum and a maximum federal price.

Two further studies have investigated the impact of environmental policies for the Canadian Federation. Böhringer et al. (2016) analyze the unilateral state incentive for overruling federal emission regulation due to the effects of regulating the same tax base on their budgets. In contrast to the fully endogenous policy setting of Williams (2012), they focus on exogenously given policy choices to comply with given emission targets. Their study shows that a state has an incentive to offset its emission pricing cost to other states by means of VFE. In addition to an analytical treatment, they apply a computational general equilibrium model to the Canadian Federation and find that the VFE enable a state to reduce its emissions by up to 20% without bearing the costs itself. In a preceding paper Böhringer et al. (2015) leave out provincial carbon pricing, and examine the federal emission price burden given different transfer rules (e.g. equal per capita and sovereignty transfers) across Canadian provinces. They find that the burden on the population in the various provinces varies greatly depending on different transfer rules and provincial heterogeneity: equal per capita transfers are most burdensome in provinces with high GDP per capita while they are least burdensome for several provinces with low GDP per capita. They find emission intensity heterogeneity to be an important factor determining carbon burden sharing. Based on Böhringer et al. (2015)'s findings, we can argue that equal per capita transfers support a progressive federal carbon price in Canada. Canadian provinces, however, have a positive correlation between GDP and carbon intensity of production while EU states have a negative correlation.

For the case of the EU, our study is – to the best of our knowledge – the first to consider multilevel EU environmental policies with strategic policy choices on all levels. Previous studies have studied the tax burden of i) energy and fuel/transport taxation (for instance Padilla and Roca (2004), and Cambridge Econometrics (2008) as cited in Kosonen (2012)), and ii) emission mitigation and transfer rules (Böhringer and Lange, 2003; Chiroleau-Assouline and Fodha, 2014). Böhringer and Lange (2005), for instance, take the emission reduction commitment from the Kyoto Protocol. Their paper is in a similar spirit as Böhringer et al. (2015) but compares overall costs of emission mitigation subject to different transfer rules. They find that different transfer rules have very different effects on overall costs. While the previously mentioned EU-related papers use numerical or econometric models, Chiroleau-Assouline and Fodha (2014) employ an analytical model to the EU context. To comply with EU tax matters, they aim at unanimity-ensuring (Pareto-improving) environmental policy. They find that an environmental tax for the EU can always be designed to be unanimity-ensuring (Pareto-improving) if its revenue is used for a wage tax reform.

In the following we will combine the insights and recommendations for action from the above-mentioned literature strands. We will show that the federal context leads to a situation where equal per capita transfers no longer have a fundamentally progressive effect.

3. The model

We consider a general equilibrium model of a federation. The federation consists of $i = 1, ..., m$ member states. Member state i is populated by $\overline{L}_i$ consumers. Consumers are immobile across states and rent out their labor to the domestic firm. We consider the case of immobile and perfectly mobile capital. If capital is immobile, then consumers only rent out their capital endowment to the domestic firm. If capital is mobile, then consumers can rent out their capital endowment to any firm $i = 1, ..., m$. Consumers own the atmosphere in which firms store harmful emissions. Governments enforce consumer property rights through emission taxation, so firms pay for polluting the atmosphere. The redistribution of tax payments is stipulated on transfer rules which we will specify below.

Each consumer derives utility from consuming a private good and dis-utility from a transboundary emission externality. To produce the private good, the representative firm in state i uses capital, labor and emissions. We suppose an emission augmenting factor to describe the emission efficiency of each state's production technology. The lower its emission efficiency, the larger its emission intensity. In addition to heterogeneity in the emission efficiency among states, we allow for heterogeneity of capital stocks and population sizes.

Federal and state governments set emission taxes. States tax domestic emissions in order to maximize the utility of domestic consumers. State emission tax revenues are returned uniformly to domestic consumers. The federal authority seeks to improve the utility of all consumers living in the federation by choosing a uniform federal tax that satisfies an environmental policy package as follows: i) federal revenues are recycled following a predefined transfer rule (equal per capita or sovereignty), ii) the federal policy package must achieve Pareto improvements relative to the sovereign state outcome[3], and iii) comprises only of Pareto-dominant solutions. Thus, if there are solutions to the federal objective, they are second best optima. Moreover, these solutions theoretically ensure the unanimity of member states towards federal policy-making.

The decision structure is as follows. In the *first* stage, the federal authority acts as the Stackelberg-leader and searches a uniform tax on federal emissions to deliver Pareto-improvements relative to the decentralized (sovereign) state policy outcome as described in the preceding paragraph. In the *second* stage, each state government non-cooperatively sets a tax on its state emissions taking all other taxes as given. In the *third* stage consumers and firms solve their optimization problem, taking all prices, taxes and transfers as given.

3.1. Economic agents

This section formulates the consumers' and firms' problems, the damage (dis-utility) and source (production) of emissions and the market clearing conditions. Thereby, it solves the third stage.

3.1.1. Consumers and revenue recycling

In state i live $\overline{L}_i$ identical working consumers. Each consumer in state i is endowed with capital $\overline{k}_i$ and one unit of labor $\bar{l}_i$ (that is $\bar{l}_i = 1$). Since consumers are immobile across states, each consumer in state i rents out its labor to the domestic firm i. When capital is immobile, each consumer in state i rents out its capital endowment to the domestic firm i. If capital is perfectly mobile, each consumer in state i can rent its capital endowment to any firm $i = 1, ..., m$. In addition, each consumer receives transfers from the recycling of state and federal emission pricing revenues. Each consumer in state i receives an equal share $1/\overline{L}_i$ of the revenues from state i's domestic emission pricing (t_iE_i). Revenues from federal emission pricing (TE) are distributed to each consumer in state i by the federal transfer rule S_i. The budget constraint of each consumer in state$i$ equals

[3]A sovereign state outcome is the outcome that would prevail when states regulate emissions absent of federal policy.

$$c_i = r_i\bar{k}_i + w_i\bar{l}_i + t_i\frac{E_i}{\bar{L}_i} + S_iTE \tag{1}$$

where r_i and w_i respectively denote the rental rate of capital and labor wage rate. E_i denotes the emissions of state i and $E \equiv \sum_{i=1}^{m} E_i$ are aggregate federal emissions. t_i denotes the emission tax rate levied by state, T is the uniform federal emission tax rate levied by the federal authority and S_i is the federal transfer rule.

Consumer i derives utility from private good consumption and dis-utility from federal emissions,

$$u^i\left(c_i, E\right) \tag{2}$$

which is assumed to be additively separable with first and second partial derivatives w.r.t. consumption and emissions being $u^i_{c_i} > 0$, $u^i_{c_ic_i} \leq 0$, and $u^i_E < 0$ and $u^i_{EE} \leq 0$, respectively. All consumers take emissions, prices, taxes and transfers as given such that the solution to each consumer's optimization problem reduces to setting consumption equal to income from endowments and transfers, equation (1).

3.1.2. Firms and emission efficiency

In each state i, a representative firm i produces a final private good Y_i. Emissions are a by product of production which we treat as an input in production. Firm technologies can differ in the emission augmenting factor which we use to describe firm i's emission efficiency, $\chi_i > 0$. We set χ_i in such a manner so that $\partial Y_i/\partial \chi_i > 0$, i.e. a greater level of χ_i corresponds to a less emission intensive production technology.

The production technology is represented by a two-layered function, supposing constant returns to scale. At the top-layer, a constant elasticity of substitution (CES) function combines emissions E_i with a second-layer Cobb-Douglas capital-labor composite input V_i to produce final output Y_i. The production function is depicted by

$$Y_i = Y^i\left(V_i, E_i\right) = A\left(\alpha V_i^{\frac{\sigma-1}{\sigma}} + z\left(\chi_i E_i\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$$

with $V_i = V^i\left(K_i, L_i\right) = BK_i^{\beta_K}L_i^{\beta_L}$. A, B are positive efficiency parameters. The elasticity of substitution between V_i and E_i is denoted by σ with $0 < \sigma \leq 1$.[4] Distribution parameters $\{\alpha, z, \beta_K, \beta_L\} \in (0,1)$ and satisfy $\alpha + z = 1$ and $\beta_K + \beta_L = 1$.

[4] We undertake this assumption since emissions are generally proportional to energy usage. Van der Werf (2007), Manne and Richels (1992) and Kemfert and Welsch (2000) estimate the elasticity of the substitution between energy and the composite input to be between 0 and 0.7, see also Carraro et al. (2011).

Taking as given the rental rate of capital r_i, the wage rate w_i and emission tax $\tau_i(t_i, T) \equiv t_i + T$ firm i maximizes profits by choosing capital K_i, labor L_i and emissions E_i. Let Y_X^i denote the marginal product of input X and treat the price of the final good as numéraire. Profit maximization implies $Y_{E_i}^i = \tau_i$ and $Y_{V_i}^i = p_i$ where p_i denotes the composite price of composite input V_i.

We solve firm i's conditional demand for K_i, L_i, and E_i as functions of output and prices by solving the cost minimization problem of firm i (see conditional demand levels in Appendix A). Zero profits imply

$$mc_i = \frac{1}{A}\left(\alpha^\sigma {p_i}^{1-\sigma} + \left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}}\right)^\sigma {\tau_i}^{1-\sigma}\right)^{\frac{1}{1-\sigma}} = 1, \tag{3}$$

where mc_i denotes the marginal cost of producing output Y_i, which is decreasing in the augmenting factor χ_i.

As we shall see below, the emission augmenting factor χ_i ambiguously impacts conditional emission demand and thereby, differences in emission intensities can influence a state's emission tax base and impact the federal tax incidence on a state.

3.1.3. Market clearing

Aggregate capital and labor supply in state i are $\overline{K}_i \equiv \overline{L}_i \overline{k}_i$. Labor market clearing is given by $L_i = \overline{L}_i$. In the case of immobile capital, capital markets clear with $K_i = \overline{K}_i$. If capital is perfectly mobile across states, capital market clearing implies $\sum_i K_i = \sum_i \overline{K}_i$ and in such case the rental rate of capital is equal for all states, $r_i = r_j = r$. Market clearing in final goods is given by $\sum_{i=1}^m \overline{L}_i c_i = \sum_{i=1}^m Y_i$. Using the market clearing conditions all variables can be expressed as a function of state and federal taxes. Let **bold** letters indicate these functions which take into account the solutions (first-order conditions) of consumers' and firms' problems. We report the relevant variables in Appendix B and Appendix C.

3.2. Technology and capital impact

Now that we have characterized all supply and demand plans and all market equilibria, and before we introduce the multilevel policy architecture, we develop intuition about our main results, namely how emission intensity and capital wealth affect the burden from policy packages.

Since the federal authority levies the emission tax payment TE_i from the representative firm in state i, and redistributes its tax revenues (TE) so that each consumer in state i receives S_iTE, then the per capita *net payment* $\overline{N}_i$ from state i to the federal authority equals

$$\overline{N}_i \equiv \left(\frac{E_i}{\overline{L}_i} - S_i E \right) T.$$

If $\overline{N}_i > 0$ state i is a *net donor* of federal emission tax revenues. On the contrary, if $\overline{N}_i < 0$, state i becomes a *net recipient*. Net payments directly feed into consumption changes as constant returns to scale properties of output and zero profits imply $c_i = Y_i/\overline{L}_i - \overline{N}_i$. Clearly, net transfers impact the incidence of federal policy.

In the following, suppose that all states have equal populations sizes normalized to one and no state policies are implemented, i.e. $\tau_i = T$ and $T > 0$. Then the federal net payment of state i reduces to $\overline{N}_i = (E_i - S_i E)\, T$, and each firm in each state faces the same emissions tax rate T such that $Y^i_{E_i} = T$. We will relax these assumptions in the numerical analysis.

We now analyze how the emissions of state i respond to changes in emission intensity and capital wealth. Recall Section 3.1.2 introducing σ as the elasticity of substitution between the capital-labor composite V_i and emissions E_i. Let el^i_{YE} denote the elasticity of output Y_i with regard to E_i, i.e. $\mathrm{el}^i_{YE} \equiv Y^i_{E_i} E_i / Y_i = T E_i / Y_i$.

Lemma 1 (Technology impact with immobile capital)**.** *Let $\chi_i > \chi_j$, $\overline{K}_i = \overline{K}_j$, $\overline{L}_i = \overline{L}_j$, and $\tau_i = \tau_j = T > 0$. If capital is immobile across states and*

$$el^i_{YE} < (1 - \sigma), \tag{4}$$

then $E_i < E_j$ (that is state i's emissions are lower than those of state j). If $el^i_{YE} > (1 - \sigma)$, then $E_i > E_j$.

