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Abstract

Renewable energy (RE) policies are widely used to decarbonize power generation and implemented at various governance levels. We use an analytically tractable two-level model to study the effects of overlapping RE policies from the federal and state governments. We find that there are contrasting incentives for states to support RE deployment, depending on whether the federal government implements a feed-in tariff (FIT) or an auction system. Under federal FIT, states that bear a greater burden in financing the federal policy under-subsidize RE in order to reduce nationwide RE deployment and thereby lower their costs. Under federal auction, states that bear a greater burden to finance federal policy over-subsidize RE to drive down the quota price, and thereby also their costs. In an application to Germany, we illustrate that the recent shift from FIT to auctions increases incentives for state governments to support RE in the demand-intensive south, while decreasing them in the wind-abundant north.

Keywords: auction, feed-in tariff, multi-level governance, fiscal federalism, overlapping regulation, energy transition
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1. Introduction

Enormous efforts are necessary to limit global warming to "well below two degrees" as agreed upon in Paris (IPCC, 2018). While carbon pricing is considered to be the most cost-effective way to reduce carbon emissions, it is often politically infeasible (e.g. Aldy & Stavins 2012). At present, RE support policies are the instrument most widely used to decarbonize the power sector (Meckling et al., 2017) and many governments have set RE targets in addition to greenhouse gas (GHG) mitigation targets. In this context, RE support policies should not necessarily be seen as a second-best option, but may closely approximate to the social optimum (Abrell et al., 2019, Helm & Mier, 2018). Additional rationales for RE policies include that they provide support for infant industries and other co-benefits for the local economy, as well as promoting energy sovereignty by reducing dependency on imported fossil fuels.

A central challenge for the efficient design of RE support policies is that they are usually implemented in multi-level governance systems. In most jurisdictions, there are several nested levels of governance,[2] whose RE targets and support instruments may differ.[3] In setting targets, lower-level governments might be particularly interested in co-benefits and economic development within their jurisdiction while upper-level governments are likely to focus on overall national welfare. RE support may be explicit, e.g. by means of direct subsidies (tariffs or premiums), quotas or renewable portfolio standards; or more implicit, e.g. through infrastructure provision, the designation of suitable or unsuitable areas, tax incentives and loans. In fact, all countries of the European Union use between two and six RE support instruments and are characterized by overlapping national and lower-level RE policies (del Río & Mir-Artigues, 2014). As RE support policies often involve large financial outlays, it is important that they are spent efficiently. For this reason, in many countries there has been a recent shift from lump-sum subsidies to more competitive schemes like auctions (REN21, 2019).

In this paper we study the design of RE policies in multi-level governance systems and assess their efficiency. In particular, we ask: (i) How are incentives for lower-level governments to support RE affected by the upper-level policy instrument(s) in place? (ii) In which circumstances can overlapping provision of RE support by 'upper' and 'lower' governance levels be efficient?

To this end, we develop a formal analytical model of optimal RE policy design in which an upper-level federal government and multiple lower-level state governments simultaneously choose their level of RE support. On the federal level, we analyze the two most prominent RE policy instruments: a price instrument (feed-in tariffs; FIT) and a quantity instrument (an auction of a RE capacity quota). On the state level, we consider a multitude of implicit RE support measures, equivalent to and expressed by a single financial subsidy per unit

[2] Governance levels may include (but are not restricted to) municipal, regional, state, federal and supranational.

[3] For instance, in Germany the RE targets of the state governments and the federal government differ widely. Aggregated state targets were for RE to contribute 50-55 % of total power generation by 2020, while the federal target was only 35 % (Goetzke & Rave, 2016).

of capacity. The costs of the federal RE policy are distributed among all states. In the context of federal and state-level policies, competitive suppliers decide on the deployment of RE capacity. RE deployment in one state can cause positive externalities for other states (spillover benefits); as well as negative (cost) externalities, by affecting the distribution of the burden of financing federal RE policy. We compute the equilibrium outcome for overlapping federal and state policies in a one-shot game. In particular, we study a second-best setting, where the federal government can only implement a nationwide (not state-specific) FIT or auctioned quota while state governments provide local subsidies.

We find that the selection by the federal government of either a price or a quantity instrument substantially affects the incentives for states to implement their own RE support measures, as well as the circumstances under which overlapping RE policies are efficient. While price and quantity instruments are equivalent if the upper-level government implements a single nationwide policy, this does not hold if lower-level governments implement additional RE support. Our key results are: (i) Under a combination of nationwide FIT and state subsidies, a state's subsidy is inefficiently high (low) if and only if its share in the marginal benefits from nationwide RE deployment is larger (smaller) than the state's relative burden share. (ii) Under a combination of a nationwide auction and state subsidies, a state's subsidy is inefficiently high (low) if and only if its RE capacity share is smaller (larger) than its relative burden share.[4] (iii) Depending on the characteristics of states' marginal cost and benefit functions national RE capacity is either inefficiently high under FIT and inefficiently low under auction or vice versa.

The differences between price and quantity instruments for RE support in multi-level governance systems merit some attention. Where there are overlapping policies, a first-best allocation of RE capacities is achieved only if all states' shares in the marginal benefit (under FIT) or in nationwide RE capacity (under auction) are equal to their relative burden share. Otherwise, certain states have incentives to offer subsidies that are too high or low, leading to surplus or deficit RE capacity, respectively. Under FIT, a state can reduce its burden share by reducing its subsidies, as this will cause a reduction in nationwide RE capacity. This strategy does not work under an auction system as capacity is fixed. Here, however, a state can reduce its burden share by increasing state subsidies, thereby reducing the national quota price. As a consequence, national-level FIT or auction-based policies give rise to opposing policy-setting incentives at the state level.

These novel theoretical results are directly relevant for the efficient design of RE support schemes in multi-level governance systems. In any real-world application, the efficiency of a price or quantity instrument and the incentives for state RE policies will depend on how the burden share is distributed among states. In applying the model to Germany, we find that the recent shift from FIT to a national auction likely increased the incentives for state support for wind energy in the demand-intensive southern states while reducing it in the wind-abundant northern states.

[4]We use the term 'burden share' for the absolute payments of a state incurred by financing the federal RE policy and add 'relative' to denote the state's fraction of all states' payments. We use the term 'capacity share' for a state's share of the nation's total RE capacity.

Our paper contributes to the analytical literature on public good provision in general and RE support in particular in multi-level governance systems. To the best of our knowledge, it is the first theoretical analysis of how the incentives of state governments to support RE depend on whether the federal government adopts a price or quantity instrument. Our work adds to seminal contributions on public good provision in federal systems. Myers (1990) showed that with labor mobility, state governments will provide efficient amounts of a public good without federal policies. In the case of imperfect mobility, interregional transfers from the federal government induce efficiency if the states' decisions precede the federal decision (Caplan et al., 2000). This also holds for correlated local and national externalities (Caplan & Silva, 2005). Contrary to those approaches, where lower-level governments decide directly on their provisions to the public good, in our setup they can only incentivize public good provision from respective suppliers. Furthermore, we consider additional incentives for public good provision created by the upper-level government via a price or quantity instrument and a Nash game between all governments.

Our approach is inspired by Williams III (2012), who develops a stylized model in which the federal and state governments use the same instrument to regulate environmental pollution. He finds that the incentive for the state governments to override federal regulations depends on whether they implement pollution caps, taxes or tradable permits. Coria et al. (2018) extend this literature by considering a tax on the federal level and command-and-control regulation from the states and test the effectiveness of this policy for a Swedish example. We extend this literature by analyzing the efficiency of combined policies where the upper-level government employs a quantity instrument and the lower-level governments price instruments. Ambec & Coria (2018) analyse regulation of a local and a global pollutant, respectively, by local and national governments.

There is an extensive literature on the efficient design of RE support. Menanteau et al. (2003), Palmer & Burtraw (2005) discuss the efficiency of different price and quantity instruments. The design of auctions was further investigated by del Río & Linares (2014), Kreiss et al. (2017). Ambec & Crampes (2017), while Abrell et al. (2019) evaluate the efficiency of different policy instruments for RE support in analytic and numerical modeling settings. Helm & Mier (2018) additionally consider policies for power storage, while Pechan (2017) shows that the RE support scheme drives the spatial distribution of wind turbines. Lancker & Quaas (2019) show that optimal RE support differs across technologies when inter-temporal learning spillovers are considered. None of these studies consider overlapping regulation from different governance levels.

Overlapping regulations are principal focus of the study by Fischer & Preonas (2010), who review economic literature and develop a stylized theoretical model. In contrast to our study, these authors focus on the interactions between RE support policies and (non-RE) climate policies like emission caps. Similarly, Goulder & Stavins (2011) analyze nested state–federal regulations. Based on a qualitative analysis, they hypothesize that price instruments for RE support may be able to avoid problems arising from overlapping regulations. Finally, in a complementary analysis to ours, Meier & Lehmann (2019) evaluate different RE regulation policies in a federal system. They study a nation that consists of two states. In their model, the federal government supports RE with a subsidy, while state governments implement subsidies or expansion caps. In comparison, we allow for the more general case of n states, compare federal FIT and auctions as instruments for RE support and consider not only their efficiency but also the conditions giving rise to under- or over-support for RE at both state and national level.

The remainder of the paper is structured as follows: First, in Section 2, we introduce the theoretical model. In Section 3 we solve the model for different configurations of RE support schemes and present results. Then in Section 4, we apply our theoretical findings to German data. We discuss implications of the model and its application in Section 5 and present an outlook and conclusions in Section 6. The Appendices contain a nomenclature and all formal proofs.

