Optimal federal co-regulation of renewable energy deployment

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February 4, 2021

Declaration of Competing Interest
The authors declare no competing interests.

Acknowledgements
The current work has been funded by the German Federal Ministry of Education and Research under Grant 01UU1703. Earlier versions of this paper were presented at the European Association of Environmental and Resource Economists Conference, at the Workshop for Young Researchers on Environmental and Resource Economics of the German Economic Association, and at the Central German Doctoral Program in Economics.

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June 7, 2022

Abstract

In federally organized countries the allocation of renewable energy (RE) deployment iss regulated by national and subnational governments. We analyze the efficiency of this federal co-regulation when different types of policy instruments – price and quantity – are applied at different government levels. Using an analytical model with two government levels, we show that efficient federal co-regulation crucially depends on the burden sharing of national subsidy costs among subnational jurisdictions. We find that national price-based regulation, i.e. feed-in tariff, is efficient if burden shares of subnational jurisdictions are distributed in proportion to their population. This holds regardless of the policy instrument applied at the subnational level as long as RE deployment causes regional costs instead of regional benefits. Under national quantity-based regulation, i.e. tenders, efficient burden sharing depends on the policy instrument applied at the subnational level. Subnational price-based regulation, e.g. state-level levies, combined with national quantity-based regulation requires burden shares to be oriented towards first-best RE deployment shares. By contrast, subnational quantity-based regulation, i.e. spatial planning, combined with national quantity-based regulation, under certain conditions, requires population-oriented burden sharing, namely, if RE deployment only causes negative regional effects. If so, we also show that national quantity-based regulation ends up to be de-facto price-based.

Keywords: multi-level governance, environmental regulation, renewable energies, tender scheme, feed-in tariff, spatial planning

JEL classification: H23, H77, Q48

We thank two anonymous reviewers for their elaborate comments which greatly improved our paper.

1 Introduction

Worldwide, national governments aim at reducing greenhouse gas (GHG) emissions (REN21, 2019). Achieving the national transition to a decarbonized power sector essentially relies on the vast expansion of large-scale renewable energy (RE) plants. To this end, national governments support RE deployment through incentives implemented via prices like feed-in tariffs (FiT) or via quantities like tender schemes. In countries with federal systems national governments co-regulate RE deployment together with subnational authorities. Commonly, subnational governments (e.g. at the state, province, or county level) pick siting areas for installations of RE power plants through spatial planning (Keenleyside et al., 2009; Pettersson et al., 2010; Iglesias et al., 2011; Power & Cowell, 2012; Cowell et al., 2017). Partly, subnational governments also resort to price incentives to guide regional RE deployment, for example in Spain, Germany, or Denmark (Iglesias et al., 2011; Lienhoop, 2018; Jørgensen et al., 2020). Thus, national support schemes that set incentives for RE deployment often overlap with subnational policies. Our work analyzes how the interplay of national with subnational regulation affects the optimal allocation of RE deployment.[1]

As subnational governments represent their own jurisdictions and are concerned about their own welfare, preferences of national and subnational governments often do not coincide (i.a. Ohl & Eichhorn, 2010; Pettersson et al., 2010). The interests of subnational governments may diverge from those of national governments for two reasons. On the one hand, subnational governments do not fully consider nationwide benefits of GHG emissions reduction, but primarily focus on regional costs and benefits of large-scale RE plants, like wind turbines or open-space solar power plants. Regional costs include noise impacts on residents or threats to ecosystems on site (Zerrahn, 2017; Krekel & Zerrahn, 2017; von Möllendorff & Welsch, 2017; Gibbons, 2015; Landry et al., 2012). Regional benefits may originate from local green preferences, positive regional economic effects, or enhanced regional energy resiliency (Kalkbrenner et al., 2017; Többen, 2017). As a result, subnational governments may have an incentive to underprovide (overprovide) promotion of RE deployment, or in other words, to over-restrict (excessively promote) RE deployment. This intra-national underprovision problem is analogous to the well-known underprovision problem of climate policy at the international level (Barrett, 1994).

On the other hand, national RE support schemes encumber subnational jurisdictions with

[1] When we refer to "RE deployment" this term comprises the construction and operation of RE power plants. The "amount of RE deployment" means the "amount of electricity produced from RE power plants". However, the latter is often roughly proportional to installed capacity of RE.

financial burden shares, i.e., subnational jurisdictions are directly or indirectly funding national subsidy costs via levies or taxes (Council of European Energy Regulators, 2018). While these financing mechanisms are irrelevant for national policy choice, they may create strategic incentives for subnational governments. By attracting RE deployment and thus national remuneration payments, subnational governments have an incentive to exploit this common pool of jointly financed RE subsidies and to overprovide promotion of RE deployment within their own jurisdictions (e.g. for Germany see Gawel & Korte, 2015).

Overall, these incentives for subnational governments may lead to an inefficient federal co-regulation of RE deployment. For example, German federal states in total had higher RE expansion targets than the national government (Goetzke & Rave, 2016), while at the same time they aimed at less wind power expansion than the national government (Meier et al., 2019).[2] This demonstrates the need for a regulatory design that provides efficient coordination among national and subnational RE policies in the presence of these strategic incentives.[3]

We take up this issue and analyze different regulatory designs of federal regulation, each regulatory design varying with respect to the policy instrument used at different administrative levels. In particular, we aim to understand how the mix of policy instruments at national and subnational levels affects the efficiency of federal co-regulation. Thus, we examine under which conditions different federal regulatory designs implement the socially optimal allocation of RE deployment.

To answer our research question, we build a stylized two-level regulation model where a national government and subnational state governments apply overlapping RE policies, steering spatial allocation of RE deployment. Of course, under centralized competences a perfectly informed national government could implement the social optimum by means of regionally differentiated price incentives. However, in federal systems regulatory powers are vertically distributed. Furthermore, due to other policy goals or constitutional rules, for example requirements of the European Union (EU) state aid law or national laws ensuring equal treatment of subnational

[2]There may be national legislation that demands for multi-level agreements, or subnational governments may put pressure on the national government when deciding about national RE support (Strunz et al., 2016). Nonetheless, in federal systems the exertion of influence is also restricted by the constitutional division of competences or majority rules. E.g. in Germany state governments are entitled to formally comment decisions by the national government concerning financial RE support, but they cannot veto the national government's decision.

[3]Most of the literature on climate change policy studies the interaction among national governments in the international arena implicitly assuming that subnational authorities have a merely executive function. In fact, subnational governments may substantially affect national policy and its outcome. This is especially true with regard to overlapping regulations of RE deployment (Goulder & Stavins, 2011). Equally, Shobe & Burtraw, 2012 highlight that interaction of national and subnational RE policies plays a substantial - but often neglected - role within federal systems when national governments aim at their climate protection goals.

regions, national policies are typically bound to spatially uniform instruments. Given these (real-world) constraints, we analyze the efficient design of federal regulation considering at the national level

(i) price-based instruments (i.e. remunerations set through administrative procedures, e.g. FiT), or

(ii) quantity-based instruments (i.e. remunerations set through tendering procedures, e.g. tender schemes),

and at the subnational level

(i) price-based instruments (e.g. compensation schemes, taxes, royalties, levies, or subsidies), or

(ii) quantity-based instruments (i.e. quantity caps for RE deployment implemented through spatial planning).

We analyze four regulatory designs of federal co-regulation which represent the possible combinations of national and subnational policy instruments depicted above. For each regulatory design we deduce *efficiency conditions* that ensure socially optimal policy choices by national and subnational governments. These efficiency conditions determine the distribution of national subsidy costs among subnational jurisdictions (burden shares). With respect to the national level, we find that national price-based regulation induces first-best RE deployment if burden shares are equal to population shares regardless of the policy instrument applied at the subnational level. In contrast, the choice of subnational policy instruments is decisive if quantity-based regulation is applied at the national level. In this case, different subnational policy instruments require different efficient designs of burden shares. While with subnational price-based regulation burden shares should be oriented towards first-best RE deployment shares, with subnational quantity-based regulation burden shares should be oriented towards population shares. These findings apply under the plausible assumption that regional costs outweigh regional benefits from RE deployment (which not only, but most clearly occur in case of wind power deployment, cf. Krekel & Zerrahn, 2017; von Möllendorff & Welsch, 2017).

Our work contributes to the branch of environmental and fiscal federalism that looks into strategic interaction among governments of different federal levels (Oates & Portney, 2003; Dijkstra & Fredriksson, 2010). More precisely, we add to the theoretical literature on optimal regulation of environmental goods in federal systems. In our model the environmental good is RE deployment and subnational governments consider RE deployment as an impure public good in that global benefits (public good or altruistic component) are tied to regional costs and benefits (private good or egoistic component) (Caplan & Silva, 2011; Meya & Neetzow, 2021). Conceptually, this problem of co-regulating multiple externalities in a federal system is mainly dealt with in the literature on pollution control. In that respect, abatement of pollution is analogous to RE deployment in our work. Accordingly, we assume that by deploying RE power plants fossil fuel-based power production is substituted such that GHG emissions are reduced.

In two comparable papers on federal co-regulation of transboundary pollution, Caplan and Silva (1997; 1999) analyze the optimal assignment of price and quantity instruments to different governmental levels within a sequential move setting. The authors do not find a strictly superior assignment of instruments to government levels, but stress that efficiency of federal co-regulation is particularly sensitive to the timing of policy actions by government levels. Settings where subnational governments move first and the national government moves second are more efficient ("decentralized leadership").[4] In Caplan and Silva (1997; 1999), results rest on the assumption that the national government can choose interregional income transfers in the second stage of the game such that subnational governments anticipate this and internalize all externalities. Adding regional pollution that is correlated with global pollution, Caplan and Silva (2005) confirm the efficiency of decentralized leadership for a three-stage game when both government levels regulate through quantity-based instruments. In a follow-up paper, Caplan (2006) shows that decentralized leadership does not implement the first-best allocation anymore when both governments regulate through price-based instruments. By contrast, first, in our model income transfers cannot be chosen by the national government but are exogenously specified in the form of burden shares. Second, when both government levels regulate through price-based instruments we find that efficient co-regulation is easy to implement. Third, we employ the concept of Nash equilibrium in a simultaneous move game. Though co-regulation often takes place in the form of successive and repeated policy-setting among national and subnational governments, a one-shot simultaneous move game can adequately represent these policy decisions. This is the case as long as national and subnational governments do not differ in their ability to react and change their own policy. On the basis that governments can equally easily adjust their policies, the

[4] In a similar manner, Caplan and Silva (2000; 2011) study sequential-move games among national and subnational governments that contribute to pure respectively impure public good provision. They show that the abovementioned efficiency of decentralized leadership still holds in light of labor mobility if the national government can make differentiated interregional income transfers.

equilibrium of the dynamic co-regulation game is the same as the equilibrium of the simultaneous move game (cf. Williams III, 2012).

Ambec and Coria (2018) analyze the regulation of local and global pollutants that exhibit (dis)economies of scope in abatement costs. They spare an explicit specification of interregional income transfers. They find that both price-based and quantity-based regulation at the global level always establish the first-best outcome. This finding holds if interregional income transfers are independent from subnational policy choices. Their result further applies independently of local regulators using taxes or abatement quotas. Unlike Ambec and Coria (2018), we explicitly include an exogenous transfer mechanism which allocates national subsidy costs to subnational jurisdictions. We find that for efficiency, first, the transfer mechanism needs to match a specific distribution rule, and second, this efficient distribution rule (efficient burden sharing) depends on the combination of national and subnational instruments (regulatory design).

