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Make or brake — Rich states in voluntary federal emission pricing[☆☆☆]

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Abstract

Voluntary participation can improve multilateral environmental governance. We model voluntary participation of states in unanimously approved federal environmental policy. A Pareto-improving federal emission price coexists with state-level emission pricing. Federal revenues are distributed equally per capita (egalitarian), in proportion to states' historical emission levels (sovereignty), or states' actual payments (juste retour). We find that the existence of Pareto-improving uniform federal prices depends on wealth differences, transfer rules, and on whether or not states anticipate transfers. Sovereignty transfers work in all cases. Differences in wealth can undermine egalitarian transfers. Juste retour transfers render federal policy ineffective if states anticipate them. The richest state prefers the lowest Pareto-optimal federal price ("minimum price") as it becomes the largest net-donor. Adding different population sizes, the richest and largest (smallest) state prefers the minimum price with sovereignty and juste retour transfers (egalitarian transfers). Therefore, rich states brake and simultaneously make possible passing unanimous federal policy.

JEL-classification: H77, Q58, H23, D62, H87

Keywords: Environmental Regulation, Fiscal Federalism, Pollution Taxes, Transfer Design, Voluntary participation, Pareto-improvements, Minimum price

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1. Introduction

Environmental pollution, pandemics, and climate change are prime examples of threats to the international community. Much scholarship in economics suggests that rich people and countries voluntarily contribute more to mitigating such threats than their poor counterparts (Olson and Zeckhauser, 1966; Bergstrom et al., 1986). From the optimality conditions of welfare maximization, it also follows that rich entities should contribute more than poor ones. When using a uniform multinational price signal, for instance, allocative efficiency alone demands higher transfers from rich to poor entities (e.g. Sheeran, 2006; Chichilnisky and Heal, 1994; Sandmo, 2007; Engström and Gars, 2015)[1]. But the necessary multinational transfers from the rich may exceed their voluntary contributions (e.g. Stavins, 1997; Shiell, 2003; Sandmo, 2007) and coexisting local policies can jeopardize the efficiency of the multinational policy (cf. Williams, 2012; Burtraw et al., 2018).

In practice, federations have a multinational (federal) government and a multi-layered environmental policy of federal and state authorities. If a federal policy represents a Pareto-improvement for its members, it can find broad acceptance among the states. The European Union (EU) is a case in point. Broad state support is crucial for EU legislation since EU policies often require unanimity to get passed. This creates difficulties because states are heterogeneous. For instance, states can differ in size and wealth. A pertinent question becomes: How does the heterogeneity of member states affect their willingness to federalize part of their environmental policies?

In this article, we investigate how federalism can help collective voluntary emission reduction of heterogeneous member states. We study the role of a federal authority that uses transfers and a uniform federal emission price to coordinate the states' emission mitigation efforts. It strives simultaneously to reduce emissions for the entire federation and to ensure voluntary participation of the states. States differ in wealth and population size and set local policies that coexist with federal policy. Improving the understanding of the obstacles and requirements for the voluntary participation of states in federal environmental policy helps with i) assessing the impact of the coexisting policies at the state and federal levels and ii) guiding burden-sharing design in federal systems, which then, in turn, allows for the identification of iii) a basis for broad

[1]Changes in land use - e.g., conversion of natural habitats to agricultural or urban ecosystems - influence the risk and incidence of zoonotic diseases in humans. Therefore, reducing the loss of natural habitats can reduce the likelihood of future epidemic and pandemic outbreaks (cf. Gibb et al., 2020; Tollefson, 2020; Olivero et al., 2017). Pigouvian pricing can, at least theoretically, reduce land use, land conversion, or deforestation rates, thereby lowering the risk of pandemic outbreaks.

consensus towards federal policy design.

Our main contribution is to show under which conditions unanimity ensuring, uniform federal emission prices exist. Specifically, we find that the richest state takes on the role of the largest donor, and its utility is maximized at the lowest of all optimal federal prices that ensure voluntary participation. This price designates the unanimity ensuring federal minimum price.

Surprisingly, the conditions for voluntary participation of states in federal environmental policy have not yet been investigated. Contributions on the voluntary provision of public goods, multinational environmental policy, and fiscal federalism, however, have already analysed individual aspects of the above research question and serve as the point of departure for the present study. The Cold War and the founding of NATO initially stimulated the research on voluntary, decentralized public good provision. This strand of literature finds that rich entities voluntarily bear a larger share of the burden of global public good provision (Olson, 1965; Olson and Zeckhauser, 1966; Bergstrom et al., 1986). Second, spurred by the necessity for mitigating climate change and the design of the Kyoto Protocol, literature emerged on centralized multinational environmental policy, finding that rich entities should bear the larger share of the burden even for reasons of allocative efficiency alone (e.g. Chichilnisky and Heal, 1994). Third, the literature on fiscal federalism considers the decentralized and centralized institutional perspectives at the same time. Böhringer et al. (2016) study tax base rivalry between states and the federal government in the context of carbon pricing. They find that a state can implement local carbon pricing largely at the expense of other states. If state and federal policies coexist, Williams (2012) finds that a federal emission tax can be superior to emission quantity controls since the additivity of the taxes prevents a mutual overruling of state and federal environmental policies. Since the second-generation theory of fiscal federalism is concerned with the viability and limited power of federal institutions (Oates, 2005), the present study contributes to this research strand in particular. We provide a detailed literature review in Section 2.

We develop a general equilibrium model with coexisting state-level and federal emission pricing. All governments use emission pricing to reduce the damage caused by transboundary emissions. Emissions are an essential input for private good production.[2] The analytical part of our study focuses on state differences in terms of different capital endowments, and we often keep population size equal across states. The numerical

[2]We assume emissions to be essential, as we are interested in finding entry points for more stringent climate policies. To date, economies are not sufficiently decarbonized (cf. Climate Action Tracker, 2020).

part more thoroughly investigates population size differences. Each state government non-cooperatively chooses a domestic emission price to maximize domestic welfare and distributes revenue from the policy equally among its consumers. Since both state- and federal-level emission policies coexist, the policy at one level affects the revenues at the other. This is known as a vertical fiscal externality (cf. Dahlby and Wilson, 2003). We explore both state behavior that internalizes the vertical fiscal externality and such behavior that is ignorant of it. In the following, we refer to these cases as "anticipation" and "no anticipation", respectively.[3] The federal government cares for the welfare of the entire federation. It has a strategic advantage over state governments such that it can influence state policy choices through its own policy choice (Stackelberg leader) (cf. Wilson, 2006). Given a revenue transfer rule and using a uniform emission price, the federal government maximizes the welfare of one state while ensuring that no other state falls below its decentralized outcome (Pareto-improvement).[4] We compare three federal transfer rules: 1) equal per capita transfers (egalitarian), 2) transfers proportional to a states' historical emission levels (sovereignty), and 3) transfers proportional to actual emission payments (juste retour). All of these rules are well-established in policy practice and theory (cf. Section 2).

We find that, under specific conditions, there exists a range of Pareto-improving, uniform federal emission prices. The conditions involve the transfer rule, the presence of federal transfer anticipation, as well as the differences in endowments across states. In the following, we denote by "feasible federal emission prices" those uniform federal emission prices that ensure Pareto-improvements (i.e., unanimity) in the federation and that cannot be Pareto-dominated. If feasible federal emission prices exist, we find that poor states benefit from federal emission pricing in terms of welfare by definition, but the more stringent the federal price, the more they benefit. Also by definition, rich states always gain in welfare in the range of feasible federal emission prices. The more stringent the federal price, however, the more they net-contribute to poor states. This

[3] For a practical example of unanticipated federal transfers, consider the German government's misgivings regarding the governance level at which the energy tax should be increased. An increase in the EU energy tax raises national concerns about losing tax revenues. In response, Germany could preemptively increase its national energy tax to ensure that the German tax base's revenue stays in Germany. The reason for such a preemptive measure could be that Germany does not anticipate benefits from EU energy tax revenues. The opposite would be true if Germany anticipates that it would benefit from EU energy taxation. In this case, Germany may even reduce its domestic tax to enable the EU to draw larger revenues from the German energy tax base. The latter example corresponds to the case of anticipated federal transfers.

[4] The uniform emission price instrument is comparable to the *"uniformity assumption"* of Oates (1972) often considered in the fiscal federalism literature. The *Pareto criterion* resembles the welfare economic counterpart of unanimity (Buchanan, [1967] 1999).

observation is reflected in the ranking of the feasible federal emission prices: The lowest feasible price (federal minimum price) prioritizes the interests of the richest state, while the poorest state gains the most at the highest feasible price.

There are two possibilities to interpret the existence and ranking of feasible federal prices concerning federal policy negotiations. The first interpretation resembles what we consider the conservative and currently more realistic case for climate policy. Suppose that net-donors' voluntary participation is a requirement for successful federal policy negotiations. Further, suppose that the negotiations start at a federal emission price of zero and incrementally bid until a state vetoes a further price increase. In that case, our results suggest that the richest state, in its position as the largest donor, would want to settle at the federal minimum price. In that sense, the richest state puts brakes on the negotiation process as it represents a bottleneck for further increases of the uniform emission price above the minimum price.[5] At the same time, by virtue of its role as the largest donor, the richest state makes federal policy feasible in the first place. The second interpretation of how the feasible price range can relate to the negotiation process is in terms of the ultimate federal price that is acceptable to all states. Suppose negotiations do not end after the first veto, but at the agreeable ultimate price [6]. Our results suggest that all states, including the richest, would accept an ultimate federal price of either zero or the maximum price.[7]

Regarding the federal transfer rules, we find that the sovereignty rule is the only rule that always yields feasible federal prices regardless of the capital heterogeneities present. Juste retour transfers perform identically to sovereignty transfers if they are unanticipated by the states. Similar to d'Autumne et al. (2016) and Shiell (2003), whose models do not cover anticipation, we also find that juste retour transfers are effective when they are not anticipated. If the states, however, anticipate the federal juste retour transfers, this rule becomes ineffective, as it always reproduces the outcomes of the situation without federal policy. Finally, if capital heterogeneity is too pronounced, egalitarian transfers fail to produce any feasible federal emission prices. Our numerical analysis distinguishes rich and poor states (in terms of capital per capita) as well as large and small states (in terms of population size). Both rich (poor) states have the same capital per capita level. Likewise, both small (large) states have the same

[5] In reverse, if negotiations started at a very high price and were bid down until unanimity was reached but the first states vetoed, then the poorest state will put brakes in the price downward spiral at the maximum federal price.

[6] Ultimate in the sense of whether the negotiations are a bidding up or bidding down of the federal price.

[7] We thank an anonymous referee for pointing out this interpretation.

population level. Thus, the numerical analysis comprises four states with four different aggregate capital levels: rich and small, rich and large, poor and small, poor and large. If egalitarian transfers are used, we find that the minimum feasible federal emission price corresponds to the richest state with a smallest population size. If, on the other hand, sovereignty transfers or unanticipated juste retour transfers are used, this role is taken on by the richest state with the largest population size (being the richest in aggregate capital endowments).

Further research should also examine the heterogeneity of states in terms of production technologies. For example, Poland, as a relatively poor but large country, has many coal-fired power plants. On the other hand, Denmark is a relatively small country that is wealthy and has many wind-farms. Roolfs et al. (2020) have analyzed heterogeneity in production technologies using a numerical model calibrated to the EU. They find that technological heterogeneity can change the results in terms of the ranking of feasible federal prices towards emission intensive states.

The rest of the paper is structured as follows. Section 2 reviews the related literature and links the considered transfer rules to commonly used equity criteria. Section 3 presents and discusses the multilevel general equilibrium model. The impact of different transfer criteria is analyzed in Section 4, divided into an analytical and a numerical part. We conclude in Section 5.

2. Literature review

This study contributes to the multinational environmental policy and environmental fiscal federalism literature. We adopt the multilevel governance structure of environmental fiscal federalism to reflect the decision processes of federations such as the European Union, Canada, Switzerland, Germany and the United States. We draw on the literature on voluntary public good provision to represent sovereign, self-interested decision making of member states in a federation. Since a voluntary multilateral environmental policy may only be feasible if it is regarded as fair by the participants, we draw on the literature on equity and burden-sharing.

A large part of the literature on *multinational environmental policy* does not consider unanimous decision making. This literature focuses instead on the efficiency and equity of uniform multinational environmental policy in first- or second-best settings. These studies investigate top-down regulation from the perspectives of a social planner and/or centralized policy (Chichilnisky and Heal, 1994; Chichilnisky et al., 2000; Shiell, 2003; Sandmo, 2007), or a top-level government with delegation authority over all lower levels of government (e.g. d'Autumne et al., 2016). Chichilnisky and Heal were the first to show that for a global public good, like carbon emission mitigation, equity and efficiency cannot be considered separately. In their seminal 1994 paper, they highlight that in poor states a high marginal utility of consumption hinders mitigation efforts. The opposite holds for rich states. This results in the need to harmonize the marginal utility of consumption across states. When focusing on a uniform multinational price to mitigate emissions, their central finding is that transfers from rich states to poor states are necessary to achieve efficiency. Engström and Gars (2015) provide a recent overview of this literature strand. These theoretical optimal transfers, however, can be very large and encounter the resistance of states or countries following their self-interest (cf. Stavins, 1997; Gruber, 2000; Sandmo, 2004, 2007; Wiener, 2007; Edenhofer et al., 2017). The regulatory top-down view is complemented by the bottom-up perspective on multinational transfers found in the literature on international environmental agreements (cf. Barrett, 2005).

The contrast between central and decentralized regulation is a key topic in the research agenda of *fiscal federalism*. Indeed, within the context of local public goods provision, the first generation of the literature on fiscal federalism focuses on determining which regulatory tasks to centralize and which tasks to leave to decentralized policy-making. Drawing mainly on efficiency and equity arguments, similarly to the multinational environmental policy literature, this literature finds that the main responsibility for federal public good provision should be left to the federal government (e.g. Musgrave, 1959; Oates, 1972, 2000). See also Oates (2005) for an overview of the literature. Early studies on fiscal federalism assume that the federal government plays a passive role, e.g. by containing horizontal fiscal externalities resulting from tax competition between states. In this context, the phenomenon of a "race to the bottom" is often discussed, a phenomenon in which states undercut each other by tax reductions when competing over mobile factors in the attempt to get a locally larger tax base. If, however, states and the federal level compete for the same tax base, vertical fiscal externalities can become as central to the analysis of federal systems as horizontal externalities (cf. Wilson, 2006; Keen, 1998). Absent of environmental regulation vertical fiscal externalities have extensively been studied in the work of Keen and Kotsogiannis (2002); Keen (1998); Bruellhart and Jametti (2006); Dahlby and Wilson (2003); Böhringer et al. (2016) and can induce state governments to overtax the local tax base (cf. Keen and Kotsogiannis, 2002). Böhringer et al. (2016) were the first to assess the importance of vertical fiscal externalities in the context of environmental regulation. For the case of the Canadian Federation, they find that due to vertical fiscal externalities, a state can implement environmental policy at low cost to itself and at the expense of other states. A literature review on fiscal federalism, and the research on decentralization of environmental policies is provided by Dalmazzone (2006).

The *second generation of fiscal federalism* is concerned with the viability of federal institutions (Oates, 2005). A key concern of these studies is that a federal government can only have limited control or competence over the political actions of its states. The EU, for example, is severely limited when it comes to EU-wide tax reforms, since they require the unanimous consent of the member states (Talus, 2013). Few studies exist that deal with limited environmental control in federal systems. Williams (2012) considers limited control by examining the coexistence of state and federal emissions policies. He finds a federal tax to be more efficient than quantity controls since the additivity of taxes prevents a mutual overruling of state and federal policies.

The literature on *voluntary provision of public goods* shifts the focus away from efficiency concerns. Instead, it investigates voluntary contributions to a public good in a decentralized setting. It was pioneered in the works of Olson (1965) and Olson and Zeckhauser (1966) and formalized in the model by Bergstrom et al. (1986). In this context, voluntary participation can be seen as another constraint that multinational policy needs to work with. Olson and Zeckhauser (1966) show that the USA, as the wealthiest NATO member, contributed the most to NATO's expenditures in the arms race with the Warsaw Pact. Similarly, Olson (1986) discusses how benevolent, yet 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 public good expenses. It does so voluntarily, as long as its own benefit from the public good outweighs the cost of providing it. The redistribution of wealth can, however, have a negative impact on the level of voluntary public good provision, as Bergstrom et al. (1986) show. This result also has its origin in the decreasing marginal utility of consumption causing the richest entities to be most willing to contribute to the public good. Via this simple mechanism, wealth redistribution results in lower overall public good contributions, as entities that are not consumption-saturated would rather use their income for consumption than public good contributions. One possible interpretation of these results may be to to oppose the redistribution of wealth. Such an analysis clearly neglects the potential positive welfare implications of decreasing the inequality across entities, as demonstrated by Chichilnisky and Heal (1994) and others. Our setting takes both considerations into account, as changes in inequality are limited by the requirement of a Pareto-improving federal policy. The present study combines the concept of voluntary contributions with the fiscal federalism literature. While the first does not consider multilevel policies, the latter traditionally does not consider the voluntary contributions of states.

Multilateral environmental policy that is considered equitable opens the space for voluntary participation. A broad spectrum of *equity criteria* is developed and discussed in the equity literature (e.g. Rawls, 1971; Burtraw and Toman, 1992; Grubb et al., 1992; Rose, 1992; Rose and Stevens, 1993; Rose et al., 1998; Cazorla and Toman, 2001; Ringius et al., 2002; Kverndokk and Rose, 2008; Pottier et al., 2017; Kverndokk, 2018). Voluntary participation in multinational policy is considered one such equity criterion. In this literature it is referred to as the "compensation" or "Pareto" criterion (e.g. Kverndokk and Rose, 2008; Cazorla and Toman, 2001). Similarly to the present paper, this criterion refers to the multinational (federal) objective of improving the welfare of all consumers in relation to the decentralized policy outcome. There is, however, no consensus on the "best" equity criterion (cf. Kverndokk, 2018). Recent surveys of this literature can be found in Kverndokk (2018); Pottier et al. (2017); Kverndokk and Rose (2008); Paterson (2001).

In this study, we consider three different criteria for federal transfer rules that are both well established in the equity literature and applied in federal policy in practice. These are the egalitarian, sovereignty and juste retour criteria. Transfers based on the egalitarian criterion presume an equal ownership of a common resource (e.g. atmosphere) implying that everyone should get an equal share of its revenues. Posner and Sunstein (2008) argue that many people find the per capita approach attractive because of its simplicity and appeal to fairness (see supporters also in Grubb et al., 1992; Klenert et al., 2018). In the federal context it is applied, for instance, by the Swiss Federal government which equally distributes part of the revenues from the Swiss CO_2 levy back to all Swiss residents (FOEN, 2016). The (ex-ante) sovereignty criterion assumes that past emissions give a right to future emissions (e.g. Böhringer et al., 2015; Grubb et al., 1992). It rewards past higher emission levels and can therefore be considered to be more attractive to richer countries with past higher levels of economic activity. In the literature, it is also referred to as “status quo” criterion (e.g. Grubb et al., 1992). In practice, the EU’s ETS revenue distribution, for instance, largely takes into account states’ emission levels before the EU ETS (EC, 2015, 2013). While the previous criteria can be determined before a federal policy is introduced (ex-ante), the juste retour criterion accounts for the actual level of emissions. It is, therefore, an outcome or an ex-post-based criterion (cf. Böhringer et al., 2015). Juste retour literally means ”fair return”. It presumes that the actual emission payments of a state to the multinational (or federal) government grant the state the right to federal revenue transfers that perfectly offset the emission payment. The literature also refers to this type of transfers as "no intercountry" transfers (e.g. Shiell, 2003; d'Autumne et al., 2016). 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. In practice, juste retour transfers are often requested from the EU by EU Member States (Warleigh, 2004). For a more technical overview of the transfer rules, see Table 1.

In a nutshell, this study combines the four previously discussed strands of literature to contribute to the understanding of environmental policy in multilateral systems and federations in particular. Studies on multinational environmental policy find that an efficient multinational emission price requires redistribution from rich to poor states. The equity literature presents a variety of fairness criteria, among which rank Pareto-improvements, and egalitarian, sovereignty, and juste retour transfers. The literature on fiscal federalism focuses on the efficiency and viability of federations and a multilevel policy structure, finding that policy interactions across multiple levels can incentivize states to override federal policy or to pass on the costs of its local (environmental) policy to other states. The literature on voluntary public good provision examines the willingness of self-interested entities to create or to contribute to a public good. It finds that a benevolent, yet hegemonic state is willing to create a multinational system, and that rich entities voluntarily contribute more to public good provision than poor entities. Conditions for voluntary participation by the states in federal environmental policy have not yet been examined. This paper combines the theories of voluntary provision of public goods and fiscal federalism. We draw on the insights into multinational environmental policy design and equitable burden-sharing since we consider a transboundary emissions damage (the mitigation of which is a public good). Specifically, this study adds the environmental focus and unanimity concerns to the second generation of fiscal federalism, which examines the institutional design of federations as a central determinant of their viability.

3. The model

The model represents a federation of m member states. Member states can differ in their capital stocks and population sizes. Population and capital are immobile across states. The entire population consists of identical consumers within a state. Each consumer rents out its capital endowment to the respective representative firm. Consumers receive transfers from the revenues of the state and federal emission prices. Firms pay for the emission of harmful transboundary emissions during the production of the final good. Each consumer derives utility from the consumption of a private good and dis-utility (damage) from emissions. Firms use emissions and capital to produce the private good. Note that since we have a single private good, our setting cannot be considered an international trade model. Our approach is comparable to Chichilnisky and Heal (1994) and net transfers can be interpreted as "gifts" from one or more states to another.[8]

State and federal governments choose optimal emission prices that strike a balance between emissions and private good consumption and recycle the revenues back to the population. Each state government charges a price on domestic emissions and distributes the revenue equally among its population. The federal government sets a uniform emission price, in addition to state prices, in case this leads to a Pareto-improvement relative to the decentralized state policy solution. It transfers federal revenues based on the egalitarian, sovereignty or juste retour criteria. Since the transfer criteria are given, the federal solution is a second-best optimum.