2. Model

Consider a two-level governance system with one upper-level government and n lower-level governments labelled $i = 1, ..., n$. For convenience, we call the upper level a nation and refer to its government as the 'federal government'; while at the lower level governance units are called states, and their governments 'state governments'. Both governance levels decide on their RE policy. Consecutively, in each state competitive RE suppliers choose their investments in RE capacity r_i taking account of the RE support provided by state and federal governments. The nation's total RE capacity, R, is then

$$R := \sum_{i=1}^{n} r_i. \tag{1}$$

On the federal level, we study two prominent types of RE support schemes: feed-in tariff (FIT) and auction. In the case of a FIT, the federal government chooses the tariff T_i to be paid per unit of installed RE capacity[5] to the suppliers in state i. When the federal government uses a nationwide FIT – as opposed to a state-specific FIT – we denote this by suppressing the index i, i.e. $\forall i : T_i = T$. Note that under a FIT the RE suppliers only receive policy support for the supplied electricity and cannot additionally sell electricity on the market as would be the case under a feed-in premium. In the case of an auction, the federal government chooses state-specific quotas Q_i for auctioned RE capacity. RE suppliers bid a quota price P_i, which they receive as a subsidy per unit of RE capacity installed. The highest accepted bid for RE capacity in an auction defines the uniform (non-discriminatory) quota price that is guaranteed to all suppliers of the state in question.[6] Analogous to FIT, we consider that RE suppliers receive revenues only from the policy and not through additional market sales. When the federal government uses a nationwide RE capacity quota we denote this by $Q := \sum_{i=1}^{n} Q_i$. Empirically, a nationwide quota is for instance auctioned from a federal level in Germany. To the contrary, in the US most states have binding RE quantity targets in the form of renewable portfolio standards (Upton & Snyder, 2017).

[5]Typically, a FIT is paid per unit of RE generation. As RE generation is approximately linear in capacity, both option are about equivalent and we consider capacity for parsimony.

[6]For risk-neutral bidders, discriminatory and non-discriminatory auctions are equivalent (cf. Holt, 1980).

On the state level, we consider a subsidy s_i paid per unit of deployed RE capacity r_i. The subsidy is the financial equivalent of all kinds of measures with which a state supports the deployment of RE, e.g. by offering land, information on geophysical conditions or RE-friendly regulation.

We consider the total cost of providing and operating RE capacity to be $C_i(r_i)$, which is twice-differentiable with $\frac{\partial C_i(r_i)}{\partial r_i} > 0$ and $\frac{\partial^2 C_i(r_i)}{\partial r_i^2} = b \geq 0$. Costs are the net present value of all costs incurred in providing a certain capacity, including investment and maintenance. We assume that there are benefits to a state i from local and national RE capacity deployment, which are denoted $B_i(r_i, R)$. The benefit function is twice-differentiable, with respect to r_i as well as R, increases in both arguments, i.e., $\frac{\partial B_i(r_i,R)}{\partial r_i} > 0, \frac{\partial B_i(r_i,R)}{\partial R} > 0$ and is concave, i.e., $\frac{\partial^2 B_i(r_i,R)}{\partial r_i^2} \leq 0, \frac{\partial^2 B_i(r_i,R)}{\partial R^2} \leq 0$. Due to positive spillover benefits, RE deployment is an impure public good from the states' perspectives (e.g. Cornes & Sandler, 1994, Kotchen, 2005). Moreover, a state's marginal benefit from any additional RE deployment is weakly decreasing in the national RE capacity, i.e. $\frac{\partial^2 B_j(r_j,R)}{\partial R \partial r_i} \leq 0$. Benefits are the net present value of all future benefits. The setup allows us to study *local benefits* in a state, e.g. from increased economic activity in the state or local environmental improvements from substitution of fossil fuels by RE, as well as inter-state *spillover benefits* ('national benefits') such as the contribution to the nation's international climate mitigation commitments, or nationwide decreases in electricity prices.

Federal costs of RE support may be distributed differently among states. This could be because federal RE policies are financed through the federal budget and tax payments differ among states; or because federal RE policies are financed by a levy on the electricity price and states' electricity consumption is not proportional to their RE capacity. To take account of this, we introduce $e_i \in [0, 1]$ as the relative burden share of federal RE support (FIT or auctions) incurred by residents in state i. The (non-relative) burden share is thus $e_i \sum_{j=1}^{n} \Phi_j r_j$, with $\Phi_i \in \{T_i, P_i\}$ denoting the respective federal payments per unit of RE capacity under FIT and auction. As all costs must be refinanced, it is

$$\sum_{i=1}^{n} e_i = 1. \tag{2}$$

In general, we assume that for political reasons the federal government is not able to freely choose e_i. However, we access the implications of (un)restricting the choice of e_i in the Discussion.

We are now able to specify the players' objectives. The federal government takes a social planner perspective. Its objective is to maximize the nation's net benefit of RE support, calculated as the sum of all costs and benefits.

$$\Pi^{FED}(r_i, R) = \sum_{i=1}^{n} \left[-C_i(r_i) + B_i(r_i, R) \right]. \tag{3}$$

Note that RE support payments do not appear in the federal government's objective as they remain within the nation.

Each state government aims to maximize welfare in its jurisdiction. States' net benefits are given by the sum of state-level costs and benefits. The states' objectives can be written as

$$\forall i: \; \Pi_i^{ST}(r_i, R, \Phi_i, e_i) = -C_i(r_i) + B_i(r_i, R) - e_i \sum_{j=1}^{n} \Phi_j \, r_j + \Phi_i \, r_i. \tag{4}$$

While a state's own subsidy does not appear in its government's objective function, a state considers support given by the federal government $\Phi_i \, r_i$ as well as its burden share. Thus, we consider a situation where governments at both levels aim at maximizing their residents' welfare and state residents are a subset of national residents.

Finally, we consider a representative supplier of RE capacity in each state. The supplier in state i obtains revenues $s_i \, r_i$ through the state subsidy and revenues $\Phi_i \, r_i$ from the federal policy and faces deployment costs C_i. The supplier's objective is then:

$$\forall i: \; \Pi_i^{SUP}(r_i, s_i, \Phi_i) = -C_i(r_i) + (s_i + \Phi_i) \, r_i. \tag{5}$$

Recall that suppliers only receive policy support. Hence, market prices are irrelevant for the suppliers' choice of RE deployment.

The game is set up as a two-stage decision-making process. The first stage is a one-shot, simultaneous move game between the federal and all state governments, i.e. a Nash equilibrium. This setup is especially appropriate if both governance levels can adjust policies equally easily (Williams III, 2012). After all policies are announced, suppliers decide on their state-specific investments in RE capacity, i.e. they are Stackelberg followers.

3. Results

In the following, we first analyze the efficiency of unilateral RE support at only one government level, i.e. state or federal (Section 3.1). Then we consider the case of combined support at both state and federal level. We first consider nationwide FIT (Section 3.2), then nationwide auctions (Section 3.3) and, finally, compare the incentives for states to support RE deployment under both federal policy instruments (Section 3.4). We denote the total RE support in state i as $\Psi_i := \Phi_i + s_i$ and the first-best level of RE support as Ψ_i^*.

3.1. Unilateral support from federal or state governments

State-specific RE policies implemented only by the federal government define the benchmark for the first-best allocation of RE capacity. The federal government faces the decision problem

$$\max_{T_1,\ldots,T_n \vee Q_1,\ldots,Q_n} \Pi^{FED} = \sum_{i=1}^{n} \left[-C_i(r_i) + B_i(r_i, R)\right], \tag{6}$$

$$\text{s.t. } \forall i: \max_{r_i} \Pi_i^{SUP} = -C_i(r_i) + T_i\, r_i. \tag{7}$$

The solution of this problem establishes Lemma 1.

Lemma 1. *A first-best allocation of RE capacity with federal support only* ($s_i = 0, \Phi_i > 0$) *is achievable with both state-specific FIT,* $\Phi_i = T_i$*, and state-specific quotas,* $\Phi_i = P_i$*. The efficient level of RE support is*

$$\forall i: \ \Psi_i^* := \frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \tag{8}$$

Proof. See Appendix B. □

Lemma 1 defines the first-best RE policy, against which the structurally more complex support schemes considered in the next section can be compared. It shows that the federal government can use either policy instrument for RE support to obtain the welfare optimum, by setting state-specific FIT or quotas so that marginal costs of an additional unit of RE capacity in a state i equal the local marginal benefits in state i plus the marginal national benefits enjoyed by all states.

By contrast, when support is provided at state level only, a first-best allocation is not achieved, due to the inter-state spillover benefits of RE. In the absence of a federal policy, state subsidies result in insufficient RE support and hence deficit RE capacity, except for the trivial case of no inter-state externalities, $\forall i: \frac{\partial B_i}{\partial R} = 0$. Hence, the spillover benefits of RE provide a rationale for a federal RE policy.

Lemma 1 only holds if the federal government can set *state-specific* FITs or quotas such that the support equals total marginal benefits. However, in practice, a federal government will often be restricted to setting up a single, *nationwide* FIT or quota system. We directly observe from Eq. (8) that a nationwide FIT, $\forall i: T_i = T$, or a nationwide quota Q with $\forall i: P_i = P$, will only yield the first-best allocation in the special case where all marginal local benefits are identical, i.e., $\forall i, j: \frac{\partial B_i}{\partial r_i} = \frac{\partial B_j}{\partial r_j}$.

3.2. State subsidies and federal FIT

We now turn to the case of combined support by federal nationwide FIT and state subsidies (the following is formally proven in Appendix C). The decision problem reads

$$\max_{T} \Pi^{FED} = \sum_{i=1}^{n} \left[-C_i(r_i) + B_i(r_i, R) \right], \tag{9}$$

$$\forall i: \max_{s_i} \Pi_i^{ST} = -\, C_i(r_i) + B_i(r_i, R) - e_i \sum_{j=1}^{n} T\, r_j + T\, r_i, \tag{10}$$

$$\text{s.t. } \forall i: \max_{r_i} \Pi_i^{SUP} = -\, C_i(r_i) + (s_i + T)\, r_i. \tag{11}$$

For given state subsidies, the federal government sets the nationwide FIT such that the marginal costs equal the average difference between state subsidies and marginal local benefits plus the sum of the inter-state externalities:

$$T(s_1, ..., s_n) = \frac{1}{n} \sum_{i=1}^{n} \left[\frac{\partial B_i}{\partial r_i} - s_i \right] + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \tag{12}$$

Thus, the federal government's RE support decreases as state subsidies increase, as this implies that RE suppliers are already operating at higher marginal costs.