Our theoretical model setup is based on Williams III (2012). He likewise analyzes the interaction of national and state policies co-regulating a pollutant that causes nationwide and regional externalities at the same time. He assumes that national and subnational governments apply the same type of instrument, i.e., both either price-based or quantity-based regulation, and models federal co-regulation as a simultaneous move game. Williams III (2012) finds that the application of price-based instruments leads to more effective pollution reductions and likely to a more efficient outcome than the application of quantity-based instruments. In his model this is because, on average, the national price-based instrument shapes the net marginal benefits of states' policy choices such that states choose to internalize their regional externalities while the national policy concurrently internalizes nationwide externalities. We extend his approach by studying the efficiency of instrument mixes where different policy instruments are applied at the national and subnational level. As Williams III (2012), we show that national price-based regulation is likely preferable to national quantity-based regulation. In our model this stems from the specification of states' burden shares that implement first-best outcomes. We find that under national price-based regulation these efficient burden shares are equal to states' population shares. In practice, the latter is likely met due to national levy-based financing schemes that are commonly in place (see Section 5.1). Moreover, within our RE setting the subnational quantity instrument, i.e. quantity caps for RE deployment, differs from the subnational quantity instrument, i.e. emissions caps, within the pollution control setting in Williams III (2012). Transferred to our model emissions caps would resemble minimum RE deployment levels. However, we model subnational spatial planning as setting maximum RE deployment levels. Therefore, and opposed to Williams III (2012), the quantity of nationwide RE deployment promoted by the national government may be effectively cut by the quantity choices of subnational governments.

Most recently, Meya and Neetzow (2021) transfered Williams III's model to the case of RE policy. They scrutinize which RE support scheme at the national tier – feed-in tariffs or tenders – performs better if state governments are able to set regional price incentives. Policy decisions again ensue from a simultaneous move game among national and state governments. According to their results, both national support schemes may be efficient depending on the specification of burden sharing among states. Analogous to Williams III (2012), they find that – given price-based instruments are applied at the national and state level – a state's burden share must be equal to its share of marginal benefits from nationwide RE deployment. In contrast, given a national tender scheme, states' burden shares must be equal to their shares of first-best nationwide RE deployment (Meya & Neetzow, 2021). We confirm this result in our model where we also allow for regional costs of RE deployment. Most importantly, unlike Meya and Neetzow (2021), we allow for a quantity instrument at the subnational level (i.e. spatial planning) which is, in our view, more realistic when formalizing subnational regulation in the context of large scale RE (Keenleyside et al., 2009; Cowell et al., 2017). This is crucial, as we demonstrate that in the presence of national tender schemes subnational spatial planning more likely implements efficient federal regulation than subnational price incentives. This result holds as long as for advanced expansion levels regional costs from RE deployment dominate positive regional benefits from RE deployment.

The paper is structured as follows. Section 2 sets up a two-level regulation model. Section 3 defines the social optimum and presents the case of optimal regulation if there are no policy constraints. Section 4 analyzes the equilibrium outcomes of the four regulatory designs of interest and defines efficiency conditions for each of them. These results are discussed in Section 5 and are linked to RE deployment and regulation in Germany. Section 6 concludes.

2 Model

We model regulation of RE deployment in a nation with a two-level federal system. The nation is composed of n states. A national government exerts nationwide RE policy that uniformly applies in all states. State governments exert RE policies that only apply within their respective jurisdictions. The regulatory design is exogenously given meaning the type of policy instruments exerted by national and state governments (price or quantity) is predetermined.

Given national and state-level RE policies, electricity suppliers decide on actual RE deployment in each state. Formally, we set up a two-stage game where firstly policies are set and secondly suppliers choose the amount of RE deployment. In the first stage, national and state governments set their mutually best policy responses, assuming governments readjust their policies given the policy decisions of other governments. In other words, we look at the Nash equilibrium of a simultaneous move game among national and state governments. In the second stage, after equilibrium policies are implemented, suppliers choose RE deployment. RE deployment means the amount of electricity produced from RE capacities installed in state i. We denote RE deployment by x_i.

National population is normalized to one and state i has a population share of η_i, hence $\sum_{i=1}^{n} \eta_i \equiv 1$.

2.1 Costs and Benefits

We include three types of costs and benefits.

First, producing a certain amount of electricity x_i comes at construction and operation costs summarized under RE deployment costs and denoted by $C_i(\cdot)$. Due to geographical characteristics, e.g. wind speed or solar irradiation, productivity of RE plants depends on their location, and consequently power production costs may differ across states. Within a state RE deployment costs increase as the productivity of sites decreases. Hence, we assume costs to be convex with $\frac{\partial C_i}{\partial x_i} > 0$ and $\frac{\partial^2 C_i}{\partial x_i^2} > 0$, $\forall i$. The underlying assumption is that with increasing RE deployment productivity declines, e.g. because wind turbines need to be installed at less windy sites or solar power plants at less sunny locations respectively (as in Lancker & Quaas, 2019).

Second, since RE plants substitute fossil-fuel based power plants they reduce GHG emissions.[5] These nationwide benefits from emissions reductions are captured by $B(\cdot)$. Benefits from emissions reductions are the same for residents nationwide.[6] We assume that $B(\cdot)$ depends

[5]Our partial equilibrium analysis assumes that electricity consumption is completely inelastic. Nationwide electricity demand is met by electricity supply from nationwide RE deployment and non-renewable energy sources. The latter adjusts their supply to meet the residual electricity demand. Thus, welfare from electricity consumption is unaltered for all citizens.

[6]We think this simplification is tenable since our analysis aims at explaining subnational policy choices in the presence of national and regional costs and benefits. Allowing for diverging regional benefits from nationwide RE expansion does not change the fundamental rationale underlying subnational policies. Of course, we thereby abstract from reality (Ricke et al., 2018).

on the amount of electricity produced from RE plants installed nationwide, $X \equiv \sum_{i=1}^{n} x_i$, and that the marginal benefits of emissions reductions are positive and decreasing, i.e. $\frac{\partial B}{\partial X} > 0$ and $\frac{\partial^2 B}{\partial X^2} < 0$.

Third, deploying RE generates regional costs and benefits for residents living in the same state. We assume that regional costs and benefits depend on the amount of RE deployment because more RE deployment implies more RE capacities and more (and larger) RE plants installed which, in turn, cause more regional costs or benefits. The regional cost and benefit function, or *disamenity function*, is denoted by $D_i(\cdot)$.[7] If regional costs outweigh regional benefits this is indicated by $D_i(\cdot) > 0$. On the contrary, if regional benefits outweigh regional costs this is indicated by $D_i(\cdot) < 0$, expressing negative disamenities respectively amenities.[8] We consider the disamenity function $D_i(\cdot)$ to be convex, $\frac{\partial^2 D_i}{\partial x_i^2} > 0$, based on the underlying assumption that marginal regional cost of RE deployment always increase faster than marginal regional benefits from RE deployment. The latter assumption seems plausible in view of relatively small positive regional effects of RE deployment (i.a. Többen, 2017; Ejdemo & Söderholm, 2015; Mauritzen, 2020) and increasing negative regional effects of RE deployment (i.a. Tafarte & Lehmann, 2019). It is straightforward to assume disamenities are absent when no RE deployment is in place, $D_i(0) = 0$.

Referring to the configuration of regional costs and benefits we propose a definition of two exemplary types of nations. We distinguish between *type-D* nations where the disamenity function is positive and strictly increasing in all states (see Figure 1a), and *type-B* nations where at least in one state the disamenity function is negative and strictly decreasing across all potential RE deployment levels (see Figure 1b). You may think of a *type-D* nation as a country that is densely populated such that in all states disamenities are positive (therefore labeled by D). Whereas you may think of a *type-B* nation as a country where some states are scarcely populated such that disamenities are negative, meaning in these states no regional costs from RE deployment occur but people receive regional benefits e.g. due to green preferences (therefore labeled by B).

[7]We use the term *disamenity* only with respect to regional effects of RE deployment. Thus, *disamenities* means negative regional effects minus positive regional effects.

[8]Deployment costs as well as regional costs and regional benefits vary across RE technologies installed on site, e.g. wind power, open-space solar power, or biomass plants (von Möllendorff & Welsch, 2017; Kim et al., 2020). Though, in our model we do not differentiate among RE technologies you could also suppose that, e.g. with solar power deployment regional benefits dominate while with wind power deployment regional costs dominate.

Formally, we define a ***type-D*** nation by:

$$\forall i : \quad \frac{\partial D_i}{\partial x_i} > 0 \qquad \text{for} \quad x_i > 0 \tag{1}$$

We define a ***type-B*** nation by:

$$\exists j : \quad \frac{\partial D_j}{\partial x_j} < 0 \qquad \text{for} \quad 0 < x_j < \check{x}_j \tag{2}$$

where $\check{x}_j$ denotes the feasible potential of RE deployment in state j that is never reached by assumption. Graphically, *type-D* nations and *type-B* nations are exemplarily depicted in Figure 1 with the upper figures illustrating the state-specific disamenity functions and the lower figures illustrating the corresponding marginal disamenity functions.

[Input: Figure 1]

The specification of *type-D* and *type-B* nations does not cover all possible constellations of disamenity functions. Of course, disamenity functions may also change from negative to positive disamenities at lower levels of RE deployment. By highlighting these two types we refer to a simple but most relevant distinction of regional cost and benefit structures which we use in our analysis.

2.2 Welfare Functions and Policy Instruments

National and state governments are assumed to be benevolent. The national government considers all costs and benefits from nationwide RE deployment, while state governments consider their respective state-specific costs and benefits. Each government cares about the welfare of the citizens in its jurisdiction, including the representative supplier's profit since the supplier is owned by citizens of the state in which it operates. In other words, governments seek to maximize their corresponding welfare.

National Government

The welfare function of the national government is defined as follows:

$$\mathscr{W}(\boldsymbol{x}) = B(X) - \sum_{i=1}^{n} \left[D_i(x_i) + C_i(x_i) \right] \tag{3}$$

The first term in eq. (3) expresses nationwide benefits from nationwide RE deployment, e.g. through climate protection. As climate protection is a public good, people in all states benefit from RE deployment in any single state. These benefits are represented by $\sum_{i=1}^{n} \eta_i B(X)$ which is equal to $B(X)$. The second term in (3) comprises all state-specific costs of nationwide RE deployment. For each state, state-specific costs consist of regional costs and benefits—which we label as *disamenities*—that affect regional residents $D_i(x_i)$ and regional power production costs $C_i(x_i)$ that are borne by the supplier.

In order to internalize nationwide benefits from emissions reduction, the national government implements a RE support scheme. This scheme be price-based (e.g. implemented through a feed-in tariff) or quantity-based (e.g. implemented through a tender scheme). For either support scheme, let p^N denote nationwide uniform remuneration for one unit of RE-based electricity.[9] With price-based regulation the national government administratively determines the level of p^N with $p^N > 0$. With quantity-based regulation the national government chooses a tender volume $\bar{X}$ such that the level of p^N is set through tendering procedures. Here, the national government also has the option to set a ceiling price $\bar{p}$ which is common practice for most tender schemes and works as a safeguard to protect against absent competition (Grashof et al., 2020).

Public expenditures, namely the sum of nationwide disbursed RE remunerations, $\sum_{i=1}^{n} p^N x_i$, are funded through a financing scheme (e.g. levy on the electricity price or general taxation). These expenditures are assumed to be irrelevant for national welfare because they simply constitute a transfer from electricity consumers to electricity producers. In other words, the national government's welfare function is quasilinear in money.[10]

State Governments

Analogous to the national government, a state government's welfare function comprises the sum of utilities of all its state residents. Firstly, this implies that each state government only cares about its own fraction of costs and benefits, $\eta_i B(X) - D_i(x_i)$. States do not per se internalize benefits from emissions reduction for other states arising from RE deployment in their own

[9] As a standard assumption in fiscal federalism literature (see Oates, 1999) the national government may be bound to uniform policy e.g. due to constitutional rules or other policy goals. If the national government can regionally-differentiate its policy, then in our model national price-based regulation induces first-best allocation of RE deployment through state-specific prices (see Section 4.1.1 and 4.2.1).