In Table 1 we provide an overview of the transfer criteria considered. We operationalize these as transfer rules in our model following the existing literature. We use s_i to represent the federal transfer share to each consumer in state $i = 1, ..., m$, while n_i denotes the number of consumers in state i. Note that for ex-ante criteria, the transfer size is independent of the federal policy outcome. We use the benchmark scenario without federal policy as the point of reference instead of historical data (cf. decentralized equilibrium). Decentralized emission levels of a state are denoted by E_i^0 and the total decentralized emission level is E^0. Actual emission levels, when state and federal policy coexist, are denoted by E_i and E.

The structure of the model can be summarized as follows. In the *first* stage, the federal government sets a federal uniform emission price. Its objective is to make at least one state better off, while no other state is worse off compared to the decentralized solution (Pareto-improvement). The federal government has information on the individual characteristics, interests and reactions of its member states and thus acts as a Stackelberg leader. In the *second* stage, based on the reactions of firms and consumers and taking the federal price as given, each state government non-cooperatively sets a price on domestic emissions. Its objective is to maximize the utility for the local population. In the *third* stage, consumers and firms in each state solve their optimization

[8]This should not be confused with trade of private goods between states (cf. Sheeran, 2006). In the spirit of Chichilnisky and Heal (1994), however, who consider an emission trading system, one can make the following trade-interpretation: If the federal government gives out emission permits to states, states can exchange (trade) these permits against the private good.

Criterion	Definition	Operationalized rule	Formula
ex-ante			
Egalitarian	Equal ownership of the atmosphere in which emissions are stored.	Every person gets the same share of federal emission price revenues.	$s_i = \frac{1}{\sum_j n_j}$
Sovereignty	Past emissions grant a right to actual emissions.	Federal revenues are distributed among the states in proportion to each decentralized emission levels.	$s_i = \frac{1}{n_i} \frac{E_i^0}{E^0}$
ex-post			
Juste Retour (no intercountry transfers)	Actual emission payments grant a right to federal revenues.	Federal revenues are distributed among consumers in a state in proportion to the actual emission level of that state.	$s_i = \frac{1}{n_i} \frac{E_i}{E}$

Table 1: **Transfer criteria and operationalized federal transfer rules.** In the formulas s_i represents the per capita transfer share of each consumer in state $i = 1, ..., m$, where i and j index the states. n_i is the number of consumers in state i. Emission levels of state i from the decentralized state policy and the state–federal policy solutions are E_i^0 and E_i, respectively. Similarly, $E^0$and E denote the aggregate federal emission levels.
Note: only Section 4.1 assumes population sizes to be equal across states, i.e. $n_M \equiv n_i = n_j$.
Table adapted from Böhringer et al. (2015); Kverndokk and Rose (2008); Grubb et al. (1992); Ringius et al. (2002); Cazorla and Toman (2001).

problems, taking all prices, and transfers as given.[9].

3.1. Private sector agents

3.1.1. Firms

In each state i a representative firm (firm i) produces a homogeneous final good Y_i which is identical across states. The final good is used as a numéraire. To produce Y_i the firm in state i uses a continuously differentiable production function $Y^i(K_i, E_i)$ that is homogeneous of degree one, where K_i and E_i are capital and emissions, respectively. Let $Y^i_x \equiv \partial Y^i(x,z)/\partial x$ and $Y^i_{xz} \equiv \partial^2 Y^i(x,z)/\partial x \partial z$. Production increases in both inputs with diminishing marginal products, i.e. $Y^i_{E_iE_i} < 0 < Y^i_{E_i}$ and $Y^i_{K_iK_i} < 0 < Y^i_{K_i}$.

Taking prices as given, firm i chooses K_i and E_i to maximize its profits. The rental rate of capital in state i is denoted by r_i, and the unit cost of emission is the sum of the state emission price p_i and the uniform federal emission price P. Since the final good's price is numéraire, firms maximize profits by setting their marginal cost of production equal to one, i.e. $mc_i = 1$, and by setting the marginal product of capital ($Y^i_{K_i}$) and emissions ($Y^i_{E_i}$) equal to their respective unit cost, i.e. $Y^i_{K_i} = r_i$ and $Y^i_{E_i} = p_i + P$.

3.1.2. Consumers

Each state i is populated by n_i identical consumers. Each consumer derives utility from consuming the final good. Aggregate federal emissions, given by $E = \sum_{i=1}^m E_i$, negatively affect each household's utility. We assume an additively separable utility function. The utility function of the representative consumer of state i is given by $u^i(c_i, E)$, where c_i denotes final good consumption. We assume that $u^i_{c_i} > 0$, $u^i_{c_ic_i} \leq 0$, which implies that the marginal utility from consumption stays equal or decreases with consumption. Further, we assume that $u^i_E < 0$, and $u^i_{EE} \leq 0$, which implies that the higher emissions are, the greater the marginal dis-utility from emissions.

Consumers take prices, emissions, policies and transfers as given. The representative consumer of state i (consumer i) chooses the level of consumption c_i that maximizes

[9]A literal interpretation of the timing in terms of real-world circumstances could run as follows. If we take the EU emission allowance price to represent a federal carbon price, then the timing of this game implies that the EU price evolved first and the member states followed with additional policies. A case which may not be unrealistic, as the EU ETS was the first large climate policy rolled out. If, however, the states move first to adopt local climate policy, then our setting would not be suitable under the literal interpretation of the timing of the game. The state of California might be an example of a first mover for the US federal system (cf. Urpelainen, 2009). Our setting can, of course, also have interpretations that involve the commitment power or strategic advantage of the federal level of government as described in Section 1.

her utility subject to her budget constraint

$$c_i = r_i \frac{\overline{K}_i}{n_i} + p_i \frac{E_i}{n_i} + s_i PE \tag{1}$$

where $\overline{K}_i$ is the aggregate capital endowment in state i and $r_i\overline{K}_i/n_i$ is the per capita return on capital, and p_iE_i/n_i and s_iPE are state level and federal level transfers to each consumer of state i that stem from coexisting state and federal emission pricing revenues. The federal per capita transfer distributes federal emission price revenues PE based on the transfer rule s_i as introduced in Table 1.

Since each consumer takes emissions as given, the solution to each consumer's optimization problem reduces to setting consumption equal to income, equation (1). Zero profits imply that $(r_i\overline{K}_i/n_i + p_iE_i/n_i) = Y_i/n_i - PE_i/n_i$. By substituting this into equation (1), state i's consumption becomes

$$c_i = \frac{Y_i}{n_i} + \left(s_i E - \frac{E_i}{n_i}\right) P. \tag{2}$$

Therefore, state i's consumption departure from local production Y_i is determined by the *net federal transfer*, $(s_iE - E_i/n_i)\, P$.[10]

3.1.3. Market clearing and reaction function of the private sector

Capital market clearing in each state implies that capital demand K_i equals the aggregate capital endowment in state i, i.e. $K_i = \overline{K}_i$. Market clearing in final goods is given by $\sum_i n_i c_i = \sum_i Y_i$.

Using the market clearing conditions together with the first order conditions of consumers and firms (private-sector agents) allows us to express the solutions for the pertinent choice variables and factor prices in terms of state and federal emission prices. We use **bold** letters to represent these functional forms.[11] These solutions can be considered reaction functions of the private sector agents. These functions are in the information set of state level and federal level governments and are taken into consideration in policy-making. We report and discuss these reaction functions in Appendix C.2 and Appendix J.2 for a Cobb-Douglas and for a more general CES production

[10] Note that emissions E_i, E and output Y_i decrease in the emission prices. See Appendix C.2 and Appendix J.2.

[11] Note, for example, that $Y^i_{E_i}\left(\overline{K}_i, E_i\right) = p_i + P$ solves for E_i as a function of p_i and P ; and since $Y^i\left(K_i, E_i\right)$ is homogeneous of degree one, $mc_i = 1$ solves for r_i as a function of p_i and P, which we respectively denote by $\boldsymbol{E}_i\left(p_i, P\right)$, and $\boldsymbol{r}_i\left(p_i, P\right)$. Similarly, $\boldsymbol{Y}^i\left(p_i, P\right) = Y^i\left(\overline{K}_i, \boldsymbol{E}_i\left(p_i, P\right)\right)$ and $\boldsymbol{E}\left(p, P\right) = \sum_i \boldsymbol{E}_i\left(p_i, P\right)$ with $p = (p_1, ...p_m)$.

function, respectively.

3.2. Multilevel emission policy

State and federal governments deal with emission reduction from their respective vantage points. They are confronted with the problem of balancing consumption and emissions on different levels (state vs federal). Since both levels set a price on and draw revenues from the same emissions, the emission price set at one level of governance can have an impact on the revenues of the other level (vertical fiscal externality). Previous environmental policy literature considers the unanticipated (Shiell, 2003; d'Autumne et al., 2016) (absent of strategic interactions across governmental layers) as well as the anticipated case (Williams, 2012). For the taxation of wage income, Dahlby (2008) considers it likely that changes in federal revenue induced by state policy are ignored (unanticipated) by the states. In such a case, this can lead to overtaxation at the state level (Dahlby, 1996; Boadway and Keen, 1996; Boadway et al., 1998; Keen, 1998). We contrast these two cases:

Definition 1 (Transfer Anticipation)**.** *Federal transfers are anticipated, if each state takes into account the effect of domestic policy on the federal transfer revenues received (indicated with *). Federal transfers are unanticipated, if each state does not take into account the effect of domestic policy on the federal revenues received.*[12] *Formally:*

$$\frac{\partial(s_i P\boldsymbol{E})}{\partial p_i} \neq 0 \text{ for all } i = 1, ..., m \qquad \text{"anticipated" federal transfers,}$$
$$\frac{\partial(s_i P\boldsymbol{E})}{\partial p_i} = 0 \text{ for all } i = 1, ..., m \qquad \text{"unanticipated" federal transfers.}$$

By comparing the anticipated and the unanticipated cases we can provide results that are valid under different structures of a federation. First, if the state is one among many or if it is small, state policy would have a negligible effect on the amount of transfers received from the federal government. In this case and under the egalitarian and sovereignty transfer rules, unanticipated transfers can be a good approximation of the decision problem. Unanticipated transfers also have the added benefit of being more analytically tractable. Second, as we will show later in this paper, the federal juste retour transfer performs very differently in the anticipated and unanticipated cases. Unanticipated juste retour transfers have already been discussed in Shiell (2003); d'Autumne et al. (2016). Third, for federations comprised of large or of only a few

[12]For an intuitive description cf. Footnote 3.

member states, anticipated transfers are the more appropriate framework for policy analysis, because individual states would then have a strong impact on federal transfers and would therefore likely incorporate this fact in their decision making.[13]

3.3. State policy

Each state government cares about the well-being of domestic consumers. The government of state i chooses the emission price p_i that maximizes the utility of its consumers while taking the federal emission price P and all other state-level emission prices p_j (for all $j \neq i$) as given.

The government of state i has perfect knowledge about its consumers and firm and uses this to arrive at the reaction functions necessary for its own optimization problem. We can thus rewrite consumer i's utility in terms of $p = p_1, ..., p_m$ and P as $\boldsymbol{u}^i(p, P) \equiv u^i(\boldsymbol{c}_i(p, P), \boldsymbol{E}(p, P))$. The problem of the local government in state i is formalized as

$$\max_{p_i} n_i \boldsymbol{u}^i(p, P) \text{ given } p_{j\ \forall j \neq i} \text{ and } P. \tag{4}$$

The first-order condition that characterizes the solution to problem (4) is $\boldsymbol{u}^i_{p_i} = (u^i_{c_i} \partial \boldsymbol{c}_i / \partial p_i + u^i_E\ \partial \boldsymbol{E} / \partial p_i) = 0$.[14] After several algebraic manipulations[15], we obtain

$$u^i_E \frac{\partial \boldsymbol{E}_i}{\partial p_i} = -u^i_{c_i} \frac{p_i}{n_i} \frac{\partial \boldsymbol{E}_i}{\partial p_i} \qquad \text{unanticipated,} \tag{5a}$$

$$u^i_E \frac{\partial \boldsymbol{E}_i}{\partial p_i} = -u^i_{c_i} \left(\frac{p_i}{n_i} \frac{\partial \boldsymbol{E}_i}{\partial p_i} + \frac{\partial (s_i P \boldsymbol{E})}{\partial p_i} \right) \qquad \text{anticipated.} \tag{5b}$$

We can see how the equilibrium state emission price is a balancing act between different effects. The left-hand side of equations (5a) and (5b) represents consumer-i's marginal benefit associated with an increase in state-i's policy p_i. This benefit is expressed in the marginal increase in utility resulting from a decline in local emissions due to state policy $u^i_E \partial \boldsymbol{E}_i / \partial p_i > 0$. [16,17] The right-hand side of equations (5a) and (5b) is the marginal cost of p_i in terms of utility. The right-hand side accounts for the impact of state policy on the marginal utility of consumption $u^i_{c_i} > 0$ through the

[13] Our discussion on unanticipated transfers can be conceptually linked to the small economy discussion in the literature on international trade, where individual countries are assumed to be unable to impact international prices and policy.

[14] Note that n_i cancels out since $n_i \boldsymbol{u}^i_{p_i} = 0$ implies that $\boldsymbol{u}^i_{p_i} = 0$.

[15] Provided in Appendix A.

[16] From Lau and Yotopoulos (1972) follows that $\partial \boldsymbol{E}_i / \partial p_i < 0$.

[17] The result $\partial \boldsymbol{E}_i / \partial p_i < 0$ is also derived in Appendix C.2 for Cobb-Douglas and in Appendix J.2 for CES production.

state policy-induced change in consumer income, which essentially reduces to emission price revenue transfers, cf. equation (1). If federal transfers are unanticipated by states, equation (5a), then each state only considers the marginal consumer income changes its policy induces on *state* transfers, $p_i/n_i \partial \boldsymbol{E}_i/\partial p_i$. Since $\partial \boldsymbol{E}_i/\partial p_i < 0$, an increase in state policy always has a negative impact on the size of state transfers. If states anticipate the *federal* transfers, equation (5b), each state additionally considers state policy-induced marginal changes in the federal transfer, where $\partial(s_i P \boldsymbol{E})/\partial p_i = \partial(s_i P \boldsymbol{E}_i)/\partial p_i$. Note that to comply with the first-order condition, the term in parenthesis of equation (5b) must be negative as the left-hand side is negative and $u^i_{c_i}$ is positive. The effect of state policy on federal transfers can be ambiguous, depending on the sign of $\partial(s_i P \boldsymbol{E})/\partial p_i$. Suppose that $\partial(s_i P \boldsymbol{E_i})/\partial p_i < 0$[18], then the state policy unambiguously generates a decline in the utility of consumption. For any federal ex-ante transfer criteria, one can see immediately that $\partial(s_i P \boldsymbol{E_i})/\partial p_i < 0$ because of $\partial \boldsymbol{E}/\partial p_i = \partial \boldsymbol{E}_i/\partial p_i < 0$[19] implying $\partial(s_i P \boldsymbol{E})/\partial p_i = s_i P \partial \boldsymbol{E}_i/\partial p_i < 0$.

Rearranging the m first-order conditions (one for each state) for both cases, i.e. equations ($5a$) and ($5b$), results in the reaction functions of state policy, which depend solely on the federal emission price:

$$\boldsymbol{p}_i\left(P\right) = -n_i \, \frac{u^i_E}{u^i_{c_i}} \qquad \text{unanticipated,} \qquad (6a)$$

$$\boldsymbol{p}^*_i\left(P\right) = n_i \left(-\frac{u^i_E}{u^i_{c_i}} - \frac{\partial(s_i P \boldsymbol{E}_i)}{\partial p_i} / \frac{\partial \boldsymbol{E}_i}{\partial p_i} \right) \qquad \text{anticipated.} \qquad (6b)$$

In case of unanticipated federal transfers, equation ($6a$), the state always chooses a positive emission price $p_i > 0$ because $u^i_E < 0$ and $u^i_{c_i} > 0$. In the case of anticipated federal transfers, equation ($6b$), the policy choice of the state can be positive or negative, depending on whether the term in parenthesis is positive or negative. If $\partial(s_i P \boldsymbol{E_i})/\partial p_i < 0$, then the state knows that it can positively influence the size of federal transfers by reducing its local policy stringency. In doing so, it provides the federal government with a larger revenue base (tax base) $\sum_i E_i$. As a result, it might even be optimal for a state government to subsidize local emissions to increase the federal revenue base, which, in turn, leads to higher federal transfers. From the fiscal federalism's perspective, anticipation of federal transfers implies that the state government

[18]This is indeed the case for all transfer rules considered in this paper, as we will show later in Section 4.1

[19]See Appendix A.

internalizes the vertical fiscal externality of its local emission price. It does it by taking into account that an increase in its local emission price leads to a decline in federal revenues (cf. Keen, 1998).[20]

States policies can differ from each other due to differences in population size n_i, and differences in the marginal rate of substitution between aggregate emission reduction and consumption $MRS_{E,c_i} \equiv -u^i_E/u^i_{c_i} > 0$. In case of anticipation, they can additionally differ due to the state policy-induced change in the federal transfer. Ceteris paribus, a larger population size and a larger marginal dis-utility of federal emissions both lead to a more stringent state policy. The opposite is true for a larger marginal utility of consumption. Ceteris paribus, if the representative consumer in state i is richer than his counterpart in state j and marginal utility decreases in consumption, then the marginal utility of consumption of each consumer in state i is lower than the marginal utility of consumption of each consumer in state j, i.e. $\overline{K}_i/n_i > \overline{K}_j/n_j$ implies $u^i_{c_i} < u^j_{c_j}$. Therefore, equations (6a) and (6b) suggest that a rich state sets a higher domestic emission price than a poor state, implying that rich states voluntarily contribute more to emission mitigation.[21] This relationship between marginal utility of consumption and emissions matches the findings in Bergstrom et al. (1986) and Chichilnisky and Heal (1994) who argue that larger gains from consumption (large $u^i_{c_i}$) increase the optimal level of emissions which is reflected here by a lower state price.

3.4. Decentralized policy equilibrium

Definition 2 (Decentralized policy equilibrium)**.** *The decentralized policy equilibrium is defined by the quantities $c^0_i, E^0_i, K^0_i, Y^0_i$ and prices p^0_i, r^0_i for $i = 1, ..., m$, such that each c^0_i solves the optimization problem of each consumer in state i; E^0_i, K^0_i and Y^0_i solve the problem of the firm located in state i; p^0_i solves the problem of state i's government; the market clearing conditions in capital and final goods hold with $K_i = \overline{K}_i$ and $\sum_i n_i c^0_i = \sum_i Y^0_i$, respectively; and $P = 0$.*

Setting $P = 0$ in equation (6a) and (6b), the emission price chosen by the government of state i reads

$$p^0_i = -n_i \frac{u^i_E}{u^i_{c_i}}\bigg|_{P=0} \qquad \text{for all } i. \tag{7}$$

In the decentralized case, the optimal local emission price in state i is an increasing function of the domestic population (consumers) size and of the MRS_{E,c_i}. The MRS_{E,c_i}

[20] See also Footnote 3.

[21] The numerical analysis in Section 4.2 elaborates more on population size differences. Thereby, one can distinguish between a high capital stock in aggregate terms and a high capital stock per capita.

decreases in the capital endowment if the marginal utility is decreasing, $u^i_{c_ic_i} < 0$. Since firms set the marginal product of emissions equal to the emission price, the policy of state i internalizes the local damage from domestic emissions and weighs it against the consumption losses from reducing emissions. Formally, we have $Y^i_{E_i} = p^0_i = n_i MRS_{E,c_i}$. According to the Bowen-Lindahl-Samuelson condition, the optimal level of emission reduction would be achieved if each state sets $p^0_i = \sum_i n_i MRS_{E,c_i}$. It follows that in the socially optimal case, the state prices would have to be the same, $p^0_i = p^0$. Suppose that all utilities are weighted equally in a social welfare function[22], then in case of wealth differences across states, all $u^i_{c_i}$ would need to be equalized by lump-sum transfers from rich to poor states (cf. Chichilnisky and Heal, 1994). Therefore, purely decentralized policies as in equation (7), fail to consider the spillover effects of emission damages to neighboring states and can be improved upon by a joint federal policy.

3.5. Federal policy

The aim of the federal government is to improve upon the inefficient decentralized equilibrium by setting a Pareto-improving uniform federal emission price that cannot be Pareto-dominated. When the federal price makes no state worse off than the decentralized outcome and at least one state does better, voluntary participation is guaranteed and we consider the federal emission price *feasible.* Feasibility is facilitated by the recycling of federal revenues, which the federal government distributes according to a transfer rule s_i (cf. Table 1). All federal revenues are distributed so that $P\boldsymbol{E} = \sum_i n_i s_i P\boldsymbol{E}$. To capture the federal government's coordinating role, we assume that it acts as a Stackelberg leader, anticipating the reaction of the member states, i.e. the response of consumers, firms, and state governments.

Formally, Pareto-improving policies are found by maximizing any member state's welfare subject to Pareto-constraints for the other member states:

$$\max_P \left\{ n_i \boldsymbol{u}^i \left(\boldsymbol{p}(P), P\right) \middle| \boldsymbol{u}^j \left(\boldsymbol{p}(P), P\right) \geq u^{0j} \quad \forall\, j \neq i \right\} \tag{8}$$

with $\boldsymbol{p}(P) \equiv \left(\boldsymbol{p}_1\left(P\right), \boldsymbol{p}_2\left(P\right), ..., \boldsymbol{p}_m\left(P\right)\right)$. Since consumers are identical *within* a state, the Lagrangian function related to problem (8) simplifies to

$$\mathcal{L}^i\left(P, \lambda\right) = \boldsymbol{u}^i\left(\boldsymbol{p}(P), P\right) + \sum\nolimits_{j \neq i} \lambda_j \left(\boldsymbol{u}^j\left(\boldsymbol{p}(P), P\right) - u^{0j}\right)$$

[22]Some normative statement concerning the welfare weights must be made to determine the socially optimal outcome. Other weights can also be meaningful. We refer here to the case of equal weights because it is the most simple one to illustrate the argument.

where $\lambda_{j\neq i}$ are the $m-1$ Karush-Kuhn-Tucker multipliers related to the utility constraints in problem (8). We provide detailed derivation of the first order conditions in Appendix B. [23] [24]

If some P satisfies $\boldsymbol{u}^j > u^{0j}$ for all $j \neq i$, this implies that $\lambda_{j\ \forall j\neq i} = 0$. If such a case exists, which we show to be true in the preceding section, matters would be greatly simplified, and further analytical insights can be attained. In such a case and using equation (2), the federal government's first-order conditions are reduced to[25]

$$-\frac{u^i_E}{u^i_{c_i}} = \frac{d\boldsymbol{c}_i}{dP} \Big/ \frac{d\boldsymbol{E}}{dP} \quad \text{with} \quad \frac{d\boldsymbol{c}_i}{dP} = \underbrace{\frac{1}{n_i}\frac{d\boldsymbol{Y}^i}{dP}}_{(a)} + \underbrace{\frac{d(s_i\boldsymbol{E} - \boldsymbol{E_i}/n_i)P}{dP}}_{(b)}. \tag{9}$$

Equation (9) indicates that the federal government sets the MRS_{E,c_i} of each consumer in state i (left-hand side) equal to its marginal change in consumption due to P relative to a marginal change in aggregate emissions due to P. Using equation (2), we see that the marginal change in consumption comprises the marginal change of domestic per capita income of a consumer in state i (a) and the net federal transfer to a consumer in state i (b).

