The good, the bad, and the useless: Multilevel emissions policy and the effectiveness of commonly used federal transfers

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Abstract

Transfers following simple criteria often aid the mitigation of transboundary environmental externalities. This paper assesses the effectiveness of a uniform federal emissions price combined with simple federal transfer criteria. To do so, we develop a general equilibrium model in which state and federal policies coexist. To ensure the consent of all states, federal policy must make all states better off relative to the decentralized outcome. By considering transfer shares equal to Decentralized Emission Share (DES) levels, equality and *juste retour* transfers, we demonstrate that the degree of wealth heterogeneity and the states' reaction to the federal transfer hamper the success of federal policy. Under equality and DES transfers, there is an effective federal minimum emissions price at which the richest state faces the largest cost of the federal policy and at which it receives a social welfare function weight of one. Such cases make the richest state a benevolent hegemon.

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Highlights

- We study the Pareto improvement potential of commonly used federal transfers.
- We model co-existing state/federal policies on transboundary emissions.
- States' reactions to transfers hamper the federal policy's effectiveness.
- The absence of interstate transfers rules out Pareto improvements.
- An effective federal policy comprises of a minimum price which benefits all states.

1. Introduction

Economic theory and political practice have demonstrated the need for transfers across heterogeneous countries to mitigate transboundary carbon emissions. In practice, the Green Climate Fund provides financial transfers at a global scale to facilitate carbon emission policy measures in poor countries. In the European Union (EU), revenues derived from the EU emissions trading scheme (ETS) are transferred back to EU member states based on low-income and historical emission levels. Similarly, at a national and subnational scale (e.g. in Switzerland and California) part of the revenues from emission policies are redistributed on an equal per capita basis and/or to finance environmental projects. In response to policy pragmatism in a complex world, transfers often follow simple criteria derived from welfare economics, moral considerations, and states' self-interests. While simple transfers are often used in actual legislation[1] and federal-multinational policy-making often requires states' consent[2], economic theory lacks understanding of the impact of such transfers on the effectiveness of federal policy. This paper provides a theoretical foundation to guide the use of commonly used federal transfers — equality and *juste retour* transfers[3] — and transfer shares equal to Decentralized Emission Share (DES) levels, which reward large decentralized emissions.

We develop a general equilibrium model of a federation with coexisting state and federal emissions policies. To ensure consent of all states to federal policy-making, we constrain the federal government to achieve Pareto improvements relative to the decentralized policy outcome. We consider states with different levels of wealth and solve a Stackelberg equilibrium among a leading federal and following state governments. Emissions are a necessary input in production that harm consumers as a local and transboundary externality and are therefore regulated by state and federal emission

[1]Of the EU ETS's auction revenues, 88 percent are transferred based on pre-EU-ETS emissions share levels, which rewards what were initially high decentralized emissions. The remaining twelve percent are transferred to less wealthy member states (EC, 2015, 2013). Details on other EU's, Swiss, and Californian revenue redistribution can be found in Warleigh (2004), Economides and Miaouli (2006), FOEN (2016), C2ES (2014), and CPL (2016).

[2]EU policies, for example, often require unanimity.

[3]*Juste retour* transfers imply that total emissions payments of firm's located in a state equal the federal transfer to the respective state.

prices. We find, inter alia, that welfare-enhancing uniform federal minimum prices for emissions mitigation emerge endogenously, when using equality and DES transfers. These minimum prices ensure states' consent toward the federal policy.

Our results describe the set of emission prices that solve the federal government's problem of finding a federal emission price that makes all states better off relative to the decentralized policy scenario. We demonstrate that the lower bound of the set of federal emission prices is the price that maximizes the utility of the richest state[4]. This price defines the uniform federal minimum price. While all states benefit, the richest state bears the largest share of the cost of the federal policy. The richest state, therefore, becomes a benevolent hegemonic state[5]. While an effective federal policy, in addition to each state's policy, further internalizes the emission externality, the federal transfer either increases the income of relatively poor states (equality) or rewards initially higher emission levels caused by higher income levels (DES). From a normative perspective, therefore, the equality transfer can be assessed as 'good' as it redistributes federal policy revenues equally per capita. The DES transfer, on the other hand, rewards initially high emission levels, making it a normatively 'bad' criterion.

We demonstrate that the applicability of the equality transfer is limited by the heterogeneity of the states' wealth. Transfers based on DES do not face such restriction as long as the federal transfer is lump-sum from the state governments' perspectives. In our numerical simulation, we examine whether the effective transfers and the related minimum price give an advantage to the rich or to the poor states in terms of individual utility improvement and consumption decreases. For both, we show that the equality transfer is better for the poor states while DES transfer is better for the rich states. In contrast, the *juste retour* transfer is ineffective (useless). This result differs from those of d'Autumne et al. (2016), Sandmo (2004), and Shiell (2003) who assume that the *juste retour* transfer is lump-sum from the state government's perspective. The *juste retour* transfer corresponds to a situation in which interstate transfers do not occur. In

[4]Maximizing the richest state's utility corresponds to the case in which the federal government assigns a weight of "one" to the richest state in the context of a social welfare function.

[5]Hegemonic state, here, refers to the neo-liberal definition where its actions are well-meaning and not coercive (Yarbrough, 2001).

Chichilnisky and Heal (1994) and Sandmo (2007), Pareto optimality is not achievable in the absence of interstate transfers. Here, we find that not even Pareto improvements are attainable in the absence of interstate transfers.

Given a simple transfer, we find that there are three key factors influencing the state's policy choice and the effectiveness of federal policy. First, the policy choice is influenced by the marginal rate of substitution between emissions and consumption, which has also been documented in previous literature (e.g Chichilnisky and Heal, 1994). Second, if each state government takes into account the influence of its policy on the federal transfer that its population receives, the model shows a reduction of the state's policy stringency. In turn, the effectiveness of the federal policy is hampered. Third, the interplay of the states' relative capital endowments, the consumers' sensitivity to the emission externality, and the output elasticity of emissions describe an institutional tipping point that determines whether or not the federal policy is effective.

In terms of emissions mitigation, we show that there is a flipping point at which the federal minimum price related to one transfer criterion becomes more effective than the other. This point is determined by capital endowments, technological, and emission sensitivity parameters. When wealth heterogeneity is large, we find that the DES transfer achieves a higher emission reduction than the equality transfer.

The rest of the paper is organized as follows: In Section 2, a short literature review is presented. In Section 3, we introduce the model and characterize equilibria. In Section 4 the impact of different transfer criteria considered is analyzed and conditions are derived that make the federal policy effective. A numerical simulation is given in Section 5. Lastly, we provide some concluding remarks in Section 6.

2. Literature review

Multinational emission mitigation by top-down regulation and the role of transfers on economic efficiency is analyzed by Chichilnisky and Heal (1994); Chichilnisky et al. (2000)[6], Sandmo (2007); d'Autumne et al. (2016). Chichilnisky and Heal (1994) show

[6]See Sheeran (2006) for an intuitive discussion of Chichilnisky and Heal (1994); Chichilnisky et al. (2000).

that to achieve efficiency with a uniform multinational price, multinational emission mitigation requires transfers from rich to poor states. Absent of a uniform price, Economides and Miaouli (2006)'s analysis of 'commonly used' transfers confirms that redistributive transfers from rich to poor can improve environmental quality. Shiell (2003) and d'Autumne et al. (2016) consider the *juste retour* transfer, which does not redistribute wealth from rich to poor states. They find it to be effective in the presence of lump sum transfers. The simultaneous existence of decentralized (state) and centralized (federal) emission policies was first investigated by Williams (2012). Depending on the federal policy instrument used, he finds that optimal transfers do not always exist. A bottom-up perspective on multinational transfers is analyzed by Helm (2003) who finds that central regulation can be less effective than decentralized regulation. A key driver to Helm's result is the transfer negotiation of the states', which takes place before the multinational policy is adopted.

The decentralized-voluntary provision of public goods is studied by Olson (1965, 1986); Bergstrom et al. (1986). Olson demonstrates how benevolent hegemonic states tend to create multinational systems for public good provision. While the public good benefits all states belonging to the system, the hegemonic state voluntarily bears a disproportionately large cost share of the public good. Bergstrom et al. (1986)find that income redistributing transfers can have a negative impact on the level of voluntary public good provision. Their finding is driven by wealth heterogeneity, which leads to different consumption levels. These, in turn, generate differing abilities to sacrifice consumption for financing public goods.

Our paper more closely relates to the work of Williams (2012) as we allow for the simultaneous existence of state and federal emission policies. We depart from Williams (2012) by considering a general equilibrium setting in which states consent to federal policy is ensured by constraining the federal government to attain Pareto improvements relative to the decentralized outcome. Since states' consent to federal policy-making translates into voluntary contributions to emissions mitigation programs, our work more closely relates to Bergstrom et al. (1986). We extend their analysis by considering commonly used transfer criteria and a federal government acting as a Stackelberg leader.

3. The model

We consider a federal system comprised of n member states ($i = 1, \ldots, n$). Across member states, an identical final good is produced using capital and emissions. In each state there is a representative household, and the population is normalized to one. Households derive utility from consuming the final good, but the federation's aggregate emissions negatively affect their well-being. The households own capital that they rent out to firms, but capital is immobile across states. In each state there is a state government that sets an emission price on local firms to regulate local emissions. In turn, state i's government transfers emission-pricing revenues to state i's household. In addition, there is a federal government that sets a uniform price on the emissions of all firms and redistributes federal revenues back to the households of all states. While federal emissions pricing revenues are redistributed as lump-sum transfers to consumers, state governments do not necessarily take the federal transfer as a lump-sum transfer.

We compare two different institutional settings. First, we derive the decentralized solution. In the decentralized solution, only state governments set emission prices. Second, we create a two-layered policy system by introducing a federal government. State governments act as Nash players by taking the emissions prices of other state and federal governments as given. In contrast, the federal government acts as a Stackelberg leader for all economic agents and state governments. The federal government redistributes its emission price revenues based on three different transfer criteria: equality, *juste retour*, and DES. Coexisting with states' policies, the federal government implements its policy if and only if it delivers Pareto improvements relative to the decentralized solution.

3.1. Economic agents

3.1.1. Firms

The firm of state i employs capital k_i and emissions e_i using a constant returns to scale technology to produce final good y_i. Taking prices as given the firm chooses k_i and e_i to maximize profits as follows

$$\max_{k_i, e_i} \left\{ (y_i - r_i k_i - (\rho_i + P)\, e_i) \,\middle|\, y_i = A k_i^{\alpha_K} e_i^{\alpha_E} \right\}.$$

The price of the final good is presumed to be numéraire. The parameters $\alpha_K > 0$, $\alpha_E > 0$ are the output elasticities of capital and emissions, respectively, with $\alpha_K + \alpha_E = 1$, and $A > 0$ is an efficiency parameter. The rental rate of capital of state i is denoted by r_i, ρ_i is state government i's price of emissions, and P is the uniform federal emissions price. Therefore, firm i's unit cost of emissions equals $\rho_i + P$. Firms maximize profits by setting the marginal product of each factor equal to its respective price. Let $\Omega = \alpha_K^{\alpha_K} \alpha_E^{\alpha_E} A$. The marginal cost ($mc_i$) of producing good y_i equals $mc_i = r_i^{\alpha_K} (\rho_i + P)^{\alpha_E} / \Omega$. Zero profits imply $mc_i = 1$. The firms' first order conditions also imply

$$k_i = \alpha_K y_i / r_i \quad \text{and} \quad e_i = \alpha_E y_i / (\rho_i + P) \,. \tag{1}$$

3.1.2. Households

Each household derives satisfaction from consuming the final good. Aggregate federal emissions, given by $e = \sum_i^n e_i$, negatively affect each household's utility. We assume an additively separable utility function. The utility function of the representative household of state i is given by $u_i(c_i, e)$, where c_i denotes final good consumption and $\partial u_i / \partial c_i > 0$, $\partial^2 u_i / \partial c_i^2 \leq 0$, $\partial u_i / \partial e < 0$, and $\partial^2 u_i / \partial e^2 \leq 0$. The latter implies that the higher are the emissions, then the greater is the marginal dis-utility from emissions.