[10] It is easy to see that spending budget on a national RE support scheme is a zero-sum game for the national government. The sum of nationwide disbursed RE remunerations, $\sum_{i=1}^{n} p^N x_i$, enters in eq. (3) with a positive sign as it depicts revenues for electricity suppliers. At the same time, national RE remunerations need to be financed through taxes or levies on citizens, thus, the same term also enters with a negative sign. Hence, expenditures and revenues cancel out and eq. (3) is unchanged regardless of the policy instrument applied at the national level.

jurisdiction, but fully take into account their disamenities, i.e. regional costs and benefits. Therefore, states tend to under-provide regional RE deployment depending on their population share η_i. Secondly, states consider profits of their citizen-owned suppliers that correspond to revenues from national RE support and power production costs of regional RE deployment, $p^N x_i - C_i(x_i)$. Additionally, each state (respectively its residents) bears some funding costs of national RE support, $\gamma_i \sum_{i=1}^{n} p^N x_i$. By $\boldsymbol{\gamma} = (\gamma_1, ..., \gamma_n)$ we denote the vector of fixed state-specific burden shares of national funding costs, representing some funding mechanism (e.g. non-tax levies or general taxation). All states together entirely finance the national RE support scheme, i.e. $\sum_{i=1}^{n} \gamma_i \equiv 1$.[11] Taken together, receiving from and paying into the jointly funded national support scheme, establishes incentives for states to exploit the common subsidy pool to a greater or lesser extent. This depends on their individual burden share γ_i. The resulting welfare function of state i's government is given by:

$$\mathscr{W}_i(x_i, \boldsymbol{x_{-i}}, p^N) = \eta_i B(X) - D_i(x_i) - C_i(x_i) + p^N x_i - \gamma_i \sum_{i=1}^{n} p^N x_i \qquad \forall i \tag{4}$$

State governments are either equipped with price or quantity instruments. Assuming the former, let p_i^S denote the state-level price incentive for one unit of RE-based electricity production in state i. State-level price incentives comprise, e.g. compensation payments for deploying RE power plants ($p_i^S < 0$) or, in contrast, state-level price incentives can promote regional RE deployment, e.g. through tax exemptions ($p_i^S > 0$). Thereby, state governments can reduce (increase) regional RE deployment, e.g. in order to avert (raise) regional costs (benefits).

Assuming quantity-based state-level regulation, state governments decide on a quantity cap (or limit) on RE deployment within their respective jurisdictions. Let $\bar{x}_i$ denote state i's quantity cap. Hence, we model spatial planning in the form of a command-and-control instrument. Formalizing spatial planning procedures in this way captures their essential feature regarding RE deployment, namely the provision of expansion areas for RE deployment (Keenleyside et al., 2009; Pettersson et al., 2010; Power & Cowell, 2012). By setting a quantity cap for regional RE deployment, state governments can confine the amount of regional costs.

Since state governments' welfare functions are quasilinear, again, under state-level price regulation expenditures and revenues from state-level price incentives cancel out at the state level.[12]

[11] It is possible that state's funding costs are very high such that state's welfare is negative. For example, in Germany national subsidy costs for wind power deployment alone amounted to 8.4 billions euros in 2017 (German Association of Energy and Water Industries, 2017).

[12] Formalizing state-specific price incentives as neutral to state welfare implies that we refer to explicit price

Equally, if states govern regional RE deployment through spatial planning policies, this does not change the composition of their welfare function assuming that spatial planning does not have any budgetary implications. Since all governments are benevolent and we assume quasilinear welfare functions, all state welfare functions add up to the national welfare function.

Electricity Suppliers

We assume that in each state a representative supplier decides on the amount of state-specific power production, x_i. Suppliers are owned by the respective state's residents, they are price takers, and they choose regional RE deployment levels x_i in order to maximize their profits. The profit function of the supplier in state i is defined as follows:

$$\pi_i(x_i, p^N) = (p^N + p_i^S)x_i - C_i(x_i) \qquad \forall i \tag{5}$$

The first term in eq. (5) expresses the supplier's revenues from national and state-level prices paid for its RE deployment in state i. Of course, if states regulate through spatial planning instead of price incentives, the first term is reduced to $p^N x_i$. In the case that states regulate through spatial planning, suppliers can expand RE deployment as far as state-specific quantity caps allow it. Formally, this is denoted by $x_i \leq \bar{x}_i$, $\forall i$. As every supplier is owned by residents living in the state where the supplier is operating this implies that revenues from regional RE deployment remain within that state.[13]

3 Social Optimum and Policy Constraints

Before analyzing the outcomes of different regulatory designs, we first determine the socially optimal (or first-best) allocation of RE deployment. This provides the benchmark against which the outcomes of the regulatory designs can be compared subsequently.

policies that spend or generate public revenues rather than implicit price policies that alter RE deployment cost. While in general spatial planning is used to regulate RE deployment at the state level, subnational price incentives are solely applied in few countries (Iglesias et al., 2011; Lienhoop, 2018; Jørgensen et al., 2020).

[13]Note that a profit maximizing supplier is in line with the assumption that intra-state expansion patterns of RE deployment are well described by $\frac{\partial^2 C}{\partial x^2} > 0$. Within each state the supplier first builds on sites with lower power production costs and continues to exploit more costly sites afterwards.

3.1 Social Optimum

The socially optimal allocation of RE deployment across states maximizes national welfare and is denoted by $\boldsymbol{x^*} = (x_1^*, ..., x_n^*)$. It is derived by differentiating eq. (3) w.r.t. x_i and setting the result equal to zero:

$$\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} = 0 \qquad \forall i \tag{6}$$

By eq. (6), the socially optimal RE deployment level for state i increases with the marginal nationwide benefit of emissions reduction. It falls with marginal state-specific disamenities from RE deployment and the marginal state-specific power production cost of RE deployment.[14]

The social optimum is characterized such that in each state the social marginal benefits from deploying one more unit of RE are equal to the social marginal costs of deploying one more unit of RE. For each state overall marginal benefits equate overall marginal cost of expanding RE. Due to homogeneous nationwide benefits from RE expansion ($\frac{\partial B}{\partial X}$ is not state-specific), at the social optimum, marginal cost per state are equalized across all states (equimarginal principle): $\frac{\partial D_i}{\partial x_i} + \frac{\partial C_i}{\partial x_i} = \frac{\partial D_j}{\partial x_j} + \frac{\partial C_j}{\partial x_j}$, $\forall j \neq i$.

We denote the nationwide first-best level of RE deployment by $X^* \equiv \sum_{i=1}^n x_i^*$.

3.2 Unitary Government

Clearly, the social optimum can be easily attained, if RE expansion is regulated by a unitary national government, and if national regulation can be differentiated. Given a regionally differentiable price instrument p_i^N a unitary government can implement the social optimum characterized by (6). To see that, we first define each supplier's deployment decision by differentiating the supplier's profit function (5) w.r.t. x_i:

$$p_i^N = \frac{\partial C_i}{\partial x_i} \qquad \forall i \tag{7}$$

Eq. (7) implicitly defines the supplier's choice for RE deployment in state i. Substituting eq. (7) into eq. (6) defines state-specific remuneration levels that implement the social optimum:

$$p_i^N = \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} \qquad \forall i \tag{8}$$

[14]We assume that $\frac{\partial B}{\partial X}\big|_{X=X^*} > \frac{\partial D_i}{\partial x_i}\big|_{x_i=0} + \frac{\partial C_i}{\partial x_i}\big|_{x_i=0}, \forall i$ such that first-best RE deployment is positive in all states.

If eq. (8) is satisfied across all states, suppliers would incorporate nationwide and regional costs and benefits into their profit maximization and produce the first-best amount of electricity from RE plants. Hence, within a unitary state the social optimum can be easily implemented through regionally differentiated price incentives. In our perfect information environment, no further analysis would be needed.

In fact, often in the literature regulatory power is assumed to be centralized at the national level, like in a unitary state (criticized by Shobe & Burtraw, 2012). Yet, in many countries national governments face two main constraints: a vertical division of regulatory power among levels of government (federal structure), and a limitation to uniform regulation policies at the national level (e.g. due to further policy goals or constitutional rules). Given these constraints, the subsequent analysis derives conditions for the co-regulation of national and state-level RE policies to be designed efficiently, meaning such that the first-best allocation is implemented.

4 RE Deployment under Federal Co-Regulation

In our analysis we compare the efficiency of four different regulatory designs. These four regulatory designs are defined by combinations of different policy instruments applied at the national and state level. For each governmental level we include two possible policy instruments – a price-based instrument and a quantity-based instrument. Table 1 summarizes the composition of the four regulatory designs. Each regulatory design is composed of a mix of policy instruments across federal levels. We label the regulatory designs by abbreviations (written in bold type in Table 1). The first capital letter represents the instrument applied at the national level and the second capital letter represents the instrument applied at the state level, e.g. PQ-regulation stands for national price-based and state-level quantity-based regulation. Table 1 also shows the corresponding policy variables chosen by national and state governments (all definitions of variables are summarized in Appendix Nomenclature).

[Input: Table 1]

In the following we derive efficiency conditions for each regulatory design. Efficiency conditions determine exogenous parameters (like states' burden shares) such that national and state governments choose equilibrium policies that lead to first-best RE deployment (cf. eq. (6)). For each regulatory design we derive the equilibrium outcome of the two-stage game among electricity suppliers and governments by backward induction. Accordingly, we first determine the suppliers' RE deployment decisions, and second derive the equilibrium policies of the simultaneous move game among national and state governments. All detailed derivations are provided in the appendices.

4.1 State-level Price-Based Regulation

First, we study the two regulatory designs where state governments use price instruments to control regional RE deployment. In the first stage of the game national and state governments simultaneously choose their policies. State governments decide on the level of their state-specific price incentives, $\boldsymbol{p^S} = (p_1^S, ..., p_n^S)$, and the national government decides on the level of the national price incentive p^N. Either the national government directly sets p^N through price-based regulation, i.e. via an administrative procedure like a nationwide feed-in tariff (Section 4.1.1), or it sets p^N indirectly through quantity-based regulation, i.e. via a tendering procedure, by determining the national tender volume $\bar{X}$ (Section 4.1.2). Once all governments have set their policies, in the second stage suppliers decide on RE deployment, $\boldsymbol{x} = (x_1, ..., x_n)$. For both regulatory designs suppliers' reaction function is implicitly defined by (see Appendix A.1):

$$p^N + p_i^S = \frac{\partial C_i}{\partial x_i} \qquad \forall i \tag{9}$$

In each state suppliers expand RE deployment until their marginal power production costs equate the effective net subsidy level $p^N + p_i^S$. Which level of national and state prices ensues depends on the regulatory design.

4.1.1 PP-Regulation

Assume that the national government regulates through a national uniform price p^N. In the first stage of the game national and state governments simultaneously decide on their policies, thus, each government takes all policy decisions by other governments as given.