Proof. See Appendix E. □

Lemma 1 shows that a larger χ_i confronts the firm in state i (firm i) with the decision whether it is more profitable to use more or less emission input in contrast to the firm in state j (firm j). Two questions play the central role: how sensitive output reacts to a small change in emission input? How easy can inputs be substituted by each other. el^i_{YE} and σ in inequality (4) reflect this decision problem of firm i. See also Figure 2 for the general relationship between production elasticities and substitution elasticities in output.

Let us consider the decision problem of firm i more closely. When capital is immobile the composite input is constant, $\overline{V}_i$. Suppose that inputs are very complementary ($\sigma \to 0$). The complementarity implies that increasing one factor without increasing the other does not increase output but would only increase production costs. When $\chi_i > \chi_j$, then firm i uses less emission input than firm j simply because of the *complementary* nature of E_i and $\overline{V}_i$. To the contrary, a large output elasticity (large el^i_{YE}) reflects a high sensitivity of output Y_i to small changes in E_i. If el^i_{YE} is large and the inputs E_i and $\overline{V}_i$ substitute each other well ($\sigma \to 1$), then it is more profitable for firm i to use more emissions than firm j because the use of emissions is less limited by fixed supply of $\overline{V}_i$.

Lemma 2 (Technology impact with mobile capital)**.** *Let $\chi_i > \chi_j$, $\overline{L}_i = \overline{L}_j$, and $\tau_i = \tau_j = T > 0$. If capital is mobile across states and*

$$el^i_{YE} < (1-\sigma)(1-\beta_k), \tag{5}$$

then $E_i < E_j$. If $el^i_{YE} > (1-\sigma)(1-\beta_k)$, then $E_i > E_j$.

Proof. See Appendix F. □

The case with mobile capital is relatively similar to the immobile case of Lemma 1. If capital is mobile, however, also its elasticity on the composite input, reflected by β_k in inequality (5), comes into play. With mobile capital, the only limited input factor for firm i is labor supply. Hence, firm i faces a similar decision as before but can now freely chose over its input levels of emissions E_i *and* capital K_i. Similar as el^i_{YE} reflects the sensitivity of output Y_i to small changes in E_i, β_K reflects the output elasticity of the composite V_i to K_i. If E_i and V_i are very complementary ($\sigma \to 0$) and/or if V_i is very insensitive to small changes in K_i ($\beta_k \to 0$), firm i will use less emissions than firm j. In contrast, if firm i can easily substitute E_i and V_i ($\sigma \to 1$), and if small changes in E_i and K_i have a large impact on Y_i and V_i (large el^i_{YE} and large β_k), respectively, firm i tends to increase its emissions with raising χ_i.[5]

Empirically, it is likely that inequality (4) or (5) holds: On the left-hand side, we have that $\text{el}^i_{YE} = \omega^i_E$, where ω^i_E is the cost share paid to emissions, which is currently

[5] We provide an alternative interpretation for the right-hand side by the relative marginal rate of substitution in Appendix G.

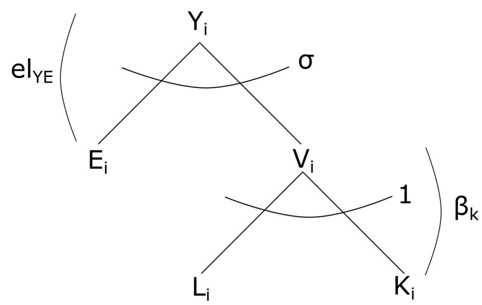

Figure 2: Schematic sketch of production function indicating interplay of output and substitution elasticities.

below 10 percent (empirical data cf. Section 4)[6]. Values of the right-hand side are $\beta_k \approx 0.3$ for the capital share and $\sigma \in (0,0.7)$ for the elasticity of substitution[7]. With these numbers, inequalities (4) or (5) hold easily and they would still hold for an emission cost share up to 20 to 30 percent for mobile and immobile capital, respectively.

We find a simpler relationship for the impact of capital on emission demand:

Lemma 3 (Capital impact)**.** *Emissions in state i increase with a marginally larger available capital stock.*

Proof. For the immobile capital case, consider equation (B.2), substitute $B\overline{K}_i^{\beta_K}\overline{L}_i^{\beta_L}$ for $\overline{V}_i$ and take the derivative of $\boldsymbol{E}_i$ w.r.t. $\overline{K}_i$ to get that $\partial \boldsymbol{E}_i / \partial \overline{K}_i > 0$. For mobile capital, proceed similar by using equation (C.1). □

All else equal, Lemma 3 follows by noticing that a larger *available* capital stock, either because of a larger capital endowment or an inflow of capital (in the case of mobile capital) increases the marginal product of emissions and hence emissions increase.

Let us combine our insights from Lemma 1, 2, and 3. In case of the EU, low capital stocks frequently coincide with low emission efficient technologies, cf. Figure 1. As such, in the absence of appropriate transfers the tax burden of a uniform federal emission tax threatens to be regressive.

The federal tax payment can be compensated by redistributing federal tax revenues to consumers. We consider two types of federal transfer rules. The equal per capita transfer rule which is self-explanatory and the sovereignty transfer rule which accounts

[6]Since Y_i is homogeneous of degree 1 it follows that$Y_i = p_i V_i + (\tau_i + T)E_i$. Division by Y_i yields $1 = \omega_V^i + \omega_E^i$, where ω_V^i is the cost share paid to the composite. If $\tau_i = 0$ then $\omega_E^i = TE_i / Y_i$.

[7]Supposing we treat σ similar to the values estimated for the elasticity of substitution between energy input and the capital-labor composite.

Transfer rule	Acronym	Formula
Equal per capita	S_{EQ}	$1/\sum_i \overline{L}_i$
Sovereignty	S^i_{SO}	$1/\overline{L}_i E^o_i / E^o$

Table 1: Transfer rules.

for a state's high emission levels before federal policy-making (denoted with superscript o). In Table 1 we report the implementation of both rules.

The equal per capita transfer rule distributes an equal share to all consumers in the federation and thus, if the federal tax payment is regressive, then also the net federal payment $\overline{N}_i$ retains the federal tax's regressive effect. The contrary is true for the sovereignty transfer rule.

3.3. Multilevel emission tax choices

State governments and federal authority, i.e. both levels of government, regulate emissions. Emission taxes generate revenues for state governments and federal authority such that their revenue recycling budget reads $t_i E_i$ and TE, respectively. The emission taxes of state governments now affect the budget of the federal authority, and vice versa (see also $\boldsymbol{E}_i$ and $\boldsymbol{E}$ in Appendix B and Appendix C). Recall that the emission tax paid by firm i is the composite of $\tau_i = t_i + T$.

3.3.1. State governments

This section presents the second stage in which state government i non-cooperatively chooses the domestic emission tax t_i that maximizes the sum of its population utility. Each state government takes all other emission taxes as given and incorporates the solution of the firm's and consumers' problem and the market clearing conditions into its optimization. Formally, it implies using (1) and (2) and substitution of the relevant variables after market clearing as in Appendix B or Appendix C for the immobile or mobile capital case, in which we now substitute the variables' dependencies on states' and federal taxes explicitly, $\tau_i = \tau_i(t_i, T)$ and $\tau = \tau(t_1, ..., t_m, T)$. The indirect utility function then reads $\mathbf{u}^i(t, T) \equiv u^i(\mathbf{c}_i(t_i, T), \mathbf{E}(t, T))$.

Since consumers within a state are identical, state i government's problem is given by

$$\max_{t_i} \overline{L}_i \mathbf{u}^i(t, T) \text{ given } t_{j\ \forall j \neq i} \text{ and } T.$$

Since[8] $\partial\mathbf{E}/\partial t_i = \partial\mathbf{E}_i/\partial t_i$ the first-order condition of state i's problem equals

$$\frac{\partial \boldsymbol{u}^i}{\partial t_i} = u^i_{c_i}\frac{\partial \mathbf{c}_i}{\partial t_i} + u^i_E\frac{\partial \mathbf{E}_i}{\partial t_i} = 0 \text{ for all } i. \tag{6}$$

The m states' first-order conditions implicitly define the states' taxes depending solely on the federal emissions tax which we denote by $\boldsymbol{t}_i(T)$. We define the vector of all these state taxes as $\boldsymbol{t}(T) \equiv (\boldsymbol{t}_1(T), ..., \boldsymbol{t}_m(T))$. For the case of capital mobility, we adopt the assumption of Zodrow and Mieszkowski (1986) that states do not take their effect on r into account.

Suppose that S_i is exogenous and constant, then, after some algebraic manipulations[9] of equation (6) we get

$$\boldsymbol{t}_i(T) = \overline{L}_i\left(-\frac{u^i_E}{u^i_{c_i}} - S_iT\right) \text{ for all } i. \tag{7}$$

All else equal, state i's tax is positively influenced by the population size $\overline{L}_i$ and a larger marginal dis-utility from emissions u^i_E, i.e. larger marginal damage. The state tax becomes lower with a larger marginal utility of consumption $u^i_{c_i}$, transfer rule S_i, and federal tax T. Depending on the magnitude of the marginal rate of substitution between total emissions and individual consumption, $-u^i_E/u^i_{c_i} > 0$, in contrast to federal transfer and tax rule (S_iT), the state tax can also become negative (subsidy). For a detailed discussion of this term, we refer to Roolfs et al. (2018a,b).

In absence of federal policy, i.e. $T = 0$, the second stage has an equilibrium solution, the *decentralized solution* denoted by subscript o. This solution will be used in the sequel to constrain the federal authority's policy choice for Pareto-improvements and to calculate the sovereignty transfer rule, S^i_{SO}.

Definition 1 (Decentralized policy equilibrium)**.** The decentralized policy equilibrium with $T = 0$ consists of quantities c^o_i, Y^o_i, K^o_i, L^o_i, E^o_i and prices r^o_i, w^o_i, and taxes $\{t^o_i\}^m_{i=1}$, such that for all i c^o_i solves the optimization problem of each consumer in state$i$; Y^o_i, K^o_i, L^o_i, and E^o_i solve the problem of firm i; t^o_i solves the problem of state i's government; and the market clearing conditions in capital, labor and final goods hold.

Let u^{oi} denote the decentralized utility level. Setting $T = 0$ into equation (7) state

[8] See also equation (D.2).

[9] See Appendix H.

i's tax equals[10]

$$t_i^o = -\overline{L}_i \frac{u_E^i}{u_{c_i}^i} \text{ for all } i.$$

Each sovereign state i, absent of federal policy, internalizes the local damage from emissions affecting its population ($\overline{L}_i u_E^i$). Their chosen emission tax levels neglect the spillover effect of transboundary emissions to other states' inhabitants, implying that there is potential for improvement beyond the decentralized solution since it lies below the social optimum (Samuelson rule).

3.3.2. Federal authority

In the first stage, the federal authority uses a policy package consisting of a uniform federal emission tax and the transfer rule S_i as specified in Section 3.2, Table 1. We constrain the federal authority to search for uniform federal taxes T which are Pareto-improving, relative to the decentralized solution, such that the federal policy package could be unanimously accepted by states and all consumers. Mathematically, the federal authority maximizes the utility of one consumer in state i such that no other consumers in any other state falls below their decentralized utility levels. Being the Stackelberg-Leader of the federation, the federal authority considers the indirect utility as defined in Section 3.3.1 and in addition the states' policy reactions to the federal tax from equation (6). In the case of mobile capital, we suppose that federal authority takes into account its policy impact on r.

The federal authority's objective is given by

$$\max_T \left\{ \mathbf{u}^i \left(\boldsymbol{t} \left(T \right), T \right) \middle| \mathbf{u}^j \left(\boldsymbol{t} \left(T \right), T \right) \geq u^{oj} \quad \forall \, j \neq i \right\}. \tag{8}$$

Let us give an intuitive explanation of the optimal federal solutions for $m = 2$ states by using Figure 3. In Figure 3 we plot the utility of each consumer as a function of the federal tax T. The decentralized utility levels are $u^{o1}$and u^{o2}. The federal authority seeks to raise the utility level of each consumer in state i above u^{oi}, as long as the level for each consumer of state j does not fall below u^{oj}. In the first case, indicated with dashed lines, consumer 1 reaches its maximum u^{*1} at T^1 and before consumers 2 who attains its maximum u^{*2} at T^2. The federal solution space then ranges from $T^1 \equiv T^{min}$

[10] In the case of mobile capital and if states would take their policy impact on r into account, the resulting state tax levels are ambiguous. In the decentralized case, capital importing states would set a higher state emission tax than in the small open economy case. Capital exporters would set lower state taxes. Proof available on request.