For a given nationwide FIT, each state government sets its subsidy to equal the received marginal benefits of RE deployment minus its marginal burden share:

$$\forall i: s_i(T) = \frac{\partial B_i}{\partial r_i} + \frac{\partial B_i}{\partial R} - e_i T. \tag{13}$$

Note, that in general a state only partly finances the federal RE support it receives back, while the remainder of the cost is borne by the other states. For a state's optimal choice of RE subsidy only its burden share is directly relevant but not the received FIT. RE is supplied such that for each change in FIT, there is an identical change in marginal costs of RE deployment. Hence, an increase in FIT results in higher capacities and thus higher state benefits. Consequently, subsidies only depend on the marginal benefits of RE deployment and the state's marginal burden share.

We denote the associated Nash equilibrium between federal FIT and states' subsidies by $\tilde{T}, \tilde{s_1}, ..., \tilde{s_n}$. The equilibrium RE support is

$$\tilde{T} = \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}, \tag{14}$$

$$\forall i: \tilde{s}_i = \frac{\partial B_i}{\partial r_i} + \frac{\partial B_i}{\partial R} - e_i \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \tag{15}$$

In equilibrium, the nationwide FIT exactly corresponds to the inter-state spillover benefits and does not depend on the local benefits. For positive marginal national benefits of

RE, the FIT is always positive. A state's subsidy equals the state's marginal benefits from RE deployment minus its marginal burden share. The equilibrium state subsidy is first-best if it corresponds to the amount of the state's own local benefits of RE deployment, $\tilde{s}_i = \frac{\partial B_i}{\partial r_i}$ (cf. Eq. B.3).

Comparing the total RE support provided by the nationwide FIT and the state subsidies with the first-best allocation derived in Lemma 1 establishes Proposition 1.

Proposition 1. *Under a combination of nationwide FIT and state subsidies ($\tilde{s}_i > 0, \Phi_i = \tilde{T} > 0$), a state's subsidy is too high (too low) if and only if its share in the marginal benefits from nationwide RE deployment is larger (smaller) than its relative burden share. The combined support is efficient if and only if both shares are equal:*

$$\forall i: \ \tilde{T} + \tilde{s}_i \gtreqless \Psi_i^* \iff \frac{\frac{\partial B_i}{\partial R}}{\sum_{j=1}^{n} \frac{\partial B_j}{\partial R}} \gtreqless e_i. \tag{16}$$

Proof. □

Proposition 1 shows that whether or not the combination of a nationwide FIT and state subsidies is efficient is determined by the relation of each state's share of marginal benefits of nationwide RE deployment to its relative burden share. Support is too high (low) in a state if its share of the marginal benefits of nationwide RE deployment exceeds (is less than) its relative burden share. As a state's RE capacity r_i increases in line with its policy support, $T + s_i$, it follows directly that RE capacity in a state is too high (low) if and only if a state's share of marginal benefits from national RE is larger (smaller) than its relative burden share. Thus, Proposition 1 shows that the efficiency condition for combined pollution control with a price instrument from both the federal and state levels extends to public goods as RE (cf. Williams III, 2012).

Intuitively, state subsidies directly affect the amount of national RE capacity. If a state's marginal benefits from federal policy are higher than its relative burden share, than the state will favor increasing capacity. By contrast, if a state's relative burden share exceeds the benefits it derives from federal policy it can improve the welfare of its citizens by reducing RE subsidies and thereby also reducing the overall national RE capacity.

Furthermore, it follows from Eq. (16) that the occurrence of structural under- or over-support in all states simultaneously is impossible. Instead, if one or more states provide too little support for RE, there must also be at least one state that is providing too much RE support. As a consequence, RE deployment might be regionally skewed and, at a national level, deviate from optimal amount.

In Proposition 2, we compare nationwide RE deployment with the first-best level for cases where the efficiency condition given in Proposition 1 is not met and hence the RE allocation is not first-best.

Proposition 2. *Consider that e_i deviates from the condition required for optimal RE support (Eq. 16) by some Δe_i and, as a consequence, there are $\mu = 1, ..., m$ under- and $\nu = 1, ..., k$ over-burdened states such that $\Delta e_\mu < 0, \Delta e_\nu > 0$. Under a combination of federal nationwide*

FIT and state subsidies, nationwide RE capacity is larger (smaller) than optimal if and only if the sum of the burden-weighted reciprocal difference between the sensitivities of marginal cost and benefit functions is larger (smaller) in the under-burdened states than in the over-burdened states. Nationwide capacity is the same as under a first-best allocation if both are equal:

$$R \gtreqless R^* \iff$$
$$-\sum_{\mu=1}^{m} \Delta e_\mu \left[\frac{\partial^2 C_\mu}{\partial r_\mu^2} - \frac{\partial^2 B_\mu}{\partial r_\mu^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\mu} \right]^{-1} \gtreqless \sum_{\nu=1}^{k} \Delta e_\nu \left[\frac{\partial^2 C_\nu}{\partial r_\nu^2} - \frac{\partial^2 B_\nu}{\partial r_\nu^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\nu} \right]^{-1}. \quad (17)$$

Proof. See Appendix D. □

Proposition 2 states under which conditions the level of nationwide RE capacity is higher or lower than under the first-best allocation given that RE support is non-optimal in at least some states. The amount of nationwide RE capacity is equal to the efficient level only in the very specific case when overcapacity in the under-burdened states exactly compensates for the undercapacity in the over-burdened states. However even though, in this case, nationwide RE capacity is efficient, its distribution is not.

3.3. State subsidies and federal quota

Next, we turn to combined support by means of a federal nationwide auction and state subsidies (the following is formally proven in Appendix E). The decision problem reads

$$\max_{Q} \Pi^{FED} = \sum_{i=1}^{n} \left[-C_i(r_i) + B_i(r_i, R) \right], \quad (18)$$

$$\forall i: \max_{s_i} \Pi_i^{ST} = -C_i(r_i) + B_i(r_i, R) - e_i R P + r_i P, \quad (19)$$

$$\text{s.t. } \forall i: \max_{r_i} \Pi_i^{SUP} = -C_i(r_i) + (s_i + P)\, r_i. \quad (20)$$

For given state subsidies, the federal government sets the nationwide quota so that the quota price P equals the sum of marginal benefits of national RE deployment and is thus identical to a nationwide FIT (cf. Eq. 14). However, the incentives for states to subsidize RE are different from under FIT. For a given quota each state sets its subsidy equal to its marginal local benefit plus its net benefit from a marginal quota price change:

$$s_i(P) = \frac{\partial B_i}{\partial r_i} + \left[r_i - e_i Q \right] \frac{\partial P}{\partial r_i}. \quad (21)$$

Note that states now internalize some of the cost externality from the burden share as they consider the impact of their choice of r_i on the quota price their suppliers receive.

It follows that in Nash equilibrium, which we denote by $\bar{P}, \bar{s_1}, ..., \bar{s_n}$, a state's subsidy is determined by the marginal local benefits and by the effect of the state's RE capacity on the marginal spillover benefits received by all states:

$$\bar{P} = \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}, \tag{22}$$

$$\forall i : \bar{s}_i = \frac{\partial B_i}{\partial r_i} + [r_i - e_i Q] \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}. \tag{23}$$

Hence, for negative cross derivatives, in equilibrium a state's subsidy decreases in its RE capacity, r_i, and increases in its burden share. Whereas under a nationwide FIT a state increases its subsidy in response to a decrease in its burden share, under a nationwide quota a state responds to a decrease in its burden share by decreasing its subsidy.

Comparing the total RE support in equilibrium for a nationwide quota with the first-best allocation (Lemma 1) establishes Proposition 3.

Proposition 3. *For* $\sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial r_i \partial R} < 0$*, under a combination of a nationwide auction and state subsidies* ($\bar{s}_i > 0, \Phi_i = \bar{P} > 0$)*, a state's subsidy is too high (too low) if and only if its capacity share is smaller (larger) than its relative burden share. The combined support is efficient if and only if both shares are equal:*

$$\forall i : \; \bar{P} + \bar{s}_i \gtreqless \Psi_i^* \iff r_i \gtreqless r_i^* \iff \frac{r_i}{Q} \lesseqgtr e_i. \tag{24}$$

For $\sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial r_i \partial R} = 0$*, combined support by federal nationwide auction and state subsidies yields the first-best outcome.*

Proof. See Appendix E. □

Proposition 3 shows that optimal RE support is achieved if and only if states' RE capacities are distributed proportionally to their burden shares.[7] If that is the case in a state, the federal RE support cancels out to zero in the state's objective (Eq. 19) and consequently in its equilibrium subsidy decision (Eq. 23). While state governments then only support RE for their local benefits, the federal government supports for all spillover benefits, thus inducing a first-best allocation.

If equilibrium RE deployment is distributed disproportionally to the policy costs, the combined RE support will be inefficiently high in some states and inefficiently low in others. RE deployment is over-supported in a particular state if the state's relative burden share of the federal RE policy is higher than its capacity share. Intuitively, since there is a fixed

[7] Assuming a state's RE capacity affects some states' marginal national benefits, $\sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial r_i \partial R} < 0$.

RE quota, lower state subsidies cannot lead to lower national RE capacity and thus a state cannot reduce its burden share by reducing its subsidy. However, when an individual state increases its support for RE this will lead to a reduced nationwide quota price. Thus, on the one hand, the state's suppliers will receive less support from the federal government, on the other hand, the state reduces its burden share. The net effect for the state is positive if its relative burden share is larger than its capacity share. In this case, the loss in federal support is outweighed by the reduction in the state's burden share. Consequently, the state's suppliers deploy RE capacity at marginal costs that exceed the marginal benefits. As opposed to that, if a state whose relative burden share is lower than its capacity share decreases its RE support, the additional support its suppliers receive will exceed that state's additional burden share resulting from a higher quota price. In this case, the state's suppliers deploy RE capacity at marginal costs that are lower than the marginal benefits. As a summary, over-burdened states have an incentive to increase their subsidies, while under-burdened states have an incentive to decrease them.