We first look at policy decisions at the state level $p_1^S, ..., p_n^S$. State governments anticipate suppliers' choices according to eq. (9). We derive state i's reaction function by differentiating state i's welfare function given in eq. (4) w.r.t. p_i^S, setting the result equal to zero $\frac{\partial \mathscr{W}_i}{\partial p_i^S} = 0$, and inserting eq. (9) (see Appendix B.1):

$$p_i^S = \eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \gamma_i p^N \qquad \forall i \tag{10}$$

According to eq. (10) when setting the state-specific price p_i^S each state government takes into account marginal benefits and costs that concern its own residents, $\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i}$. Thus, state governments do not internalize nationwide benefits from emissions reductions as long as $\eta_i < 1$. State governments' first-order conditions (see eq. (B.2)) also show that states consider net national subsidies flowing into their own jurisdiction, $(1-\gamma_i)p^N$, as well as marginal deployment cost for an additional unit of RE deployment, $\frac{\partial C_i}{\partial x_i}$.[15] The rate of net national subsidies flowing into a state, $(1-\gamma_i)$, captures a state's incentive to exploit the commonly funded national RE support. The lower is a state's burden share, the larger is this incentive, and consequently the more it promotes regional RE deployment by setting higher p_i^S (see eq. (10)). In general, state governments tax regional RE deployment ($p_i^S < 0$), if positive incentives prevail, and subsidize regional RE deployment ($p_i^S > 0$), if negative incentives dominate.[16]

The national government's reaction function is derived by differentiating the national welfare function given in eq. (3) w.r.t. p^N, setting the result equal to zero $\frac{\partial \mathscr{W}}{\partial p^N} = 0$, and inserting eq. (9) (see Appendix B.1):

$$p^N = \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^n \frac{\partial x_i}{\partial p^N} \left[\frac{\partial D_i}{\partial x_i} + p_i^S \right]}{\sum_{i=1}^n \frac{\partial x_i}{\partial p^N}} \tag{11}$$

By eq. (11) the national government sets the national price equal to the marginal nationwide benefit of RE deployment $\frac{\partial B}{\partial X}$ seeking to interalize this interregional externality. However, if state-level prices do not perfectly reflect marginal disamenities from RE deployment, $p_i^S \neq -\frac{\partial D_i}{\partial x_i}$, the national government adjusts the national price level accordingly (second term on the rhs of eq. (11)). How strongly the national government adjusts its choice of p^N depends on how sensitive suppliers react to a change in the national price depicted by $\frac{\partial x_i}{\partial p^N}$.

Using eq. (10) and (11) we derive national RE support in equilibrium (see Appendix B.2 for state-level policies):

$$p^N = \frac{\sum_{i=1}^n \frac{\partial x_i}{\partial p^N} (1-\eta_i)}{\sum_{i=1}^n \frac{\partial x_i}{\partial p^N} (1-\gamma_i)} \frac{\partial B}{\partial X} \tag{12}$$

From eq. (12) it follows that if $\sum_{i=1}^n \frac{\partial x_i}{\partial p^N} \eta_i \gtreqqless \sum_{i=1}^n \frac{\partial x_i}{\partial p^N} \gamma_i$, then $p^N \lesseqqgtr \frac{\partial B}{\partial X}$. That is, if

[15] In other words, state governments consider marginal net profit of the regional supplier (which is owned by the state's residents) less marginal financing costs of national RE support, $(1-\gamma_i)p^N - \frac{\partial C_i}{\partial x_i}$.

[16] Since RE deployment cannot be negative, we assume that if $p_i^S < 0$, it must be that $|p_i^S| \leq p^N$.

the sensitivity of RE deployment to the national price $\frac{\partial x_i}{\partial p^N}$[17] correlates more positively with states' population shares η_i than with states' burden shares γ_i, then the national support level lies below nationwide marginal benefits from emissions reduction $p^N < \frac{\partial B}{\partial X}$, and vice versa. The reason is that, on average, state governments' incentive to exploit the common pool of commonly funded national subsidies (which is decreasing in γ_i) overcompensates their incentive to internalize nationwide benefits from emissions reductions (which is increasing in η_i). Thus, eq. (12) expresses that if marginal RE deployment costs increase comparatively slowly in states with $\eta_i > \gamma_i$ ($\eta_i < \gamma_i$), then the national government sets $p^N < \frac{\partial B}{\partial X}$ ($p^N > \frac{\partial B}{\partial X}$) in order to account for too promotive (restrictive) state policies respectively in order to prevent too much (little) RE deployment within these states.

If $\gamma_i = \eta_i \; \forall i$, then the national government sets the national price equal to the nationwide benefit of producing one more unit of electricity from RE, $p^N = \frac{\partial B}{\partial X}$. In other words, if for all states the burden share is equal to the population share, then the national government's equilibrium policy is $p^N = \frac{\partial B}{\partial X}$ and in each state first-best RE deployment is realized. In contrast, first-best RE deployment is not implementable, if for at least one state $\gamma_j \neq \eta_j \; \exists j$, since then some state cannot be incentivized properly when applying a uniform national subsidy. Only state-specific national prices would remedy this problem.

Proposition 1. *When both the national and the state governments apply price-based instruments, federal co-regulation is efficient, if and only if $\gamma_i = \eta_i \; \forall i$. Then the equilibrium policies are $p^N = \frac{\partial B}{\partial X}$ and $p_i^S = -\frac{\partial D_i}{\partial x_i} \; \forall i$.*

Proof: See Appendix B.3.

Intuitively, if the efficiency condition of Proposition 1 is met, then national and state-level interests are perfectly aligned because net marginal benefits from expanding RE deployment are the same for national and state governments. Note that the population share of a state indicates its missing internalization of benefits to other states. In contrast, the burden share of a state indicates its incentive to exploit the pool of commonly funded national subsidies.[18] If

[17] The sensitivity of RE deployment to the national price is determined by the second derivative of RE deployment costs, $\frac{\partial x_i}{\partial p^N} = \frac{1}{\frac{\partial^2 C_i}{\partial x_i^2}}$. We derive $\frac{\partial x_i}{\partial p^N} = \frac{1}{\frac{\partial^2 C_i}{\partial x_i^2}}$ by differentiating eq. (9) w.r.t. p^N.

[18] If a state bears the full costs of national RE support, hence if $\gamma_i = 1$, then for this state the funding of national RE support is not a common pool anymore. In this case the national government is not able to incentivize the state's policy decision, since revenues from and expenditures for national RE support always cancel out for this state. This is depicted by eq. (B.2). The state would choose the same policy as without national RE support.

both shares are of the same size, a state's tendency to underprovide is balanced by its incentive to take advantage of the common subsidy pool (given the national government sets $p^N = \frac{\partial B}{\partial X}$).

4.1.2 QP-Regulation

Now, we assume the national government to regulate through quantity-based instruments, i.e. tenders. The national government specifies a fixed maximum quantity of RE deployment that is subsidized. This tender volume is denoted by $\bar{X}$. Nationwide all electricity suppliers submit bids to win support for their RE projects. The level of national RE support p^N is determined through the clearing price of a uniform price auction p^M. The national government can set a ceiling price $\bar{p}$ that limits the level of the clearing price, $p^N = \min(p^M, \bar{p})$. For the moment we assume that the ceiling price is not binding ($p^M < \bar{p}$), and return to that assumption at the end of this section.

To analyze national and state-level equilibrium policies, we first look at the equilibrium conditions that reflect the national tendering procedure (i.e. uniform price auction). Together with the suppliers' reaction functions given in eq. (9) the following condition determines the level of the clearing price p^M under national quantity-based regulation:

$$\sum_{i=1}^{n} x_i = \bar{X} \tag{13}$$

Eq. (13) establishes that the entire tender volume $\bar{X}$ is tendered off. Therefore, eq. (13) is also referred to as the *market clearing condition* (Helm, 2003). This means that under QP-regulation the national government prescribes the quantity of nationwide RE deployment, $\sum_{i=1}^{n} x_i \equiv X$. By eq. (9) this implies that the clearing price p^M rises until eq. (13) is satisfied. Hence, the eq. (9) and (13) implicitly define the clearing price as a function of nationwide allocation of RE deployment across states $p^M(\boldsymbol{x})$, and also indirectly as a function of the tender volume. As under PP-regulation state-specific RE deployment is a function of national and state-level price incentives, $x_i(p^M, p_i^S)$.

National and state governments consider this price mechanism when setting their RE policies. We first derive state governments' reaction functions. In equilibrium state governments take the national policy choice $\bar{X}$ as given. Since the clearing price is endogenously determined through tenders, state policies can influence p^M through increasing or decreasing their state-specific price incentives $p_1^S, ..., p_n^S$. By increasing (decreasing) p_i^S state i makes RE deployment in its jurisdiction comparatively more attractive (less attractive) and thus lowers (raises) the clearing price that ensures nationwide RE deployment of $\bar{X}$. At the same time state policies do not affect aggregate nationwide RE deployment $\sum_{i=1}^{n} x_i$. As before, we derive state i's policy choice by differentiating eq. (4) w.r.t. p_i^S, setting $\frac{\partial \mathscr{W}_i}{\partial p_i^S} = 0$, and inserting eq. (9) and (13):

$$p_i^S = -\frac{\partial D_i}{\partial x_i} + \frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X}) \qquad \forall i \tag{14}$$

Compared to PP-regulation, state governments still internalize disamenities from RE deployment within their own jurisdictions (first term). However, under QP-regulation a state cannot influence the level of nationwide RE deployment, $\frac{\partial X}{\partial x_i}\frac{\partial x_i}{\partial p_i^S} = 0$. Accordingly, when deciding on its policy, state i does not care about its benefits from emissions reduction since these are fixed at $\eta_i B(\bar{X})$. Instead, a state government considers its policy impact on the level of national RE support (second term). Though nationwide RE deployment does not change due to shifts in states' policy choices, p^M does change, $\frac{\partial p^M}{\partial x_i} < 0$ (see eq. (C.5) in Appendix C). Whether a state benefits or loses from this change depends on whether RE deployment in that state is larger or smaller than the share of nationwide RE deployment that the state is funding, $\gamma_i \bar{X}$. If state i finances a share of nationwide RE deployment that is larger (smaller) than the amount of RE deployment in its own jurisdiction, $\gamma_i \bar{X} > x_i$ ($\gamma_i \bar{X} < x_i$), then the state increases (decreases) p_i^S above (below) its marginal disamenities. Intuitively, if $\gamma_i \bar{X} > x_i$ ($\gamma_i \bar{X} < x_i$), then state i has an incentive to lower (enhance) the national clearing price, thereby reducing its funding cost from burden sharing (exploiting common pool resources from burden sharing). By increasing (decreasing) p_i^S state i makes RE deployment within its jurisdiction comparatively more attractive (less attractive) and thus indirectly lowers (enhances) the national clearing price. We refer to the above described incentive as a *burden share bias* because state governments are incentivized towards reaching RE deployment shares $\frac{x_i}{X}$ that equate to their burden shares γ_i.

For the national government we derive the implicit reaction function by differentiating the national welfare function given in eq. (3) w.r.t. $\bar{X}$, setting the result equal to zero $\frac{\partial \mathscr{W}}{\partial \bar{X}} = 0$, and inserting eq. (9) and (13) (see Appendix C.1):

$$p^M = \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M}\left[\frac{\partial D_i}{\partial x_i} + p_i^S\right]}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M}} \tag{15}$$

As under PP-regulation (cf. eq. (11)), the national government implicitly sets p^M to internalize the nationwide externality, $p^M = \frac{\partial B}{\partial X}$, and adjusts the national price level if state-level prices do not perfectly reflect marginal disamenities from RE deployment, $p_i^S \neq -\frac{\partial D_i}{\partial x_i}$. Again, this adjustment depends on how sensitive state-specific RE deployment reacts to the national price $\frac{\partial x_i}{\partial p^M}$.

Using eq. (14) and (15) we derive the national clearing price in equilibrium (see Appendix C.2 for state-level policies):

$$p^M = \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^n \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X})}{\sum_{i=1}^n \frac{\partial x_i}{\partial p^M}} \tag{16}$$

Eq. (16) implies that under QP-regulation the national government promotes a tender volume $\bar{X}$ such that the national clearing price deviates from $\frac{\partial B}{\partial X}$ dependent on the correlation of the state-specific sensitivity of RE deployment to the national price $\frac{\partial x_i}{\partial p^M}$ with state-specific incentives to change the national price level by promoting RE deployment within their own state $\frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X})$. Hence, by the choice of the tender volume the national government internalizes nationwide externalities, but it also has to consider the price mechanism of the tender scheme that sets diverging incentives for state governments to steer RE deployment. In particular, under QP-regulation the extent of these incentives depends on the ratio of $\frac{x_i}{\gamma_i \bar{X}}$, in contrast to PP-regulation where it depends on the ratio of $\frac{\eta_i}{\gamma_i}$. This is reflected by the efficiency condition for QP-regulation:

Proposition 2. *When the national government applies quantity-based and the state governments apply price-based instruments, federal co-regulation is efficient, if and only if states' burden shares are defined by $\gamma_i = \frac{x_i^*}{X^*}$ $\forall i$. Then the equilibrium policies are $\bar{X} = X^*$ and $p_i^S = -\frac{\partial D_i}{\partial x_i}$ $\forall i$, and the national clearing price is $p^M = \frac{\partial B}{\partial X}$.*

Proof: See Appendix C.3.