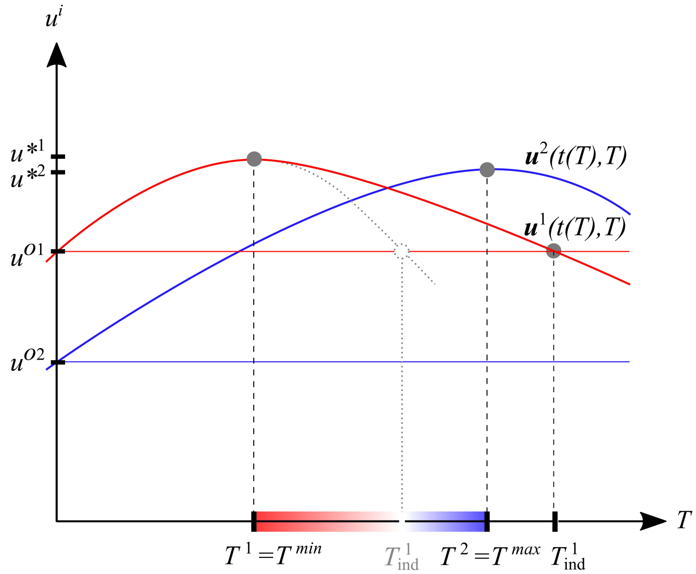

Figure 3: Stylized representation of the minimum and maximum uniform federal tax for two states adapted from Roolfs et al. (2018a). If $T^1_{ind} < T^2$ then $T^1_{ind} = T^{max}$.

to $T^2 \equiv T^{max}$. If it happens that the utility of consumer 1 falls below its decentralized level u^{o1} before consumer 2 has reached its maximum, then the federal solution space ranges from $T^1 \equiv T^{min}$ to $T^1_{ind} \equiv T^{max}$ (dotted lines).

We denote the uniform federal tax that solves equation (8) for state i with T^i. Suppose, without loss of generality, l federal tax levels are solutions and that they can be ranked as $T^1 < T^2 < ...T^l$. We will refer to T^1 as the minimum tax T^{min}. If $l = m$ we will refer to T^m as the maximum tax T^{max}. However, it may happen that the utility of one consumer in state$k$ falls to its decentralized level before other consumers have reached their maxima. Then, T^{max} no longer corresponds to T^l but to the federal tax level (T^k_{ind}) at which u^k equals u^{ok}— this case will indeed occur in some of our numerical results.

While we provide more technical details in Appendix I, let us mention two other features that are important to the federal solutions. First, any uniform federal tax that satisfies unanimity must be positive (Roolfs et al., 2018a). Intuitively, the reason is that in order to carry out transfers, the federal authority must have a positive budget, $TE > 0$. This is only the case if the federal emission tax is positive. Second, any federal tax in the interval $[T^{min}, ..., T^{max}]$ is a Pareto-dominant solution to the federal problem and denoted by T^*. It satisfies the multilevel policy equilibrium:

Definition 2 (Multilevel policy equilibrium)**.** A multilevel policy equilibrium with transfer rule S_i is the quantities $c_i^*, Y_i^*, K_i^*, L_i^*, E_i^*$, prices r_i^*, w_i^*, and taxes t_i^*, T^*, such that for all $i = 1, ..., m$ consumption c_i^* solves the optimization problem of eachconsumer in state$i$; Y_i^*, K_i^*, L_i^* and E_i^* solve the problem of firm i; t_i^* solves the problem of the state government i; T^* solves the problem of the federal authority; the market clearing conditions of capital, labor and final goods hold; and the balance of payments condition $Y_i^*/\overline{L}_i + \left(S_i E^* - E_i^*/\overline{L}_i\right) T^* = c_i^*$ is satisfied for all i.

In what follows we use subscripts EQ and SO when reporting equilibrium levels under the equal per capita and sovereignty transfers, respectively. We will refer to T^i as the 'optimal uniform federal tax from state i's perspective' or in short '*the optimal federal tax of state i*'. To compare the numerical results, we normalize T^i with the lowest minimum tax $T_{norm} \equiv min\left\{T_{EQ}^{\min}, T_{SO}^{\min}\right\}$.

4. Numerical application

Section 3.2 showed that uniform federal taxes tend to put a higher burden on emission intensive states. Where low capital and low emission efficiency coincide, the incidence of a federal policy package becomes an empirical question. In this section, we calibrate the model to the European Union and solve the general equilibrium numerically to determine the range of federal taxes that solves the federal authority's problem as wells as each state's net payments and incidence.

4.1. Data and calibration

We account for three types of heterogeneity between EU countries: Population (and labor), capital stocks, and CO_2 -emission efficiency. To help isolate the effects of the three heterogeneities the remaining parameters are set symmetrically across all member states.

Population size and labor supply $(\overline{L}_i)$ We used the most recent Census data from the year 2011 code cens_11r provided by Eurostat and extracted the number of persons per country of working age 15-64 years. In this analysis we assume that the population size is equal to the labor supply of the respective country. We will refer to countries with a small population as *small* countries and countries with a large population as *large* countries.

Aggregate capital stocks ($\overline{K}_i$) We took capital stock estimates from Berlemann and Wesselhöfft (2017; 2014) for the year 2014. Their estimates rely on the aggregate investment data provided by World Development Indicators (WDI) database. Data are in constant USD 2010. We selected capital stock data for the year 2014 as a compromise to use relatively recent data but keep the impact of the EU ETS low (ETS certificate prices were stable below 10 EUR per tonne of CO_2 during this time)[11].

Capital per capita ($\overline{k}_i$) We derived per capita capital by dividing each country's aggregate capital stock by its population size ($\overline{K}_i/\overline{L}_i$). Eastern EU-countries have, in general, lower capital per capita levels, while the largest levels are in small, non-Eastern-European countries (Luxembourg and Sweden). For simplicity, we refer to countries with low per capita capital levels as *poor* countries and countries with large capital per capita as *rich* countries.

Emission efficiency (χ_i) For a country's representative emission efficiency, we determined the relative CO_2 -emission efficiency. We took CO_2 -emission intensity data for the year 2014 from WDI (code EN.ATM.CO2E. KD.GD accessed on 1/07/2019) accounting for CO_2 -emissions from the burning of fossil fuels, the manufacture of cement and gas fuels and flaring. The database provides each country's CO_2 -emission intensity measured in kg per constant 2010 USD of GDP. We calculated the inverse of country's CO_2-emission intensity as measure of CO_2 -emission efficiency per country (CE_i) and estimated the relative share of country i's CO_2 -emission efficiency χ_i as

$$\chi_i \equiv \frac{m * \mathrm{CE}_i}{\sum_j^m \mathrm{CE}_j}$$

such that the average emission efficiency is $\chi_i = 1.0$. $m = 28$ equals the number of EU-countries.

Production We set the elasticity of substitution between the capital-labor composite and emissions equal to $\sigma = 0.5$, which falls well within the range identified in

[11] Due to a lack of sufficient investment data for Malta, we approximate it's capital stock by using the Perpetual Inventory Method for all other EU countries and take the average of their capital stock growth to extrapolate it to Malta.

empirical work.[12] We use UK data from 2004 to specify production parameters. We used data from Office of National Statics (ONS) reference number 008744 accessed on 17/12/2018 for emission tax revenues and compensation of employees from ONS code DTWM (accessed on 03/01/2019). Non-residential emissions and gross value added are taken from WDI databases codes EN.ATM.CO2E.KT and NY.GDP.DEFL.ZS.AD (both accessed on 17/12/2018), respectively. Using this data, we find the capital share of value added to be equal to $\beta_K = 0.43$, and the share parameter for the capital-labor input to be equal to $\alpha = 0.97$. We set B to unity and $A = 3.1$ using the approximation that $A \cong Y_i / (\chi_i E_i)$.[13]

Emission externality and utility We suppose that the utility of each consumer in state i equals $u^i(c_i, E) \equiv \log(c_i) - E^\gamma$. We assume the damage to be quadratic on federal emissions and thus set $\gamma = 2$.

Country-clusters We summarize the regional data in Figure 4 and plot each country's population size (y-axis) against its per capita capital levels (x-axis). The plot identifies four quadrants and three country-clusters: The top-right quadrant (group 1) comprises the cluster of *large* and *rich* countries with France, Germany, Italy, Spain, and the UK. The bottom-right quadrant (group 2) covers the cluster of *small* and *rich* countries (Luxembourg, Sweden, Denmark, Ireland, Austria, Finland, Netherlands and Belgium). In the bottom-left quadrant (group 3) *small* and *poor* countries cluster. Half of all EU countries belong to quadrant 3. Only Poland belongs to the upper upper left quadrant (group 4) which contains large and poor countries.

Whether a country's emission efficiency is above or below the EU average is indicated by the size of its data point. Small data points indicate a large emission efficiency. Countries are in the average CO_2-emission-efficiency band for $0.9 < \chi_i < 1.1$. The relative emission efficiency of almost all countries in quadrant 3 and 4 is below average, while all countries in the right quadrants 1 and 2 have average or above average emission efficiencies.

Remarkable outliers for the identified country clusters are Germany, Luxembourg

[12] Elasticities of substitution between energy and the composite input are estimated by van der Werf (2007), Manne and Richels (1992) and Kemfert and Welsch (2000) and range from $0 - 0.7$. Most empirical studies find that the elasticity of substitution between capital and labor is larger than the elasticity of substitution between energy and those inputs (Carraro et al., 2011).

[13] See derivation in Appendix J.

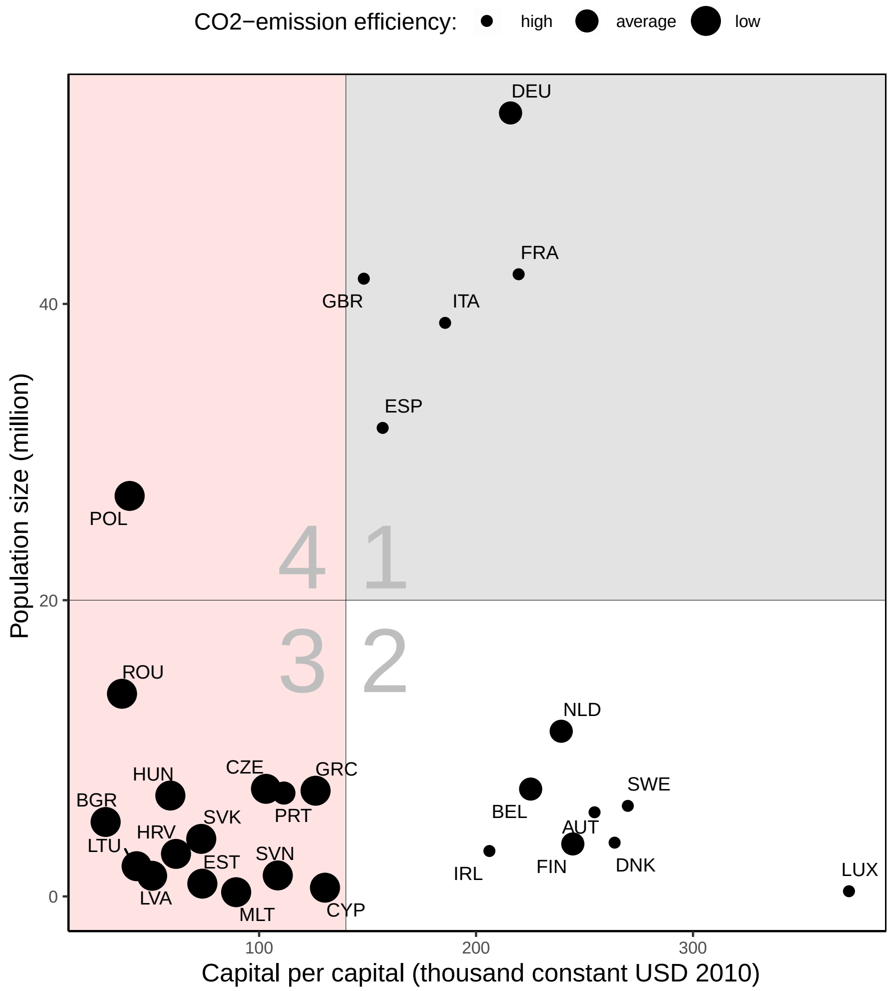

Figure 4: Countries cluster with respect to capital per capital and population size into four groups: rich and large (group 1), rich and small (group 2), poor and small (group 3), and poor and large (group 4) countries. Countries with the lowest per capita capital levels have also the lowest the CO_2 -emission efficiency.

and Poland. Germany and Luxembourg are relatively far away from the other countries in their cluster in terms of population size (Germany) or capital per capita (Luxembourg). Poland is the only country in the large and poor cluster. Additionally, Germany is the only large and rich country with only average emission efficiency.