Households receive transfers from state and federal governments as lump-sum income.[7] Taking prices and aggregate emissions as given, the household of state i chooses the level of consumption c_i that maximizes its utility subject to the budget constraint

$$c_i = r_i \bar{k}_i + \rho_i e_i + t_i \tag{2}$$

where $r_i \bar{k}_i$ is the return to capital endowment $\bar{k}_i$, and $\rho_i e_i$ and t_i are, respectively, transfers from state i's government and federal government to the household of state i. Since the household takes emissions as given, the solution to its optimization problem is reduced to setting c_i equal to income.

[7] While households take all governmental transfers as given, state governments may not and therefore may internalize the effect of their policies on federal transfers. These issues are considered in more detail in the following sections.

3.1.3. Market clearing

Capital market clearing in each state implies that capital demand k_i equals household i's capital endowment (i.e. $k_i = \overline{k}_i$). Market clearing in final goods is given by

$$\sum_{i=1}^{n} c_i = \sum_{i=1}^{n} y_i. \tag{3}$$

In what follows, we derive expressions for all variables in terms of ρ_i and P, which we then use to solve the optimization problems of state and federal governments. These expressions take into account the first-order conditions of households and firms as well as market clearing conditions. Substituting (1) into the zero profit condition and solving for r_i, we obtain

$$r_i = R_i(\rho_i, P) = \left(\Omega/(\rho_i + P)^{\alpha_E}\right)^{\frac{1}{\alpha_K}}. \tag{4}$$

r_i is clearly decreasing in $(\rho_i + P)$, reflecting that if ρ_i or P increase, the remuneration that firms can make to the owners of capital must decrease. Since $k_i = \alpha_K y_i / r_i$, using (4) and $k_i = \overline{k}_i$ it follows that

$$y_i = Y_i(\rho_i, P) = \left(\alpha_E^{\alpha_E} A/(\rho_i + P)^{\alpha_E}\right)^{\frac{1}{\alpha_K}} \overline{k}_i. \tag{5}$$

Since $e_i = \alpha_E / \alpha_K r_i / (\rho_i + P)\, \overline{k}_i$, using (4) we obtain

$$e_i = E_i(\rho_i, P) = \left(\alpha_E A/(\rho_i + P)\right)^{\frac{1}{\alpha_K}} \overline{k}_i. \tag{6}$$

As it should be, output (5) and emissions (6) decrease with the aggregate cost of emissions in state i, given by $\rho_i + P$. Thus, consumption decreases as well. The balance between these two opposing forces — the gains from decreasing emissions and the losses in consumption — and the choice of ρ_i and P are studied in Sections 3.2 and 3.4.

Aggregate emissions e equal

$$e = E(\rho, P) = \sum_{i=1}^{n} \left(\alpha_E A/(\rho_i + P)\right)^{\frac{1}{\alpha_K}} \overline{k}_i. \tag{7}$$

where $\rho = (\rho_1, p_2...\rho_n)$. The federal transfer to household i equals

$$t_i = T_i(\rho, P) = s_i PE(\rho, P)$$

where s_i is the transfer *criterion* that defines the share of federal revenues passed to the household of state i. In Section 4, we precisely define s_i, which depends on the transfer employed. Zero profits imply that $y_i - Pe_i = r_i k_i + \rho_i e_i$; by substituting this into equation (2), state i's consumption equals

$$c_i = C_i(\rho, P) = Y_i(\rho_i, P) + T_i(\rho, P) - PE_i(\rho_i, P). \tag{8}$$

Therefore, household i's consumption departure from local production is given by the net federal transfer, $T_i - PE_i$. Equations (4) – (8), defined in terms of ρ_i (for $i = 1, ...n$) and P, are known to all governments.

3.2. State governments

In each state there is a state government that cares only about the well-being of the household living in its state. The government of state i chooses the emission price ρ_i to maximize household i's utility while taking the federal emission price P and all other states' emission prices $\rho_{j\ \forall j\neq i}$ as given. The government of state i incorporates the solution of all households' and firms' optimization problems, and market clearing conditions into its optimization problem. In other words, state i incorporates equations (4) – (8) into its optimization by substituting equations (6) – (8) into $u_i(c_i, e)$. We can thus rewrite household i's utility in terms of ρ and P as follows $U_i(\rho, P) \equiv u_i(C_i(\rho, P), E(\rho, P))$. State i government's problem is given by

$$\max_{\rho_i} U_i(\rho, P) \text{ given } \rho_{j\ \forall j\neq i} \text{ and } P. \tag{9}$$

The first-order condition that solves problem (9) is given by $\partial U_i/\partial \rho_i = \partial u_i/\partial c_i$

$\partial C_i/\partial\rho_i + \partial u_i/\partial e\ \partial E/\partial\rho_i = 0$. After some algebraic manipulations, we get[8]

$$\frac{\partial U_i}{\partial \rho_i} = \frac{\partial u_i}{\partial c_i}\frac{\partial E_i}{\partial \rho_i}\rho_i + \frac{\partial u_i}{\partial c_i}\frac{\partial T_i}{\partial \rho_i} + \frac{\partial u_i}{\partial e}\frac{\partial E_i}{\partial \rho_i} = 0. \tag{10}$$

Since $\partial E_i/\partial\rho_i < 0$, the first term in equation (10) reflects how the marginal utility of consumption declines due to the impact of ρ_i on income absent from the federal transfer $(r_i\bar{k}_i + \rho_i E_i)$. An increase in ρ_i first generates a decline in income from capital returns and from the state transfer, which in turn leads to a decrease in household i's consumption. The next term in (10) indicates how the marginal utility of consumption is influenced by the impact of ρ_i on the federal transfer. If s_i in T_i is constant, then ρ_i has a negative impact on T_i via its effect on state i's emissions. We later differentiate whether or not T_i is lump-sum from the state i government's perspective. The last term in (10) reflects the marginal utility from emissions reduction due to an increase in ρ_i.

Let

$$MRS_{e,c_i} \equiv -\frac{\partial u_i}{\partial e}/\frac{\partial u_i}{\partial c_i}$$

denote the marginal rate of substitution between aggregate emission reduction and consumption in state i. Rearranging (10), the n states' first-order conditions implicitly define the states' prices depending solely on the federal emission price. We denote this relation by $\rho_i(P)$ and state i's policy choice becomes

$$\rho_i = p_i(P) = MRS_{e,c_i} - \frac{\partial T_i}{\partial \rho_i}/\frac{\partial E_i}{\partial \rho_i} \text{ for all } i. \tag{11}$$

Claim 1 (State Policy)**.** *The state government i's policy ρ_i equals the marginal rate of substitution between aggregate emissions reduction and consumption in state i, minus the ratio of partial derivatives of the federal transfer to state i and state i's emissions with regard to ρ_i.*

Focusing on the first term on the right-hand side (RHS) of equation (11), we observe

[8]Note that the first-order conditions of firm i imply that $r_i\bar{k}_i = \alpha_K/\alpha_E(\rho_i + P)e_i$. We substitute this result into the budget constraint of household i, $c_i = r_i\bar{k}_i + \rho_i e_i + T_i$, finally, use equation (6) to obtain this result.

how state policies can differ across states. *Ceteris paribus*, a larger marginal dis-utility from aggregate emissions leads to a larger ρ_i, whereas a larger marginal utility from consumption leads to a lower ρ_i. Similar to Chichilnisky and Heal (1994)'s findings, but from a social planers' perspective, the marginal utility of consumption negatively affects the stringency of the state government's policy. The impact described by the second term of equation (11), however, has largely been neglected. It takes into account how ρ_i influences the federal transfer to household i vis-à-vis the decline of emissions in state i due to an increase in ρ_i.

Definition 1 (Anticipation)**.** *If each state takes into account how its emissions price influences the federal transfer to household i, i.e.* $\partial T_i / \partial \rho_i \neq 0$*, we say that 'states anticipate the federal transfer'.*

An asterisk* indicates an anticipated solution whenever it differs from the unanticipated case. For brevity we add the asterisk only to resulting levels and not to functional forms and/or the RHS of an equation.

If the federal transfer is anticipated by state i's government and if the sign of $\partial T_i / \partial \rho_i$ is negative, which we show to hold, the state's emission price ρ_i^* falls below the MRS_{e,c_i}.

Claim 2 (Role of Anticipation)**.** *If state i's government anticipates the federal transfer and if the federal transfer to household i equals* $t_i = s_i Pe$*, where* s_i *is a positive constant, then*

$$\rho_i^* = p_i(P) = MRS_{e,c_i} - s_i P \quad \textit{for all } i.$$

In particular, each state government reduces its own policy stringency by $s_i P$. We conclude that state governments' anticipation of the federal transfer has an important reduction effect on state policy choice.

3.3. Decentralized equilibrium

Definition 2 (Decentralized Policy Equilibrium)**.** *A decentralized policy equilibrium is the quantities* $\widetilde{c}_i$, $\widetilde{y}_i$, $\widetilde{k}_i$, $\widetilde{e}_i$ *and prices* $\widetilde{r}_i$, $\widetilde{\rho}_i$*, for all i, such that* $\widetilde{c}_i$ *solves the optimization problem of household i;* $\widetilde{y}_i$, $\widetilde{k}_i$ *and* $\widetilde{e}_i$ *solve the problem of firm i;* $\widetilde{\rho}_i$ *solves the problem* *of the state government i; the capital market clearing condition and the market clearing condition in final goods* (3) *hold; and* $P = 0$.

A tilde over a variable indicates the variable's level in a decentralized solution. Setting $P = 0$ in equations (4) – (7), the first-order condition of state government i (10) is reduced to

$$\widetilde{\rho}_i = MRS_{e,c_i}\big|_{P=0} \quad \text{for all } i. \tag{12}$$

Therefore, state i's government internalizes the local externalities from state i's emissions by setting the marginal product of emissions $\widetilde{\rho}_i$ equal to the MRS_{e,c_i}. This result, however, lies below the social optimum since it fails to consider the spillover effect of state i's emissions to neighboring states (Samuelson rule).

The resulting decentralized utility levels are

$$\widetilde{U}_i \equiv U_i(\widetilde{\rho}, 0)$$

and $\widetilde{c}_i = \widetilde{y}_i = \left(\alpha_E^{\alpha_E} A/\widetilde{\rho}_i^{\alpha_E}\right)^{1/\alpha_K} \overline{k}_i$, and $\widetilde{e}_i = (\alpha_E A/\widetilde{\rho}_i)^{1/\alpha_K} \overline{k}_i$, and

$$\widetilde{e} = \sum\nolimits_{j=1}^{n} (\alpha_E A \overline{k}_j^{\alpha_K} / \widetilde{\rho}_j)^{1/\alpha_K}.$$

3.4. The federal government

We introduce a federal government that, given a transfer criterion, chooses a uniform federal emission price that guarantees that at least one state is better off, while ensuring that no other state falls below its decentralized solution (Pareto improvement). While we consider a uniform federal emission price, it might be argued that differentiated prices could fulfill the same purpose. Indeed, if emissions are regulated in a centralized fashion and optimal transfers are absent, Chichilnisky and Heal (1994) show that it is necessary to set differentiated prices to attain Pareto optimality. Our justification for using a uniform price is threefold: first, it is applied in practice and in theory; second, it is intended to counteract federal fragmentation; and third, it serves to foster states' commitment on the basis of reciprocity (Cramton et al., 2015, 2017; Edenhofer et al., 2017).