Definition 3 (Multilevel policy Stackelberg equilibrium). *The multilevel policy Stackelberg equilibrium with federal transfer rule s_i is defined by the quantities $\widehat{c}_i$, $\widehat{Y}_i$,$\widehat{K}_i$, $\widehat{E}_i$ and prices $\widehat{r}_i$, $\widehat{p}_i$, $\widehat{P}$ such that $\widehat{c}_i$ solves the optimization problem of each consumer in state i; $\widehat{Y}_i$, $\widehat{K}_i$ and $\widehat{E}_i$ solve the problem of firm i; $\widehat{p}_i$ 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 hold with $K_i = \overline{K}_i$ and $\sum_i n_i\widehat{c}_i = \sum_i \widehat{Y}_i$, respectively; and the balance of payments condition $\widehat{Y}_i + n_i s_i \widehat{P}\widehat{E} - \widehat{P}\widehat{E}_i = n_i\widehat{c}_i$ is satisfied for all i.*

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[23] The traditional concepts of Pareto optimality and Pareto constrained frontiers only make intrapersonal comparisons of utility and avoid making interpersonal comparisons of utility (Fleurbaey and Hammond, 2004). The concept of Pareto-improvement we follow only compares the utility levels of each consumer between the decentralized and multilevel outcomes. This approach, thus, leaves out making utility comparisons across consumers.

[24] With the formulation of the federal problem as in equation (8), we make use of a traditional concept: The formulation of a Pareto-improvement is equivalent to maximizing a social welfare function given specific weights (cf. Krepps, 1990; Sheeran, 2006). For each minimum level assigned to a consumer j, u^{j0}, when maximizing the utility of consumer i in the Pareto-improvement formulation as in equation (8), there is a set of social welfare weights μ_i $i = 1, ..., m$ with $\sum_j \mu_j = 1$ which produces the same Pareto result when maximizing a social welfare function of all consumers and with the same transfer rule.

[25] To get this result, note that for $\lambda_{j\ \forall j\neq i} = 0$, the first-order condition becomes $u^i_{c_i}\left(\frac{1}{n_i}\frac{d\boldsymbol{Y}^i}{dP} + \frac{d(s_i\boldsymbol{E}-\boldsymbol{E}_i/n_i)P}{dP}\right) = u^i_E\frac{d\boldsymbol{E}}{dP}$. Rearranging yields equation (9).

4. Impact of transfer rules

Having specified the model and its decision structure, we now proceed to investigate the feasibility of federal policy-making when applying specific transfer rules. We divide this into an analytical results Section 4.1, in which we derive the main argument of this paper, and a numerical Section 4.2 in which we explore the results for a plausible parameter space and check the robustness of our main findings to the simplifying assumptions we made in the analytical part of the paper. [26]

4.1. Analytical results

In order to analytically explore the mechanics of the model developed we make the following simplifying assumptions. First, we assume production by Cobb-Douglas technology $Y^i(K_i, E_i) = AK_i^{\alpha_K} E_i^{\alpha_E}$. 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. Second, population size is equal across states, i.e. $n_M \equiv n_i = n_j$. Third, we set

$$u^i(c_i, E) = c_i - gE^\gamma$$

where g and γ are constant with $g > 0$ and $\gamma \geqq 1$.[27] We report and discuss the reaction functions in Appendix C.2 for the Cobb-Douglas production function.

Let κ_i denote the capital share of state i as a fraction of the total capital in the federation, $\overline{K} \equiv \sum_i \overline{K}_i$, such that $\kappa_i \equiv \overline{K}_i/\overline{K}$. Also, let $\overline{K}_{av} \equiv \overline{K}/m$ denote the average capital endowment in the federation and

$$\kappa_{EG} \equiv \frac{1}{m}\frac{m+\gamma-\alpha_E}{1+\gamma-\alpha_E} \qquad \text{unanticipated,} \tag{10a}$$

$$\kappa^*_{EG} \equiv \frac{1}{m}\frac{m+\gamma-\alpha_E-1}{1+\gamma-\alpha_E-1/m} \qquad \text{anticipated.} \tag{10b}$$

We call κ_{EG} and κ^*_{EG} the *capital-homogeneity-restriction* for the unanticipated and

[26] In this section, we assume that the production technologies have equal technological parameters across states.

[27] We recognize that the assumption of linear consumption may seem odd at a first glance. Combining linear consumption with an emission externality where emissions are an input in a production function exhibiting limited substitutability in the presence of a fixed capital stock guarantees a utility function that is concave in emissions and the existence of interior solutions. The resulting optimization problem, thus, has features similar to those observed in settings with log-utility or power utility, while maintaining analytical tractability. In our numerical analysis, we assume log-utility. The main findings remain similar.

anticipated case, respectively. We use these assumptions and notation in the propositions to come.

4.1.1. Main findings

To isolate the impact of differences in capital endowments, the federal system and federal transfers, we now set population size to be equal across states, i.e. $n_i = n_M$ for all $i = 1, ..., m$. We will again relax this assumption in the following Section 4.2.

Proposition 1 (Juste retour (no inter-state transfers) — anticipated)**.** *If juste retour federal transfers, $s_i = 1/n_M \widehat{E}_i/\widehat{E}$, are anticipated by the states, then $dp_i/dP = -1$; and the federal government cannot achieve Pareto-improvements relative to the decentralized solution.*

Proof. See Appendix D. □

Since the federal policy addresses the effect of transboundary emissions, one would expect that each consumer could be made better off by the federal policy. However, when anticipated, juste retour transfers fail to produce Pareto-improvements. Since $dp_i/dP = -1$, state prices offset federal prices one-to-one. Therefore, state and federal prices become perfect strategic substitutes in case of anticipated juste retour transfers. In this case, the states fully internalize the vertical fiscal externality, but they internalize the transboundary emission externality only to the degree that corresponds to their decentralized policy solution.

The solution for the optimal state price, equation (6*b*), already gives us an idea why anticipated juste retour transfers cannot deliver Pareto-improvements by means of federal emission policy. The partial derivative of the federal revenue transfer ($\boldsymbol{s_i} PE$) with respect to p_i is $\partial(\boldsymbol{s}_i P \boldsymbol{E})/\partial p_i = P/n_M \partial \boldsymbol{E}_i/\partial p_i$. Substituting this result into (6*b*) we get

$$\boldsymbol{p^*}_i(P) = -n_M \frac{u^i_E}{u^i_{c_i}} - P. \tag{11}$$

Expressing (11) in terms of the effective emission price as the sum of state and federal price, we can see that the effective emission price that firm i pays under the juste retour transfer rule equals the one it pays in the decentralized solution, i.e. $Y^i_{E_i} = p_i + P = n_M MRS_{E,c_i}$. This already hints that the policy choices at the state level perfectly offset the federal policy. We show this in more detail in Appendix D. We can conclude that the *juste retour* criterion renders federal policy ineffective and therefore infeasible, as soon as it is anticipated by the states.

As in Chichilnisky and Heal (1994) and Sandmo (2007), we find that Pareto optimality cannot be established in the absence of interstate transfers. In our setting, it is also the case that, in the absence of interstate transfers and when states anticipate federal transfers, even Pareto-improvements become impossible, despite the presence of a strong federal government (Stackelberg leader). Therefore, the case of anticipated juste retour transfers highlights that it is important that when a federal government chooses a transfer rule it knows whether its states anticipate the federal transfers.

Proposition 2 (Feasible federal policy)**.** *The federal government's policy leads to a Pareto-improvement relative to the decentralized solution if*

(i) *egalitarian*[28] *federal transfers, $s_i PE = PE/n$, are anticipated (unanticipated) by the states and $\kappa_i < \kappa^*_{EG}$ ($\kappa_i < \kappa_{EG}$) for all $i = 1, ..., m$; or*

(ii) *sovereignty federal transfers, $s_i PE = (E^0_i/E^0)PE/n_M$, are unanticipated; or*

(iii) *juste retour federal transfers, $s_i PE = PE_i/n_M$, are unanticipated.*

Moreover, there is a non-empty range of prices that solves the federal government problem.

If also $\overline{K}_1 \leq ... \leq \overline{K}_m$, then the lowest uniform federal price that is not Pareto-dominated solves $\max_P \boldsymbol{u}^m(\boldsymbol{p}(P), P)$.

Proof. See Appendix E. □

We call P^{min} also the "minimum federal emission price".

Let $\kappa_1 < \kappa_2 < ... < \kappa_m$. Let P^i denote the price P that maximizes the utility of state i, that is P^i solves $\max_P \boldsymbol{u}^i(\boldsymbol{p}(P), P)$. Let $P^m_{ind} > 0$ denote the federal price that makes the consumers of the richest state indifferent between the decentralized solution and the federal solution (i.e. $u^{0m} = \boldsymbol{u}^m(\boldsymbol{p}(P^m_{ind}), P^m_{ind})$). Consider a state q (if it existed) such that P^m_{ind} equals the federal price that maximizes the welfare of state q (i.e. $P^m_{ind} = P^q$). Denote by κ_q the capital share of such state q.

Proposition 3 (Highest federal price)**.** *If $\kappa_i < \kappa_{EG}$ ($\kappa_i < \kappa^*_{EG}$* and *$\alpha_K > \alpha_E$) in the case of unanticipated (anticipated) egalitarian transfers then for unanticipated egalitarian, sovereignty and juste retour transfers and anticipated egalitarian transfers the capital share κ_q=κ^q (κ_m) is implicitly defined by γ, α_E, m and κ_m. Moreover,*

[28]Note that Proposition 2 shows that only with egalitarian transfers a restriction on capital stock differences across states is required. We will elaborate on this restriction in Section 4.1.2.

i) if $\kappa_i \geq \kappa_q$ for all $i = 1, 2, ...m$ then the highest federal price is the price of the poorest state, that is P^1 (the price P^1 is provided in the appendix for each transfer); else

ii) if any $\kappa_i < \kappa_q$, then the highest federal price equals the price that makes the richest state indifferent between the federal and decentralized solutions, that is P^m_{ind}.

Proof. See Appendix F. □

From Propositions 2 and 3 follows:

Corollary 1 (Feasible federal price range)**.** *The range of federal prices is given by*

$$P \in [P^{min} \equiv \widehat{P}^m, P^{max} \equiv \min\{\widehat{P}^1, P^m_{ind}\}].$$

The federal price associated with maximizing the utility of the richest state is always the lowest feasible price (P^{min}). Its conceptual counterpart is associated with the federal price maximizing the utility of the poorest state. [29] The federal price maximizing the utility of the poorest state, however, is not necessarily in the range of federal prices as described in Proposition 3.

For anticipated sovereignty transfers, we prove the existence of Pareto-improving federal prices for $\gamma = 1$[30]:

Proposition 4 (Feasible federal policy: sovereignty – anticipated)**.** *Let $\gamma = 1$. If <u>sovereignty</u> federal transfers, $s_i PE = (E^0_i/E^0)PE/n_M$, are anticipated by the states, then the federal government's policy leads to a Pareto-improvement relative to the decentralized solution.*

Proof. See Appendix G. □

In the following, we provide intuition for the existence and ranking of feasible federal prices. Figure 1 serves to illustrate the basic intuition underlying the proofs. Let us focus on Proposition 2 and Corollary 1 for egalitarian transfers. Suppose there are two states, one is poor, one is rich, and population sizes are equal across states (n_M), i.e. $i \in \{rich, poor\}$ and $\overline{K}_{poor}/n_M < \overline{K}_{rich}/n_M$. The utility function of state i can be expressed in terms of the federal price P alone, i.e. $\boldsymbol{u}^i(p, P) = \boldsymbol{u}^i(\boldsymbol{p}(P), P)$, by

[29] Maximizing the utility of the poorest state corresponds to the equity criterion developed by Rawls, also known as the maximin criterion (cf. Rawls, 1971).

[30] Analogously to Proposition 2. In the numerical part of the study, we specify the feasibility and the price range in the general case, see Section 4.2.

using the state reaction functions, equations (6a) and (6b)[31]. At $P = 0$, the level of $\boldsymbol{u}^i$ equals the decentralized utility level u^{0i}. To obtain a maximum of $\boldsymbol{u}^i$ for a positive P, two conditions must hold: First, the slope of $\boldsymbol{u}^i$ must be positive at $P = 0$. This is ensured by the capital-homogeneity-restrictions involving $\kappa_i < \kappa^*_{EG}$ and $\kappa_i < \kappa_{EG}$ for egalitarian transfers. Since $\kappa_{poor} < \kappa_{rich}$, only the rich state can potentially violate the inequalities $\kappa_{rich} < \kappa_{EG}$ or $\kappa_{rich} < \kappa^*_{EG}$.[32] Second, $\boldsymbol{u}^i$ must be strictly concave in P to ensure a maximum. Both conditions together imply that there exists a bounded range of positive federal prices P for which both utilities $\boldsymbol{u}^i$ are greater than the decentralized level u^{0i}.[33] If these conditions hold, then each state i reaches its maximum at P^i. P^i is thus the preferred uniform federal price of state i.

The intuition behind the ranking of the federal prices is that the largest burden of the federal policy is carried by the richest state. We define rich states to be those states that have a capital stock share larger than the average capital stock share ($\sum_i \kappa_i/m = 1/m$), i.e. $1/m < \kappa_{rich}$. Similarly, for poor states, it holds that $\kappa_{poor} < 1/m$. Let S_{poor} denote the subset of states with capital endowments shares $\kappa_i \equiv \overline{K}_i/\overline{K}$ smaller than the average share ($1/m$) and let S_{rich} denote the subset of states with κ_i larger than average.

For egalitarian transfers, state prices across poor and rich states are equal, $p_{poor} = p_{rich}$ (cf. E.1 and E.16). Since $n = mn_M$, it also follows that $0 < E_{i\epsilon S_{poor}}/n < E_{i\epsilon S_{poor}}/n_M < E/n < E_{i\epsilon S_{rich}}/n < E_{i\epsilon S_{rich}}/n_M$, implying that the net federal transfers to poor and rich states satisfy[34]

$$\left(\frac{E}{n} - \frac{E_{i\epsilon S_{poor}}}{n_M}\right) P > 0 \text{ and } \left(\frac{E}{n} - \frac{E_{i\epsilon S_{rich}}}{n_M}\right) P < 0. \tag{12}$$

The finding from equation (12) implies that rich states are net transfer donors, and their benefit from federal policy stems solely from the reduction of emission damage. Poor states, however, benefit from federal policy in two ways. First, the emission price

[31]Note that the reaction functions are known to the federal government as it is the Stackelberg leader.

[32]If these restrictions are not fulfilled, the utility of the richest state cannot be improved for any *positive* federal emission price. Instead, the richest state would attain its maximum at a negative P. As we show in Appendix E, however, P must be positive for ensuring Pareto-improvements for poor states. This implies that a negative P cannot be a solution to the federal problem.

[33]When considering differences in preferences with $u^i(c_i, E) = c_i - g_i E^\gamma$ and that $g_i \neq g_j$, we find that the federal government is also able to attain Pareto-improvements. This proof is available upon request.

[34]These net transfers translate to uncompensated transfers or "gifts" of the private good from richer to poorer states, similar to Chichilnisky and Heal (1994), and are not to be confused with the trade of private goods among countries (cf. Sheeran, 2006). For an analysis that involves trade, see, for instance, Chichilnisky et al. (2000). Their findings of necessary uncompensated transfers from rich to poor remains, however, similar to Chichilnisky and Heal (1994).

at the federal level reduces the damage of emissions in the same way as it does for rich states. Second, poor states benefit from being net transfer recipients (cf. also equation (2)).

We describe the optimal federal price range by using Figure 1 again with two states, $i \in \{rich, poor\}$. Any federal price smaller than P^{rich} is Pareto-dominated by P^{rich}, as P^{rich} would make every consumer in the federation better off than those prices below P^{rich}. Therefore, $P^{rich} = \widehat{P}^{rich}$ is the lowest feasible federal price, i.e. $P^{min} \equiv \widehat{P}^{rich}$. If the federal price P^{poor}, maximizing the utility of the poorest state, is smaller than P^{rich}_{ind} (the positive federal price at which the rich state's utility equals the utility from the decentralized outcome), i.e. $P^{poor} < P^{rich}_{ind}$, then the largest feasible federal price is $P^{poor} = \widehat{P}^{poor}$ since any price larger than $\widehat{P}^{poor}$ is Pareto-dominated by $\widehat{P}^{poor}$. This case is depicted by the middle dashed line in Figure 1. If $P^{poor} > P^{rich}_{ind}$, then the largest feasible federal price is $\widehat{P}^{rich}_{ind}$ as the rich state falls below its decentralized utility for any P above that. This case is depicted by the dotted line in Figure 1.

We interpret these findings as follows. Let us suppose that i) the voluntary participation of net donors is a prerequisite for successful federal political negotiations, and that negotiations ii) start at a federal emission price of zero (decentralized outcome), and iii) are bid up gradually until one state vetoes a further price increase. In this case, our results indicate that the richest state, in its position as the largest donor, would veto an increase beyond the federal minimum price (P^{min}). At the same time, the richest state makes federal policy possible in the first place because of its role as the largest donor. If, on the contrary, we assume that federal negotiations do not end after the first veto, but with the acceptable ultimate price (still requiring unanimity), our results suggest that all states, even the richest, would accept the federal maximum price (P^{max}) as the final price.

Based on efficiency grounds, Chichilnisky and Heal (1994) find that poorer states should be net recipients while richer states should be net donors. Our work links their work to Olson (1965; 1966; 1986) (formalized by Bergstrom et al. (1986)) by accounting for the self-interest of the states. Olson argues that a benevolent hegemonic state is willing to create a multinational system. We build on this by considering multilevel policy within the multinational system referred to as a federation. We investigate how a federal policy can ensure unanimous consent of states (voluntary participation) and can be designed such that the richest state is willing to be a member and the largest contributor at the same time. Our study thus combines the concept of voluntary

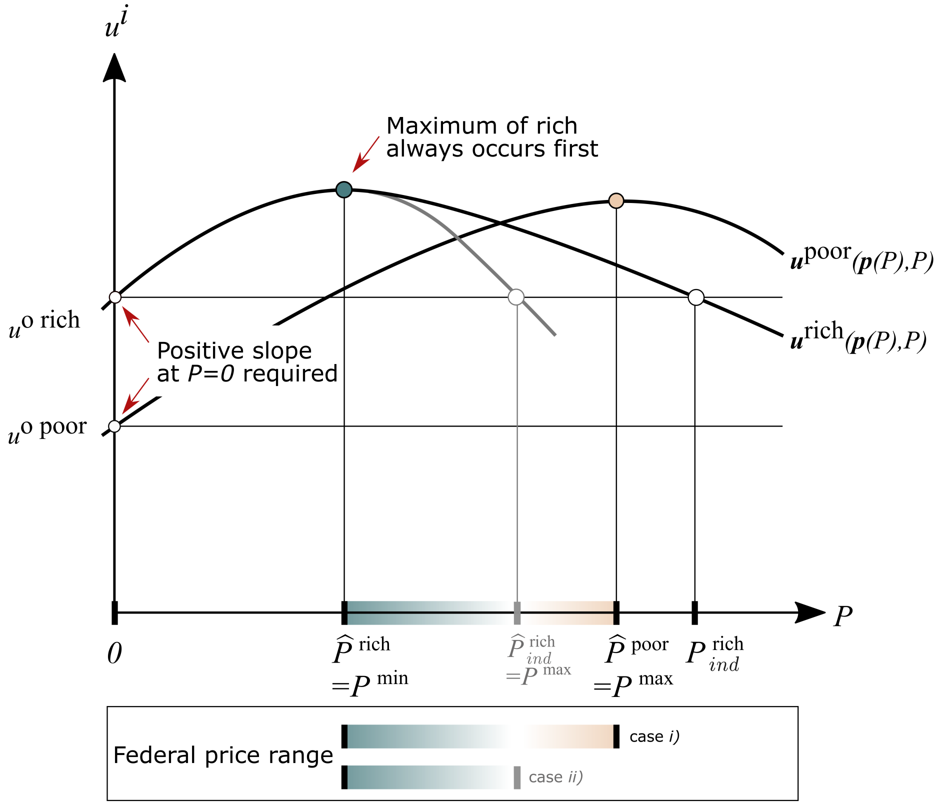

Figure 1: **Stylized illustration of the findings and proof structure of Propositions 2-4 and Corollary 1 for two states $i \in \{rich, poor\}$ where $\overline{K}_{poor} < \overline{K}_{rich}$.** The lowest Pareto-optimal federal emission price (P^{min}) always corresponds to the utility maximum of the rich state ($\widehat{P}^{rich} = P^{min}$). The highest Pareto-optimal federal emission price (P^{max}) defines the end of the federal price range, cf. Corollary 1. As shown in Proposition 3, two cases exist: i) P^{max} is located at the utility maximum of the poor state ($\widehat{P}^{poor} = P^{max}$, orange shade), or, ii) P^{max} is located at the federal price at which the rich state falls back to its decentralized outcome ($\widehat{P}^{rich}_{ind} = P^{max}$, white shade).

contributions with the fiscal federalism literature. In the literature on fiscal federalism, voluntary contributions by states have traditionally not been considered a prerequisite for federal policy-making. In that sense, we contribute to the second generation of fiscal federalism, which examines the institutional design of federations as central determinant of their viability (cf. Oates, 2005).[35]

In the proofs in Appendix E, we provide further results such as the closed form solutions of the federal prices P^i in equations (E.13), (E.19), and (E.22).