The efficiency condition for QP-regulation says that the burden share of every state γ_i must be equal to the ratio of first-best RE deployment in its jurisdiction x_i^* to first-best nationwide RE deployment X^*. Then, at the social optimum each state government only considers its own marginal disamenities from RE deployment, and states' strategic incentives to change the clearing price (i.e. burden share bias) vanish.

The efficiency condition for QP-regulation presented in Proposition 2 is very distinct from the one derived for PP-regulation summarized in Proposition 1. Under national price-based regulation state governments have an incentive to contribute to nationwide RE deployment as much as emissions reduction benefits their respective residents. This incentive depends on each state's population share. Therefore, price-based regulation at the national level (e.g. national FiT) requires states' burden shares to be distributed along states' population shares. In contrast, under national quantity-based regulation state governments have an incentive to indirectly influence the national clearing price to their favor. The scope of this incentive depends on each state's RE deployment share of nationwide RE deployment. Therefore, quantity-based regulation at the national level (e.g. tenders) requires states' burden shares to be distributed along states' first-best RE deployment shares. These results are in line with Williams III (2012) and Meya and Neetzow (2021) who also find this switch in the underlying incentive structure of state policy. However, our model additionally stresses the importance of states' population shares and the importance of state-specific sensivity of RE deployment to national policy.[19]

Finally, we discuss the possibility that the national government can set a ceiling price that ends up binding in equilibrium. Up to now, we have assumed that the clearing price is competitively determined through the tendering procedure such that $p^M < \bar{p}$, and the national tender volume is entirely tendered off, $\sum_{i=1}^{n} x_i = \bar{X}$. We label this equilibrium as *market clearing equilibrium*. However, if the ceiling price is binding such that $p^M = \bar{p}$, the national tender volume may not be fully exploited, $\sum_{i=1}^{n} x_i \leq \bar{X}$. This implies that national regulation is effectively price-based, and national and state-level policy choices are again defined as under PP-regulation. In that case we label the resulting equilibrium as *fixed price equilibrium*. In fact, it is realistic that the national government is able to set a ceiling price that is binding in tenders and thereby opts for a de-facto price-based regulation. E.g. the European Union directs their member states to grant support for RE deployment via tendering procedures.[20] Nevertheless, EU member states themselves determine to which level they limit the clearing price in tenders.

We assume that the national government sets the ceiling price $\bar{p}$ according to eq. (12) as long as this is welfare enhancing, hence, as long as the fixed price equilibrium with $p^N = \bar{p}$ implements a higher national welfare level than the market clearing equilibrium with $p^N = p^M$. Otherwise we assume the national government to set the ceiling price high enough such that $p^M < \bar{p}$. To give an example, consider the case where $\gamma_i = \eta_i \; \forall i$ and $\eta_i \neq \frac{x_i^*}{X^*} \; \forall i$. Under QP-

[19] The latter does not matter in Meya and Neetzow (2021) since they make the simplifying assumption that $\frac{\partial^2 C_i}{\partial x_i^2}$ is identical across all states.

[20] In No. 4 of Article 4 of the Renewable Energy Directive of 2018 the European Union prescribes that "Member States shall ensure that support for electricity from renewable sources is granted in an open, transparent, competitive, non-discriminatory and cost-effective manner. Member States may exempt small-scale installations and demonstration projects from tendering procedures" (European Union, 2018).

regulation the clearing price p^M settles according to eq. (15). In this case, setting the ceiling price $\bar{p}$ equal to the national price under PP-regulation (according to eq. (12)) would either leave national welfare unchanged or increase national welfare. Either, national welfare remains unchanged namely when the ceiling price is not binding in equilibrium, or, it increases when the ceiling price is binding because then by Proposition 1 it implements the social optimum (for further explanation we provide a calibrated two-state example in Appendix F).[21]

In general, for any $\gamma_1, ..., \gamma_n$ and $\eta_1, ..., \eta_n$, if national welfare in the fixed price equilibrium is greater than in the market clearing equilibrium under QP-regulation, then the national government chooses to set the ceiling price $\bar{p}$ equal to the national price level under PP-regulation. Whether this ceiling price is binding (i.e. becomes effective) primarily depends on the correlation of state-specific RE deployment costs with states' burden and population shares (see Appendix C.4).

4.2 State-level Quantity-Based Regulation

In the following two sections we alter the policy instrument applied at the state level. We now assume that state governments regulate RE deployment through quantity caps and do not set price incentives anymore. State governments decide on the level of their state-specific quantity cap, $\bar{\boldsymbol{x}} = (\bar{x_1}, ..., \bar{x_n})$.

The supplier's reaction function is defined by eq. (17a) and (17b) and is distinct from the one under subnational price-based regulation on two points (cf. eq. (9)). First, remuneration for one unit of RE-based electricity is now solely composed of the national price incentive because state governments set no price incentives. Second, in each state the supplier is constrained in its decision on the amount of RE deployment x_i. Every state implements a quantity cap $\bar{x}_i$ which limits the maximum amount of RE deployment within its jurisdiction, $x_i \leq \bar{x}_i$. Differentiating the supplier's profit function w.r.t. x_i subject to the quantity constraint yields the supplier's optimal RE deployment decision (see Appendix A.2):

$$\forall i: \quad p^N \begin{cases} = \dfrac{\partial C_i}{\partial x_i} \quad \wedge \quad x_i < \bar{x}_i & \text{(17a)} \\ \geq \dfrac{\partial C_i}{\partial x_i} \quad \wedge \quad x_i = \bar{x}_i & \text{(17b)} \end{cases}$$

[21] We provide a graphical representation for a numerical two-state example in Figure 4 in Appendix F. For the case where $\gamma_i = \frac{x_i^*}{X^*}$ $\forall i$ the national government does not set a (binding) ceiling price since the equilibrium under QP-regulation implements the social optimum.

If the supplier intends to deploy less RE than the corresponding quantity cap allows (see eq. (17a)), the supplier's first-order condition is similar to eq. (9). If the supplier would like to deploy as much as or more RE than the corresponding quantity cap approves (see eq. (17b)), the supplier deploys exactly as much as the quantity cap allows for, $x_i = \bar{x}_i$.

4.2.1 PQ-Regulation

Again, let us first assume that the national government regulates through a national uniform price p^N. State governments take the national policy p^N as given when setting their optimal policies and anticipate suppliers' choices according to eq. (17a) and (17b). For a state government there is no reason to authorize a level of RE deployment that exceeds its preferred level of RE deployment. Each state sets its quantity cap equal to its welfare maximizing RE deployment level, $\bar{x}_i = \arg\max_{x_i} \mathscr{W}_i(x_i)$. Taking the first derivative of state i's welfare function given in eq. (4) w.r.t. x_i and setting the result equal to zero, $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$, implicitly defines state i's reaction function (see Appendix D.1):

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1 - \gamma_i) p^N = 0 \qquad \forall i \tag{18}$$

States' implicit reaction function according to eq. (18) is equivalent to the one under PP-regulation (see eq. (10)). This means that given price-based regulation at the national level and regardless of the policy instrument applied at the state level (price-based or quantity-based) state governments favor the same regional RE deployment, ceteris paribus.

Before we can determine the national government's policy decision, we have to specify when states' quantity caps are binding, and when they are not. If in state i the quantity cap is not binding, then the supplier determines actual RE deployment in state i (see eq. (17a)). However, if the quantity cap is binding, then the state government determines actual RE deployment in state i (see eq. (17b)). In the latter case the supplier aims at deploying at least as much RE as the state's quantity cap allows for, formally $p^N \geq \frac{\partial C_i}{\partial x_i}$ and $x_i = \bar{x}_i$. The following lemma defines under which condition a state's quantity cap is non-binding and under which condition it is binding:

Lemma 1.

A state that sets a non-binding quantity cap enacts ***ambitious*** *policy and has subscript 'a'.*

Given p^N and $\gamma_1, ..., \gamma_n$ state a's quantity cap is non-binding, $x_a < \bar{x_a}$, if:

$$\eta_a \frac{\partial B}{\partial X} > \frac{\partial D_a}{\partial x_a} + \gamma_a p^N \qquad a \in \mathcal{A}^{PQ}. \tag{19}$$

Then state a's quantity cap is larger than the level of RE deployment preferred by the supplier. The supplier determines the actual RE deployment level in state a.[22]

*A state that sets a binding quantity cap enacts **restrictive** policy and has subscript 'r'. Given p^N and $\gamma_1, ..., \gamma_n$ state r's quantity cap is binding, $x_r = \bar{x_r}$, if:*

$$\eta_r \frac{\partial B}{\partial X} \leq \frac{\partial D_r}{\partial x_r} + \gamma_r p^N \qquad r \in \mathcal{R}^{PQ}. \tag{20}$$

Then state r's quantity cap is smaller than the level of RE deployment preferred by the supplier. The state government determines the actual RE deployment level in state r.

Proof: See Appendix D.1.1.

To derive the national government's reaction function we differentiate its welfare function given in eq. (4) w.r.t. p^N and set the result equal to zero, $\frac{\partial W}{\partial p^N} = 0$. Taking states' policies as given, the national government soley influences RE deployment in states where the quantity caps are non-binding. Given $\frac{\partial x_r}{\partial p^N} = 0 \; r \in \mathcal{R}^{PQ}$, we obtain the following reaction function of the national government (see Appendix D.1):

$$p^N = \frac{\partial B}{\partial X} - \frac{\sum_{a \in \mathcal{A}^{PQ}} \frac{\partial x_a}{\partial p^N} \frac{\partial D_a}{\partial x_a}}{\sum_{a \in \mathcal{A}^{PQ}} \frac{\partial x_a}{\partial p^N}} \tag{21}$$

Eq. (21) shows that the choice of the national support level depends on how many states implement ambitious policies $\mathcal{A}^{PQ}$, on marginal disamenities in these ambitious states $\frac{\partial D_a}{\partial x_a}$, and on the state-specific sensitivity of RE deployment to the national price $\frac{\partial x_a}{\partial p^N}$. The national government solely takes into account disamenities in those states where state-level quantity caps are not constraining RE deployment because in these states the national price incentive determines RE deployment levels. Whether p^N is larger or smaller than $\frac{\partial B}{\partial X}$ depends on the correlation of $\frac{\partial x_a}{\partial p^N}$ and $\frac{\partial D_a}{\partial x_a}$ in these *ambitious* states. The more $\frac{\partial^2 C_a}{\partial x_a^2}$ and $\frac{\partial D_a}{\partial x_a}$ are positively

[22]Note that for the same state eq. (20) may apply if values for $p^N, \gamma_1, ..., \gamma_n$ change. The set of states that enact ambitious policies $\mathcal{A}^{PQ}$ is a function of p^N and $\gamma_1, ..., \gamma_n$. Correspondingly, the same applies for the set of states that enact restrictive policies $\mathcal{R}^{PQ}$. Note also that $\mathcal{A}^{PQ} \cup \mathcal{R}^{PQ} = \mathcal{N}$ with $\mathcal{N} = \{1, ..., n\}$ and $\mathcal{A}^{PQ} \cap \mathcal{R}^{PQ} = \emptyset$.

correlated, the larger is p^N.[23] In other words, if in *ambitious* states a low (high) second derivative of RE deployment costs goes along with low (high) marginal disamenities then the national governments decides for a high (low) national price because RE deployment is mostly induced in states where disamenities are low (high).