The federal government knows the solution of the problems of households, firms, and state governments as well as all market clearing conditions, and acts as a Stackelberg leader. In other words, the federal government considers the effect of P on equations (4)-(8) and (10). Let $p = (p_1 (P), p_2 (P), ...p_n (P))$ denote the vector of states' chosen prices, which, as discussed above equation (11), solely depend on the federal price P. The federal government chooses a uniform price on emissions, P, given a federal transfer criterion s_i with $\sum_i T_i = PE (p, P)$ to solve

$$\max_P \left\{ U_i (p, P) \middle| U_j (p, P) \geq \widetilde{U}_j \quad \forall\, j \neq i \right\} \tag{13}$$

Equation (13) indicates that the federal government regulates if and only if it can attain Pareto-superior allocations relative to the decentralized solution — as to acknowledge the self-interest of the states and to ensure their consent[9]. This departs from Helm (2003), whose model allows top-level government policy to perform less efficiently than decentralized state policies, and from d'Autumne et al. (2016), whose top-level government can delegate tasks to state governments independent of any assurance of Pareto improvements.

The Lagrangian function related to problem (13) is given by

$$L (P, \lambda) = U_i (p, P) + \sum_{j \neq i} \lambda_j \left(U_j (p, P) - \widetilde{U}_j \right)$$

where $\lambda = (\lambda_1, \lambda_2, ...\lambda_n)$ are the $n - 1$ Karush-Kuhn-Tucker multipliers related to the utility constraints in problem (13). We refer the reader to AppendixA for the detailed derivation of the first order conditions.

Let $M_j^d \left(\rho_j, P\right) = R_j \left(\rho_j, P\right) \overline{k}_j + \rho_j E_j \left(\rho_j, P\right)$. If some P satisfies $U_j (p, P) > \widetilde{U}_j$ for all $j \neq i$, this implies that $\lambda_{j\, \forall j \neq i} = 0$. If such a case exists[10], matters would be greatly simplified, and further analytical insights could be attained. In such a case, the

[9]Equivalently, the federal objective can be interpreted as addressing the principle of subsidiarity. If the principle of subsidiarity is applied, the federal government should fulfill a supporting rather than a subordinating role regarding state governments' policies. The federal level shall execute only those tasks that cannot be performed effectively at the state level (Wincott, 2009).

[10]We discuss and show the existence of such cases in the sequel to this paper.

federal government's first-order conditions are reduced to

$$MRS_{e,c_i} = \left(\frac{dM_i^d}{dP} + \frac{dT_i}{dP} \right) / \frac{dE}{dP} = \frac{dc_i}{dP} / \frac{dE}{dP} \tag{14}$$

with $\frac{dM_i^d}{dP} = \frac{\partial M_i^d}{\partial \rho_i}\frac{dp_i}{dP} + \frac{\partial M_i^d}{\partial P}$, $\frac{dT_i}{dP} = \sum_{h=1}^n \frac{\partial T_i}{\partial \rho_h}\frac{dp_h}{dP} + \frac{\partial T_i}{\partial P}$, and $\frac{dE}{dP} = \sum_{h=1}^n \frac{\partial E_h}{\partial \rho_h}\frac{dp_h}{dP} + \frac{\partial E}{\partial P}$. Equations (14) implies that the federal government would chose to implement a federal price P such that household i's MRS_{e,c_i} equals the marginal change in income (including the federal transfer) relative to the marginal change of aggregate emissions due to a marginal increase in P.

Definition 3 (Multilevel Policy Stackelberg Equilibrium)**.** *A multilevel policy Stackelberg equilibrium with transfer criterion s_i is the quantities $\widehat{c}_i$, $\widehat{y}_i$,$\widehat{k}_i$, $\widehat{e}_i$ and prices $\widehat{r}_i$, $\widehat{\rho}_i$, $\widehat{P}$ such that $\widehat{c}_i$ solves the optimization problem of household i; $\widehat{y}_i$, $\widehat{k}_i$ and $\widehat{e}_i$ solve the problem of firm i; $\widehat{\rho}_i$ solves the problem of the state government i; $\widehat{P}$ solves the problem of the federal government; the market clearing conditions of capital and final goods* (3) *hold; and the balance of payments condition $\widehat{y}_i + \widehat{t}_i - \widehat{P}\widehat{e}_i = \widehat{c}_i$ is satisfied for all i.*

We use hats to denote a multilevel policy Stackelberg equilibrium solution. In the next section, we more carefully specify the federal transfer considered, and present analytical results under specific household utility functions.

4. Federal transfer criteria

We stay in the tradition of Chichilnisky and Heal (1994) by considering income level differences, which we model as differences in capital endowments. While Chichilnisky and Heal focus on Pareto optimality, we impose a multi-layered governmental structure in which the federal government chooses a uniform federal emission price while adopting a commonly used federal transfer.

4.1. Juste retour

The *juste retour* criterion transfers to each household i exactly what firm i paid to the federal government Pe_i. *Juste retour* literally means "fair return" since states' often consider it to be fair. More generally, *juste retour* transfers are often requested from the EU by EU Member States (Warleigh, 2004), and are implicitly considered in the models of d'Autumne et al. (2016) and Shiell (2003). As Shiell (2003) puts it, a state that feels relatively poor might not be willing to pay transfers to relatively richer states and might articulate this concern in its negotiation position.

We use the JR subscript to denote the *juste retour* transfer. *The juste retour criterion is* $s_{i,JR} = e_i/e$ *and the transfer becomes* $t_{i,JR} = Pe_i$ whose amount and impact of ρ_i is known to state i's government. Therefore, we consider it a reasonable assumption that the federal transfer must not be taken as lump-sum by state governments and depart from Shiell (2003); d'Autumne et al. (2016) by investigating the anticipated case.

Proposition 1 (Juste Retour)**.** *If the federal transfer to household i equals the expenditure of state i's firm due to federal policy, and if state governments anticipate the federal transfer, then the federal government cannot achieve a Pareto-superior allocation relative to the decentralized solution.*

Proof. The federal transfer $t_{i,JR}$ equals Pe_i and its partial derivative with regard to ρ_i equals $\partial T_i/\partial \rho_i = P\partial E_i/\partial \rho_i$. Substituting this result into (11) we get

$$\rho_i^* = MRS_{e,c_i} - P. \tag{15}$$

Note that the aggregate per-unit price of emissions firm i pays under the *juste retour* transfer is given by $\rho_i^* + P = MRS_{e,c_i}$ to see that it is equal to the decentralized solution. □

Since the federal policy addresses the effect of transboundary emissions, one would expect that each household could be made better off by the federal policy. Instead, equation (15) indicates that state government i reacts with a 100 percent counter-movement to the federal price such that the *juste retour* creates a pitfall, making the federal policy ineffective and therefore redundant as soon as it is anticipated by the states. Our result departs from the finding of Shiell (2003); d'Autumne et al. (2016), who show that the *juste retour* criterion is effective in the presence of lump sum transfers.

Recognizing that no interstate transfers occur under the *juste retour*, because the federal withdrawal (payment of firm i) from each state's economy equals the re-injection to each state's economy (transfer to household i) we can state the following claim.

Claim 3 (Interstate Transfers)**.** *In the absence of interstate transfers the federal policy is ineffective.*

Interestingly, as in Chichilnisky and Heal (1994) and Sandmo (2007) Pareto optimality cannot be established in the absence of interstate transfers. We find here that not even Pareto improvements are achievable without interstate transfers, despite the presence of a strong federal government (Stackelberg leader).

4.2. Equality

In this section, we present a transfer based on equality. The subscript EQ denotes variables related to this type of transfer. The equality criterion is, for instance, applied by the Swiss Federal government which equally redistributes part of the revenues from the Swiss CO2 levy back to all Swiss residents (FOEN, 2016). All households receive an identical federal transfer such that $t_{i,EQ} = t_{EQ} = 1/nPe$. To be able to provide more analytical insights, we now assume a specific utility function given by[11]

$$u_i(c_i, e) = c_i - g_i e^{\gamma_i}, \tag{16}$$

where g_i and γ_i are constants with $g_i > 0$ and $\gamma_i \geqq 1$. Let σ_i denote the ratio of the capital endowment of state i's household to the capital endowment of the entire federation, $\overline{k} \equiv \sum_i \overline{k}_i$, such that $\sigma_i \equiv \overline{k}_i/\overline{k}$. Also let

$$\sigma_{EQ} \equiv \frac{1}{n}\frac{n+\gamma-\alpha_E}{1+\gamma-\alpha_E} \quad \text{and} \quad \sigma^*_{EQ} \equiv \frac{1}{n}\frac{n+\gamma-\alpha_E-1}{1+\gamma-\alpha_E-1/n}. \tag{17}$$

Proposition 2 (Equality)**.** *Let $\overline{k}_1 \leq \ldots \leq \overline{k}_n$, $g_i = g$ and $\gamma_i = \gamma \geq 1$ for all i and $\overline{k}_1 < \overline{k}_n$. If i) the federal transfer is equal across households; ii) each state government does- not-anticipate (anticipate) the federal transfer; and iii) $\sigma_i < \sigma_{EQ}$ (σ^*_{EQ}) for all*

[11]We recognize that the assumption of linear consumption may seem odd at a first glance. Combining linear consumption with an emission externality guarantees a concave utility function and the existence of interior solutions. Therefore, it allows for the reproduction of features similar to those that would be obtained using more traditional utility functions such as $\log(c_i)$ while maintaining analytical traceability. Additionally, we ran numerical simulations with other utility functions. The main findings remain similar.

$i = 1, ..., n$, then, the federal government's policy leads to a Pareto-superior allocation relative to the decentralized solution. A uniform federal minimum price exists and is in the self-interest of all states to pay. The minimum price solves $\max_P U_n(p, P)$ *where* $U_n(p, P)$ *is the utility of the richest state.*

Proof. See AppendixB and AppendixC. □

We give a intuitive explanation of the proof by referring to Figure 1. Using $U_i(p, P) = U_i(p_1(P), ..., p_n(P), P)$, we can plot the utility function of each state solely depending on P. At $P = 0$ the level of U_i equals the decentralized utility level $\widetilde{U}_i$. In AppendixB (AppendixC) we demonstrate that if $\sigma_i < \sigma_{EQ}$ (σ^*_{EQ}) holds, then U_i is strictly concave and at $P = 0$ the derivative of U_i is positive. This implies that for some positive prices P all utilities U_i are greater than the decentralized level $\widetilde{U}_i$ (for $i = 1, ...n$). As illustrated in Figure 1, each U_i reaches its maximum at P^i for $i = 1, ..., n$ and these prices can be ranked as follows

$$P^n < P^{n-1} < ... < P^1.$$

A price smaller than P^n is not a federal optimal solution since a federal price equal to P^n would make every household better off. Therefore, P^n marks the beginning of the federal solution space and represents the uniform federal minimum price. We set $\widehat{P}^{\min} \equiv \widehat{P}^n$. The largest admissible federal price is the smallest among either P^1 (since any $P > P^1$ will make all states worse off), or the price $P^i_{ind} > 0$ at which U_i equals its decentralized level, i.e. $U_i(p_1(P^i_{ind}), ..., p_n(P^i_{ind}), P^i_{ind}) = \widetilde{U}_i$ (dotted line in Figure 1).