4.1.2. Capital-homogeneity-restriction of egalitarian transfers

As Proposition 2 i) indicates, only egalitarian transfers impose a restriction on capital stock differences across states. We now explore these restrictions in more detail. Recall the capital-homogeneity-restrictions stated in (10a) and (10b) for the unanticipated and anticipated case, respectively. Both depend on the production elasticity of emissions α_E, the externality-elasticity parameter γ[36] and the number of states in the federation m. Boundary cases for the number of states in the federation are $m = 2$ and $m \to \infty$.

Let $m = 2$. In that case, the capital-homogeneity-restrictions (equations (10a) and (10b)) can be expressed in terms of only γ and α_K. Taking the derivative w.r.t. α_K and γ we get: [37]

$$\left.\frac{\partial \kappa_{EG}}{\partial \gamma}\right|_{m=2} = \left.\frac{\partial \kappa_{EG}}{\partial \alpha_K}\right| < 0 \qquad \text{unanticipated}$$

$$\left.\frac{\partial \kappa^*_{EG}}{\partial \gamma}\right|_{m=2} = \left.\frac{\partial \kappa^*_{EG}}{\partial \alpha_K}\right|_{m=2} < 0 \qquad \text{anticipated}$$

This indicates that, ceteris paribus, larger α_K and γ make the capital-homogeneity-restrictions stricter in the sense that the two states must be more homogeneous in terms of their capital stocks.

Let $m \to \infty$. The limit of equations (10a) and (10b) is

$$\lim_{m\to\infty} \kappa_{EG} = \lim_{m\to\infty} \kappa^*_{EG} = \frac{1}{\alpha_K + \gamma} \tag{14}$$

Thus, in the limit, for a very large number of states in the federation, the capital-

[35]In our case the institutional design is represented, in particular, by the unanimity requirement for federal policy.

[36]The parameter γ can be interpreted as an elasticity since $\partial D/\partial E \;\; E/D = \gamma$, where D corresponds to the size of the dis-utility from emissions.

[37]These derivatives can be found in Appendix I.

homogeneity-restriction approaches $1/(\alpha_K + \gamma)$ for the anticipated and the unanticipated cases, and is both decreasing in α_K and γ. Equation (14) shows that anticipation plays an increasingly smaller role for egalitarian transfers, the more states there are in the federation. Equation (14) also suggests that it is easier to ensure the voluntary participation of the richest state when α_K and γ are low.

Proposition 2 case i) establishes that for egalitarian transfers to work κ_i must satisfy $\kappa_i < \kappa_{EG}$ or $\kappa_i < \kappa^*_{EG}$. We give some simple intuition for the result of equations (10a), (10b) and (14) that κ_{EG} and κ^*_{EG} decrease in γ and α_K. Since $\alpha_K = 1 - \alpha_E$, then κ_{EG} and κ^*_{EG} increase in α_E. Therefore, the larger α_E is the less restrictive κ_{EG} and κ^*_{EG} become. A larger α_E implies that the importance of emissions in production increases, while the importance of capital decreases. Intuitively, when capital becomes less important in the economy, capital heterogeneity becomes less restrictive, since the states become more homogeneous in terms of their reliance on emissions (increasing α_E) and, therefore, have more similar interests. Let us now consider the role of γ. If the states are not very vulnerable to emissions (low γ), there is not much to gain from federal emission mitigation. Thus, the federal price tends to be lower and so are the emission payments from states to the federation. In turn, the richest state does not need to contribute as much in terms of net federal transfers, making it easier to find an agreeable federal price.

We plot the capital-homogeneity-restrictions together with the average capital share $\kappa_{av} \equiv 1/m$ in Figure 2 with $\alpha_K = 0.97$ and $\gamma = 2$. The figure shows that state anticipation decreases the gap between both restrictions. By considering the distance to κ_{av}, we also see that the more member states there are, the looser the restrictions become.

4.1.3. Transfer anticipation and state policy in the multilevel equilibrium

Using the state prices from the general case, equations (6a) and (6b), and using the simplifying assumptions from the beginning of Section 4.1 allows us to express equilibrium state prices as follows. Under unanticipated transfers, state prices for the transfer rules egalitarian (EG), sovereignty (SO), and juste retour (JR) are

$$\widehat{p}_{i,rule} = n_M \, g\gamma \left(\widehat{E}\right)^{\gamma-1}\Big|_{\widehat{P}_{rule}} \quad \text{for all } i \text{ and } rule = EG, SO, JR$$

where $\widehat{E} \equiv \sum_j \widehat{E}_j$.

For the anticipated case, note that $s_{i,EG} = s_{EG} = 1/(mn_M) = \kappa_{av}/n_M$. Using the transfer definitions in Table 1 and the emission levels from the decentralized policy equi-

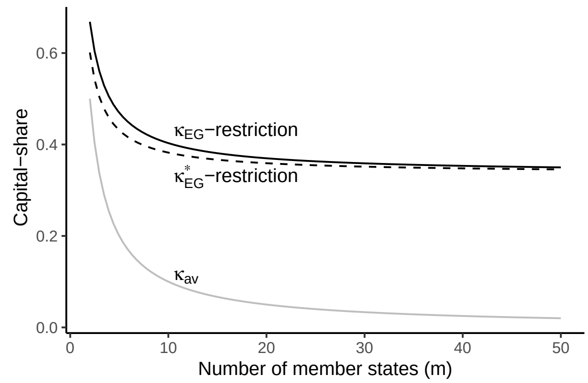

Figure 2: **Comparison of the capital-homogeneity-restriction for different numbers of member states.** To ensure that federal policy is feasible (Pareto-improving) when using egalitarian transfers, the capital share of all states κ_i with $i = 1, ..., m$ must be below κ_{EG} (solid line) in the unanticipated case, or κ^*_{EG} (dashed line) in anticipated case. κ_{av} is the average capital share which equals $1/m$.

librium, we also get that $s_{i,SO} = E^0_i/(E^0 n_M)$ reduces to $s_{i,SO} = \kappa_i/n_M = \overline{K}_i/(\overline{K} n_M)$.[38] If states anticipate the federal transfers, equation (6b), then each state sets its optimal emission prices as follows:

$$\widehat{p}^*_{i,EG} = \widehat{p}^*_{EG} = n_M \; g\gamma \left(\widehat{E}^*\right)^{\gamma-1}\Bigg|_{\widehat{P}^*_{EG}} - \kappa_{av}\widehat{P}^*_{EG}. \qquad \text{egalitarian, anticipated} \qquad (15a)$$

$$\widehat{p}^*_{i,SO} = n_M \; g\gamma \left(\widehat{E}^*\right)^{\gamma-1}\Bigg|_{\widehat{P}^*_{SO}} - \kappa_i\widehat{P}^*_{SO}. \qquad \text{sovereignity, anticipated} \qquad (15b)$$

The second term in equations (15a) and (15b) shows that, ceteris paribus, federal transfer anticipation reduces state i's domestic emission price compared to the unanticipated case. The reduction is equivalent to the federal transfer per unit of emissions its consumers receive ($n_M s_i P$). In this case, each state government takes into account the negative vertical fiscal externality, namely that a local emission price increase leads to a reduction in federal revenues and, in turn, reduces federal transfers. This observation reveals a potentially undesirable outcome of federal transfer anticipation: In the case of egalitarian transfers, the federal transfer per emission unit received by consumers in a state is higher, the fewer states there are in the federation (because $\kappa_{av} = 1/m$). For sovereignty transfers, the more wealthy a state is in comparison to other states, the higher the federal transfer per unit of emissions its consumers receive (measured by

[38] This result is obtained by using equations (C.4) and (C.5), and substitution of $p^0_i, n_i = n_M$ and $P = 0$.

κ_i). In the case of anticipation, therefore, states reduce their domestic emission prices due to their expectation of getting higher federal transfers. As we will highlight in Section 4.2, the federal emission price responds to lower state prices and will be higher in the multilevel equilibrium with anticipation than in the one without (cf. Keen, 1998; Keen and Kotsogiannis, 2002, on overtaxation in the non-environmental context). It also implies that states individually refrain from a stronger internalization of emission damages and leave this to the federal government if they subsequently receive more transfers from the federal government.

4.1.4. Aggregate emission reduction at the federal minimum price

We now analyze the relative emissions mitigation subject to the different federal transfers. We can derive analytical insights only for the unanticipated case and for $n_M = 1$. The more states in the federation, the less the anticipated and unanticipated cases differ (cf. equation (14)), which implies that our analytical results here would hold approximately for the case of many member states in a federation. Nevertheless, the assumption $n_M = 1$ is a limiting one and we, therefore, examine the role of population size more closely in our numerical analysis.

Proposition 5 (Aggregate emission reduction)**.** *Let $\overline{K}_1 < ... < \overline{K}_m$, and $n_M = 1$. If i) $\kappa_i < \kappa_{EG}$; ii) the respective federal minimum price is set; iii) state governments do not anticipate the federal transfer; and iv) $\kappa_m > \alpha_E/\gamma$, then sovereignty and juste retour transfers achieve a higher aggregate emission reduction than egalitarian transfers. If $\kappa_m < \alpha_E/\gamma$ then egalitarian transfers achieve a higher aggregate emission reduction.*

Proof. See Appendix H. □

The inequality in Proposition 5 suggests that κ_m, α_E and γ are critical parameters for assessing which federal transfer rule is superior in terms of aggregate emission reduction. A large capital share of the richest state κ_m, as well as a large elasticity of emission damage γ tend to give sovereignty and juste retour transfers the upper hand, whereas the opposite applies for a large output elasticity with respect to emissions α_E.

In Section 4.2, we numerically investigate how the relative performance of the different transfer schemes changes by exploring plausible parameter ranges and relaxing some of our simplifying assumptions. In particular, we explore plausible ranges of α_E and γ , consider cases where $n_i \neq n_j$, introduce decreasing marginal utility of consumption and the more general CES production function.

4.2. Numerical analysis

In the formal analysis in Section 4.1, we found that the richest state is both the enabler and the bottleneck for federal policy, and that its interests manifest themselves in the federal minimum price. In the numerical section, we add a nuance to the notion of the rich state by introducing population size differences. We find that in the case of federal egalitarian transfers, the federal minimum price is determined by the utility maximum of the richest smallest state. In contrast, both under sovereignty transfers and unanticipated juste retour transfers, the minimum price corresponds to the utility maximum of the richest largest state.

4.2.1. Assumptions and specific functional forms

We relax the following assumptions: the numerical model distinguishes two types of rich states and two types of poor states, $i =$ *poor small, poor large, rich small, rich large*. We fix the capital and population size of the *poor small* state at $\overline{K}_{poor} = 1$ and $n_{small} = 1$ and scale the population and capital endowments of the other states accordingly. A consumer in a rich state owns 1.2 times as much capital per capita as a consumer in a poor state. Twice as many people live in large states than in small states.[39] Table 2 gives an overview of state endowments in our model economy, where each entry in parenthesis reflects the population and capital of state i as follows $(n_i, \overline{K}_i)$.

	$\overline{K}_{poor}$	$\overline{K}_{rich}$
n_{small}	$(1, 1)$	$(1, 1.2)$
n_{large}	$(2, 2)$	$(2, 2.4)$

Table 2: Population-capital endowment matrix.
Note: We will vary the wealth and population size differences in sensitivity analyses, but we will assume throughout that all rich (poor) states have the same per capita capital levels of $\overline{k}_{rich}$ ($\overline{k}_{poor}$). Similarly, we assume that that all large (small) states have the same population sizes of n_{small} (n_{large}). Capital per capita levels are obtained by dividing state i's aggregate capital stock by its population size ($\overline{K}_i/n_i = \overline{k}_i$). As a consequence, we get four different states: *poor small*, *poor large*, *rich small*, and *rich large*.

To capture decreasing marginal utility of consumption, we assume $u^i(c_i, E) \equiv \log(c_i) - E^\gamma$. Production is modeled by a constant elasticity of substitution technology,

[39] For the illustration of our analytical findings, we start with relatively small asymmetries. This assumption allows the broadest discussion of transfer rules as all federal prices that maximize the utility of each state i are feasible (except for juste retour anticipated, which is never feasible). If we take the capital per capita levels of EU Member States and divide these into a poor and a large region then a consumer in the rich EU region owns three times as much capital than a consumer in the poor EU region, based on capital stock data from Berlemann and Wesselhöft (2017, 2014) and Census data from the year 2011 code cens_11r provided by Eurostat. Similarly, eight times more people live in large EU states than in small small EU states.

$Y^i(K_i, E_i) \equiv (\alpha_K K_i^{\frac{\sigma-1}{\sigma}} + \alpha_E E_i^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}}$ where σ is the substitution elasticity between capital and emissions. Based on own estimates or taken from other studies, we set $\alpha_E = 0.03$, $\gamma = 2$ and $\sigma = 0.5$. See details on these estimates in Appendix K and reaction functions for the CES production function in Appendix J.2.

Propositions 2 and 5 suggest that under egalitarian transfers it matters how rich the richest state is, and that α_E and γ are critical parameters for the level of emission mitigation. Since we also introduce population size heterogeneity and decreasing marginal utility of consumption, we provide sensitivity analysis along these five dimensions, which Table 3 summarizes.[40]

parameter/function	α_E	γ	$\overline{K}_{rich}$	n_{large}	σ	$u^i(c_i)$
variation	$(0, 0.3]$	$[1, 3]$	$[1, 20]$	$[1, 15]$	$[0.4, 0.98]$	$\log(c_i)$ and linear

Table 3: The different parameters and utility function specifications used in the sensitivity analysis.

4.2.2. Results

We focus the discussion on results that complement and elaborate on the findings in the analytical part of the paper. Further sensitivity analyses are provided in Appendix L.

Federal price range. Figure 3 presents the feasible federal prices as price ranges (gray bar) from the minimum (left end) to the maximum price (right end). To facilitate the discussion of the results, all prices are expressed in relative terms with the lowest minimum federal price across the different rules considered serving as the anchor. The lowest minimum price corresponds to that of the *rich small* state under the egalitarian and non anticipated case. Let $P_{norm} \equiv \widehat{P}_{EG}^{richsmall}$. If feasible federal prices exist, the range is non-empty and in all cases the minimum federal price corresponds to the utility maximum of a rich state (dark color). If the range is empty, no feasible federal prices exist which is denoted by an x in the figure and refers to anticipated juste retour transfers and Proposition 1. Figure 3 confirms the finding of Proposition 2 and complements the finding of Proposition 4, i.e. that the richest state's utility maximum determines the minimum price.

We find that in case of egalitarian transfers, the minimum price is determined by the utility maximum of the *rich small* state (hence the largest per capita capital with the lowest population size; small dark circle). In contrast, both under sovereignty transfers and under unanticipated juste retour transfers the minimum price corresponds to the

[40]We report and discuss the reaction functions in Appendix J.2 for the CES production function.

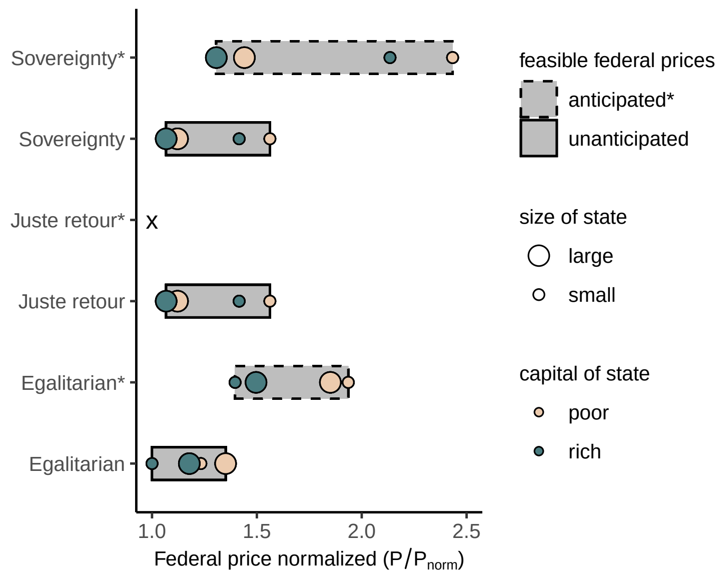

Figure 3: **Feasible federal price range** from minimum (left) to maximum federal price (right end of gray bar). Each circle corresponds to the normalized uniform federal price which maximizes the utility of the consumers in that respective state ($\widehat{P}^i_{rule}/P_{norm}$). Anticipated juste retour transfers cannot provide Pareto-improvements and are thus infeasible (x).

Note: Under these assumptions on parameter values and functional forms, capital endowments and population as in Table 2, the maximum price is determined by the utility maximum of the poorest state (also see Figure 1, case i). In Figure L.9 in the Appendix, we show cases where rich states determine the maximum price as well (Figure 1, case ii).

utility maximum of the*rich large* state – the one with the largest capital stock in absolute terms (large dark circle).

The intuition is as follows. Ceteris paribus, a rich state naturally has a larger per capita emission level than a poor state, making it a larger per capita gross donor of federal revenues, see also (Roolfs et al., 2018). Under egalitarian transfers each state receives in the aggregate a federal transfer in proportion to its population size. Because of that, any small state receives a lower aggregate federal transfer than a large state. Also, the emission damage affects small states less than large states as the damage from emissions affects fewer people. Therefore, the *rich small* state faces a high federal price burden (because it is rich), but low federal transfer receipts and little environmental benefits (as it has a small population size). Accordingly, the utility of the *rich small* state is maximized at the lowest of all feasible federal prices. As net donors, rich states might demand that their utility be maximized, making the *rich small* state the bottleneck for feasible policy under federal egalitarian transfers.

For sovereignty transfers, the intuition is similar. Sovereignty transfers, however, distribute federal revenues based on decentralized emission levels and not population size. Ceteris paribus, a large state already sets a higher decentralized state price than a small state as it faces a larger emission damage due to its larger population size. A large state, therefore, reduces its decentralized emissions more than a small state (cf. Section 3.4). Consequently, under sovereignty transfers, the utility of the *rich large* state is maximized at the lowest of all feasible federal prices, and it becomes the bottleneck for a feasible policy.

Similarly, this reasoning also holds for unanticipated juste retour transfers, since the outcomes under unanticipated juste retour and unanticipated sovereignty transfers are identical.[41] The transfers from these two rules are determined by the multilevel or decentralized emission share levels, respectively. And as they are unanticipated, the state policy choices in the multilevel setting are independent of the transfer anticipation term.

Comparing the minimum prices of the anticipated (dashed boxes) with the unanticipated case (solid boxes), it appears that anticipated transfers accommodate a higher minimum price. Intuitively, states that anticipate the transfer, know that local consumption also benefits from the transfer payments from the federal government, which raises their acceptance of higher federal prices. They are also able to include federal rev-

[41]We show analytically that results are identical for the Cobb-Douglas case in Appendix E.3 and Appendix E.4, but this result generally holds also for other constant returns to scale production technologies, simply because the transfer shares of these two transfer rules become identical.

enue recycling in their optimization and are, therefore, finding it optimal to substitute domestic for federal emission pricing in appreciation of the additional federal transfers, when balancing consumption against damage reduction. This reveals that states are willing to hand over more regulation to the federal government (higher federal price) if they can anticipate the transfer.

In Figure 4 we provide a sensitivity analyses by varying α_E and γ. The analysis shows that our results on i) the richest and poorest states defining the minimum and maximum price, as well as ii) a more pronounced coordination under transfer anticipation, are robust over wide ranges of α_E and γ. A sensitivity analysis for σ is provided in the Appendix L.8, which suggest similar robustness of the results. Similarly, in Appendix L.3 and Figure L.9, we provide examples in which the same rich state would define the minimum and the maximum federal price for particular values of α_E and γ. This implies that some states would reach their utility maximum for federal prices higher than the maximum price, but these prices are then not part of the federal price range. In other words, this rich state would reject any price above the maximum federal price as it would bring this rich state below its utility level associated with the decentralized solution. See also Figure 1's case ii, and Corollary 1 of the analytical analysis.

Effective state emission prices. Figure 5 presents the effective (consolidated) emission price that each state i faces, i.e. the sum of the federal and state i emission prices in the multilevel policy equilibrium. Each line starts at the federal minimum price and ends at the maximum federal price on the x-axis (cf. Figure 3). The bisector (45$\circ$-line) in Figure 5 helps to compare the federal price (x-axis) to the effective price (y-axis). On the bisector, the state price is zero. Above the bisector, a state complements the federal price with a positive state price. In that case, the effective state price is larger than the federal price. On the other hand, an effective state price below the bisection reveals that a state sets a negative state price and thus subsidizes local emissions.

The slope of each line in Figure 5 reflects the response of each state i to the feasible federal prices. For all transfer rules described in A) and B)[42], the states lower their price as the federal price increases, i.e. the slope is smaller than unity. All states lower their state prices only slightly if the transfers are unanticipated (solid lines) and strongly if they are anticipated (dashed lines). In the unanticipated case, the effective price always lies above the bisector, which means that states always complement the federal price

[42]We do not report anticipated juste retour transfers as the federal price range is empty and thus infeasible.