In equilibrium the national price deviates from the marginal nationwide benefit of emissions reductions as long as some states enact ambitious policies (see eq. (21) and Appendix D.2). This is the case if some states have large population shares but small burden shares, or strong positive regional effects of RE deployment (cf. Lemma 1). Whether state-specific RE deployment corresponds to the first-best depends on different factors that vary between ambitious and restrictive states. For example in an ambitious state denoted by a' equilibrium RE deployment exceeds (falls below) the first-best level if the weighted average of marginal disamenities in all ambitious states is smaller (larger) than marginal disamenities for this state, $\frac{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}\frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}} < \frac{\partial D_{a'}}{\partial x_{a'}}$ with $a' \in \mathcal{A}$ (see eq. (D.8) in Appendix D.2). In an exemplary restrictive state denoted by r' equilibrium RE deployment exceeds (falls below) the first-best level as the state's burden share $\gamma_{r'}$ becomes smaller (larger) (see eq. (D.9) in Appendix D.2).[24] Thus, by adjusting burden shares of restrictive states first-best RE deployment levels can be induced for these states. In contrast, RE deployment levels in ambitious states can only be uniformly adressed through the national price incentive. Therefore, the social optimum can only be implemented if all states enact restrictive policies.[25]

To define under which conditions the social optimum is implemented we refer to the distinction between type-D and type-B nations (see Section 2.1). First, for type-D nations, i.e. nations where in all states regional effects of RE deployment are strictly negative, $\frac{\partial D_i}{\partial x_i} > 0\ \forall i$, we summarize our result in the following proposition:

Proposition 3. *When the national government applies price-based and the state governments apply quantity-based instruments, federal co-regulation is efficient in type-D nations, if* $\gamma_i = \eta_i\ \forall i$. *Then in equilibrium all states enact restrictive policies,* $x_i = \bar{x}_i\ \forall i$, *and the national price is*

[23]Note that $\frac{\partial^2 C_a}{\partial x_a^2} = \frac{1}{\frac{\partial x_a}{\partial p^N}}$.

[24]Precisely, if $\gamma_{r'} < \frac{\eta_{r'}\frac{\partial B}{\partial X} - \frac{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}\frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}}}{\frac{\partial B}{\partial X} - \frac{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}\frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}}}$, then $x_{r'} > x^*_{r'}$.

[25] For the particular case that all ambitious states have homogeneous disamenity functions the social optimum is also implementable. See Appendix D.4.

$p^N = \frac{\partial B}{\partial X}$.

Proof: See Appendix D.3.

According to Proposition 1 and Proposition 3 both PP-regulation and PQ-regulation can implement the first-best in *type-D* nations. When RE deployment comes along with regional costs instead of regional benefits (*type-D* nation) both regulatory designs are efficient if the efficiency condition $\gamma_i = \eta_i \ \forall i$ holds. While under PP-regulation state governments tax RE deployment within their jurisdictions and thereby restrict the level of regional RE deployment, under PQ-regulation state governments restrict regional RE deployment by setting binding quantity caps. Under both regulatory designs state governments aim at the same regional RE deployment levels and apply effective instruments to implement them. Also, under both regulatory designs states are compensated for disamenities from RE deployment in the form of national subsidies flowing into the states. The only difference is that under PP-regulation these national subsidies are collected through state-level taxes or levies, whereas under PQ-regulation they are collected through additional profit for suppliers.

For type-B nations the social optimum is not implementable under PQ-regulation. The exception is when all ambitious states have homogeneous disamenity functions. We illustrate this special case in Appendix F.2 by a numerical example of a type-B nation composed of two states.

4.2.2 QQ-Regulation

Lastly, we switch the policy instrument at the national level and assume that the national government applies quantity-based regulation, i.e. tenders. The national government determines the maximum quantity of nationwide RE deployment that is subsidized through tenders $\bar{X}$, and state governments as a whole determine the maximum quantity of nationwide feasible RE deployment resulting from the sum of states' quantity caps $\sum_{i=1}^{n} \bar{x}_i$. National RE support p^N is equal to the clearing price in tenders p^M which is limited by the ceiling price $\bar{p}$. The ceiling price may be binding because the sum of state-level quantity caps is smaller than the national tender volume $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$. In that case suppliers face no competition in tenders and bid at the highest possible price resp. the ceiling price $p^N = \bar{p}$.[26] We refer to the resulting equilibrium as the *fixed price equilibrium* (as in Section 4.1.2), whereas we refer to an outcome

[26] As discussed in Section 4.1.2 the ceiling price may also be binding because the national government chooses a level of $\bar{p}$ that is too low to allow for market clearing. In that case $\sum_{i=1}^{n} \bar{x}_i \geq \bar{X} > \sum_{i=1}^{n} x_i$.

with $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$ as the *market clearing equilibrium*. In the latter equilibrium the clearing price in tenders is implicitly defined by suppliers' reaction functions (see eq. (17a) and (17b)) and the market clearing condition (see eq. (13), and see Appendix E). Similar to QP-regulation these equations define state-specific RE deployment in the market clearing equilibrium as a function of national and state-level policies, $x_i(p^M, \bar{x}_i)$.

We derive state i's implicit reaction function by differentiating eq. (4) w.r.t. x_i and setting $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$. Taking national and other state-level policies as given state i's policy decision on $\bar{x}_i$ follows different incentives depending on whether the sum of state-level quantity caps exceeds the national tender volume $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$, or not $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$ (see Appendix E.1)[27]:

$$-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^M(\boldsymbol{x}) + \frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X}) = 0 \qquad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i > \bar{X} \tag{22}$$

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1 - \gamma_i)\bar{p} = 0 \qquad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i \leq \bar{X} \tag{23}$$

State governments' reaction functions resemble the incentive structure under QP-regulation if the sum of quantity caps exceeds the national tender volume (cf. eq. (22)). In turn, if the sum of quantity caps falls short of the national tender volume states' reaction functions resemble the incentive structure under PQ-regulation (cf. eq. (23)). The former is only the case if at least one state enacts ambitious policy $x_a < \bar{x}_a$ such that $\sum_{i=1}^{n} x_i = \bar{X} < \sum_{i=1}^{n} \bar{x}_i$. The following lemma defines when state governments pursue ambitious or restrictive policies under QQ-regulation given $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$:

Lemma 2.

A state that sets a non-binding quantity cap enacts ***ambitious*** *policy and has subscript 'a'. Given $\bar{X}$ and $\gamma_1, ..., \gamma_n$ state a's quantity cap is non-binding, $x_a < \bar{x}_a$, if:*

$$\frac{\partial D_a}{\partial x_a} < 0 \qquad\qquad a \in \mathcal{A}^{QQ}. \tag{24}$$

Then state a's quantity cap is larger than the level of RE deployment preferred by the supplier. The supplier determines the actual RE deployment level in state a.

[27] For simplicity, we assume that a single state does not influence whether $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$, or not $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$. In Appendix E.6 we relax this assumption and analyze state governments' incentives when deciding on $\bar{x}_i \lesseqgtr \bar{X} - \sum_{j \neq i} \bar{x}_j$.

A state that sets a binding quantity cap enacts ***restrictive*** *policy and has subscript 'r'. Given* $\bar{X}$ *and* $\gamma_1, ..., \gamma_n$ *state r's quantity cap is binding,* $x_r = \bar{x}_r$*, if:*

$$\frac{\partial D_r}{\partial x_r} \geq \frac{\partial p^M}{\partial x_r}(x_r - \gamma_r \bar{X}) \qquad r \in \mathcal{R}^{QQ}. \tag{25}$$

Then state r's quantity cap is smaller than the level of RE deployment preferred by the supplier. The state government determines the actual RE deployment level in state r.[28]

Proof: See Appendix E.1.1.

Contrary to Lemma 1 under PQ-regulation, now, by Lemma 2 under QQ-regulation states solely set non-binding quantity caps when they have net marginal regional benefits from RE deployment, i.e negative marginal disamenities (see eq. (24)). States restrict RE deployment through binding quantity caps as long as their marginal disamenities from RE deployment (lhs of eq. (25)) outweigh their marginal benefit from expanding their quantity caps (rhs of eq. (25)).

The national government's reaction functions for $\bar{X}$ and $\bar{p}$ are similar to the reaction function under PQ-regulation. The national government chooses the national tender volume $\bar{X}$ such that the clearing price is defined by (see Appendix E.1):

$$p^M = \frac{\partial B}{\partial X} - \frac{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial D_a}{\partial x_a}}{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M}} \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i > \bar{X} \tag{26}$$

At the same time the national government sets the ceiling price $\bar{p}$ such that it maximizes national welfare in case that $\bar{p}$ is binding (see Appendix E.1). The price level is the same as the national price level under PQ-regulation:

$$\bar{p} = \frac{\partial B}{\partial X} - \frac{\sum_{a \in \mathcal{A}^{PQ}} \frac{\partial x_a}{\partial \bar{p}} \frac{\partial D_a}{\partial x_a}}{\sum_{a \in \mathcal{A}^{PQ}} \frac{\partial x_a}{\partial \bar{p}}} \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i \leq \bar{X} \tag{27}$$

Note that the second term on the rhs of eq. (26) and the second term on the rhs of eq. (27) are not the same. In eq. (26) the second term represents the weighted sum of marginal disamenities in ambitious states in a market clearing equilibrium (cf. Lemma 2). In eq. (27) the second term represents the weighted sum of marginal regional costs in ambitious states in a fixed price equilibrium (cf. Lemma 1). Whether the clearing price p^M settles below the level of the ceiling

[28]Note that in ambitious states a marginal change of the quantity cap $\bar{x}_a$ does not change the clearing price since the quantity cap is not binding and hence $\frac{\partial p^M}{\partial x_a}\big|_{x_a = \bar{x}_a} = 0$.

price $\bar{p}$ which is specified by eq. (27) depends on which states are ambitious and how disamenities and RE deployment costs are correlated in these states. As discussed at the end of Section 4.1.2 we assume that the national government only then sets the ceiling price according to eq. (27) if the fixed price equilibrium is welfare superior to the market clearing equilibrium. If the latter is welfare superior, then the national government chooses any $\bar{p} > p^M$.

Equilibrium outcomes under QQ-regulation approximate QP-regulation when a market clearing equilibrium ensues, but reflect PQ-regulation when a fixed price equilibrium ensues (see Appendix E.2). With regard to the market clearing equilibrium under QQ-regulation four features shall be shortly highlighted. First, similar to PQ-regulation also under QQ-regulation the national price in equilibrium only deviates from the marginal nationwide benefit of emissions reductions $\frac{\partial B}{\partial X}$ as long as some states enact ambitious policies. Second, in contrast to PQ-regulation, under QQ-regulation states only enact ambitious policies if they benefit from positive regional effects of RE deployment – independent of their burden or population shares. Third, as opposed to PQ-regulation but similar to QP-regulation, restrictive states choose quantity caps that exceed (fall below) the first-best RE deployment level if their burden shares become larger (smaller) (see eq. (E.21) in Appendix E.4).[29] Fourth, in comparison to QP-regulation, the burden share bias (cf. fourth term in eq. (22)) is stronger for restrictive states under QQ-regulation. This means that under QQ-regulation restrictive states have stronger incentives to aim at RE deployment shares $\frac{x_r}{X}$ that are closer to their burden shares γ_r than they have incentives under QP-regulation (see Appendix E.5).

To specify efficiency conditions under QQ-regulation, we again distinguish between type-D and type-B nations. For a type-D nation where in all states RE deployment causes no marginal regional benefits but only marginal regional costs we derive the following proposition:

Proposition 4. *When both national and state governments apply quantity-based instruments, then in type-D nations there is no market clearing equilibrium, but only a fixed price equilibrium. Formally, if* $\forall i : \frac{\partial D_i}{\partial x_i} > 0$ *then* $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$ *and* $p^N = \bar{p}$.

Proof: See Appendix E.3.