Corollary 1 (Federal Policy)**.** *The federal government's policy solution space is the interval of uniform federal emission prices that satisfy*

$$P \in [\widehat{P}^{\min}, \min\{P^1, P^2_{ind}, ..., P^n_{ind}\}].$$

Let $\overline{k}_{av} \equiv \sum_i \overline{k}_i/n = \overline{k}/n$ denote the state's average capital endowment, and $\sigma_{av} \equiv \overline{k}_{av}/\overline{k} = 1/n$. In the un-anticipated case, using equation ($B.10$) the closed form solutions of P^i is

$$P^i_{EQ} = \Phi \left(1 - \sigma_i + (\gamma - \alpha_E)(\sigma_{av} - \sigma_i)\right) \left(\frac{(1 + (\sigma_{av} - \sigma_i)\gamma)^{1-\gamma}}{(\sigma_i + (\sigma_{av} - \sigma_i)\alpha_E)^{\alpha_K}}\right)^{\frac{1}{\gamma - \alpha_E}} \tag{18}$$

with $\Phi = ((\alpha_E A)^{\gamma-1} (g\gamma \overline{k}^{\gamma-1})^{\alpha_K})^{1/(\gamma-\alpha_E)} > 0$. To get $\widehat{P}^{\min}$ simply set $i = n$. The closed form solution for the anticipated case, P^{i*}_{EQ}, is given in the AppendixC.

Equation (18) points at two crucial drivers of the solution to the federal government's problem: First, the ambivalence of emission reduction, $(\gamma - \alpha_E) > 0$. Parameters γ and α_E are, respectively, the elasticity parameter of the externality from emissions[12] and the output elasticity of emissions. Second, the individual relative capital heterogeneity $(\sigma_{av} - \sigma_i)$, which measures state i's departure from the average state's capital endowment. Note that the difference $\sigma_{av} - \sigma_i$ is negative for states with capital endowments larger than the average σ_{av}.

With this federal transfer, the burden of the federal policy is carried by the richer states. Note, when thinking about the burden imposed on the rich states, that the richer states are also those that pollute the most. For the rich states in which $\overline{k}_i > \overline{k}_{av}$, they benefit from the federal policy is solely due to a decrease in emissions. For the states in which $\overline{k}_i < \overline{k}_{av}$, which we call the poorer states, the benefit from federal policy is twofold. First, the federal emission price decreases the externality, which has a positive impact on utility. Second, poorer states are net recipients, as the federal policy injects more money into the poorer states' economies than what it withdraws from those economies.[13] Since $\widehat{t}_{EQ} > \widehat{P}\widehat{e}_i$ for poorer states, the equality criterion can also be understood as an implicit federal positive bias toward poorer states. Our results implicitly follow the claim of Chichilnisky and Heal that poorer states should become

[12] The elasticity parameter of the externality is derived as follows $D(p, P) \equiv gE(p, P)^\gamma$. Then $\partial D/\partial E \; E/D = \gamma$. Note that D corresponds to the size of the dis-utility from emissions.

[13] To prove that poorer states ($\sigma_i < 1/n$) are net recipients multiply equation (6) with $n/\overline{k}$, then $ne_i/\overline{k} = (\alpha_E A/(\rho_i + P))^{\frac{1}{\alpha_K}} n\sigma_i$. Multiply equation (7) with $1/\overline{k}$, then $e/\overline{k} = \sum_{i=1}^{n} (\alpha_E A/(\rho_i + P)\sigma_i^{\alpha_K})^{\frac{1}{\alpha_K}}$. If there exists a state i for which $\sigma_i < 1/n$, there must be a state $j \neq i$ for which $\sigma_j > 1/n$. Thus, $ne_i/\overline{k} < e/\overline{k}$ and $Pe_i < Pe/n$. Proceed similarly to prove that richer states are net donors, i.e. $Pe_i > Pe/n$.

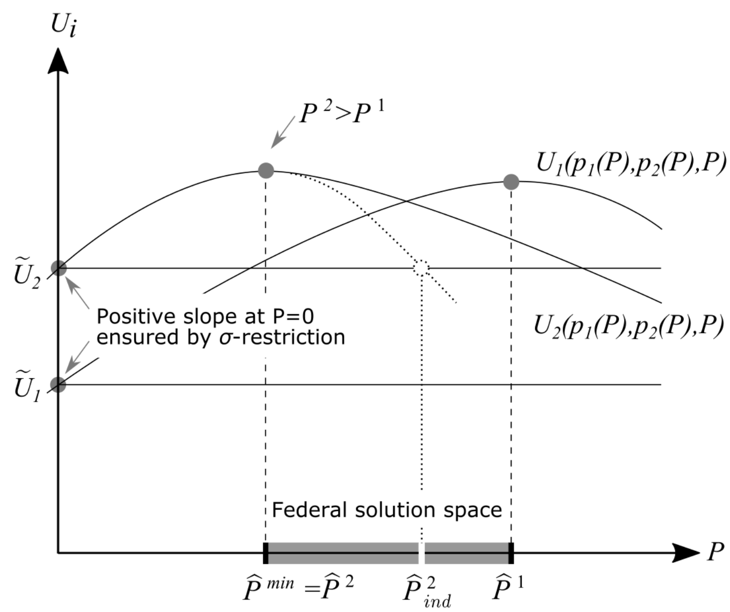

Figure 1: Stylized illustration of the proof structure for $n = 2$ and $\overline{k}_1 < \overline{k}_2$.

net recipients while richer states should become net donors based on efficiency grounds. Our work extends their considerations by accounting for the self-interest of the states.[14]

Our minimum price result allows us to connect to the theory of Olson (1965; 1986). At the minimum price, an existing federal structure can give rise to a benevolent rich state (hegemonic state) as its self-interest prevails. While Olson demonstrates that a benevolent hegemon is willing to create a multinational system, our finding turns his result upside down. We show that an existing multinational (federal) system can create a benevolent hegemonic state.

4.2.1. States' self-interest restriction

Let us discuss the role of sigma for the un-anticipated case. Parameter σ_{EQ} (refer to equation (17)) includes parameter values α_E, γ, and the number of states, n.

[14]When considering differences in preferences, such that $g_i \neq g_j$, we find that the federal government is also able to attain Pareto improvements. For brevity, we have omitted providing this proof, but it is available upon request.

The larger n is, the smaller σ_{EQ} becomes, and the smaller must be the gap among capital endowments. The larger the difference in $(\gamma - \alpha_E)$, the smaller σ_{EQ} becomes. Rearranging $\sigma_i < \sigma_{EQ}$, we get a reflection of state i's self-interest to the federal policy,

$$\underbrace{\overline{k}_i + (\gamma - \alpha_E)\,\overline{k}_i}_{\text{self-interested perspective}} \quad < \quad \underbrace{\overline{k} + (\gamma - \alpha_E)\,\overline{k}_{av}.}_{\text{federal egalitarian perspective}} \tag{19}$$

This inequality generates an institutional tipping point, which determines whether or not the federal policy is effective by guarantying that $U_i > \widetilde{U}_i$. State government i is concerned with its own economy (the left-hand side (LHS) of (19)), but it is willing to be governed by a federal policy if its gains from being part of the federal economy with an egalitarian perspective (the RHS) are higher than the gains from focusing exclusively on its own economy.

We find that state anticipation decreases the gap among capital endowments up to which all states agree to be governed by the federal policy since the σ^*_{EQ} is smaller than σ_{EQ}, see also Figure 2. In Figure 2, we plot all restrictions pertaining to σ for α_E ranging from 0.01 to 0.2, $\gamma = 1$, and $n = 20$ for the different effective transfers we consider. State anticipation, therefore, has a detrimental effect on the federal government's ability to achieve Pareto improvements. The reflection of the states' self-interest in the case of state anticipation is derived by rearranging $\sigma_i < \sigma^*_{EQ}$,

$$\underbrace{\overline{k}_i + (\gamma - \alpha_E)\,\overline{k}_i}_{\text{self-interested perspective}} \quad < \quad \underbrace{\overline{k} + (\gamma - \alpha_E)\,\overline{k}_{av}}_{\text{federal egalitarian perspective}} - \underbrace{(k - k_i)\,/n.}_{\text{status term}} \tag{20}$$

Except for the status term, the self-interest-restriction of equation (20) is similar to equation (19), and we refer the reader also to the previous discussion. As before, the RHS is the pay-off from being part of the federal economy. In contrast to the un-anticipated case, when states anticipate the federal transfer, the pay-off from being part of the federal economy is reduced the more the poorer is the rest of the federal economy.

If each state anticipates the federal transfer, then, the state's policy stringency is lowered (refer to equation (11)). Under the equality criterion, the state policy becomes

$\rho_{i,EQ}$ if state governments do not anticipate the federal transfer, and $\rho^*_{i,EQ}$ if they anticipate it,

$$\rho_{i,EQ} = MRS_{e,c_i}, \quad \text{and} \quad \rho^*_{i,EQ} = MRS_{e,c_i} - 1/nP.$$

Ceteris paribus state anticipation reduces the state policy $\rho^*_{i,EQ}$ in magnitude compared to $\rho_{i,EQ}$ precisely by the per-unit amount of the federal transfer household i receives.

4.3. Decentralized emission share levels (DES)

In this section, we set the transfer equal to the federal emission pricing revenues times the ratio of state i's decentralized emissions to aggregate decentralized emission levels ($\widetilde{e}_i/\widetilde{e}$). We use subscript DES for this criterion such that $s_{i,DES} = \widetilde{e}_i/\widetilde{e}$ and $t_{i,DES} = \widetilde{e}_i/\widetilde{e}Pe$.

As discussed in Section 4.2, firms' total payments for emissions are larger the more capital is available in a state. A federal transfer criterion which rewards initially higher emission levels may be considered more agreeable for richer states when compared to an egalitarian transfer policy. In practice, for instance, the EU's ETS revenue redistribution largely takes into account states' national emissions levels before the EU ETS (EC, 2015, 2013).

Let the utility of each state be equal to equation (16).

Proposition 3 (DES)**.** *Let $\overline{k}_i \neq \overline{k}_{j\neq i}$, $g_i = g$, and $\gamma_i = \gamma \geq 1$ for all i. If i) all capital endowments are not equal; ii) t_i equals $\widetilde{e}_i/\widetilde{e}Pe$; and iii) state governments do not anticipate the federal transfer, then the federal government's policy leads to a Pareto-superior allocation relative to the decentralized solution. A uniform federal minimum price exists and is in the self-interest of all states to pay. The minimum price solves* $\max_P U_n(p, P)$ *where $U_n(p, P)$ is the utility of the richest state.*

Proof. See AppendixD. □

When revenues are redistributed based on the DES criterion and states do not anticipate the transfer, we arrive at similar findings as under the equality criterion except for of one crucial difference: the DES criterion in the *un-anticipated* case is effective independent of the differences in capital endowments. The federal solution space is similar to the one described in Corollary 1.

Note that $s_{i,DES} = \widetilde{e}_i/\widetilde{e}$ reduces to $s_{i,DES} = \sigma_i = \overline{k}_i/\overline{k}$ such that $t_{i,DES} = \sigma_i Pe$. Using equation (11) we obtain

$$\rho_{i,DES} = MRS_{e,c_i}, \quad \text{and} \quad \rho^*_{i,DES} = MRS_{e,c_i} - \sigma_i P$$

where the latter term in $\rho^*_{i,DES}$ hints at a pitfall of the DES criterion subject to states' anticipation. *Ceteris paribus*, the richer a state is relative to other states, the larger the state's policy counter-movement to the federal policy. σ_i becomes a limiting factor for state i's policy stringency as its policy choice could even turn into emission subsidies.

Let

$$\sigma^*_{DES} \equiv (-\alpha_E + \sqrt{\alpha_E^2 + 4\alpha_K\alpha_E})/(2\alpha_K)\,.$$

Proposition 4 (DES*)**.** *Let $g_i = g$, and $\gamma_i = \gamma = 1$ for all i. If i) all capital endowments are not equal; ii) t_i equals $\widetilde{e}_i/\widetilde{e}Pe$; iii) state governments anticipate the federal transfer, and iiii) $\sigma_i < \sigma^*_{DES}$, then the federal government's policy leads to a Pareto-superior allocation relative to the decentralized solution.*

Proof. See AppendixE. □

In the case of states' transfer anticipation, the effectiveness of the DES criterion is more limited than the equality criterion, as also depicted in Figure 2. In contrast to σ^*_{EQ}, σ^*_{DES} is independent of the number of states. For $\gamma = 1$, σ^*_{DES} solely depends on α_E. The larger α_E, the larger σ^*_{DES} becomes. Since the un-anticipated DES transfer case faces no restriction on $sigma$, we plot $\sigma_{DES} = 1$.