A quota-based system thus exerts a mediating effect on RE capacity: If a state's capacity share is lower than its relative burden share, subsidies and RE deployment in the state are higher than welfare-optimal. Hence, this situation can only occur if the state's relative burden share was higher than its welfare-optimal capacity share in the first place. This effectively bounds RE capacity between the welfare-optimal capacity and its allocation in accordance with the given relative burden share: $r_i^* \leq r_i \leq e_i Q$ or $r_i^* \geq r_i \geq e_i Q$, which also follows directly from Eq. (24).

As for a nationwide FIT the combined RE support will never be too high or too low for all states. In the following, we compare nationwide RE deployment with the first-best level for cases where the efficiency condition given in Proposition 3 is not met and hence the RE allocation is not first-best.

Proposition 4. *Consider that e_i deviates from the efficiency condition in Eq. (24) by some Δe_i. As a consequence, there are $\mu = 1, ..., m$ under- and $\nu = 1, ..., k$ over-burdened states such that $\Delta e_\mu < 0, \Delta e_\nu > 0$. Under combined support by a federal nationwide auction and state subsidies, nationwide RE capacity is larger (smaller) than optimal if and only if the sum of the burden-weighted reciprocal difference between the sensitivity of marginal cost and marginal benefit functions is smaller (larger) in the under-burdened states than in the over-burdened states. Nationwide RE capacity is the same as under a first-best allocation if both are equal:*

$$R \gtreqless R^* \iff$$
$$-\sum_{\mu=1}^{m} \Delta e_\mu \left[\frac{\partial^2 C_\mu}{\partial r_\mu^2} - \frac{\partial^2 B_\mu}{\partial r_\mu^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\mu} \right]^{-1} \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\mu} \gtreqless$$
$$\sum_{\nu=1}^{k} \Delta e_\nu \left[\frac{\partial^2 C_\nu}{\partial r_\nu^2} - \frac{\partial^2 B_\nu}{\partial r_\nu^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\nu} \right]^{-1} \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\nu}. \tag{25}$$

Proof. See Appendix F. □

Proposition 4 states under which conditions the level of nationwide RE capacity is higher or lower than under the first-best allocation given that RE support is non-optimal in at least some states. Compared to the result for a nationwide FIT (Eq. 17), the sum of the cross derivatives $\sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}$ is an additional term. As the cross derivatives are strictly negative, the resulting relations between capacities, relative burden shares and the sensitivities of marginal cost and marginal benefit curves under an auction system are switched compared to under FIT. As for FIT, the resulting nationwide capacity is only equal to the first-best capacity under very specific combinations of parameters – except in the trivial case where all cross derivatives are zero, which directly induces the first-best allocation.

3.4. Comparing state subsidies under FIT and auction

Comparing nationwide FIT and nationwide auctions, we find identical support at the federal level. However, the incentives for states to support RE substantially differ: For both FIT and auctions, state governments grant subsidies in the amount of the local marginal benefits from RE in their state, which are than raised or decreased, depending on the distribution of the federal instrument's costs. If a FIT is implemented by the federal government, a state will increase its subsidy if its share of marginal benefit from national REs is higher than its relative burden share (and vice versa). If the federal government implements an auction, a state will raise its subsidy if its capacity share is lower than its relative burden share (and vice versa).

As a consequence, a high burden share leads to state RE support that is lower than the efficient level under federal FIT and higher than the efficient level under an federal auction system. Under FIT, there is a quantity effect: Reducing the subsidy in a state will also decrease the nationwide RE capacity and thus the state's burden share. In contrast, if the nationwide RE capacity is set by the federal quota, reducing the subsidy and thus the capacity in one state would fully be substituted from capacity in other states. Thus, a state cannot lower its burden share by lowering capacity. However, under an auction system, there is a price effect: If the national quota price falls as a result of one state increasing RE support and hence demand for quotas, this also reduces the burden share for all states. Hence, in contrast to FIT, there is an incentive for an over-burdened state to increase capacity by over-supporting RE (in comparison with welfare-optimal levels of support).

Table 1 summarizes our results on the efficiency of different single- and two-level RE support schemes and Proposition 5 provides the formal condition under which RE support in a state is higher under an auction scheme than under FIT and vice versa.

Proposition 5. *A state's subsidy is higher (lower) under a nationwide auction ($\bar{s}_i$) than under a nationwide FIT ($\tilde{s}_i$) if and only if the state's share of marginal national benefits, minus the marginal change in federal support received by the state's suppliers is smaller (larger) than its relative burden share:*

$$\bar{s}_i \gtreqless \tilde{s}_i \iff \frac{\frac{\partial B_i}{\partial R} - r_i \frac{\partial P}{\partial r_i}}{\sum_{j=1}^{n} \left[\frac{\partial B_j}{\partial R} - r_j \frac{\partial P}{\partial r_i} \right]} \lesseqgtr e_i. \tag{26}$$

Table 1: Results summary on efficiency of RE support schemes.

		State policy	
		none	subsidy
Federal policy	none	-	never$^{(b)}$
	state-specific FIT	always	-
	state-specific auction	always	-
	nationwide FIT	never$^{(a)}$	if$^{(b)}$ $\frac{\frac{\partial B_i}{\partial R}}{\sum_{j=1}^{n} \frac{\partial B_j}{\partial R}} = e_i$
	nationwide auction	never$^{(a)}$	if$^{(c)}$ $\frac{r_i}{R} = e_i$

In addition, efficiency is achieved in the following special cases: (a) if marginal local benefits are identical for all states; and (b) if interstate externalities are absent, i.e. marginal national benefits are zero; and (c) if all cross derivatives are zero.

Proof. See Appendix G. □

Proposition 5 shows that a state's incentive to provide RE support varies, depending on whether the federal government implements a FIT or an auction system. Whether a state's subsidy is higher or lower under FIT or an auction system depends on how marginal benefits of nationwide RE deployment are distributed among states, on how the quota price reacts to capacity changes, and on the state's relative burden share. A state will set its subsidy higher (lower) under a federal auction than under FIT if and only if the marginal spillover benefits minus the change in the amount of federal support the suppliers receive in that state relative to all states is lower (higher) than its relative burden share.

Under an auction system, in the special case where the sum of all cross derivatives is zero ($\frac{\partial P}{\partial r_i} = \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} = 0$), the level of state subsidy is always first-best (cf. Proposition 3). Under FIT, it follows from Eq. (26) that the efficiency of the state subsidies is directly determined by how the state's share of marginal national benefits relates to its relative burden share. Thus, the result resembles our finding from Proposition 1 (cf. Eq 16). Consequently, in this case, a state subsidy under FIT is larger (smaller) than under an auction system if and only if a state's share of marginal benefits from nationwide RE deployment is higher (lower) than its relative burden share.

4. Empirical application

We illustrate our findings for Germany using state-wise data for 2015 on onshore wind deployment. In Germany states have played an active role in the ongoing energy transition (Schönberger & Reiche, 2016). After applying a nationwide FIT from 1991 to 2014, the federal government started setting nationwide quotas and holding a discriminatory price auction to determine the level of federal RE support in 2017 (Meya et al., 2016).[8] The federal RE policy is financed by a surcharge on the electricity price and thus proportional to consumption.

It is thus straightforward to approximate a state's relative burden share e_i using power demand data (Kunz et al., 2017).[9] Furthermore, as support is granted for generation rather than capacity, we use RE capacity data (Kunz et al., 2017) together with state-specific full load hours (Koch et al., 2016) to obtain the average capacity available for generation, r_i. The resulting cost shares, e_i, and corrected capacity shares, $\frac{r_i}{R}$, are shown for the sixteen German states in Table 2.

Table 2: Incentives for state subsidies compared to the efficient amount under nationwide auctions in Germany.

State	**Rel. burden share,** e_i	**Capacity share,** $\frac{r_i}{R}$	**Incentive for subsidies**
NRW	0.200	0.086	↗
BY	0.182	0.026	↑
BW	0.165	0.014	↑
NI	0.092	0.249	↘
RP	0.068	0.062	→
HE	0.064	0.018	↗
SN	0.042	0.026	↗
BE	0.037	0.003	↑
HH	0.032	0.003	↑
SH	0.024	0.197	↓
BB	0.022	0.121	↘
TH	0.021	0.029	→
ST	0.020	0.102	↘
SL	0.015	0.005	↗
MV	0.013	0.057	↘
HB	0.004	0.001	↗

Legend: Northrhine-Westphalia (NRW), Bavaria (BY), Baden-Wuerttemberg (BW), Lower Saxony (NI), Rhineland Palatinate (RP), Hesse (HE), Saxony (SN), Berlin (BE), Hamburg (HH), Schleswig Holstein (SH), Brandenburg (BB), Thuringia (TH), Saxony-Anhalt (ST), Saarland (SL), Mecklenburg Western Pomerania (MV), Bremen (HB).
Data sources: Kunz et al. 2017, Koch et al. 2016.

We find that under an auction system (Proposition 3), the southern states Bavaria (BY) and Baden-Wuerttemberg (BW), with low wind generation capacity, have an incentive to

[8] In Germany, RE suppliers bid on a premium on the market price in repeated discriminatory price auctions. Assuming perfect information, this is equivalent to our setup of a single, non-discriminatory price auction for the net present value of a tariff. 2014 to 2017 was a transition phase.

[9] In Germany, large electricity consumers may be exempted from the renewable energy surcharge. This is ignored in our analysis.

provide too much support for RE which leads to higher than optimal capacity deployment. In contrast, northern states like Lower-Saxony (NI) or Schleswig-Holstein (SH) with high wind generation capacity are incentivized to offer lower than optimal RE support.