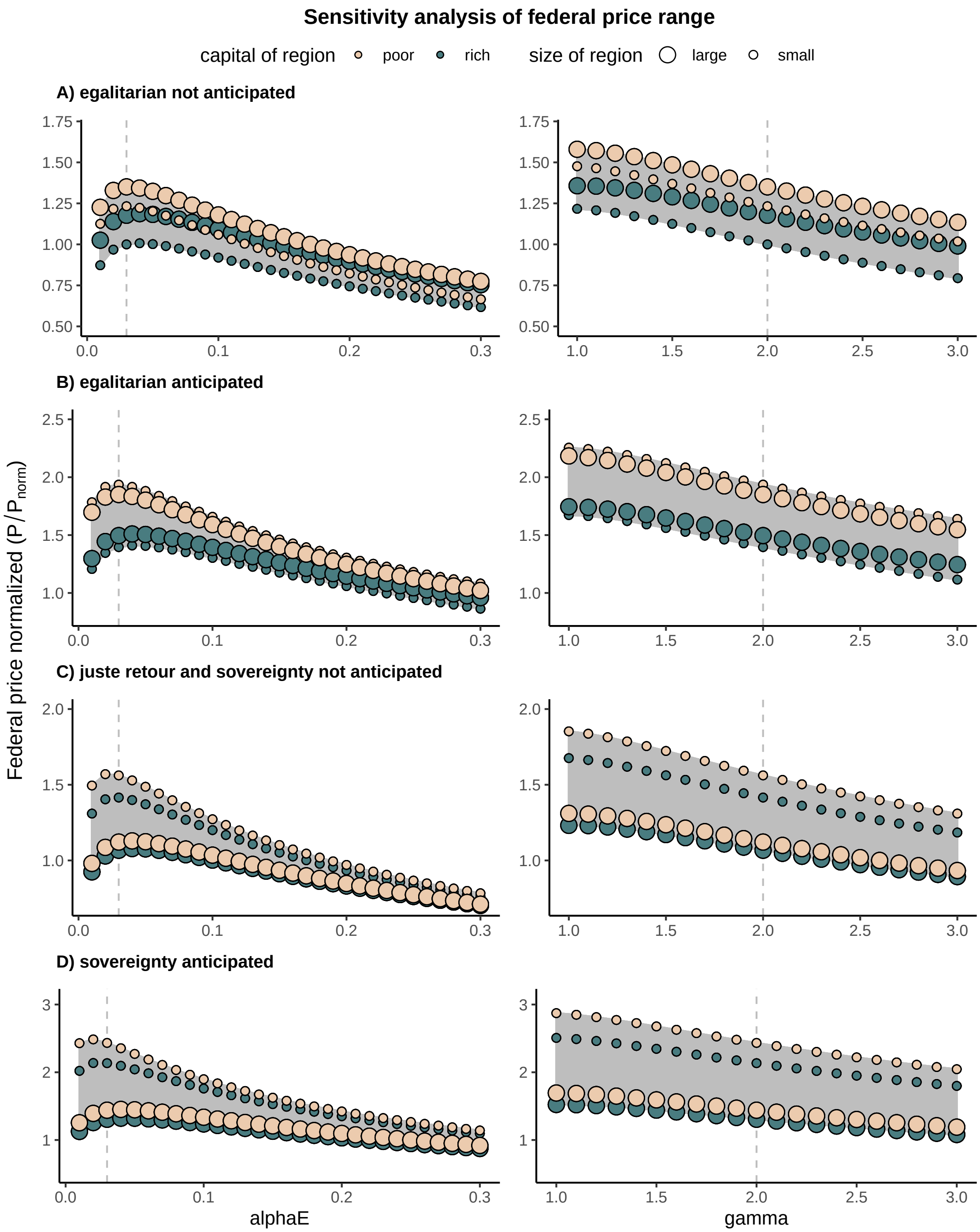

Figure 4: **Robustness check of the feasible federal price range to variations of γ and α_E.** The richest state in terms of capital per capita (under egalitarian) or aggregate capital (under sovereignty or unanticipated juste retour transfers) prefers the lowest federal emission price. The gray dashed lines represent our benchmark parameter assumption. Results under variations of σ are provided in the Appendix L.8.

Note: Under these assumptions on parameter values and functional forms, capital endowments and population as in Table 2, the maximum price is determined by the utility maximum of the poorest state and not by the lowest indifference price (P^i_{ind}) of any another state. In Figure L.9 in the Appendix, we show examples where rich states determine the maximum price as well (also cf. Figure 1 case ii).

with a positive state price.

In the anticipated case, states react to a federal price with a stronger state emission price decrease. Thus, feasible federal prices are larger in the anticipated case, but the policy response of states gets more pronounced. The intuition is as follows. If states anticipate the federal transfer, they also anticipate that setting a large local emission price will decrease federal revenues (internalization of the vertical fiscal externality), and as such, they will receive a smaller federal transfer. Therefore, states set a relatively small emission price. In turn, the federal authority, acting as a Stackelberg leader, knows that states set relatively small prices and, to compensate for that, sets a relatively high federal price. For high federal prices, states' prices with anticipation can turn into local emission subsidies.

Figure 5 also shows that the *rich large* state always faces the highest effective emission price regardless of the federal transfer rule. Intuitively, its large population leads to a larger local marginal emission damage than that of small states. In contrast, its wealth leads to a marginal utility of consumption smaller than the one of poor states. The combined effect leads to the *rich large* state choosing the highest state price. The same reasoning applies for the poor small state, which sets the lowest state price.

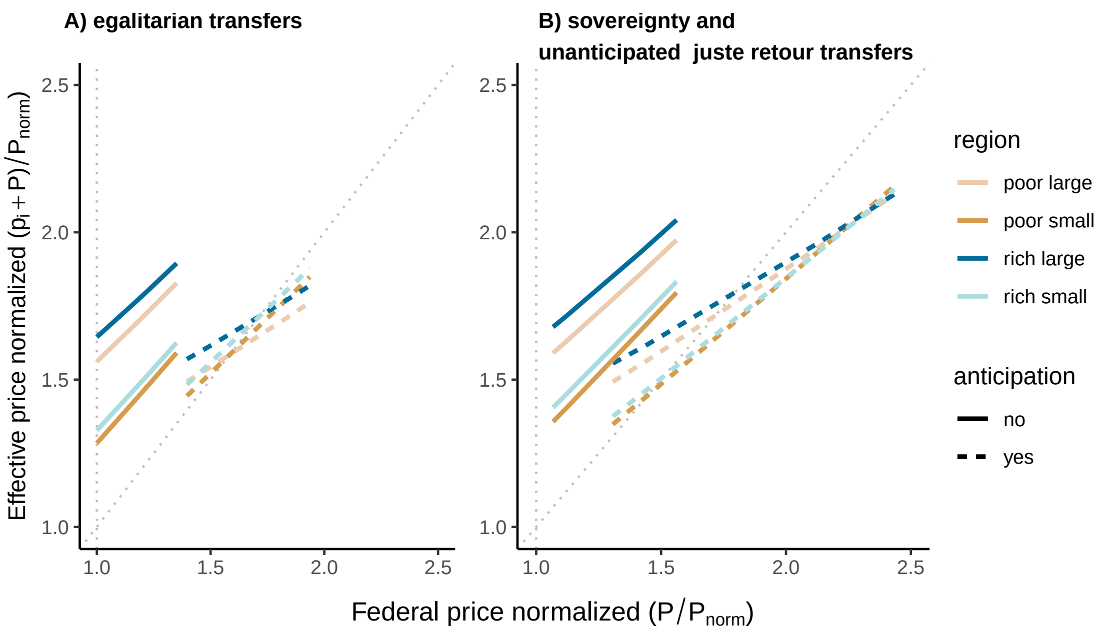

Figure 5: **Effective (consolidated) emission price per state** given by the sum of state i's price p_i and the federal price P in the feasible federal price range. The dotted vertical line corresponds to P_{norm} and the dotted 45○-line is the bisector.

In the following, we discuss some sensitivity analyses, while providing further ones in Appendix L.

Impact of population size on the minimum prices and aggregate emissions. In Figure 6, we report the A) respective minimum prices and B) federal emission reduction in relation to the decentralized solution with varying population size in large states. While we keep the population size constant for small states, we increase the amount of people living in large states $n_{large} \in [1, 15]$, which corresponds to 50 to 90% of the federal population living in large states, but keep capital per capita as in Table 2.

Figure 6 A) shows that for small population size differences, all transfers accommodate similar federal minimum prices. This is due to the fact that a larger population increases the weight of the marginal damage caused by emissions. An increase in the minimum feasible federal price internalizes this larger damage. In the range where all minimum prices increases, it is ambiguous whether the minimum feasible federal price in the anticipated case is higher for egalitarian or sovereignty transfers.

When population size differences get larger, i.e. when roughly 80% or more of the federal population lives in large states, the minimum feasible federal price with egalitarian transfers begins to fall until finally federal policy becomes infeasible (see drop to $P^{min}/P_{norm} = 0$). As before, the reason for that is that under egalitarian transfers, the smaller the relative size of the state, the less federal transfers it tends to receive and, therefore, as population differences increase, at some point, the burden becomes too large for voluntary participation in federal policy. The minimum price with sovereignty transfers and unanticipated juste retour transfers increases with a larger population.

After looking at the ranking of all governmental emission price choices, a final comparison of feasible aggregate emission reduction (i.e. level of public good provision) is in order. In Figure 6 B) we compare aggregate emissions reduction achieved by federal policy. To do so, we compute the relative changes across the multilevel policy outcome at the federal minimum price to the decentralized policy outcome, $\left[(\widehat{E} - E^0)/E^0\right] |_{P^{min}_{rule}}$.

We highlight four findings presented in 6 B) to conclude our numerical analysis. First, the larger the population differences, the smaller the benefits in terms of emission reduction from federal policy as compared to the decentralized solution. With large population differences, large states' decentralized policies alone internalize a relatively large portion of emission damages, cf. equation (7). Second, anticipation generally results in lower aggregate emission reduction under sovereignty transfers relative to the decentralized solution. Results are ambiguous for egalitarian transfers and federal policy becomes infeasible when population size differences get too large (roughly at 80% in B)). Third, when the population in large states is significantly larger than in small states (with our model assumptions roughly above 70% of the total population), federal sovereignty transfers are superior in terms of emission reduction than egalitarian transfers. Thus, if differences in population size are too large, sovereignty transfers are preferable because they always guarantee voluntary participation of states in federal policy-making. Fourth, federal transfer anticipation enables states to internalize their vertical fiscal externality with respect to federal revenues received. However, this fiscal internalization can be at the expense of overall emissions reductions, since in the multilevel equilibrium, unanticipated federal transfers, in many cases, achieve more overall emissions reductions than anticipated transfers (compare the dashed with the solid lines in B)). This reflects some key findings from the fiscal federalism literature, which suggests that states tend to overtax locally if they do not internalize the vertical fiscal externality (cf. Keen, 1998; Keen and Kotsogiannis, 2002). In our environmental fiscal federalism model, there is a fiscal and an environmental externality. In this case, the internalization of the vertical fiscal externality of each state government results in a reduction of each state's emission price. As Figure 6 B) shows, the internalization of the vertical fiscal externality (anticipation) can go at the expense of the internalization of transboundary emission damages.[43]

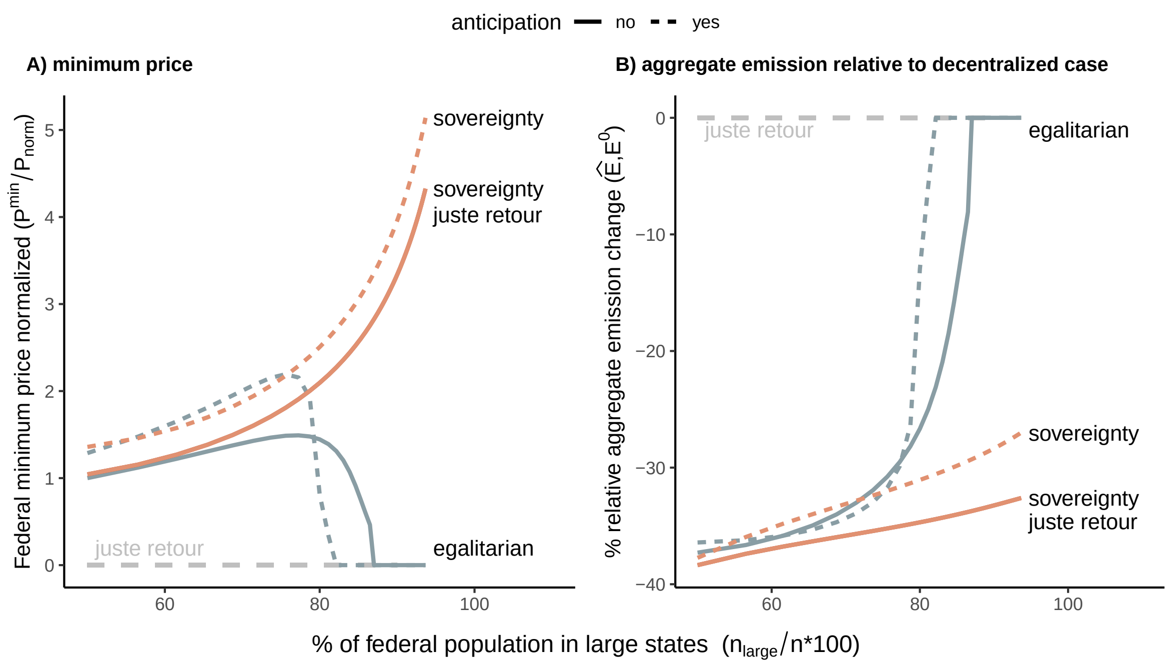

Figure 6: **Impact of population size differences** on the size of the A) feasible federal minimum prices and on the B) aggregate emission reduction relative to the decentralized aggregate emission level. Crossing the zero mark on the y-axis implies that the federal policy is infeasible.

[43] In Appendix L, we report the sensitivity of aggregate emissions and consumption w.r.t. variations of α_E and γ. There, we also provide a sensitivity analysis with larger capital per capita differences and compare log to linear utility from consumption (cf. Figure L.7).

5. Conclusion

> *"Given the slowness and conflict involved in achieving a global solution to climate change, recognizing the potential for building a more effective way of reducing greenhouse gas emissions at multiple levels is an important step forward."* Ostrom (2009, p. 38)

If we focus solely on efficiency, public good provision such as transboundary emission mitigation requires centralized policy solutions. Still, concerns about excessive burdens on individual actors and regions dominate political reality, which in turn jeopardizes voluntary participation in collective action. A prominent example is the mitigation of climate change in the European Union, where policy is lagging far behind what is required to achieve set targets. Creating a multinational political regime based on the voluntary participation of sovereign nations can serve as an entry point for more ambitious policies.

This paper examines the prerequisites for such an entry point. It analyzes the conditions for voluntary participation of states in federal emission policy if there are differences in wealth across states. Instead of seeking the first-best solution, which would require an omnipotent central regulator, we study three commonly used transfer rules and a uniform price to extract practically relevant insights for federal policy design. We consider the coexistence of federal-state policies so that member states can implement companion emissions pricing tailored to their individual needs.

We show that the existence of uniform federal emission prices guaranteeing the unanimity of the states depends on the wealth differences across them, the federal transfer rules, and on whether or not the states anticipate the federal transfers. We find that the internalization of vertical fiscal externalities (transfer anticipation) can go at the expense of internalizing transboundary emission damages. We also find that the richest state's utility is maximized at the lowest Pareto-dominant federal emission price (federal minimum price) as it is always the largest net donor of federal revenues. This is good news for environmental policy because from an efficiency point of view with a multinational uniform emission price, the richest entity should be the largest donor (cf. Chichilnisky and Heal, 1994; Shiell, 2003; Sandmo, 2007). If federal price negotiations start at zero and are raised until a state vetoes a further increase, then the richest state becomes both the enabler of federal policy (make) and the bottleneck (brake) on its stringency. If states also differ in population size, then the richest and largest state prefers the minimum price under federal sovereignty transfers and unanticipated juste retour transfers. In contrast, under federal egalitarian transfers, the richest and smallest state prefers the minimum price. Poor states always favor higher prices than the minimum price under any federal transfer considered. While the minimum federal price is always the price preferred by the richest state, our findings are ambiguous for the maximum federal price. The maximum federal price can either be the price preferred by the poorest state, or the price that makes the richest state indifferent between the federal and decentralized solutions. As both cases are possible, the ultimate answer depends on specific parameter values and functional forms. Last but not least, our simple analytical model proposes a structural approach to assess the willingness of individual states to participate in federal environmental or multinational policy.

Our results contribute to a better understanding of federal and multinational systems by showing i) how to find a federal emission price that ensures voluntary participation of all states; ii) how local and federal environmental policies interact in this context; and iii) which states represent a potential bottleneck for federal policy. Since our study finds that the richest state represents a bottleneck if negotiations start from very low policy stringency levels, our findings provide a starting point for informed negotiations on more ambitious federal environmental policies and regional minimum prices. Because the effectiveness of federal policy can be hampered if states adjust their policies in anticipation of the transfer, federal policymakers are well-advised to use egalitarian or sovereignty transfers rather than juste retour transfers. Moreover, in case of large differences in capital per capita across the states, sovereignty transfers are preferable because they always guarantee voluntary participation.

Some conclusions can be drawn for fostering international cooperation, which is also a key element of Article 6 of the Paris Climate Agreement. We show how and why the heterogeneity of countries in terms of wealth and population size can be an obstacle to multinational policies. When countries are too different, they may struggle to agree on joint policy because donor countries may perceive their burden as too substantial. Our study suggests that grouping negotiations around similar countries helps to form clubs that voluntarily establish international uniform carbon pricing schemes, as all cooperating parties would more easily agree on rules as every party would win. For instance, a uniform carbon pricing scheme can be achieved by linking carbon markets. For negotiating a uniform multinational minimum price in such a club, only the richest countries would need to come to the negotiating table. Depending on the transfer rule, one of the richest member countries of the club will favor the lowest of the consensual but optimal prices. All other countries would prefer even higher uniform prices.

Future research could build upon the present study. From a technical perspective, it can be interesting to explore other transfer rules and how they fare against an appropriately specified social optimum. In the same category, one could also study the implications of changing the structure of governmental decisions such that all governments are Nash-players or the richest state becomes the Stackelberg leader. Adding trade in private goods across states can provide additional insights into the incentives of net-importing and -exporting states. Some politically relevant extensions also come to mind. Population could be made mobile across states or, what is arguably even more relevant, immigration from outside the federation could be introduced. Migration could indeed have a substantial impact as it could change the patterns of capital per capita across states, the impact of environmental damages, and thus burden-sharing. Another pertinent extension would be to explore the role of mobile capital and technological change, when access to global capital markets can trigger or hamper investments into climate neutral technologies.

Appendix

Appendix A. First-order conditions of states

Note that $Y^i_{E_i}\left(\overline{K}_i, E_i\right) = p_i + P$ solves for E_i as a function of p_i and P, which we denote with **bold** letters by $\boldsymbol{E}_i\left(p_i, P\right)$. Moreover, since $Y^i\left(K_i, E_i\right)$ is homogeneous of degree one, the cost of producing Y^i is linear in output. Profits, thus, equal $\left(1 - mc_i\left(r_i, p_i, P\right)\right) Y^i$ where $mc_i\left(r_i, p_i, P\right)$ is marginal cost of producing Y^i. Zero profits, in turn, imply $mc_i = 1$, which solves for r_i as a function of p_i and P, which we denote $\boldsymbol{r}_i\left(p_i, P\right)$. Similarly, $\boldsymbol{Y}^i\left(p_i, P\right) = Y^i\left(\overline{K}_i, \boldsymbol{E}_i\left(p_i, P\right)\right)$ and $\boldsymbol{E}\left(p, P\right) = \sum_i \boldsymbol{E}_i\left(p_i, P\right)$ with $p = \left(p_1, ..., p_m\right)$. Consumption can thus be written as

$$\boldsymbol{c}_i\left(p, P\right) = \frac{1}{n_i}\left(Y^i\left(\overline{K}_i, \boldsymbol{E}_i\right) - P\boldsymbol{E}_i\right) + s_i\boldsymbol{E}P.$$

Since $\boldsymbol{E}\left(p, P\right) = \sum_i \boldsymbol{E}_i\left(p_i, P\right)$ and $\partial\boldsymbol{E}/\partial p_i = \partial\boldsymbol{E}_{\boldsymbol{i}}/\partial p_i$, the derivative of (2) with regards to p_i yields

$$\frac{\partial\boldsymbol{c}_i}{\partial p_i} = \frac{1}{n_i}\left(Y^i_{E_i} - P\right)\frac{\partial\boldsymbol{E}_i}{\partial p_i} + \frac{\partial s_i P\boldsymbol{E}_i}{\partial p_i}$$

and since $Y^i_{E_i} = p_i + P$ then

$$\frac{\partial\boldsymbol{c}_i}{\partial p_i} = \frac{p_i}{n_i}\frac{\partial\boldsymbol{E}_i}{\partial p_i} + \frac{\partial(s_i P\boldsymbol{E}_i)}{\partial p_i} \tag{A.1}$$

Maximizing $n_i\boldsymbol{u}^i\left(p, P\right) = n_i u^i\left(\boldsymbol{c}_i\left(p, P\right), \boldsymbol{E}\left(p, P\right)\right)$ w.r.t. p_i, state i sets

$$n_i\boldsymbol{u}^i_{p_i} = n_i\left(u^i_{c_i}\frac{\partial\boldsymbol{c}_i}{\partial p_i} + u^i_E\frac{\partial\boldsymbol{E}}{\partial p_i}\right) = 0,$$

which implies that

$$\boldsymbol{u}^i_{p_i} = u^i_{c_i}\frac{\partial\boldsymbol{c}_i}{\partial p_i} + u^i_E\frac{\partial\boldsymbol{E}}{\partial p_i} = 0.$$

Substitution of (A.1) yields

$$\boldsymbol{u}^i_{p_i} = u^i_E\frac{\partial\boldsymbol{E}_i}{\partial p_i} + u^i_{c_i}\left(\frac{p_i}{n_i}\frac{\partial\boldsymbol{E}_i}{\partial p_i} + \frac{\partial(s_i P\boldsymbol{E}_i)}{\partial p_i}\right) = 0$$

for all $i = 1, ..., m$. The unanticipated case* is derived by setting $\partial(s_i P\boldsymbol{E}_i)/\partial p_i = 0$. These m first order conditions (one per state) implicitly define p_i as a function of P, which we denote $\boldsymbol{p}_i\left(P\right)$.