4.4. Aggregate emission reduction at the federal minimum price

We now analyze the relative emissions mitigation potential between the equality and DES transfer criteria at the federal minimum price.

Proposition 5 (Aggregate Emissions)**.** *Let $\overline{k}_1 < \ldots < \overline{k}_n$, $g_i = g$ and $\gamma_i = \gamma \geq 1$ for all i. If i) $\sigma_i < \sigma_{EQ}$; ii) the respective federal minimum price is set; iii) state governments do not anticipate the federal transfer; and iv) $\sigma_n > \alpha_E/\gamma$ ($\sigma_n < \alpha_E/\gamma$), then the*

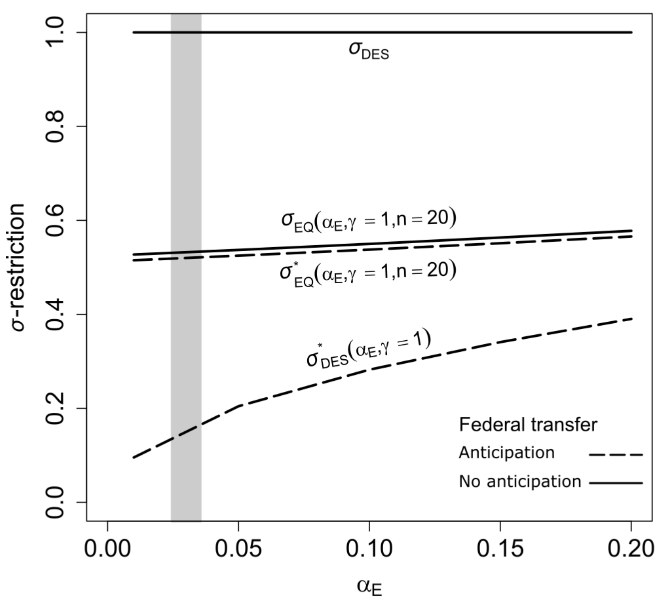

Figure 2: σ-restrictions under the equality (EQ) and DES criteria in case of anticipation (*) and no anticipation. The gray shaded area indicates the range of empirical proxies for α_E based on authors' calculations using BEA (2008) and Destatis (2017) data.

DES criterion (equality criterion) achieves a higher aggregate emission reduction than the equality criterion (DES criterion). Both transfer criteria are equally effective if $\sigma_n = \alpha_E/\gamma$.

Proof. See AppendixF. □

The inequality of Proposition 5 specifies the flipping point at which one transfer criterion becomes superior to the other in terms of aggregate emission reduction. When the DES criterion delivers a higher emission reduction, σ_n faces no upper bound, while the superiority of the equality criterion requires σ_n to be below α_E/γ. This observation connects to Propositions 2 and 3. Proposition 3 shows that the DES criterion imposes no limits on σ_n such that the federal government can attain Pareto-improvements independent of the states' heterogeneity in capital endowments. Proposition 2 shows that the equality criterion has an admissible range of $\sigma_n < \sigma_{EQ}$.

In Section 5 we numerically investigate the sensitivity of α_E and γ.

5. Numerical simulation at the federal minimum price

We compare the effectiveness of the equality and DES criteria at the respective federal minimum price in terms of aggregate emission reduction, relative utility improvement, and consumption changes for rich and for poor states. We draw upon our theoretical results (Proposition 2, 3, 5) and extend the specific case of Proposition 4 when states anticipate the DES transfer.

We estimate a proxy for the share of emissions on output (α_E) in two ways[15]. Our first estimate is the ratio between aggregate expenditure on carbon emission generating raw inputs denoted COG (coal mining and oil and gas extraction), and net value added plus COG as reported in the BEA (2008) 2007 input-output tables for the US. The second estimate is the ratio between aggregate expenditure on emission generating processed inputs denoted PI (petroleum refineries, manufactured petroleum and coal products, petrochemical and gas manufacturing) and net value added plus PI, also from BEA (2008). Both procedures lead to the same estimate of 0.042. Following the same

[15]Since the model assumes perfect competition, α_E represents the share of emissions on output.

procedure but using German data for the year 2013 from Destatis (2017) leads to an estimate of 0.027 for the former and 0.02 for the latter. Since carbon emission pricing was either not existing or was very low in the data considered, our numerical simulations consider values for α_E going from 0.01 to 0.2.

Estimates for emission externalities related to climate change are a subject of ongoing research. The dis-utility from emissions widely remains a theoretical concept (Hsiang, 2017; Diaz and Moore, 2017). In theoretical models, climate change damages were often assumed to be linear or quadratic (e.g. Dietz and Stern, 2015; Buchholz et al., 2013), largely for reasons of analytical tractability. Recent studies, however, come up with regional estimates, for instance Hsiang et al. (2017) finds the value of damages in the US to be quadratically increasing in global mean temperature. Therefore, we report the sensitivity for γ ranging from 1 to 3.

We set $g_i = g_j = 2$, $A = 1$ and take the utility function from equation (16) to ensure the tractability of our theoretical results. The number of states and their capital endowments are chosen so that the ratios $\overline{k}_i/\overline{k}$ satisfy equation (17). We consider 20 states grouped into poor (p), average (a) and rich (r) states. We set $\overline{k}_p = 4$, $\overline{k}_a = 5$, and $\overline{k}_r = 9$ denoting the capital endowment of a poor, average or rich state, respectively.

In the top-part of Figure 3 we plot the ratio of aggregate emissions under the equality and DES criterion for either different values of α_E with a fixed $\gamma = 1.2$ and different values of γ with a fixed $\alpha_E = 0.1$. In line with our analytical result from Proposition 5, the solid line indicates that the equality and DES criterion perform equally well in terms of aggregate emission reduction when $\sigma_r = \alpha_E/\gamma$ implying that the flipping occurs at $\alpha_E = 0.108$. The DES criterion is superior, in terms of emissions mitigation, to the equality criterion for α_E-values below the flipping point and inferior above the flipping point. The dashed line depicts the case in which states anticipate the federal transfer. It shows similar results except for a slight deviation to a lower value of α_E for the flipping point. Comparing the α_E- and γ-variation, Figure 3's upper part shows that for large α_E the equality criterion is better than the DES criterion for aggregate emission reduction, while the DES criterion achieves a higher emission reduction for larger γ.

Note that all states are made better off in our numerical simulation since the federal policy is effective. In the middle part of Figure 3, we plot the ratio of the utility levels of the equality criterion and DES criterion for the households of poor and rich states. As also discussed in Section 4.2, we see here that the equality criterion always leads to higher utility for poor states than the DES criterion, while the opposite is true for rich states. States' anticipation does not change but slightly amplifies the effects of both transfers (dashed line). While the amplification becomes larger the larger α_E is, the amplification is relatively constant with different γ.

Since we find that the difference in consumption decreases is similar with or without state anticipation, we only provide the un-anticipated case at the bottom of Figure 3. It shows that consumption drops under the equality and DES criterion for both the poor and rich states. Compared to the decentralized solution, however, consumption decreases less for the poor states when the equality criterion is used, due to its income redistributive nature. Therefore, the rich states face a relatively higher consumption reduction under the equality criterion. Instead, when the DES criterion is used, the poor and the rich states' consumption is reduced by the same magnitude relative to their decentralized consumption levels. This reflects the DES criterion's property of rewarding emission levels from the decentralized solution, as shown in Section 4.3.

By comparing the α_E and γ-variation for consumption decreases at the bottom part of Figure 3, we can deduce two general mechanisms of the impact of these parameters. First, the larger α_E, the larger is the difference between the decentralized solution ($\widetilde{c_i}$) and the multilevel policy solution ($\widehat{c_i}$). For instance, both levels are almost equal for $\alpha_E = 0.01$, while for $\alpha_E = 0.2$ consumption under the multilevel policy solution is between half to two-thirds of the decentralized consumption levels. Since in the decentralized policy case local production equals local consumption, this result implies that a reduction in state's output is accompanied by a decrease in consumption. The larger α_E, the stronger is the resulting output decrease implied by the state policy. Thus, the more restrained is a state government to reduce local production by regulating emissions as the state policy causes consumption and utility decreases. In the multilevel policy case, however, federal transfers to increase local consumption become possible and can substitute for the state's restraint to local production decreases. This substitution effect explains why a larger α_E leads to larger differences between the decentralized and the multilevel policy consumption levels. Second, refer to equation (12) to confirm that

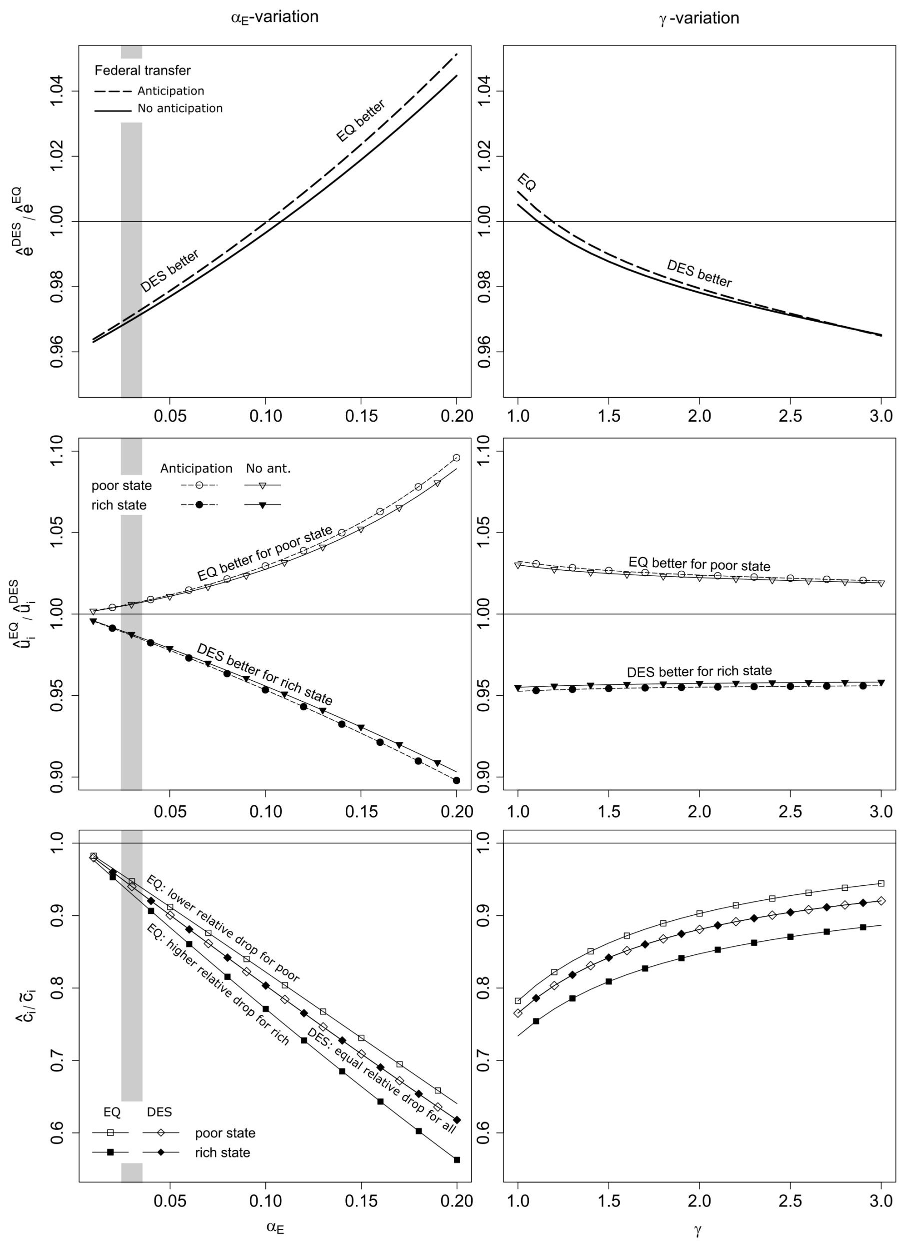

Figure 3: Results for the richest and poorest state at the federal minimum price under equality (EQ) and DES criteria, with 20 member states. The shaded area indicates our empirical proxy for α_E. *Top panels*: Ratio of total emission reduction under EQ and DES. *Middle panels*: Ratio of state i's utility improvements achieved under EQ and DES. *Bottom panels*: Ratio of state's consumption relative to its decentralized consumption level.

a larger γ induces a more stringently decentralized state policy. Therefore, with a larger γ, the consumption deviations of the multilevel policy solution from the decentralized solution are smaller.