The state incentives arising from the burden share of the nationwide auctions are the reverse of those under the previously prevailing nationwide FIT (see Proposition 1).[10] Before 2014, states with abundant wind in the north likely over-supported RE while states with a relative scarcity of wind in the south under-supported it. Our model suggests that these incentives were reversed due to the change in the federal RE policy instrument. As a consequence, in future, RE support and deployment might shift from the north to the south of the country. This would be beneficial for the German power system as currently the transmission of RE generated in the north to consumers in the south is often limited by scarce grid capacity. In fact, harmonization of RE deployment and grid capacity expansion was one of the principal motivations for implementing federal auctions (German Federal Ministry for Economic Affairs and Energy, 2015).

5. Discussion

In this section, we discuss several critical assumptions and the extent to which these might limit the generality of our results. These include (i) the static setting, (ii) the assumption that suppliers have perfect information, (iii) the focus on RE capacity rather than generation, (iv) the exogenous distribution of policy costs, (v) the focus on positive inter-state spillovers, (vi) the neglect of non-local RE deployment costs, (vii) the empirical application to Germany, and (viii) the choice of the policy mixes.

First, we consider a static setting only and a one-shot game between both governance levels and suppliers. We thus ignore complex dynamics, such as cost changes due to technological progress. Moreover, in practice, the regulations governing financial support for RE are frequently adjusted. This might give rise to dynamic strategic interactions between governments. However, when both levels of government have the same opportunities to adjust their support for RE, a repeated game will yield results identical to the Nash equilibrium (Williams III, 2012). A dynamic setup would hence increase complexity without yielding additional insights.

Second, we assume that suppliers have perfect information on the maximum acceptable quota price and thus all suppliers (nationally, or in each state if quota prices are state-specific) receive the same quota price. In practice, this is not necessarily the case. In fact, information asymmetries are a main reason for the introduction of auctions. Also, pay-as-bid auctions, where the price paid to each supplier is commensurate with its bid, are gaining in popularity. However, uncertainty due to imperfect information is reduced when repeated auctions are held, as is typical for RE (assuming that the quota market is sufficiently liquid). Even under information asymmetry, implementing pay-as-bid remuneration would affect the

[10]It is certainly more difficult to specify marginal national benefits with empirical data under FIT, which would be necessary to evaluate its efficiency (Proposition 1).

distribution of rents between governments and suppliers, but would not change the rationale of the marginal supplier and hence not influence the efficient amount of capacity.

Third, by computing tariffs and quota prices on the basis of capacity, we implicitly assume proportionality of RE capacity and generation, because usually support is paid in proportion to generation. As a consequence, in order to translate our model into a real-world setting using numerical simulations it would be necessary to correct for regional heterogeneity in the efficiency of RE capacity use. This could be done using data from each state on full load hours. This would also make it possible to take account of some operational costs of RE instead of just focusing on capacities. However, capacity deployment costs of RE far exceed operational costs and thus the general results would not be affected.

Fourth, we assume an exogenously given burden sharing e_i. This assumption is appropriate in the context of current policy alternatives or for a given burden sharing rule (cf. Böhringer et al., 2015). For instance, if national RE policy is financed out of the central budget, costs are distributed in accordance with general taxation structure, which is fixed from the perspective of the energy agency or energy policymaker. Similarly, if federal RE policy is financed by a premium on the electricity price, then the distribution of costs corresponds to the distribution of energy consumption among states. Nevertheless, future work could include the distribution of costs as a decision variable in the federal government's decision problem, which might be a reasonable assumption for the long run. The literature on federal transfers and Lindahl prices (cf. e.g. Caplan et al., 2000) indicates that this might allow the first-best allocation to be achieved even with a nationwide policy instrument.

Fifth, we focus exclusively on positive inter-state spillover benefits of RE and negative cost externalities incurred in financing federal policies. Positive inter-state spillovers include contributions to national climate targets, lower electricity prices and increased security of supply. These constitute a major rationale for federal RE policy. However, in principle, negative externalities of RE deployment are also possible and it would be straightforward to include these in our analysis by assuming $\frac{\partial B_i(r_i,R)}{\partial R} < 0$. Negative RE externalities could include effects on biodiversity, landscape aesthetics (Meyerhoff et al., 2010), well-being of residents (due to exposure to noise and visual impacts) (von Möllendorff & Welsch, 2017, Krekel & Zerrahn, 2017), house prices (Dröes & Koster, 2016) or grid stability (Zerrahn, 2017). However, as these occur mostly on local scales, net negative inter-state spillovers of RE are rather unlikely and we therefore exclude these secondary effects from the analysis, in the interests of readability.

Sixth, we assume that costs of installing RE capacity are entirely local. While this is accurate with regards to the land area needed for RE capacity development, provision of the necessary (grid) infrastructure may be wholly or partly financed by the federal government. Furthermore, since many RE suppliers operate nationally, it is unlikely that their costs can be allocated perfectly to a single state. This could be taken into account by incorporating spillover costs – or equivalently negative spillover benefits (see above) – into the model. For now, however, we assume that the majority of costs are incurred locally and leave consideration of these spillovers for future research.

Seventh the application of our results to the case of Germany could be criticized as being over-simplistic. While this case study analysis is intended only as an illustration, it still reveals substantial differences between the cost shares and capacity shares across states. The regional distribution of incentives under nationwide quota or FIT suggested by our theoretical analysis seems to be in line with the federal government's motive for the policy instrument change implemented in 2017. And indeed, there have been shifts in some states' policies and RE deployments that tend to support our model predictions. For instance, installation of RE capacity has increased recently in BW and declined sharply in SH (Bundesverband Windenergie, 2019). Nevertheless, our analysis ignores several factors that might in practice determine state subsidies, such as the geophysical conditions or the party-political composition of the state government. We leave a systematic consideration of these heterogeneities and thorough empirical investigation for future work.

Finally, we analyze a particular mix of policies: state subsidies with federal FIT or federal auctions. However, most other RE policies are similar to these as they provide either quantity-based (e.g. renewable portfolio standards) or a price-based (e.g. market premium) support. For instance, if regulators have perfect information on prices, RE support by optimal FIT or market premium will give rise to the same outcome (Abrell et al., 2019). We are thus confident that our general findings also hold for other combinations of price and quantity-based RE support policies. A limitation of the model is that it incorporates both a price and quantity instrument only at the federal level. It would be worthwhile to extend the model to incorporate a quantity instrument on the state level as well. This would be suitable for the US energy system in particular, where many states have implemented portfolio standards (Upton & Snyder, 2017).

6. Conclusion

In this paper, we have shown that the incentives for state governments to subsidize RE substantially depend on whether the federal government implements a price or quantity instrument, i.e. a nationwide FIT or a nationwide auction, and on how the costs of this federal RE policy are distributed among states. Under FIT, states that bear a higher (lower) burden in financing the federal policy tend to reduce (increase) their subsidies while under an auction system they tend to increase (reduce) them. In all cases this likely leads to RE subsidies that are either too low or too high compared to first-best levels and, correspondingly, to deficit or surplus RE capacity.

Furthermore, whether or not the level of national RE capacity is efficient depends on the characteristics of the over- and under-burdened states. Under FIT, the national capacity is greater than optimal if the differences between sensitivities of marginal cost and marginal benefit functions are smaller in the under-burdened states than in over-burdened states and vice versa. Under nationwide auctions, this relation is reversed such that the national capacity is lower than optimal if the differences between sensitivities of marginal cost and marginal benefit functions are lower in the under-burdened states than in over-burdened states and vice versa.

Our results offer conceptual guidance for the selection of instruments to support RE in federal government systems: As RE deployment creates benefits on different spatial scales, actions at a single government level will generally not attain an optimal level of RE support.

However, due to interaction between national-level and state-level strategies, implementing state-level RE support in addition to a nationwide federal policy does not necessarily lead to a first-best allocation of RE capacities either. A nationwide FIT creates incentives for efficient state policies whenever marginal national benefits of RE are distributed in proportion to the burden share incurred by national RE policy. A nationwide auction creates incentives for efficient RE policies when RE capacities are distributed proportionally to the distribution of the burden share. Moreover, a nationwide auction system will always be efficient if states' marginal national benefits do not depend on other states' RE capacities, which is not the case for FIT. In particular, the derived efficiency condition for an auction system is easy to specify using empirical data on RE capacity. Circumstances in which state support under an auction system might be inefficient are illustrated by the case of Germany, where wind capacity is greatest in the sparsely populated north, while private energy consumption is highest in the densely populated west and south, and federal RE policy is refinanced by a surcharge on consumption.

In addition to RE, our model could also be applied to analyze any policy setup where two government levels provide financial support for the provision of impure public goods. This could include, for example, the deployment of transport and communication infrastructure, or finance for research and development. Overall, in a second-best setting, where the federal government can only implement a nationwide policy, state governments have an incentive to implement their own policies. The efficiency of these state policies substantially depends on whether the federal government uses a price or a quantity instrument and how the cost of federal policy is distributed.