4.2. Results immobile capital

Federal tax ranking. We now report each of the optimal uniform federal tax levels that would be preferred by each member state (T^i). That is, the equivalent taxes as those presented in the stylized illustration of Figure 3.

With equal per capita transfers, Figure 5 shows that lowest optimal uniform taxes belong to several small and poor countries. Among these, Estonia is the country that prefers the lowest tax; the largest optimal tax is preferred by Sweden. Tax levels marked with dark gray bars violate the Pareto improvement restriction as other countries would fall below their decentralized results. Comparing the ranking of taxes under sovereignty transfers to the country-clusters of Figure 4 shows that large and emission intensive countries rank at the lowest optimal federal tax levels: The lowest optimal tax $T_{SO}^{\min}$ belongs to Germany, a rich and large country with EU-average emission efficiency, followed by Poland, which is the only poor and large country and has a low emission efficiency.

When comparing the levels of normalized federal tax ranges under sovereignty and equal per capita transfers, we see that i) the level of the minimum tax under sovereignty transfers is roughly two times larger than under equal per capita transfers. ii) The spread of the minimum to the largest optimal federal tax is also larger under sovereignty transfers, i.e. while $T_{EQ}^{\max}$ is more than four times larger than $T_{EQ}^{\min}$ the maximum tax $T_{SO}^{\max}$ is more than 20 times larger than $T_{EQ}^{\min}$.

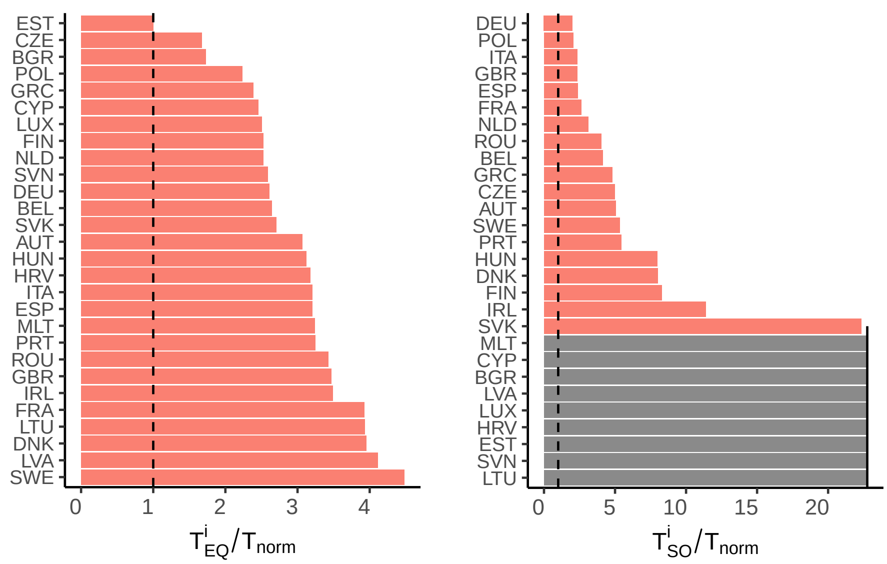

Figure 5: Optimal uniform federal tax rates T^i subject to equal per capita (EQ) and sovereignty (SO) transfers. Each T^i maximizes the utility of the respective country i and provide solutions to the federal problem (red). Each T^i is normalized by $T_{norm} \equiv min\{T^i\} = T_{EQ}^{EST}$. Gray bars are truncated tax levels and indicate that the optimal federal tax of that respective country is too large and therefore is not a solution to the federal problem (no Pareto improvements).

In Table 2 we further disentangle the optimal federal tax ranking by reporting Bravais-Pearson-correlations, between the optimal federal taxes from each country's perspective and endowments and technological heterogeneities of the countries.

	$\overline{K}_i$	$\overline{k}_i$	$\overline{L}_i$	χ_i
T^i_{EQ}	0.18	0.18	0.13	0.68
T^i_{SO}	-0.48	-0.16	-0.55	-0.08

Table 2: Correlation coefficients between ranking of T^i and countries' heterogeneities.

The correlations identify CO_2 -emission efficiency as the driving force of the ranking of federal taxes with equal per capita transfers. Clean production is associated with preference for a high EU wide emissions tax. Capital stocks, capital per capita and population size have a much less positive impact on the ranking of optimal taxes.

With sovereignty transfers all correlations are negative. The dominating correlation is found for population size, followed by countries' capital stocks. Capital per capita and CO_2 -emission efficiency have a weak correlation and thus less impact on the ranking of optimal taxes. Comparing the correlations of the two transfer rules it becomes apparent that the signs are always opposite. This indicates that the rules impose contrary burden distribution. In the following we will further examine this at the minimum taxes.

Net federal payments at the federal minimum tax. In Figure 6 we report the federal transfer to consumers (negative, blue bars), the per capita tax payment to the federation (positive, red bars) and the net payment (black dots) which is simply the difference between payments and transfers. Under equal per capita transfers only the payment side creates diversity in the net payments. Per capita payments are the largest for Estonia and Luxembourg. Many small countries — being emission intensive or rich — face a positive net payment and thus become net donors to federal tax revenues, while several rich countries become net recipients.

Under sovereignty transfers per capita payments to the federation are relatively homogeneous and similar to the equal per capita case. Whereas transfers from the federation are relatively low for consumers in large and rich countries and vice-versa for small and poor countries. Rich and large countries' consumers are net donors and smaller countries' consumers are net recipients. The top five countries with the highest net payments are all from the rich and large country cluster. In contrast, almost all other countries become recipients of net payments under sovereignty transfers (only Poland is a exemption) and thus, we have a first indication that sovereignty transfers tend to turn federal emission pricing progressive. The order of magnitude between the positive and negative net payments with sovereignty transfers is larger than with equal per capita transfers.

Why does the federal net payment per capita with sovereignty transfers appear to

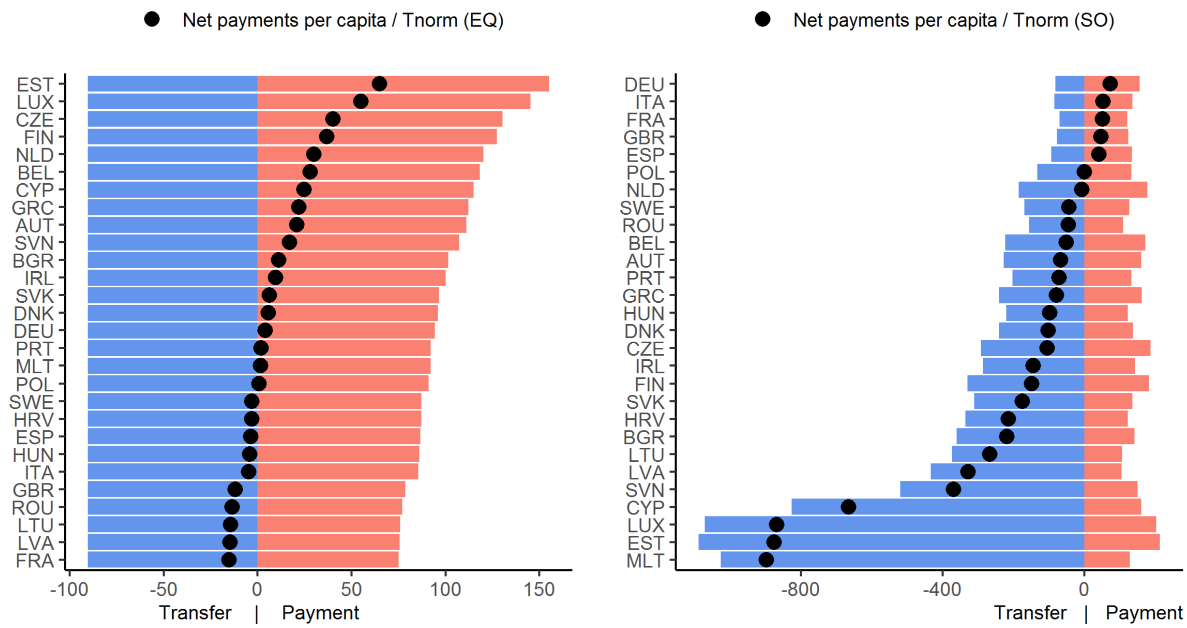

Figure 6: Federal payment (positive, red) and transfer (negative, blue) and the resulting net payment at the federal minimum tax given equal per capita (EQ) and sovereignty (SO) transfers per capita.

draw from relatively few countries, while there are large transfers to many others? The CO_2 -emission level of a country represents its emission tax base. As shown in Lemma 3, larger capital stocks imply a larger emission tax base and thus a larger federal tax payment. If the largest net payment lies on rich and large countries then the majority of federal revenues is collected from these largely populated countries. But due to their large population sizes still each of these net donating countries faces a low per capita net payment.

Let us consider Figure 7 which illustrates the previously identified tax-base-effect by measuring net payments per country instead of per capita payments. We report the federal transfer, the federal payment, and the net federal payment $(\overline{N}_i \overline{L}_i)$ per country. The tax payment per country translates to the size of each country's emission tax base. The larger the bar of the tax payment, the larger is its tax base, and vice versa. Under equal per capita transfer, countries with a positive net payment (net donors) do not necessarily have the largest emission tax base. Whereas the picture changes under sovereignty transfers. Countries with large emission tax bases take the largest positive gross tax payment but also take the largest positive net payment.

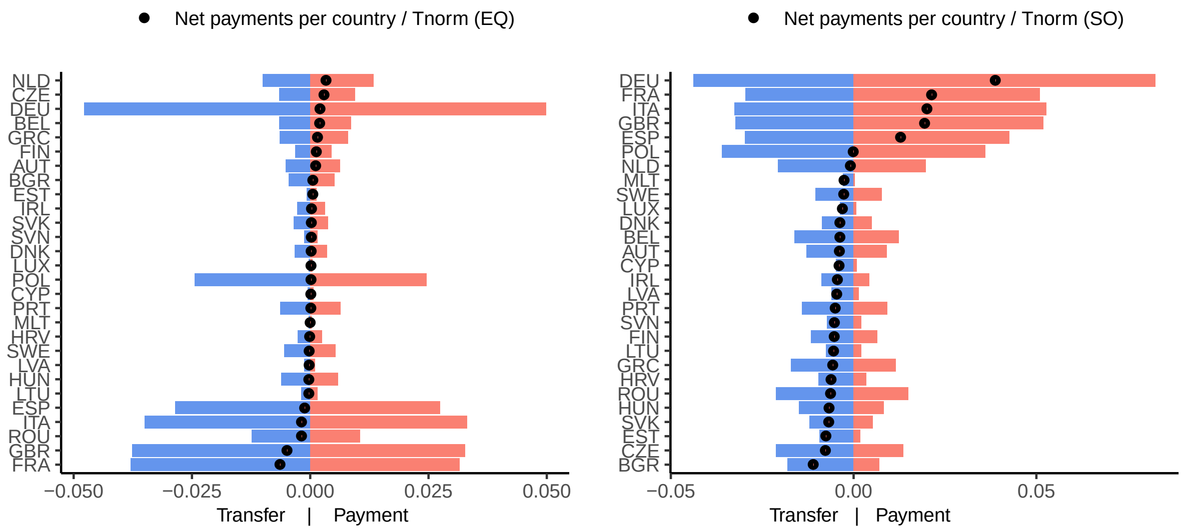

Figure 7: Federal payment (positive, red) and transfer (negative, blue) and the resulting net payment at the federal minimum tax given equal per capita (EQ) and sovereignty (SO) transfers per country. The size of the red bars reflects the size of a country's emission tax base. With sovereignty transfers, net payments are mostly proportionally increasing with a larger tax base. Equal per capita transfers show no positive correlation with the tax base size.