6. Concluding remarks

This paper considers multilevel emissions policy, and takes the states' consent to federal policy-making as a means to identify an entry point for transboundary emission mitigation. We consider the federal policy to be effective if it leads to Pareto-improvements relative to the decentralized state policy solution. Our results show that redistributive transfers based on equality and decentralized emission shares (DES) levels criteria can be effective, while the absence of interstate transfers (*juste retour*) makes federal policy ineffective. The federal policy's effectiveness depends on the number of states and their relative wealth levels, a parameter that controls the utility's sensitivity to emissions, and the elasticity of emissions on output. If the federal policy is effective, we find that a range of uniform federal emission prices exists that makes all states better off. The lower bound of the federal price range marks the uniform federal minimum price on emissions.

Our results connect to the minimum price debate, which is a subject of lively discussions in the context of multinational carbon emission trading such as in the European Union Emissions Trading System (EU ETS). The EU ETS debate focused mainly on the minimum price benefit of reducing price uncertainty, e.g. by Abrell and Rausch (2017); Philibert (2009). We show that an appropriate minimum price can ensure states' consent.

Our findings add a new explanation to the existing literature, specifically in terms of decentralized voluntary public good provision (emission mitigation) in a multi-layered system. If federal transfers are chosen wisely, all states can be made better off by the federal policy. Moreover, the richest states become voluntary donors that carry a disproportionately large share of the cost of the federal policy — the richest state carries the largest cost share, corresponding to the definition of a benevolent hegemonic state. Our interpretation turns the theory of Olson (1965) upside down. While Olson demonstrates that a benevolent hegemonic state is often willing to create a multinational system, we demonstrate how a multinational system can create a benevolent hegemonic state. In contrast to common wisdom assuming that multilateralism can work best when a hegemon provides a public good, we emphasize that the hegemon emerges from a federal system and makes multilateralism work.

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References

Jan Abrell and Sebastian Rausch. Combining Price and Quantity Controls under Partitioned Environmental Regulation. *Journal of Public Economics*, 145:226–242, 2017. doi: http://doi.org/10.1016/j.jpubeco.2016.11.018.

BEA. Industry Economic Accounts, The Use of Commodities by Industry after Redefinitions (1987–2006). Bureau of Economic Analysis., 2008.

Theodore Bergstrom, Lawrence Blume, and Hal Varian. On the private provision of public goods. *Journal of Public Economics*, 29:25–49, 1986.

Wolfgang Buchholz, Alexander Haupt, and Wolfgang Peters. International Environmental Agreements, Fiscal Federalism, and Constitutional Design. *Review of International Economics*, 21(4):705–718, 2013.

C2ES. California Cap and Trade. Center for Climate and Energy Solutions. `www.c2es.org/us-states-regions/key-legislation/california-cap-trade`, 2014.

Graciela Chichilnisky and Geoffrey Heal. Who should abate carbon emissions? *Economics Letters*, 44:443–449, 1994. doi: http://doi.org/10.1016/0165-1765(94)90119-8.

Graciela Chichilnisky, Geoffrey Heal, and David Starrett. Equity and Efficiency in Environmental Markets: Global Trade in Carbon Dioxide Emissions. In Graciela Chichilnisky and Geoffrey Heal, editors, *Environmental Markets. Equity and Efficiency*, pages 46–67. Columbia University Press, New York, 2000.

CPL. What Are the Options for Using Carbon Pricing Revenues? Carbon Pricing Leadership. \pubdocs.worldbank.org/en/668851474296920877/CPLC-Use-of-Revenues-Executive-Brief-09-2016.pdf, 2016. Accessed 19-October-2016.

Peter Cramton, Axel Ockenfels, and Steven Stoft. An International Carbon-Price Commitment Promotes Cooperation. *Economics of Energy & Environmental Policy*, 4 (2):51–64, 2015. doi: http://dx.doi.org/10.5547/2160-5890.4.2.aock.

Peter Cramton, David MacKay, Axel Ockenfels, and Steven Stoft, editors. *Global Carbon Pricing. We Will if You Will.* MIT press, Cambridge, Massachusetts, 2017.

Antoine d'Autumne, Katheline Schubert, and Cees A. Withagen. Should the carbon price be the same in all countries? *Jounal of Public Economic Theory*, 18:709–725, 2016. doi: doi:10.1111/jpet.12162.

Destatis. VGR des Bundes - Input-Output-Rechnung - Fachserie 18 Reihe 2 - 2013 (Revision 2014, Stand: August 2016). Federal Statistical Office Germany, 2017.

Delavane Diaz and Frances Moore. Quantifying the economic risks of climate change. *Nature Climate Change*, 7(11):774–782, 2017.

Simon Dietz and Nicolas Stern. Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions. *The Economic Journal*, 125(583):574–620, 2015.

European Commission EC. The EU Emissions Trading System (EU ETS). Factsheet. ec.europa.eu/clima/publications/docs/factsheet_ets_en.pdf, 2013.

European Commission EC. EU ETS Auctioning. \ec.europa.eu/clima/policies/ets/auctioning{_}en, 2015. Accessed 6-April-2017.

George Economides and Natasha Miaouli. Federal transfers, environmental policy and economic growth. *Journal of Macroeconomics*, 28(4):680–699, 2006.

Ottmar Edenhofer, Christina Roolfs, Beatriz Gaitan, Paul Nahmmacher, and Christian Flachsland. Agreeing on an EU ETS price floor to foster solidarity, subsidiarity and efficiency in the EU. In Ian W.H Parry, Karen Pittel, and Herman Vollebergh, editors, *Energy Tax and Regulatory Policy in Europe: Reform Priorities*. MIT press, 2017.

Swiss Federal Office for the Environment FOEN. www.bafu.admin.ch/bafu/en/home/topics/climate.html, 2016. Accessed 6-October-2016.

Carsten Helm. International emissions trading with endogenous allowance choices. *Journal of Public Economics*, 87(12):2737–2747, 2003. doi: http://doi.org/10.1016/S0047-2727(02)00138-X.

Solomon Hsiang. Building a better damage function. www.g-feed.com/2017/06/building-better-damage-function.html, 2017.

Solomon Hsiang, Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, D. J. Rasmussen, Robert Muir-Wood, Paul Wilson, Michael Oppenheimer, Kate Larsen, and Trevor Houser. Estimating economic damage from climate change in the United States. *Science*, 356(6345):1362–1369, 2017.

Mancur Olson. *The Logic of Collective Action: Public Goods and the Theory of Groups*, volume 20 printing, 2002. Harvard University Press, Cambridge, Massachusetts and London, England, 1965.

Mancur Olson. A Theory of the Incentives Facing Political Organizations. Neo-Corporatism and the Hegemonic State. *International Political Science Review*, 7 (2):165–189, 1986. doi: https://doi.org/10.1177/019251218600700205.

Cédric Philibert. Assessing the value of price caps and floors. *Climate Policy*, 9(6): 612–633, 2009. doi: 10.3763/cpol.2008.0586.

Agnar Sandmo. Environmental taxation and revenue for development. In A.B Atkinson, editor, *New Sources of Development Finance*. Oxford University Press, 2004. doi: http://dx.doi.org/10.1093/0199278555.003.0003.

Agnar Sandmo. Global Public Economics: Public Goods and Externalities: mis en ligne le 17 octobre 2007, consulté le 30 septembre 2016. *Economie publique / Public economics [En ligne]*, 18-19, 2007.

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

Leslie Shiell. Equity and efficiency in international markets for pollution permits. *Journal of Environmental Economics and Management*, 46(1):38–51, 2003. doi: http://doi.org/10.1016/S0095-0696(02)00028-1.

Alex Warleigh. *European Union: The basics*. Routledge, London and New York, 2004. ISBN 0415303311. doi: 10.4324/9780203331620.

Roberton 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. doi: http://doi.org/10.1016/j.jpubeco.2011.08.003.

Daniel Wincott. Subsidiarity. www.oxfordreference.com/10.1093/acref/9780199207800.001.0001/acref-9780199207800-e-1342, 2009. ISBN 9780199207800. Accessed 9-December-2016.

Beth V. Yarbrough. Hegemonic stability theory. In R.J.B. Jones, editor, *Routledge Encyclopedia of International Political Economy: Entries G-O*, Routledge Encyclopedia of International Political Economy, pages 664–668. Routledge, 2001. ISBN 9780415243513.

AppendixA. Stackelberg leader's first order conditions

The n first-order conditions for a maximum are given by

$$-\sum_{j=1}^{n} \lambda_j \frac{\partial u_j}{\partial e} \frac{dE}{dP} = \sum_{j=1}^{n} \lambda_j \frac{\partial u_j}{\partial c_j} \left(\frac{dM_j^d}{dP} + \frac{dT_j}{dP} \right) \tag{A.1}$$

with $\lambda_i = 1$ and $\partial M_j^d / \partial \rho_j < 0$, $\partial M_j^d / \partial P < 0$ and

$$\lambda_j (U_j (p, P) - \widetilde{U}_j) = 0 \quad \text{for all } j \neq i \text{ .}$$

Equation $(A.1)$ indicates that the federal government considers the direct impacts of P on $u_i (c_i, e)$, as well as indirect impacts by considering the impact of P on states' prices $p_h (P)$ (for $h = 1, ..., n$). The first-order conditions also indicate that either the federal government takes into account how aggregate emissions impact all households' utilities and how consumption in each state i influences state i's utility, or the federal government does this only for some households $j \neq q$ while ensuring that the other households' utilities are greater than the decentralized solution, $U^q (p, P) > \widetilde{U}^q$, in such case $\lambda_q = 0$.