By Proposition 4 under QQ-regulation in a type-D nation it ensues de-facto national price-based regulation because the ceiling price is binding in equilibrium. Consequently Proposition

[29] Precisely, if $\gamma_r > \frac{x_r^*}{X^*} - \frac{1}{\frac{\partial p^M}{\partial x_r} X^*} \frac{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial D_a}{\partial x_a}}{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M}}$, then $x_{r'} > x_{r'}^*$.

3 applies, and the efficiency condition is the same as under PQ-regulation in a type-D nation, namely $\gamma_i = \eta_i \; \forall i$.

For type-B nations under QQ-regulation the social optimum is not implementable.[30] This reflects the findings for PQ-regulation. In contrast to a type-D nation, there may either ensue a fixed price equilibrium or a market clearing equilibriium in a type-B nation under QQ-regulation. In Appendix F.2 we illustrate these equilibrium outcomes for a numerical example of a type-B nation composed of two states. This stylized example again explains the connection of equilibrium outcomes under QQ-regulation with outcomes under PQ- and QP-regulation.

4.3 Comparison of Regulatory Designs

We summarize our results by comparing whether and under which conditions the four regulatory designs implement the social optimum.

Firstly, we conclude that the first-best allocation of RE deployment is not attainable under all regulatory designs. In fact, it depends on whether RE deployment exhibits also positive marginal regional effects (like in type-B nations), or whether only negative marginal regional effects from RE deployment prevail (like in type-D nations). In a type-B nation the social optimum is only attainable under PP- and QP-regulation, that is when the state level applies price-based regulation. In a type-D nation the social optimum is attainable under all four regulatory designs.

[Input: Table 2]

Secondly, given the social optimum is attainable we identified efficiency conditions which ensure that the social optimum is implemented in equilibrium, see Table 2. These efficiency conditions refer to the optimal specification of states' burden shares $\boldsymbol{\gamma}^* = \gamma_1^*, ..., \gamma_n^*$. Under state-level price-based regulation (Section 4.1) the specification of efficient burden shares varies with the policy instrument at the national level (upper row in Table 2). If a price instrument is applied at the national level, then states' burden shares should equate states' population shares, $\gamma_i^* = \eta_i \; \forall i$. If a quantity instrument is applied at the national level, then states' burden shares should equate states' first-best deployment shares, $\gamma_i^* = \frac{x_i^*}{X^*} \; \forall i$. These findings for state-level

[30] The social optimum is implementable in the exceptional case that all ambitious states have homogenoues disamenity functions. For this particular case the efficiency condition is derived in Appendix E.4.

[30] An exception is the specific case when all ambitious states are homogenous. In that case an adjustment of state-specific burden shares implements the social optimum under PQ- and QQ-regulation. See Appendix D.4 and E.4.

price-based regulation are vaild for both type-B and type-D nations. Under state-level quantity-based regulation (Section 4.2) the social optimum is not attainable in type-B nations (bottom row in Table 2). In contrast, in type-D nation the social optimum is implemented if states' burden shares equate states' population shares, $\gamma_i^* = \eta_i \; \forall i$ independent of the policy instrument applied at the national level.

These diverging efficiency conditions result from diverging incentives for states' policy choices under the different regulatory designs. Under national price-based regulation (left column in Table 2) states act according to the same incentives, no matter which policy instrument is applied at the state level (states' first-order conditions are identical, cf. eq. (B.2) and (D.1)).[31] Under PP- and PQ-regulation each state needs to be incentivized to internalize the positive interregional externalities that arise from RE deployment within its own jurisdiction. Accordingly, for these regulatory designs efficiency conditions are identical and oriented towards states' population shares.[32]

Under national quantity-based regulation (right column in Table 2) incentives for states may vary with the policy instrument applied at the state level. Under state-level price-based regulation state policies only affect the level of national RE support but not the level of nationwide RE deployment. Accordingly, states consider whether they benefit or lose from a change in the national support level. For each state, in turn, this depends on the ratio of RE deployment in a state's jurisdiction compared to nationwide RE deployment. Therefore, efficient burden sharing is oriented towards first-best RE deployment shares. In contrast, under state-level quantity-based regulation states may affect the level of nationwide RE deployment. In type-D nations states act according to the same incentives as under national price-based regulation. Here, efficient burden sharing is thus oriented towards states' population shares. In type-B nations states' incentives may resemble the incentive structure under PQ- or QP-regulation.

5 Discussion

In the following, we present several policy implications by taking federal co-regulation of wind power deployment in Germany as an example. Subsequently, we discuss limitations of our model

[31] Merely the channel through which states benefit from national support payments alters with the state-level policy instrument. Under state-level price-based regulation states are compensated for their disamenities through public revenues collected via negative price incentives such as state-specific levies or taxes. Under state-level quantity-based regulation states are compensated through higher profits for electricity suppliers via national RE remunerations exceeding marginal power production costs.

[32] Efficiency conditions may differ, but only for the special case mentioned in Fn. 30.

and point out to areas of further research.

5.1 Policy Implications

It is especially instructive to evaluate some real-world examples against the background of our model results. First, let us look at countries with national RE support schemes that are financed through levies. These regulatory designs are widely observed in practice. In the beginning, most RE support schemes were set up as feed-in tariffs (i.e. national price-based regulation), and the latter were financed through levies imposed on the electricity price and thus paid by all (or most) electricity consumers (Council of European Energy Regulators, 2018).[33] Effectively, these levy-based systems establish that the shares of national subsidy costs borne by subnational jurisdictions (i.e. states' burden shares) closely correspond to their population shares. For example, in Germany burden shares of the *Bundesländer* (German states) almost reflect their population shares (see Table 3). So, our first policy implication is that levy-based financing schemes combined with national feed-in tariffs can bring about efficient federal co-regulation (cf. Proposition 1 and Proposition 3). When countries are type-D nations this implication holds regardless of the policy instrument applied at the subnational level. Germany may reasonably be seen as a type-D nation since here a growing number of local conflicts related to the deployment of wind power plants indicates to predominantly negative regional effects (e.g. noise impacts, landscape degradation, threats to protected species). At the same time, empirical evidence indicates to only minor positive marginal regional effects that unlikely offset regional costs from wind power deployment (Brown et al., 2012; Többen, 2017; Mauritzen, 2020).

Secondly, in recent years Germany and various other EU member states have introduced national tender schemes (REN21, 2019; Council of European Energy Regulators, 2018).[34] When national RE support changes from feed-in tariff to tenders, our results point out that it depends on subnational regulation under which conditions burden sharing is efficient. In practice, in most federally organized countries the subnational level (e.g. German states) controls wind

[33]Most European countries finance their national support schemes through non-tax levies that are calculated in proportion to people's electricity consumption. In 2017, 21 out of 27 EU member states funded their RE support schemes through non-tax levies (Council of European Energy Regulators, 2018). Electricity consumption per region is roughly proportional to population per region, especially, if energy-intensive companies are (partially) exempted from paying levies, like in Germany.

[34]These regime shifts mainly aimed at reductions of national subsidy costs. After the passage of the EU's Renewable Energy Directive in 2009, countries like France, Germany, Italy, Netherlands or UK introduced tender schemes to comply with the requirements of higher competitiveness and cost-effectiveness (Council of European Energy Regulators, 2018). Worldwide more countries rely on RE support schemes with tendering procedures, e.g. Brazil, China, India, South Africa (for an overview see Grashof et al., 2020).

power deployment through quantity caps, i.e. spatial planning policies that provide areas for wind power deployment (Keenleyside et al., 2009; Pettersson et al., 2010; Power & Cowell, 2012). If these countries are type-D nations, our model results suggest that despite a shift from feed-in tariffs to national tenders national price-based regulation is de facto maintained because RE projects are always rewarded at the chosen ceiling price. Then, a population-oriented burden sharing can also maintain an efficient incentive structure for federal co-regulation (cf. bottom row in Table 2).

For Germany, our model results square with the situation that is observed since national tenders are in place. Because German states provide little area for wind power deployment through their spatial planning policies, few wind power projects can apply for RE support in tenders (Meier et al., 2019).[35] Consequently, the sum of volumes bid is much smaller than the national tender volume, there is almost no competition in the tendering procedures, and hence electricity suppliers bid at the ceiling price. In fact, since 2018 in most national tender rounds the tender volume was not exploited and the clearing price settled at the ceiling price (Federal Network Agency, 2021a).[36] This outcome is similar to our findings summarized in Proposition 4 for national and subnational quantity-based regulation in type-D nations.[37]

[Input: Table 3]

Thirdly, in a growing number of countries price instruments are introduced at the subnational level. For example, in Germany since 2021 compensatory levies are paid to communities with wind power plants and open-space solar power plants. Also in other countries some forms of subnational price instruments are already established (Rodi, 2017; Kerr et al., 2017; Jørgensen et al., 2020). There is an important policy implication for regulatory changes from subnational quantity-based to price-based regulation. If this change occurs, under national quantity-based regulation (i.e. tender schemes) subnational burden sharing may need to be adjusted to allow attaining a first-best allocation of RE deployment (cf. right column in Table 2). In type-D nations

[35] Of course, the observed development of wind power expansion in Germany also originates in other factors, e.g. legal complaints against approvals for wind power projetcs (Grashof et al., 2020).

[36] Although the German tender scheme is designed as a pay-as-you-bid auction, average winning bids have reached the ceiling price in the majority of tender rounds since the beginning of 2018 (Federal Network Agency, 2021a).

[37] The picture is quite different for open-space solar power plants in Germany. With regard to open-space solar power Germany may be seen as a type-B nation because the technology causes no regional costs but generates small regional benefits. Ever after tendering procedures were introduced, in all tender rounds the sum of volumes bid exceeded the tender volume and the clearing price always settled well below the ceiling price (Federal Network Agency, 2021b). This was mainly possible because German states steadily expanded areas available for the construction of solar power plants and electricity suppliers were competing for awards. In model terms we describe this outcome as a market clearing equilibrium under QQ-regulation.

this regulatory change requires a restructuring of burden shares towards first-best deployment shares. As the example of Germany shows, first-best deployment shares may substantially differ from population shares (see Table 3) such that the national financing scheme may need to be completely revised.

Fourthly, many countries - including Germany - switch from levy-based to tax-based funding. With this switch, burden sharing among German states may also change. Instead of population-oriented burden shares, a tax-based financing scheme may distribute burdens in proportion to e.g. gross domestic product of German states. Therefore, states' incentives to promote or restrict RE deployment are modified and federal co-regulation may not be coordinated efficiently.

Generally, it should be noted that what we refer to as 'states' in the model equivalently applies to other subnational entities like provinces or municipalities. For some countries, referring to lower subnational levels may even more properly account for who is in charge of subnational RE policies, e.g. in Sweden municipalities decide on the designation of wind power areas (Lauf et al., 2020). Hence, our results can be similarly applicable to federal co-regulation that is carried on by a national and a regional (or local) level, and implications from our model generally pertain to RE policies in federally structured countries.

5.2 Model Limitations

Our model results rely upon some main assumptions that need to be scrutinized. Firstly, we set up our model with perfectly informed policy-makers. A more realistic setting would include that policymakers on lower federal levels are better informed about regional costs and benefits than policymakers on higher federal levels. In fact, this is a standard argument of the fiscal federalism literature in favor of subsidiarity (Oates, 1999). When information about regional costs and benefits is not (perfectly) available at the national level, the national government may not be able to implement first-best allocation even if it could control subnational burden shares. This is particularly the case under QP-regulation because in this case the national government needs to know first-best deployment shares in order to design efficient burden shares. Asymmetric information of the national government is less of an issue under national price-based regulation because here it only needs to know the population shares of the subnational units.