Appendix B. Stackelberg-Leader's first order conditions

Let $\boldsymbol{p} = (\boldsymbol{p}_1(P), ..., \boldsymbol{p}_m(P))$. Using equation (2) and the reaction function of the firms, consumers and states (indicated with **bold** letters) from the market clearing and state problem (indicated with **bold** letters), the first-order condition when maximizing the utility of state i subject to $\boldsymbol{u}^j(\boldsymbol{p}(P), P) \geqq u^{0j}$ is

$$-\sum\nolimits_{j=1}^{m} \lambda_j u_E^j \frac{d\boldsymbol{E}}{dP} = \sum\nolimits_{j=1}^{m} \lambda_j u_{c_j}^j \left(\frac{1}{n_j} \frac{d\left(\boldsymbol{Y}^j - P\boldsymbol{E}_j\right)}{dP} + \frac{ds_j \boldsymbol{E} P}{dP} \right)$$

with $\lambda_i = 1$. For any function $\boldsymbol{F_i}(p, P)$ its total derivative with respect to P equals $\frac{d\boldsymbol{F}_i}{dP} = \frac{\partial \boldsymbol{F}_i}{\partial p_i}\frac{d\boldsymbol{p}_i}{dP} + \frac{\partial \boldsymbol{F}_i}{\partial P}$ and for $\boldsymbol{G}(p, P)$ is $\frac{d\boldsymbol{G}}{dP} = \sum_j \frac{\partial \boldsymbol{G}_j}{\partial p_j}\frac{d\boldsymbol{p}_j}{dP} + \frac{\partial \boldsymbol{G}}{\partial P}$ and

$$\lambda_j(\boldsymbol{u}^j(\boldsymbol{p}, P) - u^{0j}) = 0 \quad \text{for all } j \neq i \ .$$

Appendix C. Cobb-Douglas technology

Appendix C.1. Firm's problem

Suppose the production function is represented by a Cobb-Douglas technology, $Y^i(K_i, E_i) = AK_i^{\alpha_K} E_i^{\alpha_E}$. The objective of firm i reads

$$\max_{K_i, E_i} \left\{ (Y_i - r_i K_i - (p_i + P) E_i) \,\middle|\, Y^i = AK_i^{\alpha_K} E_i^{\alpha_E} \right\}.$$

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. Let $\Omega = \alpha_K^{\alpha_K} \alpha_E^{\alpha_E} A$. The marginal cost ($mc_i$) of producing good Y_i equals

$$mc_i = r_i^{\alpha_K} (p_i + P)^{\alpha_E} / \Omega. \tag{C.1}$$

Zero profits imply $mc_i = 1$. The first order conditions of firm i also imply the following conditional demand functions:

$$K_i = \alpha_K Y_i / r_i \quad \text{and} \quad E_i = \alpha_E Y_i / (p_i + P). \tag{C.2}$$

Appendix C.2. Market clearing and reaction functions of firms and consumers

Note that **bold** letters indicate functional forms solely depending on emission prices. Substituting equation (C.1) into the zero profit condition ($mc_i = 1$) and solving for r_i, we obtain

$$\boldsymbol{r}_i(p_i, P) = \left(\frac{\Omega}{(p_i + P)^{\alpha_E}} \right)^{\frac{1}{\alpha_K}}. \tag{C.3}$$

$\boldsymbol{r}_i$ is clearly decreasing in $(p_i + P)$, reflecting that if p_i or P increase, the remuneration that firms can make to the owners of capital must decrease. Using equation $(C.2)$, setting $Y^i = A\overline{K}_i^{\alpha_K} E_i^{\alpha_E}$ and solving for E_i it follows that

$$\boldsymbol{E}_i\,(p_i, P) = \left(\frac{\alpha_E A}{p_i + P}\right)^{\frac{1}{\alpha_K}} \overline{K}_i. \tag{C.4}$$

and, in turn

$$\boldsymbol{Y}^i\,(p_i, P) = \left(\frac{\alpha_E^{\alpha_E} A}{(p_i + P)^{\alpha_E}}\right)^{\frac{1}{\alpha_K}} \overline{K}_i.$$

Clearly, the return to capital, output and emissions of state i decrease with the per unit cost of emissions $p_i + P$. Aggregate emissions equal

$$\boldsymbol{E}\,(p, P) = \sum\nolimits_{j=1}^{m} \left(\frac{\alpha_E A}{p_j + P} \overline{K}_j^{\alpha_K}\right)^{\frac{1}{\alpha_K}}. \tag{C.5}$$

Consumption reads

$$\boldsymbol{c}_i\,(p, P) = \frac{\boldsymbol{Y}_i}{n_i} + \left(s_i \boldsymbol{E} - \frac{\boldsymbol{E}_i}{n_i}\right) P. \tag{C.6}$$

Equations equations $(C.3) - (C.6)$, represented in terms of p_i for $i = 1, ...m$ and P, are known to all governments and allow them to derive the reaction functions of consumers and firms.

Appendix D. Proof anticipated juste retour*

Using equation (C.6) a and the juste retour transfer criterion (Table 1) with anticipation, state governments set

$$\boldsymbol{c}_i = \frac{1}{n_i}\frac{p_i + P}{\alpha_E}\boldsymbol{E}_i.$$

The m first order conditions of all states (one per state) form a square system of equations in terms of $p_i + P$ for $i = 1, ...m$. This system of equations simultaneously solves for $p_i + P$ in terms of exogenous parameters which we denote by h_i for $i = 1, ...m$. Solving for p_i implies $p_i = h_i - P$ resulting in

$$\frac{d\boldsymbol{p}_i}{dP} = -1 \text{ for all } i = 1, ..., m.$$

Hence, the state governments react with a state price decrease of proportionally one unit in response to the federal government's price. This suggests that state prices offset federal prices one-to-one.

Moreover, one can readily verify that all the equations of the decentralized solution are equal to those of the juste retour with anticipation by setting $p_i^0 = p_i + P$. $\square$

Appendix E. Proofs Proposition 2

We indicate functions with **bold** letters but drop the dependencies for ease of reading. We use the assumptions as introduced in Section 4.1.

Unless otherwise specified, the following proofs all follow the same **steps**:

1) Express the indirect utility function in terms of P alone and calculate the first-order conditions.

2) Solve for the federal price P that maximizes the utility of state i, and denote this by P^i.

3) Evaluate the slope of the utility function of all consumers at $P = 0$. If it has a positive slope there are Pareto-improving federal prices. We then prove that each indirect utility function is concave in P and thus P^i globally maximizes the utility of consumer i.

4) Rank the prices $P^1, P^2, ..., P^m$.

Appendix E.1. Unanticipated egalitarian transfers

Step 1

If state government i does not anticipate the federal transfer this implies that $\partial (s_i P\boldsymbol{E}) / \partial p_i = 0$. Thus, the emission price of state i is

$$\boldsymbol{p}_i = n_M g\gamma \boldsymbol{E}^{\gamma-1} \quad \text{for } i = 1, ..., m. \tag{E.1}$$

Note that $p_i = p_j$. Substituting p_i from equation $(E.1)$ into equation $(C.5)$, we get

$$\boldsymbol{E} = \left(\frac{\alpha_E A}{n_M g\gamma \boldsymbol{E}^{\gamma-1} + P}\right)^{\frac{1}{\alpha_K}} \overline{K}. \tag{E.2}$$

from $(C.4)$ and $(C.5)$ it follows that

$$\boldsymbol{E}_i = \kappa_i \boldsymbol{E}, \tag{E.3}$$

Substituting for E_i from $(E.3)$ into $Y^i = AK_i^{\alpha_K} E_i^{\alpha_E}$ we get

$$\mathbf{Y}_i = A\overline{K}_i \left(\frac{\boldsymbol{E}}{\overline{K}}\right)^{\alpha_E}. \tag{E.4}$$

Using $(E.3)$ and $(E.4)$ implies

$$\mathbf{c}_i = \frac{1}{n_M}\left(Y^i - P\boldsymbol{E}_i\right) + s_i \boldsymbol{E} P = A\frac{\overline{K}_i}{n_M}\left(\frac{\boldsymbol{E}}{\overline{K}}\right)^{\alpha_E} + \left(s_i - \frac{\kappa_i}{n_M}\right) P\boldsymbol{E}. \tag{E.5}$$

Rearranging equation $(E.2)$ to solve for P we get

$$\boldsymbol{P} = \alpha_E A \left(\frac{\overline{K}}{\boldsymbol{E}}\right)^{\alpha_K} - n_M g\gamma \boldsymbol{E}^{\gamma-1} \tag{E.6}$$

Let $\boldsymbol{U}^i$ denote indirect utility as a function of P alone. Substituting $(E.6)$ into $(E.5)$, the indirect utility function $\boldsymbol{U}^i$ equals

$$\boldsymbol{U}^i = A\left(\alpha_K \frac{\kappa_i}{n_M} + \alpha_E s_i\right)\overline{K}^{\alpha_K}\boldsymbol{E}^{\alpha_E} - \left(\left(s_i n_M - \kappa_i\right)\gamma + 1\right) g\boldsymbol{E}^{\gamma}. \tag{E.7}$$

Step 2
Setting $s_i = 1/\left(m n_M\right) = \kappa_{av}/n_M$, $\boldsymbol{U}^i$ equals

$$\boldsymbol{U}^i = \frac{A}{n_M}\left(\alpha_E \kappa_{av} + \alpha_K \kappa_i\right)\overline{K}^{\alpha_K}\boldsymbol{E}^{\alpha_E} - \left(\left(\kappa_{av} - \kappa_i\right)\gamma + 1\right) g\boldsymbol{E}^{\gamma}.$$

If for some P and some j all the constraints $\boldsymbol{U}^{j\neq i} \geqq u^{0j\neq i}$ are not binding (that is, $\boldsymbol{U}^{j\neq i} > u^{0j\neq i}$), then the federal government's first-order condition becomes

$$\frac{d\boldsymbol{U}^i}{dP} = \boldsymbol{Z}_i \frac{d\boldsymbol{E}}{dP} \overset{!}{=} 0, \tag{E.8}$$

where $\boldsymbol{Z}_i$ reads

$$\boldsymbol{Z}_i = \frac{\alpha_E A}{n_M}\left(\chi_i - \theta_i\right)\left(\frac{\overline{K}}{\boldsymbol{E}}\right)^{\alpha_K} - \chi_i g\gamma\boldsymbol{E}^{\gamma-1} \tag{E.9}$$

with

$$\chi_i = 1 + \left(\kappa_{av} - \kappa_i\right)\gamma \text{ and } \theta_i = \chi_i - \left(\alpha_E \kappa_{av} + \alpha_K \kappa_i\right) \tag{E.10}$$

From the first-order condition in equation (E.8) follows that either $\boldsymbol{Z}_i$ or $d\boldsymbol{E}/dP$ or both must equal zero. Implicit differentiation of equation $(E.2)$ leads to

$$\frac{d\boldsymbol{E}}{dP} = -\frac{E}{\alpha_E \alpha_K A\left(\frac{\overline{K}}{E}\right)^{\alpha_K} + n_M g\gamma\left(\gamma - 1\right)E^{\gamma-1}}. \tag{E.11}$$

Since α_K, α_E, A, and g are positive, $\gamma \geq 1$, and $E > 0$, the numerator and denominator of the right-hand side are positive. It follows that $d\boldsymbol{E}/dP < 0$.Thus, $\boldsymbol{Z}_i$ must equal zero to satisfy the federal first-order condition (E.8).

Let E^i denote the federation's aggregate emissions E that makes $\boldsymbol{Z}_i$ equal to zero. To avoid introducing more notation we used E^i to denote the federation's aggregate emissions that maximize the utility of state i while E_i denotes state i 's emissions. We set $\boldsymbol{Z}_i = 0$ and solve equation (E.9) for $E = E^i$ which gives

$$E^i = \left(\frac{\alpha_E A}{n_M g\gamma}\frac{\alpha_E \kappa_{av} + \alpha_K \kappa_i}{1 + \left(\kappa_{av} - \kappa_i\right)\gamma}\overline{K}^{\alpha_K}\right)^{\frac{1}{\gamma - \alpha_E}} = \left(\frac{\alpha_E A}{n_M g\gamma}\frac{\chi_i - \theta_i}{\chi_i}\overline{K}^{\alpha_K}\right)^{\frac{1}{\gamma-\alpha_E}}. \tag{E.12}$$

Let P^i define the federal price P that maximizes the utility of a consumer in state i. Substitution of equation $(E.12)$ into equation $(E.6)$ and after some manipulations gives

$$P^i = \theta_i \left(\frac{\alpha_E A}{\chi_i} \overline{K}^{\alpha_K} \right)^{\frac{\gamma-1}{\gamma-\alpha_E}} \left(\frac{n_M g \gamma}{\chi_i - \theta_i} \right)^{\frac{\alpha_K}{\gamma-\alpha_E}} . \tag{E.13}$$

We proceed to show that P^i, if it exists, must be positive.

Step 3

Let l denote the subset of (low wealth or "poor") states with capital endowments shares $\kappa_i \equiv \overline{K}_i/\overline{K}$ smaller than the average share ($\kappa_{av} = \sum_i \kappa_i/m = 1/m$) and let h denote the subset of (high wealth) states with κ_i larger than average.

For $\chi_{i\in l}$ and $\theta_{i\in l}$ from equation $(E.10)$, follows that

$$\chi_{i\in l} > 1 \text{ and } \theta_{i\in l} > 0 \text{ and } \chi_{i\in l} - \theta_{i\in l} > 0.$$

Together with equation $(E.13)$, it follows that any $P^{i\in l} > 0$.

Let us examine the behavior of $\boldsymbol{U}^{i\in l}$ on the interval $[0, P^{i\in l})$ by evaluating the slope of $\boldsymbol{U}^{i\in l}$ at $P = 0$. We know from equation $(E.11)$ that $d\boldsymbol{E}/dP < 0$. Substitution of χ_i, θ_i and $\boldsymbol{E}|_{P=0}$ into $\boldsymbol{Z}_i$ from equation (E.9) and some algebraic manipulations yields

$$\boldsymbol{Z}_i|_{P=0} = -\,\theta_i g \gamma \boldsymbol{E}^{\gamma-1}\big|_{P=0} . \tag{E.14}$$

Since the parameters of equation $(E.14)$ are positive for $i \in l$, it follows that $\boldsymbol{Z}_{i\in l}|_{P=0} < 0$. As $d\boldsymbol{E}/dP < 0$, it follows from equation $(E.8)$ that $\boldsymbol{U}_{i\in l}$ has a positive slope at $P = 0$. Implying that if $\boldsymbol{U}^i$ is concave, only positive federal prices can make poorer states better off relative to the decentralized solution, whereas negative federal prices make them worse off. Consequently, if there is a role for the federal government, then any feasible P must be positive.

Let us examine what $P > 0$ implies for states in set h where $\kappa_{av} = 1/m < \kappa_{i\in h}$. To ensure a Pareto-improvement via $P > 0$ for all $i \in h$ the slope of $\boldsymbol{U}^{i\in h}$ must increase at $P = 0$. As in Proposition (2) let

$$\kappa_i < \kappa_{av} \frac{m + \gamma - \alpha_E}{1 + \gamma - \alpha_E} \text{ for } i = 1, ..., m$$

then $\theta_{i\in h} > 0$ and therefore $\boldsymbol{Z}_{i\in h}|_{P=0} < 0$, implying that $d\boldsymbol{U}^i/dP\big|_{P=0} > 0$ for all states $i = 1, ..., m$. This also implies that for a range of positive federal prices, the constraints $\boldsymbol{U}^j \geqq u^{0j}$ are not binding ($\boldsymbol{U}^j > u^{0j}$).

We now prove that $\boldsymbol{U}^i$ decreases on the interval (P^i, ∞). Let $P^b > P^i$ and evaluate the slope of equation $(E.8)$ at P^b. Using equation $(E.12)$ we get

$$\left(E^i\right)^{\gamma-\alpha_E} = \frac{\alpha_E A}{n_M g \gamma} \frac{(\chi_i - \theta_i)}{\chi_i} \overline{K}^{\alpha_K}.$$

Since $d\boldsymbol{E}/dP < 0$, then $P^b > P^i$ implies

$$E^{\gamma-\alpha_E}\big|_{P=P^b} < (E^i)^{\gamma-\alpha_E} = \frac{\alpha_E A}{n_M g \gamma} \frac{(\chi_i - \theta_i)}{\chi_i} \overline{K}^{\alpha_K}.$$

Rearranging yields

$$0 < \frac{\alpha_E A\left(\chi_i - \theta_i\right)}{n_M}\left(\frac{\overline{K}}{E}\right)^{\alpha_K} - \chi_i g\gamma\ E^{\gamma-1}\Big|_{P=P^b}. \tag{E.15}$$

The right-hand side of equation $(E.15)$ is nothing other than $\boldsymbol{Z}_i|_{P=P^b}$ and hence $\boldsymbol{Z}_i|_{P=P^b} > 0$ implying that $d\boldsymbol{U}^i/dP\big|_{P=P^b} = \boldsymbol{Z}_i d\boldsymbol{E}/dP|_{P=P^b} < 0$ for all i. This proves that $\boldsymbol{U}^i$ is a concave function with maximum $P^i > 0$.

Step 4

We now rank the different P^is for $i = 1, ..., m$. From equation $(E.12)$ one can readily verify that $\frac{\partial E^i}{\partial \kappa_i} > 0$, and from equation $(E.11)$ follows that the higher E^i is the lower P^i must be. Therefore, the federal prices rank $P^m < ... < P^1$. □

*Appendix E.2. Anticipated egalitarian transfers**

This proof is analogous to (*Appendix* E.1), 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. We omit the asterisk *.

Step 1

$$\boldsymbol{p_i} = n_M g\gamma \boldsymbol{E}^{\gamma-1} - \frac{P}{m} \tag{E.16}$$

Note that $p_i = p_j$.

$$\boldsymbol{E} = \left(\frac{\alpha_E A\overline{K}^{\alpha_K}}{n_M g\gamma \boldsymbol{E}^{\gamma-1} + \left(1 - \frac{1}{m}\right)P)}\right)^{\frac{1}{\alpha_K}} \tag{E.17}$$

$$\boldsymbol{U}^i = A\overline{K}^{\alpha_K}\boldsymbol{E}^{\alpha_E}\frac{\left(\alpha_K m - 1\right)\kappa_i + \alpha_E}{n - n_M} + \left(\left(\frac{m\kappa_i - 1}{m-1}\right)\gamma - 1\right)g\boldsymbol{E}^{\gamma}$$

Step 2

$$\frac{d\boldsymbol{U^i}}{dP} = \boldsymbol{Z}_i\frac{d\boldsymbol{E}}{dP} \stackrel{!}{=} 0$$

where

$$\boldsymbol{Z}_i = \frac{n\chi_i - n_M}{n - n_M}\left(m\alpha_E A\left(\frac{\overline{K}}{\boldsymbol{E}}\right)^{\alpha_K}\frac{\chi_i - \theta_i - \kappa_i\kappa_{av}}{n\chi_i - n_M} - g\gamma\boldsymbol{E}^{\gamma-1}\right)$$

and

$$\frac{d\boldsymbol{E}}{dP} = -\frac{m-1}{m}\frac{\boldsymbol{E}}{\alpha_E\alpha_K A\left(\frac{\overline{K}}{\boldsymbol{E}}\right)^{\alpha_K} + n_M g\gamma\left(\gamma - 1\right)\boldsymbol{E}^{\gamma-1}} < 0.$$

Solving $\boldsymbol{Z}_i = 0$ for E yields

$$E^i = \left(\frac{m\alpha_E A}{g\gamma} \frac{\chi_i - \theta_i - \kappa_i \kappa_{av}}{n\chi_i - n_M} \overline{K}^{\alpha_K} \right)^{\frac{1}{\gamma - \alpha_E}} . \tag{E.18}$$

Substituting equation (E.18) into equation (E.17) and solving for P leads to

$$P^i = \frac{(\alpha_E A)^{\frac{\gamma-1}{\gamma-\alpha_E}}}{(m-1)\kappa_{av}} \left(g\gamma \frac{\kappa_{av}\,(n\chi_i - n_M)}{\chi_i - \theta_i - \kappa_i\kappa_{av}} \overline{K}^{\gamma-1} \right)^{\frac{\alpha_K}{\gamma-\alpha_E}} \left(1 - \frac{\chi_i - \theta_i - \kappa_i \kappa_{av}}{\chi_i - \kappa_{av}} \right). \tag{E.19}$$

Step 3

Evaluating Z_i at $P = 0$ yields

$$Z_i|_{P=0} = -\frac{g\gamma n}{n - n_M} \left(\theta_i + (\kappa_i - 1)\kappa_{av}\right) \boldsymbol{E}^{\gamma-1}\Big|_{P=0} .$$

Substitute θ_i from (E.10) to get

$$0 < \theta_i + (\kappa_i - 1)\kappa_{av} = \underbrace{1 + (\gamma - \alpha_E)(\kappa_{av} - \kappa_i) + \kappa_i\kappa_{av}}_{>1} - \underbrace{(\kappa_i + \kappa_{av})}_{<1} \text{ for } i \in l.$$

Thus, for $i \in l$ follows that $Z_{i\in l}|_{P=0} < 0$. Just as argued in the previous proof, it must be that $P^i > 0$ for $i \in l$.

Let

$$\kappa_i < \kappa_{av} \frac{m - \alpha_E + \gamma - 1}{1 - \alpha_E + \gamma - \kappa_{av}} \text{ for } i = 1, ..., m.$$

then also for $i \in h$ it follows that $\theta_i + (\kappa_i - 1)\kappa_{av} > 0$ and consequently $Z_i|_{P=0} < 0$ for all i.

Consider equation (E.18). Since $d\boldsymbol{E}/dP < 0$ and $P^b > P^i$, we have

$$\boldsymbol{E}^{\gamma-\alpha_E}\big|_{P^b} < \left(E^i\right)^{\gamma-\alpha_E} = \frac{\alpha_E A}{g\gamma n_M} \frac{\chi_i - \theta_i - \kappa_i\kappa_{av}}{\chi_i - \kappa_{av}} \overline{K}^{\alpha_K}.$$

After rearranging, we get

$$0 < \boldsymbol{Z}|_{P^b} = \frac{n\chi_i - n_M}{n - n_M} \left(m\alpha_E A \left(\frac{\overline{K}}{\boldsymbol{E}|_{P^b}} \right)^{\alpha_K} \frac{\chi_i - \theta_i - \kappa_i\kappa_{av}}{n\chi_i - n_M} - g\gamma\ \boldsymbol{E}|_{P^b}{}^{\gamma-1} \right)$$

and hence $Z_i|_{P^b} > 0$. Therefore, it follows that $\boldsymbol{U}^i$ is a concave function with a unique maximum at $P^i > 0$.