4.3. Results contrasting mobile to immobile capital

This section extends our numerical consideration by introducing perfect capital mobility across states. As we will show, the tendency of the results remains robust to mobile capital but gets more pronounced.

With mobile capital this paper connects to the inter-regional tax competition literature which was first investigated by Zodrow and Mieszkowski (1986), and Wilson (1986). In a similar spirit as the previous literature but motivated by the overlapping political architecture in the EU, Habla and Winkler (2018) investigate the interaction of states' capital taxation and federal emission policy on the provision of public goods. They find that capital mobility can result in too low or too large public good provision in a state depending on the in- or outflow of capital. We refer to their paper also for a more extensive literature review. While that specific literature focuses on capital taxation, our paper keeps the model setup with only emission taxation but contrasts the result given immobile and mobile capital.

We select three metrics to compare the case of mobile to immobile capital. First, we discuss the ranking of the uniform federal taxes T^i when capital is mobile. Second, we compare the net federal payment under mobile and immobile capital. Third, we compute the burden (incidence) as change in per capita consumption levels for both

	$\overline{K}_i$	$\overline{k}_i$	$\overline{L}_i$	χ_i
T^i_{EQ}	0.40	0.56	0.26	0.88
T^i_{SO}	-0.40	-0.39	-0.42	-0.28

Table 3: Correlation coefficients given mobile capital.

capital cases. The basic mechanisms of the following observations and discussed effects base on our statements in Lemma 1, 2 and 3.

Federal tax ranking with mobile capital. We find an almost similar order of the ranking of optimal federal taxes as in Section 4.2 and present a comparable Figure in Appendix L.

Table 3 reports on the correlation of the ranking of the optimal tax levels and the considered heterogeneities when capital is mobile. With equal per capita transfer we see a strong increase in the correlation of all heterogeneities. In particular, the effect of emission efficiency χ_i now dominates the ranking of optimal federal tax levels even stronger. The change in the correlation of state heterogeneities under sovereignty transfers is much less pronounced.

Comparison of net payments. In Figures 8 and 9 we present the per capita federal net payments. On the x-axis, we plot capital per capita levels per country ranked from the lowest (Bulgaria) to the largest (Luxembourg) level. On the y-axis, the net federal payment per capita indicates if the country is a per- capita net donor (a positive number) or a net recipient (a negative number) of federal tax revenues. We mark the net federal payment per capita for the immobile and mobile capital case with black squares or red circles, respectively. We connect these two data points corresponding to the consumer in state i with a vertical line. A longer vertical line signals a larger difference between the net payment level under mobile and immobile capital.

Figure 8 shows that under federal equal per capita transfers and mobile capital, consumers belonging to the the small and poor-cluster (group 3) and Poland are net donors of federal emission tax revenues while in the case of immobile capital, five of these countries are still net recipients. All consumers from countries belonging to the rich and large cluster face a negative net payment. Most rich and small countries' consumers are net donors in the immobile capital case, but become less strongly net donors or even net recipients with mobile capital.

Figure 9 suggests that our claim that sovereignty transfers make a federal tax progressive gets more pronounced under capital mobility. But the net difference between

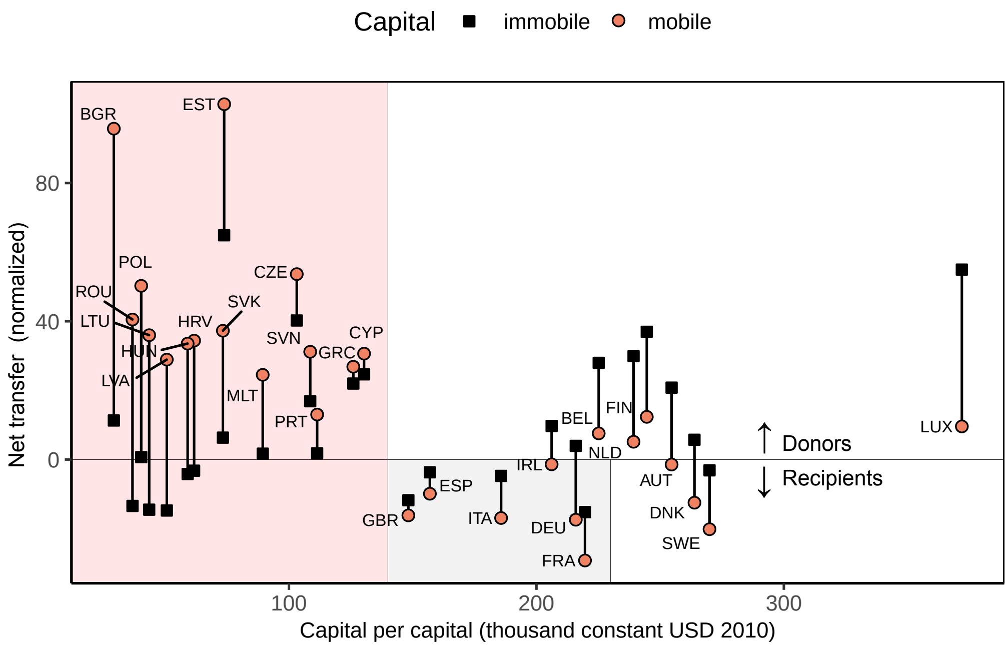

Figure 8: Net federal payment under equal per capita transfers ranked by capital per capita. The net payment lies on poor (group 3 and 4, red) and small and rich countries (group 2, white) are net donors.

	Capital	$\overline{K}_i$	$\overline{k}_i$	$\overline{L}_i$	χ_i
$\overline{N}_{i,EQ}$	immobile	-0.31	0.34	-0.40	-0.22
$\overline{N}_{i,EQ}$	mobile	-0.61	-0.69	-0.50	-0.85
$\overline{N}_{i,SO}$	immobile	0.50	0.07	0.57	0.29
$\overline{N}_{i,SO}$	mobile	0.49	0.26	0.55	0.38

Table 4: Correlation coefficients of net payments and heterogeneous country data.

mobile and immobile capital assumption are much smaller in almost all cases (length of vertical lines). Capital poor consumers, except for Poland, become net recipients. Poland's exemptions can be explained by its remarkably large population size which makes it an exception to the cluster of all other low-capital countries. Population size links to labor supply. Thereby, Poland's large population size acts similar as a large capital stock and increases production. As a by-product emissions increase as well[14]. Table 4 reports more correlations between net payments and heterogeneous country data.

Why do our previous observations become stronger with the introduction of mobile capital? The reason is that mobile capital reinforces the effects of the technologies'

[14]Technically speaking, this is due to the gross complementarity between the composite input of capital-labor, and emissions.

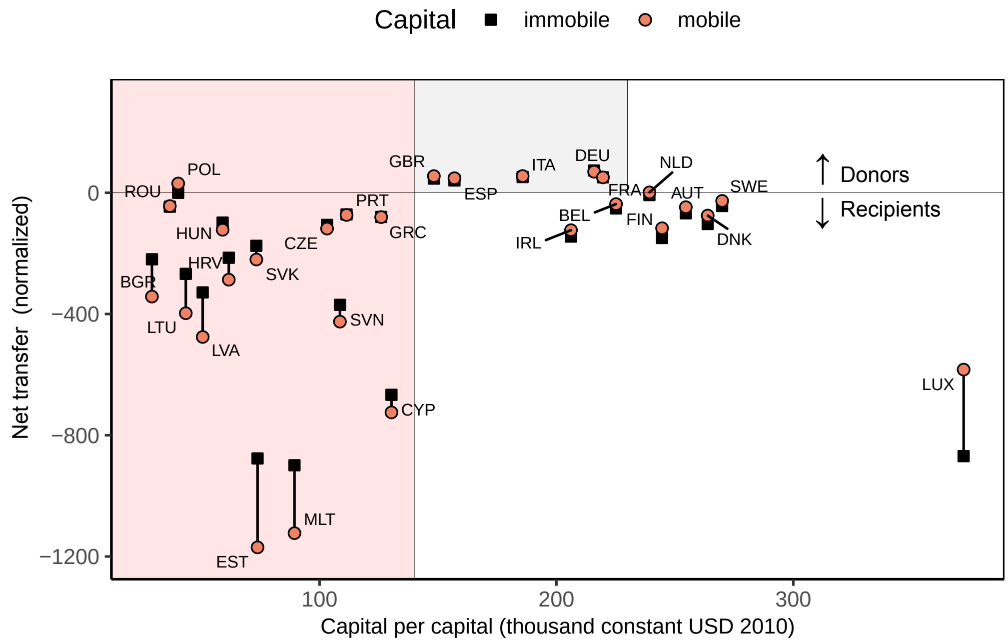

Figure 9: Net federal payment under sovereignty transfers ranked by capital per capita. Most of the net payment lies on the large and rich country-cluster (group 1, gray).

emission efficiencies. i) Low-capital EU countries tend to have lower emission efficiencies in production, leading to higher emission levels compared to other countries that are otherwise identical (cf. Lemma 1 and 2). ii) With the additional capital-inflow due to mobile capital[15], capital-poor EU countries can take over more of the production of the federal economy (cf. Lemma 3). The capital-inflow thus further increases their emission levels.

In other words, capital-rich countries not only export their capital, but also implicitly export emissions to capital-poor countries and thereby increase the multinational emission tax burden on poor countries. Absent of appropriate revenue transfers, capital mobility retains the observed regressive effect of a uniform federal emission tax.

Federal tax incidence. Figure 10 reports the welfare changes due to consumer burden resulting from the federal minimum tax. We report the relative percentage change of per capita consumption between the multilevel policy equilibrium relative to the decentralized outcome, $(c_i^* - c_i^o)/c_i^o$. To conceptualize our results, we add the group clusters from Figure 4.

[15]In the absence of capital mobility, the marginal product of capital is larger in poor countries than in rich countries. With capital mobility, capital flows from rich to poor countries as to equalize the marginal product of capital across countries.

We find that consumption in small and rich and all poor countries decreases with federal equal per capita transfers compared to the decentralized case (triangles). The changes in consumption in large and rich countries with equal per capita transfer are almost zero. Under sovereignty transfers (squares), all consumers in large and rich countries are exposed to a larger decline in per capita consumption in contrast to equal per capita transfers but also in contrast to other country clusters. Many poor countries and some rich and small countries' consumers experience an increase in consumption. While we find most consumption changes to be in a similar range as in Böhringer et al. (2015) we find larger differences in direction and magnitude for poor states given sovereignty transfers. We attribute these departures to the characteristic negative correlation between emission intensity and capital per capita in many EU countries. In the case of the Canadian provinces the relation between GDP per capita and carbon intensity is positive.

When comparing Figure 10 to Figures 8 and 9 we see that the net payments to the federal authority are an indicator of the resulting tax burden. Countries may be rightly concerned about the regressive tax incidence if they focus on net payments by the federal government.

5. Conclusion

When a government plans an environmental tax reform, public support for the reform is closely linked to the tax burden on consumers. Public support can be improved by strategically complementing tax reform by transfer rules that recycle tax revenues to consumers. In practice, policy-makers, scientists, lobby groups and policy advisers are confronted with limitations and different opinions about the "best" transfer rule to use (Kverndokk, 2018; Delbeke, 2017; Burtraw et al., 2009; Williams, 2019). Furthermore transfer heuristics often follow rules of thumb based on welfare economics, moral considerations, and state self-interests.