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Appendix A. Nomenclature

$i = 1, ..., n$	Index for states
$\mu = 1, ..., m$	Index for under-burdened states
$\nu = 1, ..., k$	Index for over-burdened states
r_i	RE deployment in state i
Δr_i	Deviation of RE deployment from optimum
R	RE deployment in the whole nation
s_i	RE subsidy in state i
$T_{(i)}$	(State-specific) feed-in tariff
$Q_{(i)}$	(State-specific) auctioned quota
$P_{(i)}$	(State-specific) quota price for all suppliers defined by last acceptable bid under auction
$\Phi_{(i)} \in \{T_{(i)}, P_{(i)}\}$	(State-specific) federal RE support
Ψ_i	Total RE support in state i
$C_i(r_i)$	Cost of RE deployment in state i
$B_i(r_i, R)$	Benefit of RE deployment in state i
e_i	State i's relative burden share of federal RE support
Δe_i	Deviation of relative burden share from optimum
$\Pi_i^{SUP}, \Pi_i^{ST}, \Pi^{FED}$	Objectives of RE supplier i, state i, and nation

Appendix B. Proof of Lemma 1

Consider a *state-specific FIT*. The decision problem of the federal government is given by Eq. (6), Eq. (7) with choice variables $T_1, ..., T_n$. It follows from the first order condition of the suppliers' maximization problem (Eq. 7) that in equilibrium in each state the FIT equals marginal costs

$$\forall i : \frac{\partial C_i(r_i)}{\partial r_i} - T_i = 0. \tag{B.1}$$

Let $r_i(T)$ be the reaction function of the supplier satisfying Eq. (B.1). Inserting this in Eq. (6), using $R = \sum_{i=1}^{n} r_i$ and differentiating with respect to T_i gives

$$\begin{aligned}\forall i : \frac{\partial \Pi^{FED}}{\partial T_i} = &- \frac{\partial C_i(r_i)}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}T_i} + \frac{\partial B_i(r_i, R)}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}T_i} \\ &+ \sum_{j=1}^{n} \frac{\partial B_j(r_j, R)}{\partial R}\frac{\partial R}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}T_i}.\end{aligned}$$

Setting $\frac{\partial \Pi^{FED}}{\partial T_i} = 0$ for all i yields n first order conditions. Dividing by $\frac{\mathrm{d}r_i}{\mathrm{d}T_i}$ and recognizing that $\frac{\partial R}{\partial r_i} = 1$ these simplify to

$$\forall i: \frac{\partial C_i(r_i)}{\partial r_i} = \frac{\partial B_i(r_i, R)}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j(r_j, R)}{\partial R}. \tag{B.2}$$

Using Eq. (B.1) in Eq. (B.2) yields the optimal state-specific FIT:

$$\forall i: T_i = \frac{\partial B_i(r_i, R)}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j(r_j, R)}{\partial R}. \tag{B.3}$$

Next, we consider *state-specific quotas*. The decision problem of the federal government is given by Eq. (6), Eq. (7) with choice variables $Q_1, ..., Q_n$. Assuming that P_i is unbound and chosen competitively by the suppliers in each state, it follows directly from the supplier profit maximization and the market clearing (cf. Helm 2003) that

$$\forall i: \frac{\partial C_i(r_i)}{\partial r_i} = P_i, \tag{B.4}$$

$$\forall i: r_i = Q_i, \tag{B.5}$$

$$Q := \sum_{i=1}^{n} Q_i = R. \tag{B.6}$$

Substituting Eqs. (B.5) and (B.6) in Eq. (3) and differentiating with respect to Q_i yields the first order conditions of the federal government:

$$\forall i: \frac{\partial C_i(Q_i)}{\partial Q_i} = \frac{\partial B_i(Q_i, Q)}{\partial Q_i} + \sum_{j=1}^{n} \frac{\partial B_j(Q_i, Q)}{\partial Q}. \tag{B.7}$$

Eq. (B.5) allows to rewrite the suppliers' first order conditions (Eq. B.4) as $\forall i: P_i = \frac{\partial C_i(Q_i)}{\partial Q_i}$. Inserting this into Eq. (B.7) gives the optimal state-specific quota price

$$\forall i: P_i = \frac{\partial B_i(Q_i, Q)}{\partial Q_i} + \sum_{j=1}^{n} \frac{\partial B_j(Q_i, Q)}{\partial Q}, \tag{B.8}$$

which is identical to the support with a state-specific FIT (cf. Eq. B.3).

Appendix C. Proof of Proposition 1

Consider a situation of combined *nationwide FIT* and *state subsidies*. The decision problem is given by Eq. (9) – Eq. (11). The first order conditions of the suppliers' profit maximization problem are

$$\forall i : \frac{\partial C_i}{\partial r_i} = s_i + T. \tag{C.1}$$

In the following, let $r_i(T, s_i)$ denote the amount of capacity that satisfies Eq. (C.1).

For a given federal tariff, T, and given subsidies, s_{-i}, a state i's maximization problem reads

$$\forall i : \max_{s_i(T, s_{-i})} \Pi_i^{ST} = -C_i(r_i) + B_i(r_i, R) - e_i \sum_{j=1}^{n} T\, r_j + T\, r_i. \tag{C.2}$$

Differentiating each state's objective function with respect to the state's subsidy, we obtain the first order conditions[11]

$$\forall i : \frac{\partial \Pi_i^{ST}}{\partial s_i} = -\frac{\partial C_i}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}s_i} + \frac{\partial B_i}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}s_i} + \frac{\partial B_i}{\partial R}\frac{\partial R}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}s_i} - e_i T\,\frac{\mathrm{d}r_i}{\mathrm{d}s_i} + T\,\frac{\mathrm{d}r_i}{\mathrm{d}s_i} = 0.$$

Dividing by $\frac{\mathrm{d}r_i}{\mathrm{d}s_i}$ and recognizing $\frac{\partial R}{\partial r_i} = 1$ yields

$$\forall i : 0 = -\frac{\partial C_i}{\partial r_i} + \frac{\partial B_i}{\partial r_i} + \frac{\partial B_i}{\partial R} - e_i T + T. \tag{C.3}$$

Using Eq. (C.1) in Eq. (C.3) and rearranging gives the optimal choice of state subsidies, $\{s_1, ..., s_n\}$, for a given federal FIT, T:

$$\forall i : s_i(T) = \frac{\partial B_i}{\partial r_i} + \frac{\partial B_i}{\partial R} - e_i T. \tag{C.4}$$

For given state subsidies, $\{s_1, ..., s_n\}$, the federal government faces the maximization problem

$$\max_{T(s_1,...,s_n)} \Pi^{FED} = \sum_{i=1}^{n} \left[-C_i(r_i) + B_i(r_i, R)\right]. \tag{C.5}$$

Differentiating with respect to T yields

$$\frac{\partial \Pi^{FED}}{\partial T} = \sum_{i=1}^{n} \left[-\frac{\partial C_i}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}T} + \frac{\partial B_i}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}T} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}\frac{\partial R}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}T}\right]. \tag{C.6}$$

[11] Note from Eq. (C.1) that the supplier's choice of r_i depends on s_i, T but not on s_{-i} and thus $\frac{\mathrm{d}r_j}{\mathrm{d}s_i} = 0, \forall i \neq j$.

Recall, that by assumption $\frac{\partial^2 C_i(r_i)}{\partial r_i^2}$ is constant and identical for all states. Differentiating both sides of Eq. (C.1) with respect to T and rearranging gives $\frac{\mathrm{d}r_i}{\mathrm{d}T} = \left[\frac{\partial^2 C_i(r_i)}{\partial r_i^2}\right]^{-1} = b^{-1}$. Thus, the assumed cost structure implies that $\forall i, j : \frac{\mathrm{d}r_i}{\mathrm{d}T} = \frac{\mathrm{d}r_j}{\mathrm{d}T}$.

Setting Eq (C.6) to zero, $\frac{\partial \Pi^{FED}}{\partial T} = 0$, dividing by $\frac{\mathrm{d}r_i}{\mathrm{d}T}$, recognizing $\frac{\partial R}{\partial r_i} = 1$ and rearranging yields the simplified first order condition

$$\sum_{i=1}^{n} \frac{\partial C_i}{\partial r_i} = \sum_{i=1}^{n} \left[\frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}\right] = \sum_{i=1}^{n} \frac{\partial B_i}{\partial r_i} + n \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \tag{C.7}$$

Using Eq. (C.1) in Eq. (C.7) gives the optimal choice of the federal FIT, T, depending on the state subsidies $\{s_1, ..., s_n\}$:

$$\begin{aligned} \sum_{i=1}^{n} [s_i + T] &= \sum_{i=1}^{n} \frac{\partial B_i}{\partial r_i} + n \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} \\ \iff nT + \sum_{i=1}^{n} s_i &= \sum_{i=1}^{n} \frac{\partial B_i}{\partial r_i} + n \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} \\ \iff T(\{s_1, ..., s_n\}) &= \frac{1}{n} \sum_{i=1}^{n} \frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} - \frac{1}{n} \sum_{i=1}^{n} s_i \\ &= \frac{1}{n} \sum_{i=1}^{n} \left[\frac{\partial B_i}{\partial r_i} - s_i\right] + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \end{aligned} \tag{C.8}$$

Solving the system of reaction functions, given by Eq. (C.4) and Eq. (C.8), for T and $\{s_1, ..., s_n\}$ yields the RE support in Nash equilibrium, which we denote by $\tilde{T}$ and $\{\tilde{s_1}, ..., \tilde{s_n}\}$.

$$\begin{aligned} \tilde{T} &= \frac{1}{n} \sum_{j=1}^{n} (n-1) \frac{\partial B_j}{\partial R} + \frac{1}{n} \tilde{T} \sum_{i=1}^{n} e_i \\ &\overset{(2)}{=} \frac{n-1}{n} \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} + \frac{1}{n} \tilde{T} \\ \iff \tilde{T} &= \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \end{aligned} \tag{C.9}$$

Using Eq. (C.9) in Eq. (C.4) we obtain the equilibrium state subsidies

$$\forall i : \tilde{s}_i = \frac{\partial B_i}{\partial r_i} + \frac{\partial B_i}{\partial R} - e_i \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \tag{C.10}$$

The total support of RE in state i is then

$$\tilde{T} + \tilde{s}_i = \frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} + \frac{\partial B_i}{\partial R} - e_i \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \tag{C.11}$$

Eq. (C.11) differs from the first-best given in Eq. (8) only in the two additional two last terms. It follows from $\frac{\partial B_j}{\partial R} > 0$, that REs are over-supported (under-supported), if the term's sum is positive (negative), or, following some simple algebra, if a state's share of marginal benefits from national RE is higher (lower) than its relative burden share

$$\tilde{T} + \tilde{s}_i \gtreqless \Psi_i^* \iff \frac{\frac{\partial B_i}{\partial R}}{\sum_{j=1}^{n} \frac{\partial B_j}{\partial R}} \gtreqless e_i. \tag{C.12}$$

Appendix D. Proof of Proposition 2

Consider that RE support in some states is non-optimal as the efficiency condition Eq. (17) is not satisfied due to $\Delta e_i := e_i - \frac{\frac{\partial B_i}{\partial R}}{\sum_{j=1}^{n} \frac{\partial B_j}{\partial R}} \neq 0$. Following Eqs. (14-16), total RE support can be written as

$$\begin{aligned}\forall i:\ \tilde{T} + \tilde{s}_i &= \frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} - \left[\frac{\frac{\partial B_i}{\partial R}}{\sum_{j=1}^{n} \frac{\partial B_j}{\partial R}} + \Delta e_i\right] \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} + \frac{\partial B_i}{\partial R} \\ &= \frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} - \Delta e_i \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}.\end{aligned} \tag{D.1}$$

From the optimality conditions of the RE capacity supplier, we know that $\frac{\partial C_i}{\partial r_i} = T + s_i$ (cf. Eq. C.1). If the equilibrium of marginal costs and RE support (Eq. D.1) changes due to $\Delta e_i \neq 0$, RE deployment r_i deviates from its first-best by an amount, which we call $\Delta r_i := r_i - r_i^*$. The shift of total RE support from FIT and subsidy from its optimal amount is $-\Delta e_i \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}$ (cf. Eq. D.1, Eq. 8), which directly corresponds to a shift Δr_i. This correspondence is visualized in Figure D.1.