Step 4

The P^is can be ranked by considering

$$\frac{\partial E^i}{\partial \kappa_i} = \frac{n - n_M}{\gamma - \alpha_E} \frac{E^i}{\chi_i - \theta_i - \kappa_i\kappa_{av}} \frac{\alpha_K + \kappa_{av}\,(\gamma - 1)}{n\chi_i - n_M}$$

From (E.18) it follows that the product $(\chi_i - \theta_i - \kappa_i\kappa_{av})(n\chi_i - n_M)$ is positive and $\partial E^i/\partial\kappa_i$ is therefore positive. Just as in the previous proof it follows that $P^m < ... < P^1$.
$\square$

Appendix E.3. Unanticipated sovereignty transfers

Note that decentralized state prices equal $p_i^0 = n_M g\gamma \left(E^0\right)^{\gamma-1}$. Hence, the decentralized state emission prices are all equal and the ratio of state-i's emissions to aggregate federal emissions equals κ_i. In turn, implying that $s_i^{SO} = E_i^0/(E^0 n_M) = \kappa_i/n_M$.

Step 1

Almost all equations are analogous to those in Proof Appendix E.1, more specifically, equations (E.1)-(E.3). Consumption and utility equal

$$\boldsymbol{c}_i = \frac{\kappa_i}{n_M} A\overline{K}^{\alpha_K}\boldsymbol{E}^{\alpha_E}$$

$$\boldsymbol{U}^i = \frac{\kappa_i}{n_M} A\overline{K}^{\alpha_K}\boldsymbol{E}^{\alpha_E} - g\boldsymbol{E}^{\gamma}$$

Step 2

$$\frac{d\boldsymbol{U}^i}{dP} = \boldsymbol{Z}_i\frac{d\boldsymbol{E}}{dP} = 0 \tag{E.20}$$

where $\boldsymbol{Z}_i = \alpha_E A\frac{\kappa_i}{n_M}\left(\frac{\overline{K}}{\boldsymbol{E}}\right)^{\alpha_K} - g\gamma\boldsymbol{E}^{\gamma-1}$and $d\boldsymbol{E}/dP < 0$ as it equals equation (E.11). Thus, $\boldsymbol{Z}_i$ must equal zero. Setting $\boldsymbol{Z}_i = 0$ and solving for E^i we get

$$E^i = \left(\frac{\alpha_E A}{g\gamma}\frac{\kappa_i}{n_M}\overline{K}^{\alpha_K}\right)^{\frac{1}{\gamma-\alpha_E}}. \tag{E.21}$$

By substituting the right-hand side of E^i for E in equation $(E.2)$ and into $(E.6)$, we get

$$P^i = (1-\kappa_i)\left(\left(\alpha_E A\overline{K}^{\alpha_K}\right)^{\gamma-1}\left(\frac{g\gamma n_M}{\kappa_i}\right)^{\alpha_K}\right)^{\frac{1}{\gamma-\alpha_E}}. \tag{E.22}$$

Note that all terms in equation $(E.22)$ are positive. Thus, prices that solve the federal government's problem exist and are independent of any restriction or capital heterogeneity constraints.

Step 3

Consider P on the interval $[0, P^i)$. Since $d\boldsymbol{E}/dP < 0$, using $\boldsymbol{Z}_i$ from equation $(E.20)$ and substituting E^0 we get

$$\boldsymbol{Z}_i|_{P=0} = -(1-\kappa_i)\, g\gamma\left(\boldsymbol{E}|_{P=0}\right)^{\gamma-1} < 0.$$

Thus, $d\boldsymbol{U}^i/dP\big|_{P=0} = \boldsymbol{Z}_i d\boldsymbol{E}/dP|_{P=0} > 0$ and $\boldsymbol{U}^i$ increases on the interval $[0, P^i)$.

Consider P on the interval (P^i, ∞). From equation $(E.21)$ follows that

$$\left(E^i\right)^{\gamma-\alpha_E} = \frac{\alpha_E A}{g\gamma}\frac{\kappa_i}{n_M}\overline{K}^{\alpha_K}. \tag{E.23}$$

Since $d\boldsymbol{E}/dP < 0$ it follows that $P^b > P^i$ implies $\boldsymbol{E}^{\gamma-\alpha_E}\big|_{P=P^b} < (E^i)^{\gamma-\alpha_E}$. Using equation (E.23) we get

$$0 < \alpha_E A \frac{\kappa_i}{n_M} \left(\frac{\overline{K}}{\boldsymbol{E}}\right)^{\alpha_K} - g\gamma \boldsymbol{E}^{\gamma-1}\Bigg|_{P=P^b}. \tag{E.24}$$

The right-hand side of equation $(E.24)$ is $\boldsymbol{Z}_i|_{P=P^b}$, implying $d\boldsymbol{U}^i/dP < 0$ in the interval (P^i, ∞). Hence $\boldsymbol{U}^i$ is a concave function with a unique maximum at $P^i > 0$.

Step 4

Consider equation $(E.21)$ and calculate $\partial E^i/\partial\kappa_i$ to see that federal prices rank as $P^m < ... < P^1$. □

Appendix E.4. Unanticipated juste retour transfers

Note that

$$\boldsymbol{s}_i = \frac{1}{n_M}\frac{\boldsymbol{E}_i}{\boldsymbol{E}} = \frac{\kappa_i}{n_M}.$$

and, therefore, the solution reduces to that of the sovereignty transfer rule under the unanticipated case, refer to (Appendix E.3). □

Appendix F. Proof of Proposition 3

Since feasible federal prices are those that leave consumers at least as well off as the decentralized solution, the decentralized solution becomes a reference point for the highest admissible federal price. Using equation (7), the decentralized emission price of state j equals

$$p^0 \equiv p_j^0 = n_M \gamma g E^{\gamma-1} \tag{F.1}$$

Substituting p^0 from (F.1) into equation (C.5), and setting $P = 0$ decentralized aggregate emissions equal

$$E^0 = \left(\frac{A\alpha_E}{n_M\gamma g}\right)^{\frac{1}{\gamma-\alpha_E}} \overline{K}^{\frac{\alpha_K}{\gamma-\alpha_E}} \tag{F.2}$$

Setting $P = 0$ in equation (C.4) and adding over all i implies $E_j^0 = \kappa_j E^0$.Using (C.6) and setting $P = 0$, decentralized consumption in state j equals

$$c_j^0 = \frac{A\overline{K}_j^{\alpha_K}\left(E_i^0\right)^{\alpha_E}}{n_M} = \frac{\kappa_j}{n_M} A \left(\frac{A\alpha_E}{n_M\gamma g}\right)^{\frac{\alpha_E}{\gamma-\alpha_E}} \overline{K}^{\frac{\alpha_K\gamma}{\gamma-\alpha_E}} \tag{F.3}$$

Substituting (F.2) and (F.3) into the utility function $c_j - gE^\gamma$, the decentralized utility level of state j equals

$$u^{0j} = \left(\frac{A\alpha_E}{n_M\gamma g}\right)^{\frac{\alpha_E}{\gamma-\alpha_E}} \frac{A}{n_M} \overline{K}^{\frac{\alpha_K\gamma}{\gamma-\alpha_E}} \left(\kappa_j - \frac{\alpha_E}{\gamma}\right) \tag{F.4}$$

Let us now introduce a dummy type variable π that equals zero in the case of unanticipated transfers and equals one in the case of anticipated transfers. Noticing that the proposition considers all unanticipated transfers, but only anticipated egalitarian transfers, the indirect utility function of state j similar to that in equation (E.7) equals

$$\boldsymbol{U}^j = \frac{\left(\alpha_E s_j n_M + \left(\alpha_K - \frac{\pi}{m}\right)\kappa_j\right)\frac{A\overline{K}^{\alpha_K}E^{\alpha_E}}{n_M} - \left(1 + \left(s_j n_M - \kappa_j\right)\gamma - \frac{\pi}{m}\right) gE^{\gamma}}{1 - \frac{\pi}{m}}. \tag{F.5}$$

We now search for the federal price P^j_{ind} that would leave consumers in state j indifferent between the decentralized and federal solution. If a state q existed such that the federal price that maximizes the utility of consumer q (denote by P^q) equals $P^q = P^j_{ind}$, then using equations (E.12), (E.18) and (E.21) the aggregate level of emission associated with price P^q would equal

$$E^q = \left(\frac{\alpha_E s_q n_M + (\alpha_K - \frac{\pi}{m})\kappa_q}{1 + \left(s_q n_M - \kappa_q\right)\gamma - \frac{\pi}{m}}\frac{\alpha_E A}{n_M \gamma g}K^{\alpha_K}\right)^{\frac{1}{\gamma - \alpha_E}}$$

with s_q equal to $1/(n_M m)$ in the case of egalitarian transfers and equal to κ_q/n_M in the case of sovereignty and juste retour transfers. We now find which conditions guarantee that the decentralized utility level of a consumer in state j equals the utility level at $P^j_{ind} = P^q$. Substituting E^q into (F.5) and setting $\boldsymbol{U}^j$ equal to u^{0j} and simplifying we get

Egalitarian unanticipated: $\kappa_j - \frac{\alpha_E}{\gamma} = \left(\frac{(\chi_q - \theta_q)^{\gamma}}{\chi_q^{\alpha_E}}\right)^{\frac{1}{\gamma-\alpha_E}}\left(\frac{\chi_j - \theta_j}{\chi_q - \theta_q} - \frac{\chi_j}{\chi_q}\frac{\alpha_E}{\gamma}\right)$

Egalitarian anticipated: $\kappa_j - \frac{\alpha_E}{\gamma} = \frac{m}{m-1}\left(\frac{\left(\chi_q - \theta_q - \frac{\kappa_q}{m}\right)^{\gamma}}{\left(\chi_q - \frac{1}{m}\right)^{\alpha_E}}\right)^{\frac{1}{\gamma-\alpha_E}}\left(\frac{\chi_j - \theta_j - \frac{\kappa_j}{m}}{\chi_q - \theta_q - \frac{\kappa_q}{m}} - \frac{\chi_j - \frac{1}{m}}{\chi_q - \frac{1}{m}}\frac{\alpha_E}{\gamma}\right)$

Sovereignty unanticipated: $\kappa_j = \frac{\alpha_E}{\gamma}\frac{1 - \kappa_q^{\frac{\gamma}{\gamma-\alpha_E}}}{1 - \kappa_q^{\frac{\alpha_E}{\gamma-\alpha_E}}}$

Juste retour unanticipated: $\kappa_j = \frac{\alpha_E}{\gamma}\frac{1 - \kappa_q^{\frac{\gamma}{\gamma-\alpha_E}}}{1 - \kappa_q^{\frac{\alpha_E}{\gamma-\alpha_E}}}$

with $\chi_j = 1 + (\kappa_{av} - \kappa_j)\gamma$, $\theta_j = \chi_j - (\alpha_E\kappa_{av} + \alpha_K\kappa_j)$, and $\kappa_{av} = 1/m$. While explicitly solving for κ_q is impossible, parameters α_E, γ, the number of states m, and the capital share of state j (κ_j) characterize $\kappa_q = \kappa^q(\kappa_j)$. The solution to κ_q substituted for κ_i into prices (E.13), (E.19) and (E.22) leads to the highest federal price that state j would be willing to "allow". Clearly, if $\kappa_i > \kappa_q$ for all i then $P^m < P^{m-1} < ... < P^1 < P^i_{ind}$ and the highest federal price equals P^1as any price higher than P^1 would make all consumers worse off. In that case the prices P^i_{ind} become irrelevant. Instead if κ_i¡κ_q for some i then prices P^j_{ind} matter. We next show that if $\kappa_i < \kappa_q$ for some i the price P^j_{ind} of the richest sate (P^m_{ind}) is the highest admissible federal price. To do so we show that $P^m_{ind} < P^j_{ind}$ for all $j \neq m$. Let E^j_{ind} denote the level of emissions that would leave consumer j indifferent between her decentralized utility level and the utility level with aggregate emissions E^j_{ind} (at that point the corresponding federal price would be

P^j_{ind}). Equating decentralized utility (F.4) to the utility of state j (F.5) for all j implies

$$G = \underbrace{\frac{\left(\alpha_E s_j n_M + \left(\alpha_K - \frac{\pi}{m}\right)\kappa_j\right)\frac{A\overline{K}^{\alpha_K}E^{\alpha_E}}{n_M} - \left(1 + \left(s_j n_M - \kappa_j\right)\gamma - \frac{\pi}{m}\right) gE^{\gamma}}{1 - \frac{\pi}{m}}}_{\boldsymbol{U}^j}$$
$$- \underbrace{\left(\frac{A\alpha_E}{n_M\gamma g}\right)^{\frac{\alpha_E}{\gamma-\alpha_E}} \frac{A}{n_M}\overline{K}^{\frac{\alpha_K\gamma}{\gamma-\alpha_E}}\left(\kappa_j - \frac{\alpha_E}{\gamma}\right)}_{u^{0j}}$$
$$= 0$$

Implicit differentiation implies that in the neighborhood of E^j_{ind} the following holds

$$\frac{dE}{d\kappa_j}\mid_{E\in(E^j_{ind}-\epsilon,E^j_{ind}+\epsilon)} = -\frac{\frac{\partial G}{\partial \kappa_j}}{\frac{\partial G}{\partial E}}$$

Notice that since the utility function is concave in P, it follows that in the neighborhood of P^j_{ind} the derivative dU^j/dP is negative. Because dE/dP is negative then it follows that the derivative of G with regard to E around E^j_{ind} is positive (i.e. $\frac{\partial G}{\partial E} > 0$).

Appendix F.1. Egalitarian transfers

The derivative $\partial G/\partial \kappa_j$ in the case of egalitarian transfers, and after some simplifications, reduces to

$$\frac{\partial G}{\partial \kappa_j} = -a\left[b - \gamma g\left(E^j_{ind}\right)^{\gamma}\right]$$

with

$$a = \frac{1}{\gamma}\left(\frac{\alpha_K + \gamma\kappa_{av} - \pi\kappa_{av}}{\alpha_K\kappa_j + \alpha_E\kappa_{av} - \pi\kappa_{av}\kappa_j}\right) > 0$$

and

$$b = \left(\frac{A\alpha_E}{n_M}\right)^{\frac{\gamma}{\gamma-\alpha_E}}\left(\frac{1}{\gamma g}\right)^{\frac{\alpha_E}{\gamma-\alpha_E}}\overline{K}^{\frac{\alpha_K\gamma}{\gamma-\alpha_E}} > 0$$

When π equals zero a is clearly positive, and when π equals one a is positive as long as $\alpha_K > \alpha_E$ (i.e. $\alpha_K > 1/2$). Notice that since $P^j < P^j_{ind}$ then $E^j > E^j_{ind}$ and, therefore, $b - \gamma g E^j < b - \gamma g E^j_{ind}$. Thus, if $0 < b - \gamma g E^j$ then also $0 < b - \gamma g E^j_{ind}$. Using E^j from (E.12), and (E.18) and simplifying we get

$$b - \gamma g E^j = \left[1 - \left(\frac{\alpha_K\kappa_j + \kappa_{av}\alpha_E - \frac{\pi}{m}\kappa_j}{1 + (\kappa_{av} - \kappa_j)\gamma - \frac{\pi}{m}}\right)^{\frac{\gamma}{\gamma-\alpha\mathrm{E}}}\right] b \tag{F.6}$$

One can readily verify that since the restriction for egalitarian unanticipated (anticipated) $\kappa_i < \kappa_{EG}$ ($\kappa_i < \kappa^*_{EG}$) holds then the term in brackets in (F.6) is positive and, therefore, $0 < b - \gamma g E^j_{ind}$. This implies that $\frac{\partial G}{\partial \kappa_j}$ is negative, and thus $\frac{dE}{d\kappa_j} > 0$ in the neighborhood of E^j_{ind}. In other words, the richer a state is (larger κ_i) the larger the aggregate level of emission E_{ind}^{j} that leaves sate j indifferent between decentralized utility and the utility level when emissions equal E_{ind}^{j}. Thus, $E_{ind}^{m} > E_{ind}^{m-1} ... > E_{ind}^{1}$. Since $dE/dP < 0$ it follows that $P_{ind}^{m} < P_{ind}^{m-1} ... < P_{ind}^{1}$. Thus, any price higher than P_{ind}^{m} violates the Pareto constraint of state m. Therefore, if any κ_i is smaller than the associated $\kappa_q = \kappa^q(\kappa_m)$ of state m then P_{ind}^{m} is the highest federal price that makes no state worse off compared to the decentralized solution.

Appendix F.2. Unanticipated sovereignty and juste retour transfers

For the case of unanticipated sovereignty and just return transfers $\frac{\partial G}{\partial \kappa_j}$ reduces to

$$\frac{\partial G}{\partial \kappa_j} = -\frac{A}{n_M}\overline{K}^{\alpha_K}\left(\left(E^0\right)^{\alpha_E} - E^{\alpha E}\right)$$

which is always negative since $E^0 > E$. Similar arguments as those above lead to the conclusion that P_{ind}^{m} is the highest federal price.

Appendix G. Anticipated sovereignty transfers*

This proof is analogous to Appendix E.3, except for the assumption that each state government anticipates the federal transfer and we set $\gamma = 1$.

Step 1

Using (6b) and $s_i^{SO} = E_i^0/(E^0 n_M) = \kappa_i/n_M$ state prices equal

$$\boldsymbol{p}_i = n_M g - \kappa_i P$$

and, therefore

$$\boldsymbol{E}_i = \left(\frac{\alpha_E A}{n_M g + (1-\kappa_i)P}\right)^{\frac{1}{\alpha_K}}\overline{K}_i,$$

rearranging yields

$$\left(\frac{\boldsymbol{E}_i}{\overline{K}_i}\right)^{\alpha_K} = \frac{\alpha_E A}{n_M g + (1-\kappa_i)P} \tag{G.1}$$

or

$$P = \left(\alpha_E A\left(\frac{\overline{K}_i}{\boldsymbol{E}_i}\right)^{\alpha_K} - n_M g\right)\frac{1}{1-\kappa_i}.$$

Aggregate emissions equal

$$\boldsymbol{E} = \sum_j \left(\frac{\alpha_E A}{n_M g + (1-\kappa_j)P}\right)^{\frac{1}{\alpha_K}}\overline{K}_j$$

and consumption (using $s_i^{SO} = E_i^0/(E^0 n_M) = \kappa_i/n_M$) reads

$$\boldsymbol{c}_i = \frac{1}{n_M}\left(\boldsymbol{Y}_i + (\kappa_i \boldsymbol{E} - \boldsymbol{E}_i)P\right)$$

Using $Y_i = (p_i + P)\, E_i/\alpha_E$ and $\boldsymbol{p}_i = n_M g - \kappa_i P$ we get

$$\boldsymbol{U}_i = \frac{1}{n_M}\left(\frac{n_M g + (\alpha_K - \kappa_i)\, P}{\alpha_E}\boldsymbol{E}_i + (\kappa_i P - n_M g)\, \boldsymbol{E}\right)$$

Step 2

Taking the derivative of $\boldsymbol{U}^i$ and using (G.1) we get

$$\frac{d\boldsymbol{U}_i}{dP} = \frac{1}{n_M}\left(\kappa_i \boldsymbol{E} + (-g n_M + \kappa_i P) \sum\nolimits_j \frac{(1-\kappa_j)\, \boldsymbol{E}_j}{A\alpha_E\alpha_K \left(\frac{K_j}{\boldsymbol{E}_j}\right)^{\alpha_K}}\right. \tag{G.2}$$

$$\left. + \left(\frac{\alpha_K - \kappa_i}{\alpha_E} - \frac{\left(\frac{\boldsymbol{E}_i}{K_i}\right)^{\alpha_K} g n_M + A\,(\alpha_K - \kappa_i)}{A\alpha_E\alpha_K}\right)\boldsymbol{E}_i. \right. \tag{G.3}$$

Step 3

Evaluate $d\boldsymbol{U}^i/dP$ at $P = 0$ by substituting E_i^0 and E^0 to get

$$\left.\frac{d\boldsymbol{U}^i}{dP}\right|_{P=0} = \frac{E^0}{n_M\alpha_K}\sum\nolimits_{j\neq i}(1-\kappa_j)\,\kappa_j > 0.$$

□

Appendix H. Proof of Proposition 5

Let $n_M = 1$ and $\overline{K}_1 < \ldots < \overline{K}_m$. Suppose that $\alpha_E/\gamma < \kappa_i$.

Consider the definitions of χ_i and θ_i given by $\chi_i = 1 + (\kappa_{av} - \kappa_i)\,\gamma$ and $\theta_i = \chi_i - (\alpha_E\kappa_{av} + \alpha_K\kappa_i)$. After some algebraic manipulations, we get that $\alpha_E/\gamma < \kappa_i$ implies

$$\kappa_i < \frac{\chi_i - \theta_i}{\chi_i}. \tag{H.1}$$

Consider the emission levels in closed form with unanticipated federal transfers from equations (E.12), and (E.21) to see that if inequality (H.1) holds, then $E^i_{SO} = E^i_{JR} < E^i_{EG}$. Proceed in a similar manner to prove that $\alpha_E/\gamma > \kappa_i$ implies $E^i_{SO} = E^i_{JR} > E^i_{EG}$.