In this paper, we trace the consumers' burden of uniform federal tax payments to member state differences in wealth and technological emission intensity for two commonly used transfer rules in a simple general equilibrium. We find that the gross emission tax payment is larger for countries that are wealthier or for those with a large emission intensity of the production technology or both. When countries with a high emission intensity also rank lower on the distribution of wealth, an environmental policy reform threatens to become regressive. We show that equal per capita transfers do not counteract this regressive effect, but a transfer to consumers based on historical

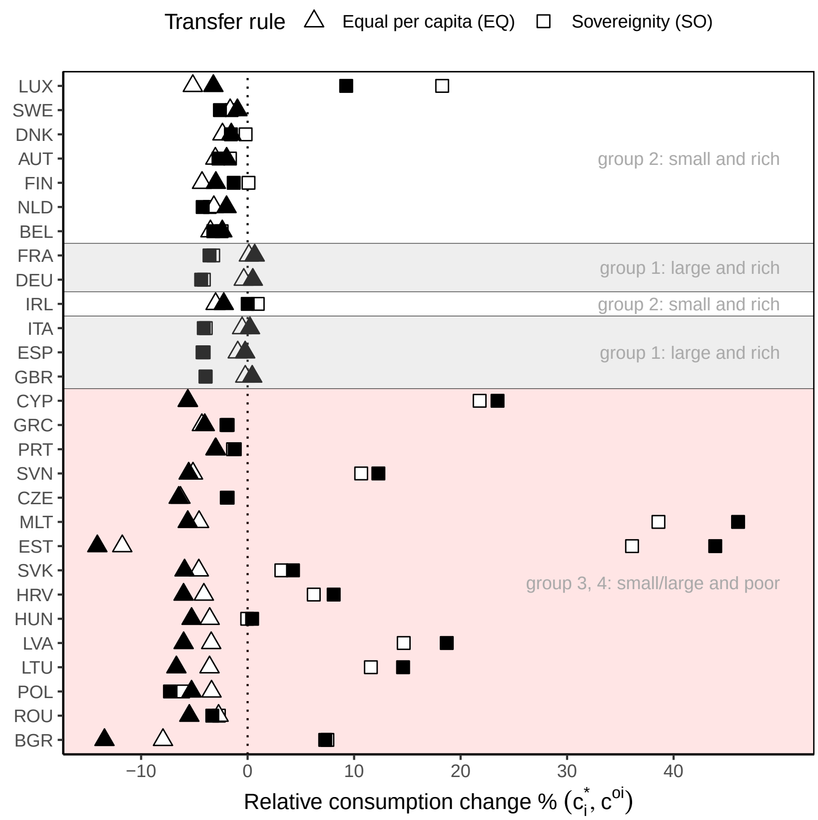

Figure 10: Incidence of the federal minimum emission tax. Filled symbols correspond to mobile capital and hollow symbols to immobile capital simulation.

emissions (sovereignty) can result in a progressive emission tax reform. For our numerical simulation to the EU, we extend the model with population difference and with coexisting state and federal governments that non-cooperatively choose their emission tax levels to maximize state or federal welfare. We have constrained the federal policy to theoretically ensure unanimous consent of states (Pareto-improvement with respect to their sovereign policy outcome) towards the federal tax and transfer policy.

Our findings contribute to the understanding of how to increase acceptance of federal environmental policies by citizens and state-level governments. We know from earlier studies that in the single country context a uniform tax (or a uniform price) combined with equal per capita transfers are progressive policy for citizens. One might think that this result holds, when it is applied to the member states of a federal CO_2 price system. This paper shows that this is not the case when, as in the EU, wealth and CO_2 intensity of production affect the burden in opposite ways. Sovereignty transfers, i.e. the way the EU has calculated the bulk of revenues from the ETS, produce – perhaps surprisingly – an egalitarian result.

We see a number of ways to extend the current analysis. First, the analysis could be extended to cover other transfers discussed in literature and politics. A particular interesting case are strategic transfers that reward consumers in a state according to the state's mitigation ambition, setting an incentive for more mitigation to receive more transfers. Alternatively, one could include the historical accountability of those who have generated large prosperity from historical emissions and thus partially reverse the effects of sovereignty transfers. Second, our analysis assumes homogeneity within countries. Accounting for income differences *within* states would allow a deeper discussion of welfare and inequality consequences of the policy packages. Third, while the above considerations relate exclusively to emissions policy, environmental taxes can also interact with a distortive tax system. In how far the revenues from the emission tax can be used to reduce other distorting taxes in a Pareto improving and progressive reform would add another perspective to the research interest of this study. Fourth, one could calculate the socially optimal transfers and emission tax in this federal set-up with differences in emission intensity and wealth. Fifth, one could analyze the outcome with a dynamic model in which the technology in a state improves in the long run with available capital or produced output. We plan to address some of these issues in future research.

Acknowledgments

Financial support by the German Research Foundation (DFG) grant number LE 782/2-1 is gratefully acknowledged. For their helpful comments and suggestions we thank in alphabetical order Wolfgang Habla, Achim Hagen, Biung-Ghi Ju, Zarko Kalamov, Linus Mattauch, Samuel Okullo, Marco Runkel, Emilie Soysal, Oliver Tietjen, Boyan Yanovski, and participants of the Public Economic Theory 2019 conference. For technical assistance we thank Lavinia Baumstark, Lukas Feldhaus, Anastasis Giannousakis, and David Klein. For proof-reading we thank Andrew McConnell.

References

D. Acemoglu. Directed Technical Change. *The Review of Economic Studies*, 69(4): 781–809, 2002. Appendix G

T. Bergstrom and Blume, L., Varian, H. On the private provision of public goods. *Journal of Public Economics*, 29:25–49, 1986. 2

M. Berlemann and J.E. Wesselhöft. Estimating aggregate capital stocks using perpetual inventory method - new empirical evidence for 103 countries -: Working Paper Series. *Review of Economics*, 65:1–34, 2014. 1, 4.1

M. Berlemann and J.E. Wesselhöft. Aggregate Capital Stock Estimations for 122 Countries: An Update. *Review of Economics*, 68(2):1158, 2017. 1, 4.1

C. Böhringer and A. Lange. On the Design of Optimal Grandfathering Schemes for Emission Allowances. *ZEW Discussion Papers, No. 03-08*, 2003. 2

C. Böhringer and A. Lange. Economic Implications of Alternative Allocation Schemes for Emission Allowances*. *Scandinavian Journal of Economics*, 107(3):563–581, 2005. 2

C. Böhringer, N. Rivers, T.F. Rutherford, and R. Wigle. Sharing the burden for climate change mitigation in the Canadian federation. *Canadian Journal of Economics*, 48 (4):1350–1380, 2015. 1, 2, 4.3

C. Böhringer, N. Rivers, and H. Yonezawa. Vertical fiscal externalities and the environment. *Journal of Environmental Economics and Management*, 77:51–74, 2016. 1, 2

J.K. Boyce and M. Riddle. Cap and Dividend: How to Curb Global Warming While Protecting the Incomes Of American Families: Working Papers wp150, Political Economy Research Institute, University of Massachusetts at Amherst., 2007. 1, 2

D. Burtraw, R. Sweeney, and M. Walls. The Incidence of U.S. Climate Policy: Alternative Uses of Revenues from a Cap-and-Trade Auction. *National Tax Journal*, LXII (3):497–518, 2009. 1, 2, 5

Cambridge Econometrics. Review of the Energy Taxation Directive: final modeling results'. A report for DG TAXUD, European Commission., 2008. 2

C. Carraro, E. de Cian, and L. Nicita. Modeling biased technical change. In S. Dietz, J. Michie, and C. Oughton, editors, *Political Economy of the Environment*, pages 167–185. Taylor & Francis, 2011. ISBN 9781136823978. 4, 12

M. Cazorla and M. Toman. International Equity and Climate Change Policy. Climate change Economics and Policy:235–247, 2001. 1

M. Chiroleau-Assouline and M. Fodha. From Regressive Pollution Taxes to Progressive Environmental Tax Reforms. *European Economic Review*, 69:126–142, 2014. 1, 2

J. Delbeke. A Comment on "Agreeing on an EU ETS Price Floor to Foster Solidarity, Subsidiarity, and Efficiency in the EU". In Ian W. H. Parry, Karen Pittel, and H. R. J. Vollebergh, editors, *Energy tax and regulatory policy in Europe*, CESifo seminar series. MIT press, Cambridge MA, 2017. ISBN 9780262036399. 5

I.I. Dorband, M. Jakob, M. Kalkuhl, and J.C. Steckel. Poverty and distributional effects of carbon pricing in low- and middle-income countries – A global comparative analysis. *World Development*, 115:246–257, 2019. 2

D. Fullerton, editor. *Distributional Effects of Environmental and Energy Policy*. Routledge, London, 2016. 1

M. Grubb, J. Sebenius, A. Magalhaes, and S. Subak. Sharing the burden. In I. M. Mintzer, editor, *Confronting Climate Change: Risks, Implications and Responses*, pages 305–322. Cambridge University Press, Cambridge UK, 1992. 1

W. Habla and R. Winkler. Capital Tax Competition under a Centralized Emissions Cap: WCERE manuscript. 2018. 4.3

B.G. Ju, M. Kim, S. Kim, and J.D. Moreno-Ternero. Climate Change Justice: An Axiomatic Approach. *PET 2019 conference paper*, 2019. 1

C. Kemfert and H. Welsch. Energy-Capital-Labor Substitution and the Economic Effects of CO2 Abatement: Evidence for Germany. *Journal of Policy Modeling*, 22(6): 641–660, 2000. 4, 12

D. Klenert and L. Mattauch. How to make a carbon tax reform progressive: The role of subsistence consumption. *Economics Letters*, 138:100–103, 2016. 1, 2

D. Klenert, L. Mattauch, E. Combet, O. Edenhofer, C. Hepburn, R. Rafaty, and N. Stern. Making carbon pricing work for citizens. *Nature Climate Change*, 8(8): 669–677, 2018. 1, 2

B. Knopf, N. Koch, G. Grosjean, S. Fuss, C. Flachsland, M. Pahle, M. Jakob, and O. Edenhofer. The European Emissions Trading System (EU ETS): ex-post analysis, the market stability reserve and options for a comprehensive reform: Nota di Lavoro 79.2014, Milan Italy: Fondazione Eni Enrico Mattei, 2014. 2

K. Kosonen. *Regressivity of environmental taxation: Myth or reality?*, volume 32 of *Taxation papers*. Publ. Office of the Europ. Union, Luxembourg, 2012. ISBN 9789279250262. 2

D.M. Krepps. *A Course in Microeconomic Theory*. Princeton University Press, Princeton NY, 1990. Appendix I

S. Kverndokk. Climate Policies, Distributional Effects and Transfers Between Rich and Poor Countries. *International Review of Environmental and Resource Economics*, 12 (2-3):129–176, 2018. 1, 5

S. Kverndokk and A. Rose. Equity and Justice in Global Warming Policy. International Review of Environmental and Resource Economics(2):135–176, 2008. 1

N. Lutsey and D. Sperling. America's bottom-up climate change mitigation policy. *Energy Policy*, 36(2):673–685, 2008. 2

A. Manne and R. Richels. *Buying Greenhouse Insurance: The Economic Costs of CO2 Emission Limits*, volume 1. The MIT Press, 1 edition, 1992. 4, 12

R.A. Musgrave. *The Theory of Public Finance*. McGraw-Hill, New York NY, 1959. 2

W.E. Oates. An Essay on Fiscal Federalism. *Journal of Economic Literature*, 37: 1120–1149, 1972. 2

W.E. Oates. Fiscal competition and European Union: contrasting perspectives. *Regional science & urban economics*, 31:133–145, 2000. 2

W.E. Oates. A Reconsideration of Environmental Federalism. Discussion Paper 01–54, 2001. 2, 2

E. Padilla and J. Roca. The Proposals for a European Tax on CO2 and Their Implications for Intercountry Distribution. *Environmental and Resource Economics*, 27: 273–295, 2004. 2

S. Rausch, G.E. Metcalf, J.M. Reilly, and S. Paltsev. Distributional Implications of Alternative U.S. Greenhouse Gas Control Measures. 2010. 1, 2

C. Roolfs, B. Gaitan, and O. Edenhofer. The good, the bad and the useless: Multilevel emissions policy and the effectiveness of commonly used federal transfers. *Revise and Resubmit JEEM*, 2018a. 2, 3.3.1, 3, 3.3.2

C. Roolfs, B. Gaitan, and O. Edenhofer. Assessing EU minimum prices and revenue distribution from a multilevel policy perspective. *WCERE 2019 conference-paper*, 2018b. 3.3.1

K.A. Sheeran. Who Should Abate Carbon Emissions? A Note. *Environmental and Resource Economics*, 35(2):89–98, 2006. Appendix I

T. Sterner and E.Z.J. Robinson. Selection and design of environmental policy instruments. In Partha Dasgupta, Subhrendu K. Pattanayak, and V. Kerry Smith, editors, *Handbook of Environmental Economics*, Handbook of Environmental Economics, pages 231–284. Elsevier, 2018. 1

E. van der Werf. Production Functions for Climate Policy Modeling: An Empirical Analysis, Nota di Lavoro, NOTA DI LAVORO 47.2007, 2007. 4, 12