AppendixB. Proof of Proposition 2. The un-anticipated case

Let $s_{EQ} = 1/n$, $g_i = g > 0$, $\gamma_i = \gamma \geq 1$, and $\partial T_i / \partial \rho_i = 0$ for all $i = 1, ..., n$. Let l denote the subset of states with capital endowments that are less than or equal to the average capital endowment so that $l = \{i \in \{1, ..., n\} \mid \sigma_i \leq \sigma_{av}\}$. Note that the average capital endowment equals $k_{av} = \overline{k}/n$, implying that $k_{av}/\overline{k} = 1/n$. Since $\sigma_i = \overline{k}_i/\overline{k}$, then the $sigma$ of a state with an average capital endowment is $\sigma_{av} = 1/n$. Also let h denote the set of states with capital endowments larger than the average capital endowment $h = \{i \in \{1, ..., n\} \mid \sigma_i > \sigma_{av}\}$. Suppose, without loss of generality, that $\overline{k}_1 < \overline{k}_2 < ... < \overline{k}_n$. We substitute these assumptions into equation (11) to obtain

$$\rho_{i,EQ} (P) = g\gamma E (p, P)^{\gamma - 1} \quad \text{for } i = 1, ..., n. \tag{B.1}$$

We replace ρ_i from equation $(B.1)$ into equation (7),

$$E (p, P) = \left(\frac{\alpha_E A \overline{k}^{\alpha_K}}{g\gamma E (p, P)^{\gamma - 1} + P} \right)^{\frac{1}{\alpha_K}} . \tag{B.2}$$

Rearranging equation $(B.2)$, $E(p,P)$ is implicitly defined in terms of P,

$$P = \alpha_E A \left(\frac{\overline{k}}{E(p,P)}\right)^{\alpha_K} - g\gamma E(p,P)^{\gamma-1}. \tag{B.3}$$

Substituting equations $(B.1)$ and $(B.3)$ into (5), (6), and (8), y_i, e_i, c_i are implicitly defined in terms of P as follows

$$Y_i(p,P) = A\left(\frac{E(p,P)}{\overline{k}}\right)^{\alpha_E} \overline{k}_i,$$

$$E_i(p,P) = \sigma_i E(p,P), \tag{B.4}$$

and

$$C_i(p,P) = A\left(\frac{E(p,P)}{\overline{k}}\right)^{\alpha_E} \overline{k}_i + T_i(p,P) - P\sigma_i E(p,P). \tag{B.5}$$

We replace equations $(B.3)$, $(B.4)$, and $(B.5)$ in equation (16)[16] to implicitly express U_i in terms of P,

$$U_i(p,P) = A\left(\frac{E(p,P)}{\overline{k}}\right)^{\alpha_E} \overline{k}_i + (\sigma_{av} - \sigma_i) PE(p,P) - gE(p,P)^{\gamma}.$$

Simplifying yields

$$U_i(p,P) = A(\alpha_K\sigma_i + \sigma_{av}\alpha_E)\overline{k}^{\alpha_K} E(p,P)^{\alpha_E} - ((\sigma_{av} - \sigma_i)\gamma + 1) gE(p,P)^{\gamma}.$$

The federal government chooses P to maximize U_i while, at the same time, ensuring that U_j does not fall below the decentralized level $\widetilde{U}_j$ $\forall j$,

$$\max\left\{U_i(p,P) \middle| U_{j\neq i}(p,P) \geqq \widetilde{U}_{j\neq i} \ \forall\ j\right\}$$

We will now demonstrate that the P that maximizes U_n also implies that $U_j > \widetilde{U}_j$ for all j. If for some P and some i all the utility constraints are not binding (that is,$U_{j\neq i} > \widetilde{U}^{j\neq i}$), then the federal government's first-order conditions equal

$$\frac{dU_i}{dP} = Z_{i,EQ}(p,P)\frac{dE}{dP} = 0, \tag{B.6}$$

[16]Note that p represents the vector of all emission price levels chosen by the state governments. It depends on the federal price P as defined in Section 3.4.

where

$$Z_{i,EQ}(p,P) = \alpha_E A(\chi_i - \theta_i)\left(\frac{\overline{k}}{E(p,P)}\right)^{\alpha_K} - \chi_i g\gamma E(p,P)^{\gamma-1},$$

and

$$\chi_i = (\sigma_{av} - \sigma_i)\gamma + 1 \text{ and } \theta_i = \chi_i - \alpha_K\sigma_i - \sigma_{av}\alpha_E. \tag{B.7}$$

Thus, either $Z_{i,EQ}$ or dE/dP or both must equal zero. Implicit differentiation of equation $(B.2)$ leads to

$$\frac{dE}{dP} = -\frac{E(p,P)}{\alpha_E\alpha_K A\left(\overline{k}/E(p,P)\right)^{\alpha_K} + g\gamma(\gamma-1)E(p,P)^{\gamma-1}}. \tag{B.8}$$

By definition, α_K, α_E, A, and g are positive, $\gamma \geq 1$, and $E(p,P) \geq 0$. We rule out the case of $E(p,P) = 0$, and therefore, the denominator of the RHS is positive. It follows that $dE/dP < 0$. Thus, $Z_{i,EQ}$ must equal zero. Let P^i_{EQ} denote the P that makes $Z_{i,EQ}$ equal to zero, and e^i the related level of E. Then, setting $Z_{i,EQ} = 0$ and solving yields

$$\widehat{e}^i_{EQ} = \left(\frac{\alpha_E A}{g\gamma}\frac{\chi_i - \theta_i}{\chi_i}\overline{k}^{\alpha_K}\right)^{\frac{1}{\gamma-\alpha_E}}. \tag{B.9}$$

We then substitute e^i in equation $(B.3)$. After some manipulations, we obtain

$$P^i_{EQ} = \theta_i\left(\frac{\alpha_E A}{\chi_i}\right)^{\frac{\gamma-1}{\gamma-\alpha_E}}\left(\frac{g\gamma\overline{k}^{\gamma-1}}{\chi_i - \theta_i}\right)^{\frac{\alpha_K}{\gamma-\alpha_E}}. \tag{B.10}$$

As the federal government seeks to determine a uniform P, which ensures Pareto improvements for all states, let us examine which P suffices. Considering states in set l and examining χ_i and θ_i from equation $(B.7)$, we see that

$$\chi_i \geq 1,\ \theta_i > 0 \text{ and } \chi_i - \theta_i > 0 \text{ for all } i \in l.$$

Together with equation $(B.10)$, it follows that $P^i_{EQ} > 0$ for all $i \in l$.

Let us examine the behavior of $U_{i\in l}$ on the interval $[0,\ P^{i\in l}_{EQ})$ by evaluating the slope of $U_{i\in l}$ at the decentralized solution, $P = 0$. We know from equation $(B.8)$ that $dE/dP < 0$. We substitute χ_i, θ_i and $E(p,P)|_{P=0}$ into $Z_{i,EQ}$. After some manipulations, we obtain

$$Z_{i,EQ}(p,P)|_{P=0} = -\theta_i g\gamma E(p,P)^{\gamma-1}\Big|_{P=0}. \tag{B.11}$$

Since all parameters of equation $(B.11)$ are always positive for $i \in l$, we find that $Z_{i,EQ}\big|_{P=0} < 0$. As $dE/dP < 0$, it follows from equation $(B.6)$ that $U_{i\in l}$ has a positive slope at $P = 0$. Consequently, if there is a role for the federal government, then P must be positive, or else a negative P would make states in set l worse off than in the decentralized solution.

Let us examine what $P > 0$ implies for states in set h. To ensure a Pareto improvement, and hence a role for the federal government, for all $i \in h$ the slope of $U_{i\in h}$ must increase at $P = 0$. Let

$$\sigma_i < \frac{1 + \sigma_{av}(\gamma - \alpha_E)}{\alpha_K + \gamma} \text{ for } i = 1, ..., n$$

to imply $\theta_{i\in h} > 0$ and therefore $Z_{i\in h,EQ}\big|_{P=0} < 0$ demonstrating that $dU_{i\in h}/dP|_{P=0} > 0$.

We now prove that U_i decreases at the interval (P^i_{EQ}, ∞). Let $P^b > P^i_{EQ}$ and evaluate the slope of equation $(B.6)$ at P^b. Since we know that $dE/dP < 0$, it suffices to evaluate $Z_{i,EQ}\big|_{P=P^b}$. We take equation $(B.9)$ to see that $\left(e^i\right)^{\gamma-\alpha_E} = \alpha_E A(\chi_i - \theta_i)\overline{k}^{\alpha_K}/(g\gamma\chi_i)$. Since $dE/dP < 0$, then $P^b > P^i_{EQ}$ implies

$$E(p,P)^{\gamma-\alpha_E}|_{P=P^b} < (e^i_{EQ})^{\gamma-\alpha_E} = \frac{\alpha_E A}{g\gamma}\frac{\chi_i - \theta_i}{\chi_i}\overline{k}^{\alpha_K}.$$

Rearranging, we get

$$0 < \left(\alpha_E A(\chi_i - \theta_i)\left(\frac{\overline{k}}{E(p,P)}\right)^{\alpha_K} - \gamma\chi_i g E(p,P)^{\gamma-1}\right)\Bigg|_{P=P^b}. \tag{B.12}$$

The RHS of equation $(B.12)$ is nothing other than $Z_{i,EQ}\big|_{P=P^b}$ and hence $Z_{i,EQ}\big|_{P=P^b} > 0$. This proves that U_i is a concave function with a unique maximum at $P^i_{EQ} > 0$.

We now rank the different P^i_{EQ}s for $i = 1, ..., n$. To do so, we first rank e^i for $i = 1, ...n$. Since the e^is only differ with regard to σ_i, we now take the derivative of e^i_{EQ} from equation $(B.9)$ with respect to σ_i. After several manipulations and the substitution of χ_i from equation $(B.7)$, we obtain

$$\frac{\partial e^i_{EQ}}{\partial \sigma_i} = \frac{\alpha_K + \gamma\sigma_{av}}{\gamma - \alpha_E}\left(\frac{\alpha_E A\overline{k}^{\alpha_K}}{g\gamma}\frac{(\chi_i - \theta_i)^{1-\gamma+\alpha_E}}{\chi_i^{\alpha_K+\gamma}}\right)^{\frac{1}{\gamma-\alpha_E}}.$$

The first term of the RHS is always positive. Since $\theta_i > 0$ and $\chi_i - \theta_i > 0$, it follows that $\chi_i > 0$. Hence $\partial e^i_{EQ}/\partial\sigma_i > 0$ for all i. We can, therefore, conclude that the higher is σ_i, the higher is e^i_{EQ}. From equation $(B.8)$, it follows that the higher e^i_{EQ} is the lower P^i_{EQ} must be. Therefore,

$$P^n_{EQ} < \ldots < P^1_{EQ}.$$

implying $U_j\big|_{P=P^n_{EQ}} > \widetilde{U}_j$ for all j. □

AppendixC. Proof of Proposition 2. The anticipated case *

All else is equal as in $(AppendixB)$, except for the assumption that state governments anticipate the federal transfer. If not mentioned explicitly, the steps are similar to the previous proof such that we only provide the equations without description. To keep the equations clear, we omit the asterisk * as long as we do not provide the closed form solution.

$$p_i(P) = g\gamma E(p,P)^{\gamma-1} - P/n$$

$$E(p,P) = \left(\frac{\alpha_E A \overline{k}^{\alpha_K}}{\left(g\gamma E(p,P)^{\gamma-1} + (n-1)/nP\right)}\right)^{\frac{1}{\alpha_K}}. \tag{C.1}$$

$$U_i(p,P) = A\frac{(\alpha_K n - 1)\sigma_i + \alpha_E}{n-1}\overline{k}^{\alpha_K} E(p,P)^{\alpha_E} + \left(\left(\frac{n\sigma_i - 1}{n-1}\right)\gamma - 1\right) gE(p,P)^{\gamma}.$$

If $U_j > \widetilde{U}_j$ for all $j \neq i$ for some P^* and some i, then, the federal government's first-order condition equals

$$\frac{dU_i}{dP} = Z_{i,EQ}(p,P)\frac{dE}{dP} = 0$$

where

$$Z_{i,EQ}(p,P) = \frac{1}{(n-1)\sigma_{av}}\left(\alpha_E A(\chi_i - \theta_i - \sigma_i\sigma_{av})\left(\frac{\overline{k}}{E(p,P)}\right)^{\alpha_K} + (\sigma_{av} - \chi_i)\, g\gamma E(p,P)^{\gamma-1}\right).$$

Thus, either $Z_{i,EQ}$ or dE/dP or both must equal zero. Implicit differentiation of equation $(C.1)$ leads to

$$\frac{dE}{dP} = (1-n)\sigma_{av}\frac{E(p,P)}{\alpha_E\alpha_K A\left(\overline{k}/E(p,P)\right)^{\alpha_K} + g\gamma(\gamma-1)E(p,P)^{\gamma-1}} < 0.$$