In the plane of RE support and capacity and for linear marginal functions, the difference of the slopes of the marginal cost and benefit functions (i.e., of the curvatures of the original functions, also referred to as *sensitivity of the marginal functions*), respectively multiplied with Δr_i on the horizontal axis, directly corresponds to the shift in total support on the vertical axis:

$$\forall i:\ \frac{\partial^2 C_i}{\partial r_i^2} \Delta r_i - \left[\frac{\partial^2 B_i}{\partial r_i^2} + \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}\right] \Delta r_i = -\Delta e_i \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \tag{D.2}$$

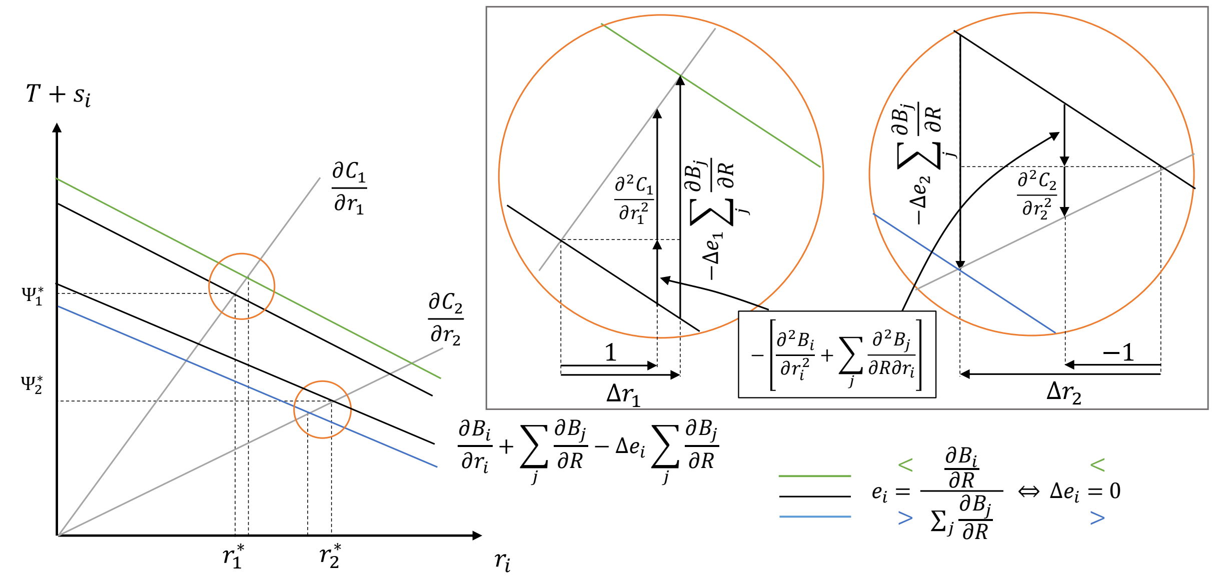

Figure D.1: Equilibrium allocation of RE capacities and policies exemplified for two states when federal cost distribution is under-burdened to state 1 ($\Delta e_1 < 0$) and over-burdened to state 2 ($\Delta e_2 > 0$). There is over-deployment of RE in state 1 and under-deployment in state 2. The change in RE deployment Δr_i is determined from the slopes of the marginal RE support and cost functions. The orange circles detail the situation.

Rearrange to get

$$\forall i: \ \Delta r_i = -\Delta e_i \left[\frac{\partial^2 C_i}{\partial r_i^2} - \frac{\partial^2 B_i}{\partial r_i^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} \right]^{-1} \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \tag{D.3}$$

Now, let $\mu = 1, ..., m$ be the states, which are under-burdened and $\nu = 1, ..., k$ the ones that are over-burdened (i.e., $\Delta e_\mu < 0, \Delta e_\nu > 0$). If follow directly that $\Delta r_\mu > 0, \Delta r_\nu < 0$. Summing Eq. (D.3) over μ and ν, respectively, adding up RE capacities in under- and over-burdened states, and recognizing that $\sum_{j=1}^{n} \frac{\partial B_j}{\partial R} > 0$ does not depend on i, we obtain

$$\begin{aligned} R \gtreqless R^* \iff \sum_{\mu=1}^{m} \Delta r_\mu + \sum_{\nu=1}^{k} \Delta r_\nu \gtreqless 0 \iff \\ -\sum_{\mu=1}^{m} \Delta e_\mu \left[\frac{\partial^2 C_\mu}{\partial r_\mu^2} - \frac{\partial^2 B_\mu}{\partial r_\mu^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\mu} \right]^{-1} \gtreqless \\ \sum_{\nu=1}^{k} \Delta e_\nu \left[\frac{\partial^2 C_\nu}{\partial r_\nu^2} - \frac{\partial^2 B_\nu}{\partial r_\nu^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\nu} \right]^{-1}. \end{aligned} \tag{D.4}$$

Appendix E. Proof of Proposition 3

The decision problem for a *nationwide quota* and *state subsidies* is given by Eq. (18) – Eq. (20). Assuming that P, depicting the equilibrium price on the quota market, is unbound and determined competitively, it follows directly from suppliers' profit maximization and market clearing (cf. Helm 2003):

$$\forall i : \frac{\partial C_i}{\partial r_i} = s_i + P, \tag{E.1}$$

$$R := \sum_{i=1}^{n} r_i = Q. \tag{E.2}$$

We write $r_i(P, s_i)$ as the amount of capacity that satisfies Eq. (E.1).

For given state subsidies, $\{s_1, ..., s_n\}$, the federal government's optimisation problem reads

$$\max_{Q(s_1,...,s_n)} \Pi^{FED} = \sum_{i=1}^{n} \left[-C_i(r_i) + B_i(r_i, R) \right]. \tag{E.3}$$

Differentiating with respect to Q yields

$$\frac{\partial \Pi^{FED}}{\partial Q} = \sum_{i=1}^{n} \left[-\frac{\partial C_i}{\partial r_i} \frac{\mathrm{d}r_i}{\mathrm{d}Q} + \frac{\partial B_i}{\partial r_i} \frac{\mathrm{d}r_i}{\mathrm{d}Q} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} \frac{\partial R}{\partial r_i} \frac{\mathrm{d}r_i}{\mathrm{d}Q} \right].$$

Setting to zero, $\frac{\partial \Pi^{FED}}{\partial Q} = 0$, dividing by $\frac{\mathrm{d}r_i}{\mathrm{d}Q}$, recognizing $\frac{\partial R}{\partial r_i} = 1$ and rearranging yields the simplified first order condition[12]

$$\sum_{i=1}^{n} \frac{\partial C_i}{\partial r_i} = \sum_{i=1}^{n} \left[\frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} \right] = \sum_{i=1}^{n} \frac{\partial B_i}{\partial r_i} + n \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}, \tag{E.4}$$

which is identical to the condition for choosing an optimal FIT (Eq. C.7).

Using Eq. (E.1) in Eq. (E.4) we obtain the condition for the federal government's optimal quota choice, for given state subsidies

$$\sum_{i=1}^{n} [s_i + P] = \sum_{i=1}^{n} \frac{\partial B_i}{\partial r_i} + n \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}$$

$$\Longleftrightarrow \; n\,P + \sum_{i=1}^{n} s_i = \sum_{i=1}^{n} \frac{\partial B_i}{\partial r_i} + n \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}$$

$$\Longleftrightarrow \; P(s_1, ..., s_n) = \frac{1}{n} \sum_{i=1}^{n} \frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} - \frac{1}{n} \sum_{i=1}^{n} s_i. \tag{E.5}$$

[12]The assumption $\forall i : \frac{\partial^2 C_i(r_i)}{\partial r_i^2} = b$ implies $\forall i : \frac{\mathrm{d}r_i}{\mathrm{d}Q} = b^{-1} \frac{\mathrm{d}P}{\mathrm{d}Q}$ which is thus identical for all states.