Appendix I. Capital-homogeneity-share consideration

$$\left.\frac{\partial\kappa_{EG}}{\partial\gamma}\right|_{m=2} = \left.\frac{\partial\kappa_{EG}}{\partial\alpha_K}\right|_{m=2} = -\frac{1}{2}\frac{1}{(\alpha_K+\gamma)^2} < 0 \qquad \text{unanticipated}$$

$$\left.\frac{\partial\kappa^*_{EG}}{\partial\gamma}\right|_{m=2} = \left.\frac{\partial\kappa^*_{EG}}{\partial\alpha_K}\right|_{m=2} = -\frac{1}{(2(\alpha_K+\gamma)-1)^2} < 0 \qquad \text{anticipated}$$

Appendix J. General CES-function

Appendix J.1. Firm's problem

Suppose the production function is represented by a CES technology. The objective of firm i reads

$$\max_{K_i,E_i}\left\{(Y_i - r_iK_i - (p_i+P)\,E_i)\,\middle|\, Y^i = A\left(\alpha_K K_i^{\frac{\sigma-1}{\sigma}} + \alpha_E E_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}\right\}$$

where parameters $\alpha_K > 0$, $\alpha_E > 0$ are the output elasticities of capital and emissions, respectively, with $\alpha_K + \alpha_E = 1$, σ is the substitution elasticity, and $A > 0$ is an efficiency parameter. Due to zero profits marginal cost (mc_i) of producing good Y_i equals

$$mc_i = 1 = \left(\alpha_K^\sigma r_i^{1-\sigma} + \alpha_E^\sigma (p_i+P)^{1-\sigma}\right)^{\frac{1}{1-\sigma}} A^{-1}. \tag{J.1}$$

The first order conditions of firm i also imply the following conditional demand levels of capital and emissions:

$$K_i = \left(\frac{\alpha_K A^{\frac{\sigma-1}{\sigma}}}{r_i}\right)^\sigma Y^i \text{ and } E_i = \left(\frac{\alpha_E A^{\frac{\sigma-1}{\sigma}}}{p_i+P}\right)^\sigma Y^i.$$

Appendix J.2. Market clearing and reaction functions of firms and consumers

From equation (J.1) follows that

$$0 < \alpha_K^\sigma r_i^{1-\sigma} = A^{1-\sigma} - \alpha_E^\sigma (p_i+P)^{1-\sigma} \equiv \boldsymbol{\phi}_i(p_i, P)$$

and

$$\frac{\partial \boldsymbol{\phi}_i}{\partial p_i} = \frac{\partial \boldsymbol{\phi}_i}{\partial P} = -\frac{\alpha_E^\sigma(1-\sigma)}{(p_i+P)^\sigma} < 0.$$

$$\boldsymbol{r}_i\,(p_i, P) = \left(\frac{\boldsymbol{\phi}_i}{\alpha_K^\sigma}\right)^{\frac{1}{1-\sigma}}$$

Using the market clearing condition for capital and $Y^i_{E_i} = p_i + P$ we obtain

$$\boldsymbol{E}_i\,(p_i, P) = \left(\frac{\alpha_E}{p_i+P}\right)^\sigma \left(\frac{\boldsymbol{\phi}_i}{\alpha_K}\right)^{\frac{\sigma}{1-\sigma}} \overline{K}_i \tag{J.2}$$

and

$$\boldsymbol{E}\,(p, P) = \sum\nolimits_{j=1}^m \left(\frac{\alpha_E}{p_j+P}\right)^\sigma \left(\frac{\boldsymbol{\phi}_j}{\alpha_K}\right)^{\frac{\sigma}{1-\sigma}} \overline{K}_j.$$

These equations correspond to the reaction functions of firms and consumers. Since ϕ_i decreases with the per unit cost of emissions $p_i + P$, also $\boldsymbol{r}_i, \boldsymbol{Y}^i, \boldsymbol{E}_i$and $\boldsymbol{E}$ decrease in $p_i + P$, and

$$\frac{\partial \boldsymbol{E}_i}{\partial p_i} = \frac{\partial \boldsymbol{E}}{\partial p_i} = -\frac{A^{1-\sigma}\sigma \boldsymbol{E}_i}{(p_i + P)\boldsymbol{\phi}_i} < 0.$$

Substituting E_i from (J.2) into $Y^i = A\left(\alpha_K K_i^{\frac{\sigma-1}{\sigma}} + \alpha_E E_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$, output can be written as a function , of p_i, and P as follows

$$\boldsymbol{Y}^i\left(p_i, P\right) = \left(\frac{(p_i + P)A^{\frac{1-\sigma}{\sigma}}}{\alpha_E}\right)^{\sigma} \boldsymbol{E}_i(p_i, P).$$

Appendix K. Estimation of $\boldsymbol{\alpha_E}, \boldsymbol{\gamma}$ and $\boldsymbol{\sigma}$

We estimated a proxy for α_E in two ways. Since the model assumes perfect competition, α_E represents the cost share of emissions in output. 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 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.

The actual dis-utility or damage from emissions and climate change is still subject to ongoing research. Recent studies 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. 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. Therefore, we report the sensitivity for γ ranging from 1 to 3.

van der Werf (2007), Manne and Richels (1992) and Kemfert and Welsch (2000) find the elasticity of substitution between energy and a composite input with capital to range from $0 - 0.7$.

Appendix L. Sensitivity analysis

Appendix L.1. Linear vs log utility and capital stock differences

In Figure L.7, we vary the capital stock of rich states from $\overline{K}_{rich} \in [1, 10]$ and report the respective minimum prices. In Figure A), we assume $\log(c_i)$ and in B) we assume utility to be linear in consumption. Comparison of A) and B) shows that the observed capital-homogeneity-restriction for egalitarian transfer of Section Appendix I vanishes, when assuming $\log(c_i)$, while when assuming linear consumption, under egalitarian transfers, federal pricing becomes quickly infeasible with increasing $\overline{K}_{rich}$. Therefore, in case of $\log(c_i)$ the effect of consumption saturation dominates the restriction from capital stock differences (for $n_{large} = 2$). In this case, rich consumers hardly gain from consumption increases in contrast to emission mitigation and are thus are willing to accept larger federal prices.

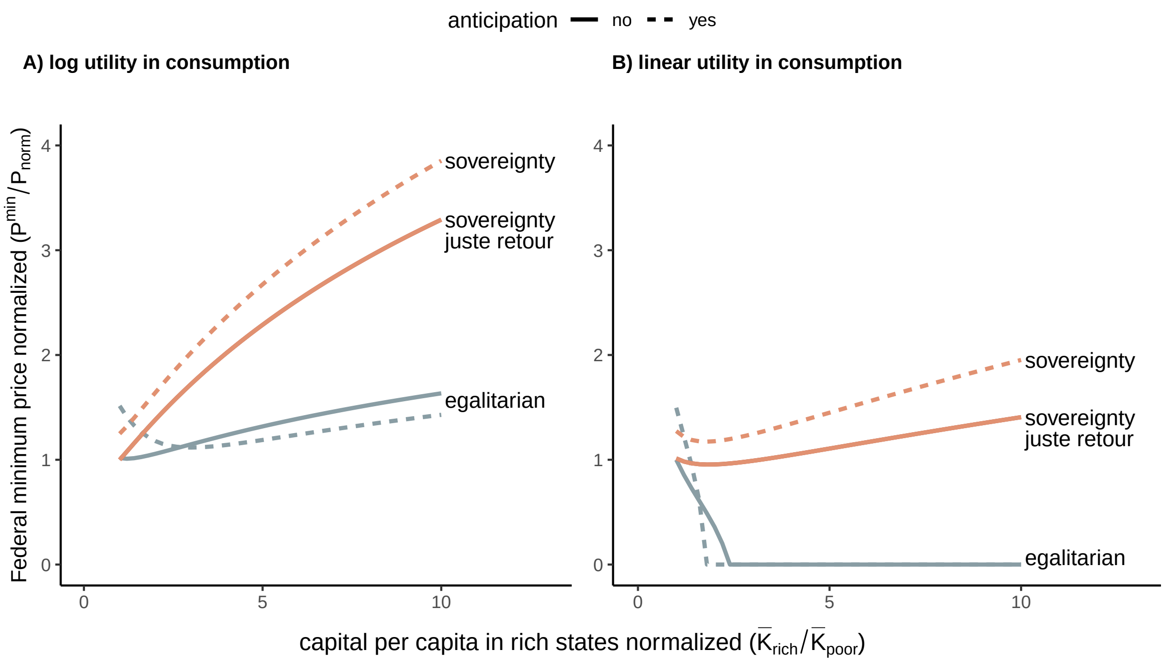

Figure L.7: Sensitivity analysis of capital stock differences across states. Contrasting log with linear utility from consumption.

Appendix L.2. Robustness check for variations of σ

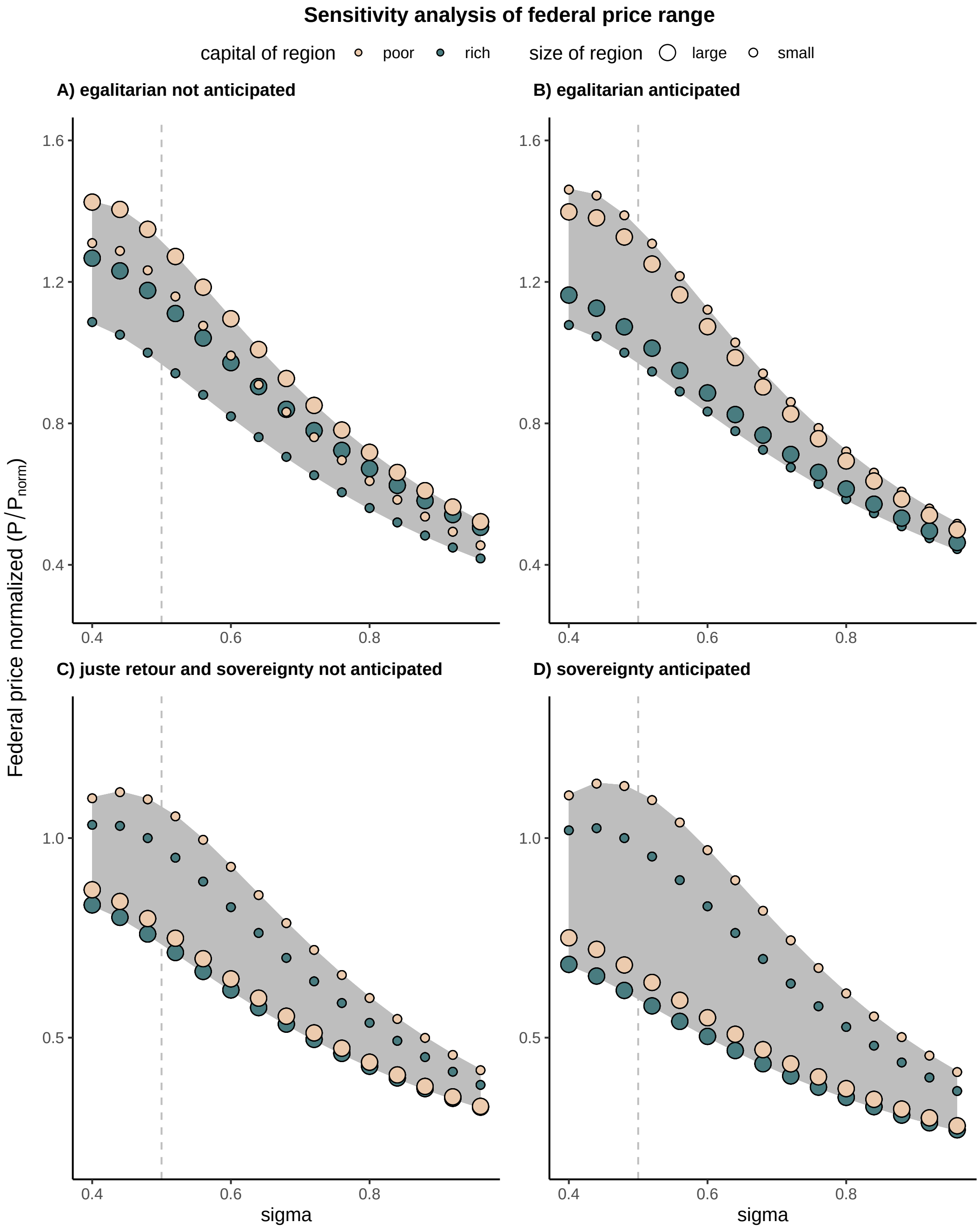

Figure L.8: **Robustness check of the feasible federal price range to variations of σ.** The richest state in terms of capital per capita (under egalitarian) or aggregate capital (under sovereignty or unanticipated juste retour transfers) prefers the lowest federal emission price. The gray dashed lines represent our benchmark parameter assumption.

Appendix L.3. Example of federal maximum price driven my indifference prices

Increasing the capital per capita of *rich* states to 2 instead of 1.2 as indicated in Table 2 allows us to show an example of specific rich states determining the minimum and maximum price. Figure L.9 is to be understood as a counterpart of Figure 4. In all the simulations the lowest federal indifference price ($min\left\{P_{ind}^{\forall j}\right\}$), which is the lowest federal price that leaves states indifferent between the decentralized and federal solutions, corresponds to the price of a *rich* state. Figure L.9 shows that the Pareto constraint of the *rich small* state binds as we vary α_E and γ so that $P_{ind}^{richsmall}$ becomes the highest feasible federal price with egalitarian transfers.

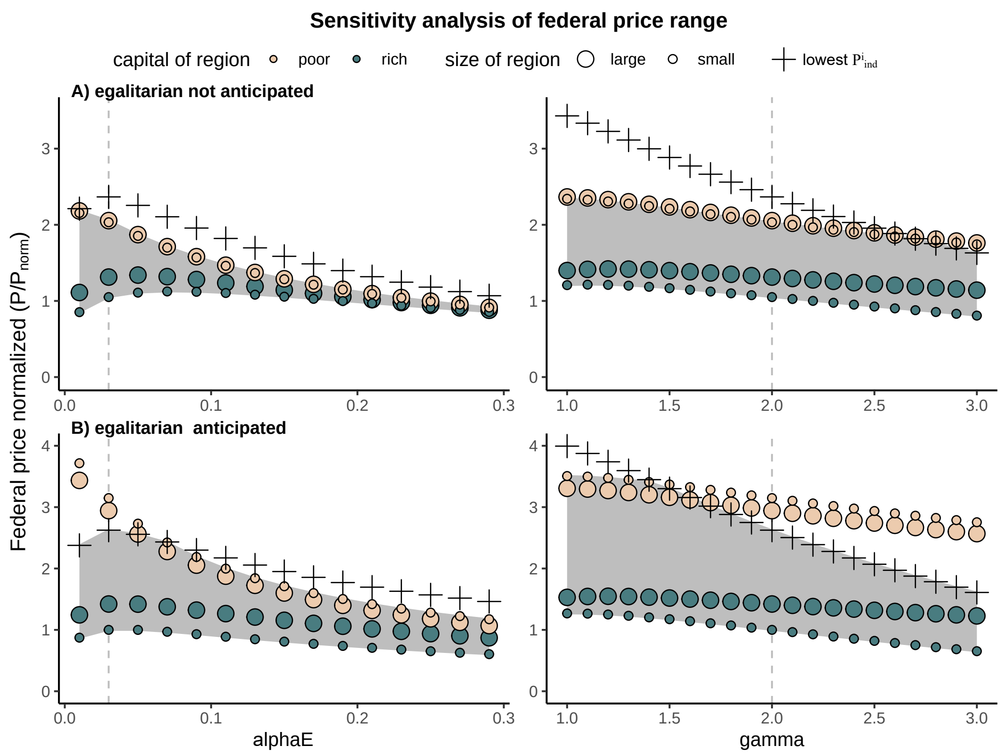

Figure L.9: Feasible federal price range with variations of γ and α_E for cases i and ii of Figure 1 with larger capital per capita differences across states. The upper bound of the range of federal price fluctuates between the price that maximizes the utility of a *poor* state and the lowest price P_{ind}^{i} which corresponds to: the *rich small* state in the case of egalitarian transfers; and the *rich large* in the case of sovereignty transfers. These findings correspond to Corollary 1 and Figure 1, cases i and ii. Here, we normalized the federal prices with the federal minimum price at $\alpha_E = 0.03, \gamma = 2$ (indicated gray dashed lines) under anticipated egalitarian transfers.

Appendix L.4. Consumption changes at minimum prices

We report consumption changes relative to the decentralized outcome for poor and rich states in Figures L.10 and L.11, respectively. Consumption changes always decline in α_E and increase in γ.

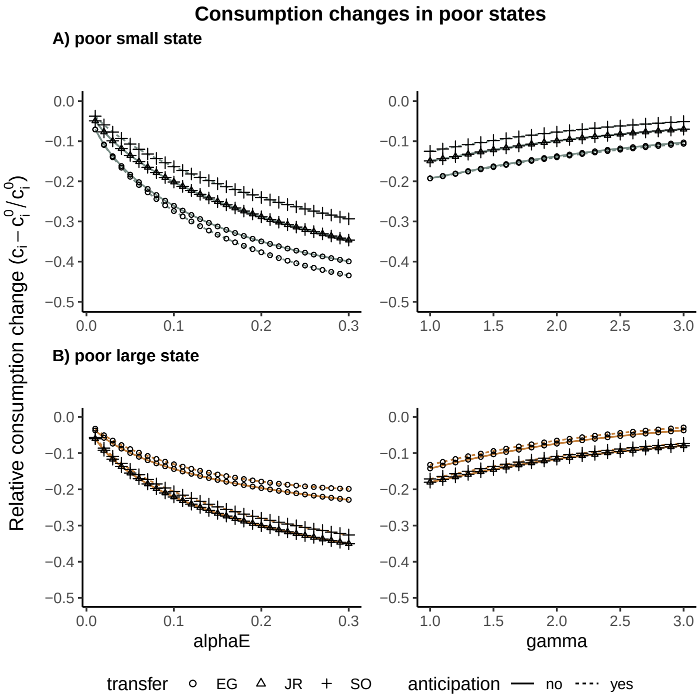

Figure L.10: Sensitivity analysis of consumption changes evaluated at the respective minimum prices relative to the decentralized levels in poor states.

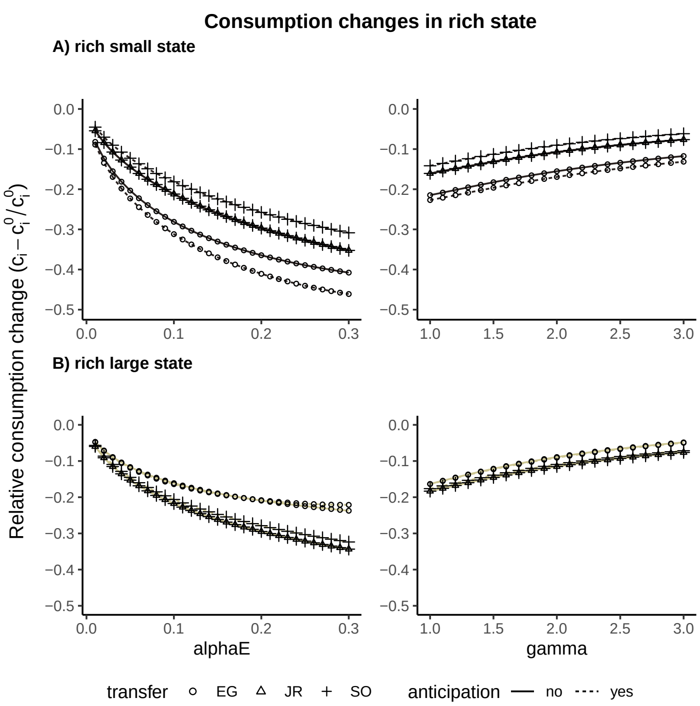

Figure L.11: Sensitivity analysis of consumption changes evaluated at the respective minimum prices relative to the decentralized levels in rich states.

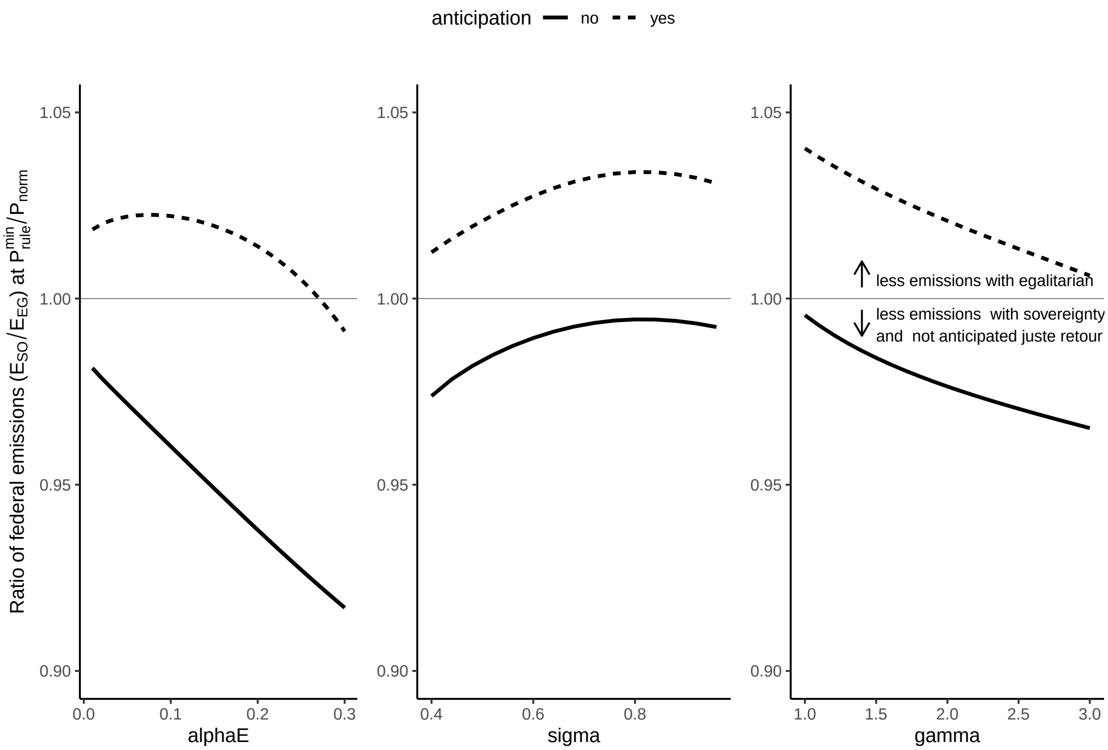

Figure L.12: Ratio of aggregate federal emissions under different transfer rules at the respective minimum prices when varying α_E, σ and γ. In case of unanticipated transfers, juste retour transfers perform similar to sovereignty transfers (SO). Egalitarian transfers are denoted with EG.

Appendix L.5. Aggregate emission levels at minimum prices

We plot the ratio of aggregate emission levels at the respective minimum price and transfer rules in Figure L.12. When transfers are anticipated, egalitarian transfers result in lower aggregate emissions than sovereignty transfers. When transfers are unanticipated, sovereignty and juste retour transfers are superior in terms of aggregate emission reduction.

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