Thus, at the optimum, $Z_{i,EQ}$ must equal zero. Solving $Z_{i,EQ} = 0$ for $E(p,P)$ yields

$$e^{i*} = \left(\frac{\alpha_E A}{g\gamma}\frac{\chi_i - \theta_i - \sigma_i\sigma_{av}}{\chi_i - \sigma_{av}}\overline{k}^{\alpha_K}\right)^{\frac{1}{\gamma-\alpha_E}}. \tag{C.2}$$

Substituting equation $(C.2)$ into equation $(B.3)$ leads to

$$P_{EQ}^{i*} = \frac{1}{(n-1)\,\sigma_{av}}\left(\theta_i + (\sigma_i - 1)\,\sigma_{av}\right)\left(\frac{\alpha_E A}{\chi_i - \sigma_{av}}\right)^{\frac{\gamma-1}{\gamma-\alpha_E}}\left(\frac{g\gamma\overline{k}^{\gamma-1}}{\chi_i - \theta_i - \sigma_i\sigma_{av}}\right)^{\frac{\alpha_K}{\gamma-\alpha_E}}.$$

Evaluating $Z_{i,EQ}^{*}$ at $P = 0$ yields

$$Z_{i,EQ}(p,P)\big|_{P=0} = -\frac{g\gamma}{(n-1)\,\sigma_{av}}\left(\theta_i - (1-\sigma_i)\,\sigma_{av}\right)E(p,P)^{\gamma-1}\Big|_{P=0}.$$

For $i \in l$ we see that $Z_{i,EQ}\big|_{P=0} < 0$. Just as we argued in the previous proof, it must be that $P_{EQ}^{i*} > 0$ for $i \in l$. Let

$$\sigma_i < \sigma_{av}\frac{n - \alpha_E + \gamma - 1}{1 - \alpha_E + \gamma - \sigma_{av}} \text{ for } i = 1, ..., n.$$

then $(1-\sigma_i)/n < \theta_i$ and consequently $Z_{i,EQ}^{*}\big|_{P=0} < 0$ for all i. We take equation $(C.2)$ to see that $\left(\widehat{e}^{i*}\right)^{\gamma-\alpha_E} = \left(\alpha_E A\,(\chi_i - \theta_i - \sigma_i\sigma_{av})\,\overline{k}^{\alpha_K}\right)/(g\gamma\,(\chi_i - \sigma_{av}))$. Since $dE/dP < 0$ and $P^b > \widehat{P}_{EQ}^{i*}$, then

$$\left(E(p,P)\right)^{\gamma-\alpha_E}|_{P^b} < \left(\widehat{e}^{i*}\right)^{\gamma-\alpha_E} = \frac{\alpha_E A}{g\gamma}\frac{\chi_i - \theta_i - \sigma_i\sigma_{av}}{\chi_i - \sigma_{av}}\overline{k}^{\alpha_K}.$$

Rearranging, we get

$$0 < \left(\alpha_E A\,(\chi_i - \theta_i - \sigma_i\sigma_{av})\left(\frac{\overline{k}}{E(p,P)}\right)^{\alpha_K} - g\gamma\,(\chi_i - \sigma_{av})\,E(p,P)^{\gamma-1}\right)\Bigg|_{P^b}. \quad \text{(C.3)}$$

The RHS of equation $(C.3)$ is nothing other than $(n-1)\,\sigma_{av}Z_{i,EQ}\big|_{P^b}$, and hence $Z_{i,EQ}\big|_{P^b} > 0$. Therefore, it follows that U_i is a concave function with a unique maximum at $P_{EQ}^{i*} > 0$. The P_{EQ}^{i*}s can be ranked by considering

$$\frac{\partial e^{i*}}{\partial\sigma_i} = (n-1)\,\sigma_{av}\frac{\alpha_K + (\gamma-1)\,\sigma_{av}}{\gamma - \alpha_E}\left(\frac{\alpha_E A}{g\gamma}\frac{(\chi_i - \theta_i - \sigma_i\sigma_{av})^{1-\gamma+\alpha_E}}{(\chi_i - \sigma_{av})^{\alpha_K+\gamma}}\overline{k}^{\alpha_K}\right)^{\frac{1}{\gamma-\alpha_E}}.$$

Just as in the previous proof $P^{n*} < ... < P^{1*}$ follows. □

AppendixD. Proof of Proposition 3

All else is equal as in AppendixB, except that the federal transfer $T_i(p, P)$ equals $s_{i,DES} PE(p, P) = \sigma_i PE(p, P)$. If not explicitly mentioned, the steps are similar to the previous proofs such that we only provide the equations without description. We substitute the assumptions into equation (11) to obtain

$$p_i(P) = g\gamma E(p, P)^{\gamma-1} \text{ for all } i = 1, ..., n,$$

$$E(p, P) = \left(\frac{\alpha_E A\overline{k}^{\alpha_K}}{g\gamma E(p, P)^{\gamma-1} + P}\right)^{\frac{1}{\alpha_K}}, \tag{D.1}$$

and

$$U_i(p, P) = A\sigma_i\overline{k}^{\alpha_K} E(p, P)^{\alpha_E} - gE(p, P)^{\gamma}.$$

If $U_j > \widetilde{U}_j$ (for all $j \neq i$) for some P and some i, then the federal government's first-order condition equals

$$\frac{dU_i}{dP} = \left[\alpha_E A\sigma_i \left(\frac{\overline{k}}{E(p, P)}\right)^{\alpha_K} - g\gamma E(p, P)^{\gamma-1}\right] \frac{\partial E}{\partial P} = 0. \tag{D.2}$$

Thus, either the term in parenthesis or dE/dP or both equal zero. Implicit differentiation of equation $(D.1)$ leads to

$$\frac{dE}{dP} = -\frac{E(p, P)}{\alpha_E\alpha_K A\left(\frac{\overline{k}}{E(p,P)}\right)^{\alpha_K} + g\gamma(\gamma-1) E(p, P)^{\gamma-1}} < 0.$$

We solve the term in parentheses of equation $(D.2)$ to obtain

$$e^i_{DES} = \left(\frac{\alpha_E A\sigma_i}{g\gamma}\overline{k}^{\alpha_K}\right)^{\frac{1}{\gamma-\alpha_E}}. \tag{D.3}$$

By substituting equation $(D.1)$ into $(B.3)$, we get

$$P^i_{DES} = (1-\sigma_i)\left(\left(\alpha_E A\overline{k}^{\alpha_K}\right)^{\gamma-1}\left(\frac{g\gamma}{\sigma_i}\right)^{\alpha_K}\right)^{\frac{1}{\gamma-\alpha_E}}. \tag{D.4}$$

Note that all terms in equation $(D.4)$ are positive. Thus, the federal price is always positive.

Consider the interval $P \in [0, \widehat{P}^i_{DES})$. Since $dE/dP < 0$, we take the term in parentheses of equation (D.2) and substitute $\widetilde{e}$ to see

$$(\sigma_i - 1)(g\gamma)^{\frac{\alpha_K}{\gamma-\alpha_E}}\left(\alpha_E A\overline{k}^{\alpha_K}\right)^{\frac{\gamma-1}{\gamma-\alpha_E}} < 0.$$

Thus, $dU_i/dP|_{P=0} > 0$. We use equation (D.3) to see that $\left(e^i\right)^{\gamma-\alpha_E} = \alpha_E A\sigma_i\overline{k}^{\alpha_K}/(g\gamma)$. Since $dE/dP < 0$, note that $E^{\gamma-\alpha_E}|_{P=P^b} < \left(e^i\right)^{\gamma-\alpha_E}$ for $P^b > P^i_{DES}$, and thus $E^{\gamma-\alpha_E}|_{P=P^b} < \left(e^i\right)^{\gamma-\alpha_E} = \alpha_E A\sigma_i\overline{k}^{\alpha_K}/(g\gamma)$. Rearranging, we get

$$0 < \left.\left(\alpha_E A\sigma_i\left(\frac{\overline{k}}{E(p,P)}\right)^{\alpha_K} - g\gamma E(p,P)^{\gamma-1}\right)\right|_{P=P^b} \tag{D.5}$$

The RHS of equation (D.5) is nothing other than the term in square brackets of equation (D.2), implying $dU_i/dP < 0$ at the interval (P^i_{DES}, ∞). Hence $U_i(p,P)$ is a concave function with a unique maximum at $P^i_{DES} > 0$. Consider $\partial e^i_{DES}/\partial\sigma_i$ to see that federal prices rank as $P^n < \ldots < P^1$. □

AppendixE. Proof of Proposition 4

All else is equal as in AppendixD, except for the assumption that each state government takes into account how its policy influences the federal policy ($\partial T_i/\partial\rho_i \neq 0$) and $\gamma = 1$. We get

$$p_i(P) = g - \sigma_i P,$$

$$E_i(p,P) = \left(\frac{\alpha_E A\overline{k}_i^{\alpha_K}}{g + (1-\sigma_i)P}\right)^{\frac{1}{\alpha_K}},$$

$$E(p,P) = \sum_i\left(\frac{\alpha_E A\overline{k}_i^{\alpha_K}}{g + (1-\sigma_i)P}\right)^{\frac{1}{\alpha_K}},$$

and

$$U_i(p,P) = \frac{g + (\alpha_K - \sigma_i)P}{\alpha_E}E_i(p,P) + (\sigma_i P - g)E(p,P).$$

The derivative of U_i with regard to P is

$$\begin{aligned}\frac{dU_i}{dP} = \quad & \frac{(\alpha_K - \sigma_i)E_i(p,P)}{\alpha_E} - \frac{g + (\alpha_K - \sigma_i)P}{(g + (1-\sigma_i)P)^{\frac{1+\alpha_K}{\alpha_K}}}\left(\alpha_E^{\alpha_E}A\right)^{\frac{1}{\alpha_K}}\frac{k_i}{\alpha_K}\\ & + \sigma_i E + (\sigma_i P - g)\frac{dE}{dP}\end{aligned}$$

Evaluate dU_i/dP at $P = 0$ by substituting $\widetilde{e_i}$ and $\widetilde{e}$ to get

$$\left.\frac{dU_i}{dP}\right|_{P=0} = \left(\frac{\alpha_E A}{g}\right)^{\frac{1}{\alpha_K}} \left(\left(\alpha_K - \sigma_i - \frac{1}{\alpha_K}\right)\frac{\overline{k}_i}{\alpha_E} + \frac{1+\alpha_K\sigma_i}{\alpha_K}\overline{k}\right). \tag{E.1}$$

Rearranging equation $(E.1)$ and imposing a positive slope, we obtain

$$\sigma_i < (-\alpha_E + \sqrt{\alpha_E^2 + 4\alpha_K\alpha_E})/(2\alpha_K) = \sigma^*_{DES} \tag{E.2}$$

The σ-restriction σ^*_{DES} ensures that $(E.2)$ holds and hence $U_i > \widetilde{U}_i$. □

AppendixF. Proof of Proposition 5

Suppose $\alpha_E/\gamma < \sigma_n$. Then, $0 < \gamma\sigma_n - \alpha_E$. Since $0 < \sigma_n - \sigma_{av}$ we get

$$0 < (\sigma_{av} - \sigma_n)(\gamma\sigma_n - \alpha_E).$$

Using equations $(B.9)$ and $(D.3)$ evaluated at the respective federal minimum price and after some algebraic manipulations, we arrive at $e_{DES}|_{P=P^{\min}} < e_{EQ}\big|_{P=P^{\min}}$. In a similar procedure, we prove that $\alpha_E/\gamma > \sigma_n$ implies $e_{DES}|_{P=P^{\min}} > e_{EQ}\big|_{P=P^{\min}}$, and $\alpha_E/\gamma = \sigma_n$ implies $e_{DES}|_{P=P^{\min}} = e_{EQ}\big|_{P=P^{\min}}$. □