R.C. Williams. Growing state–federal conflicts in environmental policy: The role of market-based regulation. *Journal of Public Economics*, 96(11-12):1092–1099, 2012. 2

R.C. [Roberton3Will] Williams. # We need to pay more attention to distributional effects. Economists far too often call the most efficient policy "best", even when it has problematic distributional effects. And distribution is a key element of political feasibility. [Tweet]. `https://twitter.com/Roberton3Will/status/1081957953907974144`, Twitter, 2019. 5

J.D. Wilson. A theory of Interregional tax Competition. *Journal of Urban Economics*, 19:296–315, 1986. 4.3

P. Zhou and M. Wang. Carbon dioxide emissions allocation: A review. *Ecological Economics*, 125:47–59, 2016. 1

G.R. Zodrow and P. Mieszkowski. Pigou, Tiebout, Property Taxation, and the Underprovision of Local Public Goods. *Journal of Urban Economics*, 19(3):356–370, 1986. 2, 3.3.1, 4.3

Appendix

Appendix A. Conditional input demand

Using equation (3) the conditional demand function for E_i is

$$E_i = \left(\frac{zp_i}{\chi_i^{\frac{1-\sigma}{\sigma}}}\right)^{\sigma} \left(\frac{\alpha^{\sigma}}{\tau_i^{1-\sigma}} + \frac{\left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}}\right)^{\sigma}}{p_i^{1-\sigma}}\right)^{\frac{\sigma}{1-\sigma}} \frac{Y_i}{A} \tag{A.1}$$

$$= \left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}}\frac{1}{\tau_i}\right)^{\sigma} \frac{Y_i}{A^{1-\sigma}}. \tag{A.2}$$

The corresponding conditional demand function for V_i is

$$V_i = (\alpha\tau_i)^{\sigma} \left(\frac{\alpha^{\sigma}}{\tau_i^{1-\sigma}} + \frac{\left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}}\right)^{\sigma}}{p_i^{1-\sigma}}\right)^{\frac{\sigma}{1-\sigma}} \frac{Y_i}{A} = \left(\frac{\alpha}{p_i}\right)^{\sigma} \frac{Y_i}{A^{1-\sigma}}. \tag{A.3}$$

Appendix B. Market clearing with immobile capital

Rearranging equation (3) yields

$$0 < \alpha^{\sigma} p_i{}^{1-\sigma} = A^{1-\sigma} - \left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}}\right)^{\sigma} \tau_i^{1-\sigma} \equiv \boldsymbol{\phi}_i\left(\tau_i\right). \tag{B.1}$$

Using the market clearing conditions and $\boldsymbol{\phi}_i$, we can describe the rental rate of capital in state i as

$$\mathbf{r}_i\left(\tau_i\right) = \frac{\beta_K B}{\alpha^{\frac{\sigma}{1-\sigma}}} \left(\frac{\overline{L}_i}{\overline{K}_i}\right)^{\beta_L} \boldsymbol{\phi}_i^{\frac{1}{1-\sigma}}$$

Successive replacement of $\mathbf{r}_i\left(\tau_i\right)$ provides us with the other variables, which are exclusively depend on τ_i. The wage rate in state i equals

$$\mathbf{w}_i\left(\tau_i\right) = \frac{\beta_L B}{\alpha^{\frac{\sigma}{1-\sigma}}} \left(\frac{\overline{K}_i}{\overline{L}_i}\right)^{\beta_K} \boldsymbol{\phi}_i^{\frac{1}{1-\sigma}}.$$

Since $V_i = B\overline{K}_i^{\beta_K}\overline{L}_i^{\beta_L} \equiv \overline{V}_i$,output in state i equals

$$\mathbf{Y}_i\left(\tau_i\right) = A^{1-\sigma}\left(\frac{\boldsymbol{\phi}_i}{\alpha}\right)^{\frac{\sigma}{1-\sigma}} \overline{V}_i$$

State i's emission level is given by

$$\mathbf{E}_i\left(\tau_i\right) = \left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}} \frac{1}{\alpha^{\frac{1}{1-\sigma}}} \right)^{\sigma} \left(\frac{\boldsymbol{\phi}_i{}^{\frac{1}{1-\sigma}}}{\tau_i} \right)^{\sigma} \overline{V}_i. \tag{B.2}$$

and aggregate federal emissions are

$$\mathbf{E}\left(\tau\right) = \sum\nolimits_{j=1}^{m} \mathbf{E}_j \tag{B.3}$$

where $\tau \equiv (\tau_1 ..., \tau_m)$.

Appendix C. Market clearing with mobile capital

From market clearing follows that the rental rate of capital is

$$\boldsymbol{r}(\tau_i) = \frac{B\beta_k}{\alpha^{\frac{\sigma}{1-\sigma}}} \frac{\sum_i \left(\boldsymbol{\phi}_i^{\frac{1}{(1-\sigma)\beta_l}} \overline{L}_i \right)^{\beta_l}}{\overline{K}^{\beta_l}}$$

and the wage rate in state i is

$$\mathbf{w}_i\left(\tau_i\right) = \left(\frac{B\left(\frac{\beta_k}{\boldsymbol{r}}\right)^{\beta_k}}{\alpha^{\frac{\sigma}{1-\sigma}} \phi_i^{\frac{1}{1-\sigma}}} \right)^{\frac{1}{\beta_l}} \beta_l.$$

Firm i's first order conditions imply

$$\mathbf{E}_i\left(\tau_i\right) = \left(\frac{z}{\alpha^{\frac{1}{1-\sigma}}} \right)^{\sigma} \left(\frac{\boldsymbol{\phi}_i{}^{\frac{1}{1-\sigma}}}{\tau_i} \right)^{\sigma} \frac{\boldsymbol{V}_i}{\chi_i^{1-\sigma}}. \tag{C.1}$$

and capital demand is

$$\mathbf{K}_i\left(\tau_i\right) = \left(\frac{\beta_k B}{\alpha^{\frac{\sigma}{1-\sigma}}} \right)^{\frac{1}{\beta_l}} \left(\frac{\boldsymbol{\phi_i}^{\frac{1}{1-\sigma}}}{\boldsymbol{r}} \right)^{\frac{1}{\beta_l}} \overline{L}_i.$$

Substitution of $\boldsymbol{V}_i = BK_i^{\beta_K} \overline{L}_i^{\beta_L}$ into equation $(C.1)$ yields

$$\mathbf{E}_i\left(\tau_i\right) = \left(\frac{B}{\alpha^{\frac{\sigma}{1-\sigma}}} \left(\frac{\beta_k}{\boldsymbol{r}} \right)^{\beta_k} \boldsymbol{\phi_i}^{\frac{\sigma}{1-\sigma}+\beta_k} \right)^{\frac{1}{\beta_l}} \left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}} \right)^{\sigma} \frac{\overline{L}_i}{\tau_i^{\sigma}}.$$

Appendix D. Few comparative statics

Now that we have characterized all supply and demand plans and all market equilibria, we can calculate the comparative statics of small emission tax increases in one state. Recall that $\tau_i(t_i, T) = t_i + T$ and consequently $\partial\tau_i/\partial t_i = \partial\tau_i/\partial T = 1$, equation (B.1) implies

$$\frac{\partial \boldsymbol{\phi}_i}{\partial \tau_i} < 0. \tag{D.1}$$

From equations $(D.1)$, it follows that $\partial\mathbf{r}_i/\partial\tau_i < 0$ and $\partial\mathbf{w}_i/\partial\tau_i < 0$. This shows that an increase in the emission tax in state i reduces firm i's remuneration to capital and labor. Similarly as before, using equation $(D.1)$ it follows that $\partial\mathbf{Y}_i/\partial\tau_i < 0$ implying that an increase in the emission tax in state i reduces the production of firm i.

From equations $(B.2)$ and $(B.3)$ follows

$$\frac{\partial \mathbf{E}_i}{\partial \tau_i} = \frac{\partial \mathbf{E}}{\partial t_i} = \frac{\partial \mathbf{E}_i}{\partial T} < 0, \text{ and } \frac{\partial \mathbf{E}}{\partial T} < 0. \tag{D.2}$$

A greater emission tax in state i decreases state i's emissions demand. Further, from equation $(B.2)$ follows that $\partial\mathbf{E}_i/\partial t_j = 0$ which tells that, at the partial equilibrium, emission demand of state i is is unaffected by tax changes of other states $j \neq i$. We use this result to solve the state tax level in Section 3.3.1.

Appendix E. Proof of Lemma 1

Suppose $t_i = 0$. Then $\boldsymbol{\tau}_i(t_i, T) = \boldsymbol{\tau}_i(0, T) = T$. Further let $T > 0$ and capital is immobile across states.

First, let us consider equation (A.2)

$$E_i = \left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}}\frac{1}{T}\right)^{\sigma}\frac{Y_i}{A^{1-\sigma}}. \tag{E.1}$$

With $\text{el}_{YE} \equiv TE_i/Y_i$ denoting the output elasticity of Y_i subject to E_i and rearranging (E.1) yields

$$T = (\text{el}_{YE})^{\frac{1}{1-\sigma}}\frac{\chi_i A}{z^{\frac{\sigma}{1-\sigma}}}. \tag{E.2}$$

Since firm i is a price taker it ignores its impacts on r_i. The derivative of $\mathbf{E}_i$, from (B.2), w.r.t. χ_i and after some algebraic manipulations and using the definition of $\boldsymbol{\phi}_i > 0$ from equation (B.1) we get

$$\mathbf{E}_i\left(\tau_i\right) = \left(\frac{z}{\chi_i^{\frac{1-\sigma}{\sigma}}}\frac{1}{\alpha^{\frac{1}{1-\sigma}}}\right)^{\sigma}\left(\frac{\boldsymbol{\phi}_i^{\frac{1}{1-\sigma}}}{\tau_i}\right)^{\sigma}\overline{V}_i.$$

$$\frac{\partial \mathbf{E}_i}{\partial \chi_i} = \underbrace{-\frac{E_i}{\chi_i\boldsymbol{\phi}_i}\left(\frac{T}{\chi_i}\right)^{1-\sigma}}_{+}F. \tag{E.3}$$

with $F \equiv \left((1-\sigma)\left(\frac{\chi_i A}{T}\right)^{1-\sigma} - z^{\sigma}\right)$. While we can sign all terms except F in the equation (E.3) clearly positive, we can only say so far that if $F > 0$ then $\partial \boldsymbol{E}_i / \partial \chi_i < 0$ and vice versa. Suppose $F > 0$ and solve for T from F to get

$$T < (1-\sigma)^{\frac{1}{1-\sigma}} \frac{\chi_i A}{z^{\frac{\sigma}{1-\sigma}}}. \tag{E.4}$$

Equate equation (E.2) with the left-hand side of inequality (E.4) to get

$$T = (\mathrm{el}_{YE})^{\frac{1}{1-\sigma}} \frac{\chi_i A}{z^{\frac{\sigma}{1-\sigma}}} < (1-\sigma)^{\frac{1}{1-\sigma}} \frac{\chi_i A}{z^{\frac{\sigma}{1-\sigma}}}$$

indicating that the decisive terms to sign F are el_{YE} and $(1-\sigma)$. Thus, as long as

$$\mathrm{el}_{YE} < (1-\sigma)$$

then $\partial \boldsymbol{E}_i / \partial \chi_i < 0$.Proceed similarly to show that from $\mathrm{el}_{YE} > (1-\sigma)$ follows $F < 0$ and thus $\partial \boldsymbol{E}_i / \partial \chi_i > 0$. □

Appendix F. Proof of Lemma 2

We provide less explanatory text and refer to the previous one for further explanations.

Suppose $t_i = 0$. Then $\boldsymbol{\tau}_i(t_i, T) = \boldsymbol{\tau}_i(0, T) = T$. Further let $T > 0$ and capital is mobile across states.

For the derivative of $\mathbf{E}_i$, from (C.1), w.r.t. χ_i and after some algebraic manipulations and using the definition of $\boldsymbol{\phi}_i > 0$ from equation (B.1) we get

$$\frac{\partial \mathbf{E}_i}{\partial \chi_i} = -\underbrace{\frac{E_i}{\chi_i \beta_l \boldsymbol{\phi_i}} \left(\frac{T}{\chi_i}\right)^{1-\sigma}}_{+} G. \tag{F.1}$$

with $G \equiv \left((1-\sigma)\beta_l \left(\frac{\chi_i A}{T}\right)^{1-\sigma} - z^{\sigma}\right)$. While we can sign all terms except G in equation (F.1) clearly positive, we can only say so far that if $G > 0$ then $\partial \boldsymbol{E}_i / \partial \chi_i < 0$ and vice versa.