Next, we turn to the states' reaction functions. Note, that a state takes the auctioned quota Q as given, but a state's RE capacities affect the equilibrium quota price $P(r_i(s_i))$. Using Eq. (E.1) and Eq. (E.2) in the states' objectives (Eq. 19) and differentiating with respect to s_i yields

$$\forall i : \frac{\partial \Pi_i^{ST}}{\partial s_i} = -\frac{\partial C_i}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}s_i} + \frac{\partial B_i}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}s_i} - e_i Q \frac{\partial P}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}s_i} + P\frac{\mathrm{d}r_i}{\mathrm{d}s_i} + r_i \frac{\partial P}{\partial r_i}\frac{\mathrm{d}r_i}{\mathrm{d}s_i}.$$

Setting to zero, dividing by $\frac{\mathrm{d}r_i}{\mathrm{d}s_i}$ and rearranging yields the simplified first order condition to the states' maximization problem

$$\forall i : \frac{\partial C_i}{\partial r_i} = \frac{\partial B_i}{\partial r_i} + [r_i - e_i Q]\frac{\partial P}{\partial r_i} + P. \tag{E.6}$$

The states' reaction functions are obtained by using Eq. (E.1) in Eq. (E.6)

$$\begin{aligned} \forall i : s_i + P &= \frac{\partial B_i}{\partial r_i} + [r_i - e_i Q]\frac{\partial P}{\partial r_i} + P \\ \iff \forall i : s_i(P) &= \frac{\partial B_i}{\partial r_i} + [r_i - e_i Q]\frac{\partial P}{\partial r_i}. \end{aligned} \tag{E.7}$$

Note, that by assumption $\forall i : \frac{\partial^2 C_i(r_i)}{\partial r_i^2} = b$. Differentiating both sides of Eq. (B.4) with respect to P and rearranging gives $\forall i : \frac{\partial P}{\partial r_i} = b$. Thus, under a nationwide quota the marginal effect of RE capacities on the quota price is identical across all states. We denote the Nash equilibrium of the federal and state governments RE support as $\bar{P}, \bar{s_1}, ..., \bar{s_n}$. The equilibrium quota price is given by inserting Eq. (E.7) in Eq. (E.5):

$$\begin{aligned} \bar{P} &= \frac{1}{n}\sum_{i=1}^{n}\frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n}\frac{\partial B_j}{\partial R} - \frac{1}{n}\sum_{i=1}^{n}\left[\frac{\partial B_i}{\partial r_i} + [r_i - e_i Q]\frac{\partial P}{\partial r_i}\right] \\ &= \sum_{j=1}^{n}\frac{\partial B_j}{\partial R} - \frac{1}{n}\sum_{i=1}^{n}[r_i - e_i Q]\frac{\partial P}{\partial r_i} \\ &= \sum_{j=1}^{n}\frac{\partial B_j}{\partial R} - \frac{1}{n}\frac{\partial P}{\partial r_i}\left[\sum_{i=1}^{n} r_i - Q\sum_{i=1}^{n} e_i\right] \\ &\overset{(E.2),(2)}{=} \sum_{j=1}^{n}\frac{\partial B_j}{\partial R} - \frac{1}{n}\frac{\partial P}{\partial r_i}[Q - Q] \\ \iff \bar{P} &= \sum_{j=1}^{n}\frac{\partial B_j}{\partial R}. \end{aligned} \tag{E.8}$$

Inserting the equilibrium quota price from Eq. (E.8) into the reaction function in Eq. (E.7), we obtain the state subsidies in Nash equilibrium:

$$\begin{aligned}\forall i : \bar{s}_i &= \frac{\partial B_i}{\partial r_i} + [r_i - e_i Q] \frac{\partial}{\partial r_i} \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} \\ &= \frac{\partial B_i}{\partial r_i} + \left[\frac{r_i}{Q} - e_i\right] Q \frac{\partial}{\partial r_i} \sum_{j=1}^{n} \frac{\partial B_j}{\partial R}. \end{aligned} \tag{E.9}$$

In equilibrium total RE support in a state is:

$$\bar{P} + \bar{s}_i \overset{(E.7),(E.8)}{=} \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} + \frac{\partial B_i}{\partial r_i} + \left[\frac{r_i}{Q} - e_i\right] Q \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}. \tag{E.10}$$

The total support, Eq. (E.10), differs from the first-best, Eq. (8), only in the additional last term. Writing this observation formally, we obtain under which conditions RE is over-supported, under-supported or optimal:[13]

$$\begin{aligned} & \bar{P} + \bar{s}_i \gtreqless \Psi_i^* \\ \overset{(E.10),(8)}{\Longleftrightarrow} \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} + \frac{\partial B_i}{\partial r_i} + \left[\frac{r_i}{Q} - e_i\right] Q \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} &\gtreqless \frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} \\ \overset{Q>0}{\Longleftrightarrow} \left[\frac{r_i}{Q} - e_i\right] \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} &\gtreqless 0. \end{aligned} \tag{E.11}$$

Consequently, a nationwide quota is first-best in two cases: (i) the marginal benefits of national RE deployment are independent of the inter-state distribution of RE, i.e. $\sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} = 0$, or (ii) in each state the RE deployment is proportional to the relative burden share, i.e. $r_i = e_i Q$.

For a strictly negative sum of cross derivatives, $\sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} < 0$, it follows from Eq. (E.11) that

$$\bar{P} + \bar{s}_i \gtreqless \Psi_i^* \iff \frac{r_i}{Q} \lesseqgtr e_i. \tag{E.12}$$

[13] Note that Eqs. (E.1), (E.10) provide the solution for the chosen r_i's. However, an explicit formulation is impossible for our approach with general functions. Thus, it is more insightful to analyze the optimality via the support instead of the RE quantities.

Appendix F. Proof of Proposition 4

We can obtain the efficiency condition for national deployment following the same steps as for the support with FIT and subsidy (Eq. D.1–D.4). First, we write the total amount of RE support where Δe_i depicts the derivation from the efficiency condition in Eq. (E.12):

$$\forall i:\ \bar{P} + \bar{s}_i = \frac{\partial B_i}{\partial r_i} + \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} - \Delta e_i R \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}. \tag{F.1}$$

Assuming, again, linear marginal costs and benefits, and considering the shift in total support as a function of the slopes of the marginal cost and benefit curves multiplied respectively with Δr_i we obtain

$$\forall i:\ \frac{\partial^2 C_i}{\partial r_i^2} \Delta r_i - \left[\frac{\partial^2 B_i}{\partial r_i^2} + \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} \right] \Delta r_i = -\Delta e_i R \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial r_i \partial R} \tag{F.2}$$

$$\forall i:\ \Delta r_i = -\Delta e_i \left[\frac{\partial^2 C_i}{\partial r_i^2} - \frac{\partial^2 B_i}{\partial r_i^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} \right]^{-1} R \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial r_i \partial R}. \tag{F.3}$$

Let again $\mu = 1, ..., m$ be the states, which are under-burdened and $\nu = 1, ..., k$ the ones that are over-burdened. Summing over μ and ν, respectively, and adding up the deployment changes we find

$$\begin{aligned} R \gtreqless R^* \iff \sum_{\nu=1}^{k} \Delta r_\nu + \sum_{\mu=1}^{m} \Delta r_\mu \gtreqless 0 \iff \\ -\sum_{\mu=1}^{m} \Delta e_\mu \left[\frac{\partial^2 C_\mu}{\partial r_\mu^2} - \frac{\partial^2 B_\mu}{\partial r_\mu^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\mu} \right]^{-1} \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} \gtreqless \\ \sum_{\nu=1}^{k} \Delta e_\nu \left[\frac{\partial^2 C_\nu}{\partial r_\nu^2} - \frac{\partial^2 B_\nu}{\partial r_\nu^2} - \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_\nu} \right]^{-1} \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}. \end{aligned} \tag{F.4}$$

Appendix G. Proof of Proposition 5

Comparing a state's equilibrium subsidy under nationwide auction (Eq. E.9) and FIT (Eq. C.10) yields

$$
\begin{aligned}
&\bar{s}_i \gtreqless \tilde{s}_i \\
\overset{(E.9),(C.10)}{\Longleftrightarrow}\ & \frac{\partial B_i}{\partial r_i} + [r_i - e_i\, R] \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} \gtreqless \frac{\partial B_i}{\partial r_i} + \frac{\partial B_i}{\partial R} - e_i \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} \\
\Longleftrightarrow\ & r_i \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} - e_i\, R \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} \gtreqless \frac{\partial B_i}{\partial R} - e_i \sum_{j=1}^{n} \frac{\partial B_j}{\partial R} \\
\Longleftrightarrow\ & r_i \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} - \frac{\partial B_i}{\partial R} \gtreqless -e_i \left[\sum_{j=1}^{n} \frac{\partial B_j}{\partial R} - R \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} \right]. \qquad \text{(G.1)}
\end{aligned}
$$

For strictly negative cross derivatives, $\sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i} < 0$, the term in parenthesis is strictly positive, so that Eq. (G.1) simplifies to

$$
\Longleftrightarrow \frac{\frac{\partial B_i}{\partial R} - r_i \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}}{\sum_{j=1}^{n} \frac{\partial B_j}{\partial R} - R \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}} \lesseqgtr e_i. \qquad \text{(G.2)}
$$

Equivalently, Eq. (G.2) can be written for a marginal quota price change from an increase in state i's RE capacities, $\frac{\partial P}{\partial r_i} = \sum_{j=1}^{n} \frac{\partial^2 B_j}{\partial R \partial r_i}$, (by inserting Eq. E.8 in Eq. G.2)

$$
\begin{aligned}
\bar{s}_i \gtreqless \tilde{s}_i \Longleftrightarrow\ & \frac{\frac{\partial B_i}{\partial R} - r_i \frac{\partial P}{\partial r_i}}{\sum_{j=1}^{n} \frac{\partial B_j}{\partial R} - R \frac{\partial P}{\partial r_i}} \lesseqgtr e_i \\
\Longleftrightarrow\ & \frac{\frac{\partial B_i}{\partial R} - r_i \frac{\partial P}{\partial r_i}}{\sum_{j=1}^{n} \left[\frac{\partial B_j}{\partial R} - r_j \frac{\partial P}{\partial r_i} \right]} \lesseqgtr e_i, \qquad \text{(G.3)}
\end{aligned}
$$

where $r_i \frac{\partial P}{\partial r_i}$ is the change in federal support received in state i due to a marginal change in the state's RE capacities and, analog, $R \frac{\partial P}{\partial r_i}$ is the change in federal support received for the total nationwide RE capacities.

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