Suppose $G > 0$ and solve $G$for T to get

$$T < \left((1-\sigma)\, \beta_l\right)^{\frac{1}{1-\sigma}} \frac{\chi_i A}{z^{\frac{\sigma}{1-\sigma}}}. \tag{F.2}$$

Note that equations (E.1) and (E.2) apply to the mobile capital case, too. Equate equation (E.2) with the left-hand side of inequality (F.2) to get

$$T = (\mathrm{el}_{YE})^{\frac{1}{1-\sigma}} \frac{\chi_i A}{z^{\frac{\sigma}{1-\sigma}}} < \left((1-\sigma)\, \beta_l\right)^{\frac{1}{1-\sigma}} \frac{\chi_i A}{z^{\frac{\sigma}{1-\sigma}}}$$

indicating that the decisive terms to sign G are el_{YE} and $(1-\sigma)\, \beta_l$ where $\beta_l = 1 - \beta_k$.

Thus, as long as

$$\text{el}_{YE} < (1-\sigma)(1-\beta_k)$$

then $\partial \boldsymbol{E}_i / \partial \chi_i < 0$.

Proceed similarly to show that from $\text{el}_{YE} > (1-\sigma)(1-\beta_k)$ follows $G < 0$ and thus $\partial \boldsymbol{E}_i / \partial \chi_i > 0$. □

Appendix G. Alternative interpretation of Lemma 1 and Lemma 2: The relative marginal rate of technical substitution

Adjustments of capital and emissions inputs are determined by the marginal rate of technical substitution[16] between emissions and capital ($MRTS^i_{EK}$). Its slope equals the negative relative marginal product of emissions:

$$\text{rel.}Y_E \equiv -MRTS^i_{EK} = \frac{Y^i_{E_i}}{Y^i_{K_i}} = \frac{z}{\alpha} \underbrace{\left(\frac{1}{\chi_i}\right)^{\frac{1-\sigma}{\sigma}}}_{(*)} \underbrace{\left(\frac{K_i^{\beta_k+\sigma\beta_l}\overline{L}_i^{(1-\sigma)\beta_l}}{E_i}\right)^{\frac{1}{\sigma}}}_{(**)} \frac{1}{\beta_k} \tag{G.1}$$

where $Y^i_{K_i}$ is the marginal product of capital.

Ceteris paribus, we see that the E_i-augmenting factor χ_i reduces the relative marginal product of E_i, cf. term (*) in (G.1) and the firm will change K_i more strongly than E_i. Acemoglu (2002) refers to this effect as K-bias induced by χ_i-change.

However due to a nested CES function as sketched in Figure 2, term (**) in equation G.1 points at the ambivalence of the role of K_i: Larger K_i can potentially induce an E-bias. Whether χ_i-change is E or K-biased depends on the relative abundance of K_i and E_i known as the substitution effect[17] and determined by the $MRTS^i_{EK}$. We calculate the total elasticity of the $MRTS^i_{EK}$ with regard to both variable inputs K_i, E_i stating how output would change if both inputs change in one percent:

$$\text{el}^{MRTS}_{E,K} = -\left(\frac{\partial \text{rel.}Y^i_{E_i}}{\partial E_i}\frac{E_i}{\text{rel.}Y^i_{E_i}} + \frac{\partial \text{rel.}Y^i_{E_i}}{\partial K_i}\frac{K_i}{\text{rel.}Y^i_{E_i}}\right) = \frac{1}{\sigma} - \beta_k\frac{1}{\sigma} - \beta_l.$$

As long as $0 < \sigma < 1$, the slope $MRTS^i_{EK}$ is different for any combination of K_i and E_i and thus depends on the actual input share of K_i to E_i to which a χ-change would impose marginal input adjustments. Therefore, we calculate the elasticity of the $MRTS^i_{EK}$ with regard to changes in the input share, stating how the $MRTS^i_{EK}$ would change if the input share changes in one percent:

[16] Graphically speaking, the $MRTS^i_{EK}$ measures the slope of the isoquant along which the firm finds its optimal input bundles of K_i, E_i.

[17] Leading to a downward sloping relative demand curve for E_i if K_i increases.

$$\mathrm{el}^{MRTS}_{KEshare} = -\frac{\partial \mathrm{rel}.Y^i_{E_i}}{\partial K_i/E_i}\frac{K_i/E_i}{\mathrm{rel}.Y^i_{E_i}} = \frac{1}{\sigma}.$$

The *relative elasticity of the marginal substitution rate* (or elasticity of the substitution effect) measured in the respective input bundle K_i/E_i is

$$\frac{\mathrm{el}^{MRTS}_{E,K}}{\mathrm{el}^{MRTS}_{KEshare}} = (1-\sigma)(1-\beta_k)$$

which is the right-hand side of inequality (5). Therefore, if the relative elasticity of the marginal substitution rate outweighs the output elasticity of emissions, K_i but also E_i will decrease with a χ_i-change. Vice versa, K_i decreases (strongly) but E_i increases. Proceed similar for the case of immobile capital. □

Appendix H. State *i*'s first-order conditions

Use equation $(D.2)$ with $\partial \mathbf{E}/\partial t_i = \partial \mathbf{E}_i/\partial t_i$. It follows that that the first-order condition of state i's problem reduces to $\partial \mathbf{u}^i/\partial t_i = u^i_{c_i}\ \partial \mathbf{c}_i/\partial t_i + u^i_E\ \partial \mathbf{E}_i/\partial t_i = 0$. Algebraic manipulations allows to rewrite it as

$$\frac{\partial \mathbf{u}^i}{\partial t_i} = \frac{1}{\overline{L}_i} t_i \frac{\partial \mathbf{E}_i}{\partial t_i} u^i_{c_i} + S_i T \frac{\partial \mathbf{E}_i}{\partial t_i} u^i_{c_i} + u^i_E \frac{\partial \mathbf{E}_i}{\partial t_i} = 0.$$

and solving for t_i yields the state tax chosen by state i.

Appendix I. Technical description of federal solutions

With the formulation of the federal problem as in equation (8), we make use of a traditional concept: The formulation of a Pareto improvement and targeting at Pareto dominant taxes is equivalent to maximize a social welfare function given specific weights (cf. Krepps, 1990; Sheeran, 2006). For each minimum level assigned to a consumer in state$j$, u^{oj}, when maximizing the utility of aconsumer in state$i$ in the Pareto-improvement form as in equation (8), there is a set of social welfare weights λ_i with $\sum_j \lambda_j = 1$ which produces the same Pareto result when maximizing a social welfare function of all consumers and with the similar rule, and vice versa and T^i corresponds to $\lambda_i = 1$.

Appendix J. A proxy

The cost share of emissions in production is $\omega_E \equiv \tau_i E_i/Y_i$. We set $\omega_E = z$. Solving for A from equation $(A.1)$ we get $A = 1/\chi_i Y_i/E_i$.

Appendix K. Replication of utility structure

Figure K.11 replicates the structure of utility curves, the federal tax range and ranking of federal taxes as discussed in Section 3.3.2 and Figure 3. We report utility levels by plotting the relative change between the multilevel and decentralized equilibrium levels. The different curvature of the slopes shows that different transfer rules impact the slope and ranking of the utilities' maxima and thus the ranking of optimal uniform federal taxes.

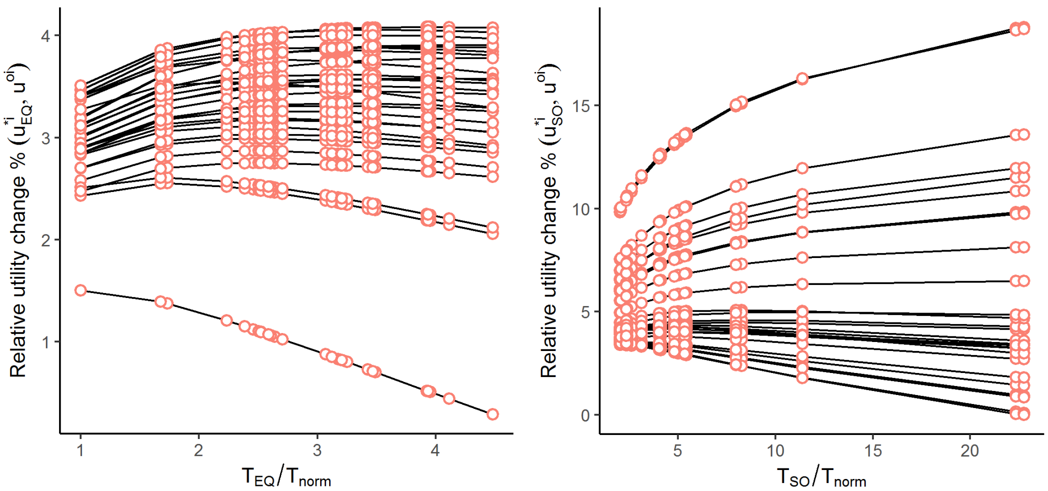

Figure K.11: Relative change of utility levels between the multilevel and decentralized equilibrium under equal per capita (EQ) and sovereignty transfers (SO). The points on the lines correspond to T^i/T_{norm}. Utility levels approaching 0 with increasing T/T_{norm} indicate that each consumer in the respective country falls back to or below her decentralized utility level with a further increasing federal tax level.

Appendix L. Tax ranking with mobile capital

Figure L.12 shows the optimal federal emission tax of each country under equal per capita and sovereignty transfers is relatively similar to the immobile capital case, Figure 5. However, when comparing the immobile (closed) to the mobile (open economy) capital case, we see that i) optimal federal taxes are generally lower in the mobile than in the immobile capital case, as shown by the fact that the lowest tax under equal per capita transfers is below the dotted line (corresponding to the federal minimum tax under equal per capita transfers in the immobile capital case). ii) Under capital mobility, the total federal tax differences increases, that is we see a larger difference between the lowest and highest taxes increases.

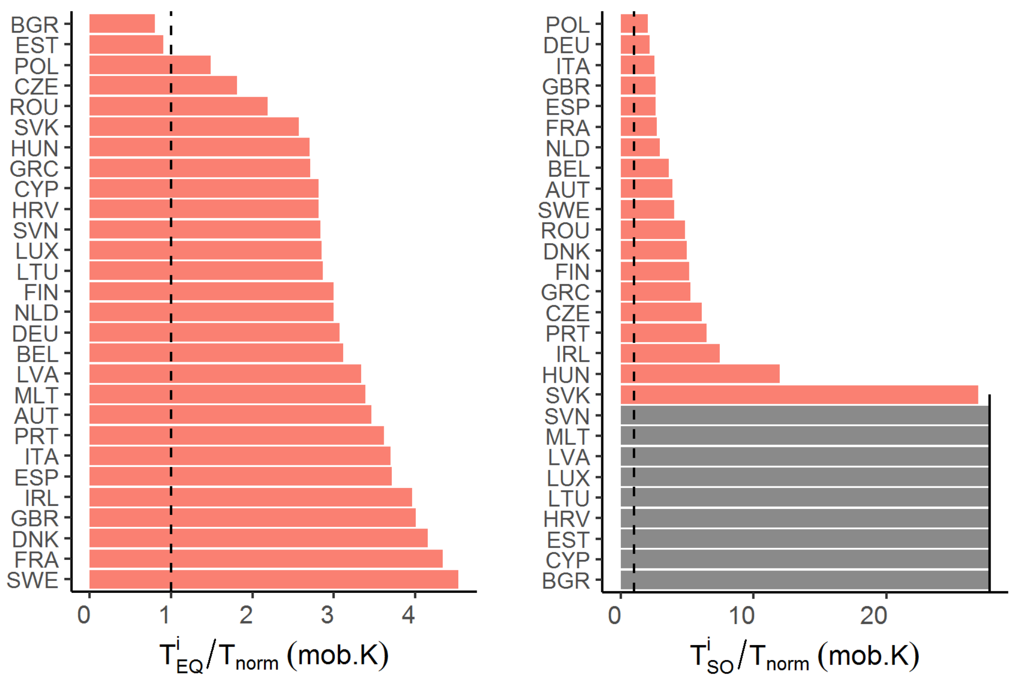

Figure L.12: Normalized uniform federal tax rates that maximize the utility of the respective country given mobile capital.