Secondly, we assume that each supplier solely operates RE plants in one jurisdiction and is completely owned by citizens of this jurisdiction. This implies that national subsidies that are paid to suppliers for RE deployment also benefit the corresponding jurisdictions – either via profits of suppliers, or via subnational levies on regional RE deployment. In reality, of course, suppliers are not always citizen-owned and often operate RE plants in various jurisdictions such that national subsidies for RE deployment do not fully flow into those jurisdictions where RE plants are deployed. The ongoing debate on financial benefits for communities where RE plants are situated mirrors this fact. Here, further research may scrutinize the possible effects of other design options within federal regulation, like actor-specific national support schemes that promote local ownership of RE projects.[38]

Thirdly, we model national and subnational RE policies in a simplified manner. We assume national policy to be spatially uniform. Even though in practice national support schemes partly include elements of spatial differentiation[39], this is rather limited because national subsidy policies (must) pursue further policy goals like cost-effectiveness and competitiveness[40]. Furthermore, the toolbox of national governments contains more instruments like rules of planning law, building law, energy law, etc. Through these channels a national government additionally sets the scope for subsequent governmental levels and constrains their policy discretion. However, such complementary regulation generally imposes uniform requirements on subnational decision-making.

Fourthly, results may be altered if the shape of subutility functions fails to reflect reality.[41] Marginal benefits from emissions reductions may possibly not decrease monotonically since usually the merit order of power plants determines whether CO_2-intensive power plants are actually the first to be crowded out. Marginal disamenity functions may exhibit kinks at certain thresholds, e.g because regional costs of RE deployment kick in after all 'costless' construction sites for RE plants are exploited within the jurisdiction. Our model assumes that those sites with lowest power production cost concurrently have lowest disamenities, such that marginal dis-

[38]This design option intends to accrue national RE remunerations for RE deployment to residents. Boyle et al. (2019) find that residents who favor wind energy also support wind power plants within their neighborhood if they are financially compensated.

[39]E.g. in Germany regional adjustment of remuneration and regional control of awards are in place. However, they do not have a significant steering effect on spatial distribution of wind energy (Grashof et al., 2020; Lauf et al., 2020). Hitaj and Löschel (2019) compare the actual wind-dependent support scheme in Germany with a counterfactual uniform support scheme and find small differences between the resulting spatial allocations.

[40]Among others, these are prescribed for EU member states in the EU Renewable Energy Directive, see European Union (2018).

[41]Moreover, we assume homogeneous benefits from nationwide emissions reductions for all regions. Despite geographical variation of climate change mitigation benefits, or in other words, spatially heterogeneous social cost of carbon (Ricke et al., 2018), we leave this distinction aside for subnational regions for reasons of clarity. However, if we account for heterogeneous benefits at the subnational level (as in Williams III (2012) and Meya and Neetzow (2021)), our main messages change only in the sense that population shares need to be complemented by region-specific benefits.

amenities and marginal power production cost are monotonically increasing in each jurisdiction. This relationship is more likely, the smaller is the administrative unit considered, e.g. counties rather than states. Regarding our numerical simulation of first-best wind power deployment in Germany, we find that deviations from this assumed relationship are negligible for the level of the *Bundesländer*.

Fifthly, our static framework also simplifies the dynamics of the policymaking process among national and subnational governments. Indeed, it may take years for national governments to reform RE support levels or for subnational governments to plan areas for RE deployment. Still, as long as governments can equally easily or hardly change their policies, our model should suitably describe equilibrium policies. If, however, one government level can adopt policy changes more easily, then a sequential move game should be regarded instead (Williams III, 2012). With respect to our example case Germany, it is not evident that national and subnational governments differ in their ability to adjust policy decisions, and accordingly both government levels similarly steadily revise their RE policies.[42]

Finally, within our model the regulatory design of federal co-regulation, including the use of policy instruments and the specification of burden shares, is assumed to be exogenous. Though the national government is usually in charge of designing the RE financing scheme, empirically it seems to be constant over a long period (Council of European Energy Regulators, 2018). Therefore, when making their decisions, governments of all federal levels may regard the financing scheme, respectively subnational burden sharing, as exogenously given. Similarly, the application of policy instruments can be regarded as exogenous because it is constitutionally constrained, in particular for subnational governments like in Germany, or it is prescribed, e.g. due to agreements or other political goals (see Fn. 20). However, an extension of our model could include a preceding decision stage where the national government chooses the applied policy instrument before both government levels play the simultaneous move game of federal co-regulation. In such a setting, the national government would make its instrument choice dependent on the subnational policy instrument and actual burden sharing, intending to match efficient and actual burden sharing (cf. Table 2). Certainly, endogeneity of the regulatory design as well as implications of instrument choices for distributive issues among regions need further research.

[42] While the national RE support scheme has been reformed six times since its introduction in 2000, each of the 16 state governments has changed its state-level RE policies several times within the same period.

6 Conclusion

Which combination of policy instruments applied at different federal levels leads to efficient federal co-regulation? We answer this question by using a simple two-level regulation model of federal RE policies. We analyze strategic interactions between national and subnational governments under different combinations of price-based and quantity-based regulation. Our analysis extends the existing (theoretical) literature on federal RE regulation by including subnational quantity-based regulation, i.e. subnational spatial planning. The focus on spatial planning is crucial as it is the standard policy instrument of subnational governments to regulate the deployment of large-scale renewable power plants, like wind turbines and open-space solar power plants. Since subnational governments effectively pick the available siting areas for RE deployment, we formalize spatial planning policies through 'quantity caps' which define the upper limit for regional RE deployment.

Our results show how the efficiency of federal co-regulation hinges upon burden sharing of national subsidy costs among subnational jurisdictions. We find that national price-based regulation, i.e. feed-in tariffs, is efficient if burden shares of subnational jurisdictions are distributed in proportion to their population. This holds regardless of the policy instrument applied at the subnational level as long as RE deployment causes regional costs instead of regional benefits. Under national quantity-based regulation, i.e. tenders, efficient burden sharing depends on the policy instrument applied at the subnational level. Subnational price-based regulation, e.g. state-level levies, combined with national quantity-based regulation requires burden shares to be oriented towards first-best RE deployment shares. By contrast, subnational quantity-based regulation, i.e. spatial planning, combined with national quantity-based regulation, under certain conditions, requires burden shares to be proportional to population, namely, if RE deployment only causes negative regional effects. If so, we also show that national quantity-based regulation ends up to be de-facto price-based.

Notwithstanding, the present work leaves aside other relevant aspects of multi-level policy coordination which may merit further research. It might be of further interest to consider endogenous instrument choice as well as an analysis of welfare distribution among subnational jurisdictions (Böhringer et al., 2015). In our work we also abstract from instrument-specific effects. In particular, the application of price-based versus quantity-based instruments has distributive implications which are reflected in the cost-effectiveness of RE support schemes (Gephart et al., 2017), and the plurality of electricity suppliers (i.e. the chances of success for certain groups of investors) (Grashof, 2019). Thus, quantity instruments (e.g. tender schemes) may reduce national subsidy costs while they may crowd out small citizen-owned projects. Both the reduction of national subsidy costs and (financial) citizen participation are political objectives pursued by national and subnational governments. As both objectives play an important role for the success of future RE deployment, including instrument-specific effects into the analysis demands for further research.

Appendices

Nomenclature

$i = 1, ..., n$	Index for states
r	Index for 'restrictive' states
a	Index for 'ambitious' states
η_i	State i's population share
γ_i	State i's burden share of national subsidy costs
x_i	Amount of electricity produced from RE in state i
$\bar{x_i}$	State-level quantity cap of state i
X	Nationwide amount of electricity produced from RE
p^N	National remuneration per unit of electricity from RE
p_i^S	State-level price incentive per unit of electricity from RE in state i
p^M	Clearing price in tenders for national remuneration per unit of electricity from RE
$\bar{p}$	Ceiling price in tenders for national remuneration per unit of electricity from RE
$\bar{X}$	National tender volume
$C_i(x_i)$	Cost of electricity production from RE in state i
$D_i(x_i)$	Disamenities (= Net regional costs and benefits) from RE deployment in state i
$B(X)$	Nationwide benefit from nationwide RE deployment

Appendix A Suppliers and their reaction function

After national and state governments have set their policies in the first stage of the game, in the second stage electricity suppliers decide on the level of RE deployment. We assume that national and state governments concurrently decide on their policies in a simultaneous move game as in Williams III (2012).

We assume that in each state a single supplier decides on the amount of state-specific power production, x_i. Suppliers are owned by the respective state's residents, they are price takers, and they choose regional RE deployment levels x_i in order to maximize their profits.

A.1 Reaction function under state-level price-based regulation

Under state-level price-based regulation the supplier's optimization problem in state i is defined as follows:

$$\underset{x_i}{max} \quad \pi_i(x_i) = (p^N + p_i^S)x_i - C_i(x_i) \qquad \forall i \tag{A.1}$$

The first term in eq. (A.1) expresses the supplier's revenues from national and state-level prices paid for its RE deployment in state i. Under state-level price-based regulation suppliers' reaction function is implicitly defined by:

$$\forall i: \quad p^N + p_i^S = \frac{\partial C_i}{\partial x_i} \ . \tag{A.2}$$

A.2 Reaction function under state-level quantity-based regulation

Under state-level quantity-based regulation the supplier's constrained optimization problem in state i is defined as follows:

$$\underset{x_i}{max} \quad \pi_i(x_i) = p^N x_i - C_i(x_i) \quad \text{subject to} \quad x_i \leq \bar{x}_i \quad \forall i \tag{A.3}$$

In the case that states regulate through quantity caps, e.g. via spatial planning, suppliers can expand RE deployment as far as state-specific quantity caps allow it. Formally, this is denoted by $x_i \leq \bar{x}_i$, $\forall i$. When states set quantity caps $\bar{x}_i$ suppliers' implicit reaction function is defined by:

$$\forall i: \quad p^N \begin{cases} = \dfrac{\partial C_i}{\partial x_i} \quad \text{and} \quad x_i < \bar{x}_i & \text{(A.4a)} \\ \geq \dfrac{\partial C_i}{\partial x_i} \quad \text{and} \quad x_i = \bar{x}_i & \text{(A.4b)} \end{cases}$$

If the state-specific quantity cap is not binding then suppliers deploy the amount of RE that maximizes their profits (eq. (A.4a)). If the state-specific quantity cap is binding then suppliers deploy as much RE as possible (eq. (A.4b)).

In the following for each regulatory design we first derive the national and state governments' FOCs respectively reaction functions. Second, we find the Nash equilibrium of the simultaneous move game at the intersection of the national and state governments' reaction functions.

Appendix B PP-Regulation

B.1 Reaction functions

State-level Policy

We derive state i's policy choice of p_i^S given the national policy p^N by differentiating state i's welfare function given in eq. (4) w.r.t. p_i^S and setting the result equal to zero, $\frac{\partial \mathscr{W}_i}{\partial p_i^S} = 0$:

$$\frac{\partial x_i}{\partial p_i^S}\left[\eta_i \frac{\partial B}{\partial X}\frac{\partial X}{\partial x_i} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1-\gamma_i)p^N\right] = 0 \qquad \forall i \tag{B.1}$$

Note that $\frac{\partial X}{\partial x_i} = 1 \; \forall i$. Dividing eq. (B.1) by $\frac{\partial x_i}{\partial p_i^S}$ gives eq. (10):

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1-\gamma_i)p^N = 0 \qquad \forall i \tag{B.2}$$

Inserting eq. (A.1) and solving for p_i^S gives the state government's reaction function as a function of p^N:

$$p_i^S = \eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \gamma_i p^N \qquad \forall i \tag{B.3}$$

National Policy

We derive the national government's policy choice of p^N by differentiating the national welfare function given in eq. (3) w.r.t. p^N and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial p^N} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\left[\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i}\right] = 0 \tag{B.4}$$

Inserting eq. (A.1) and solving for p^N gives the national government's reaction function as a function of $p_1^S, ..., p_n^S$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\left[\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - (p^N + p_i^S)\right] = 0$$
$$\iff p^N = \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\left[\frac{\partial D_i}{\partial x_i} + p_i^S\right]}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}} \tag{B.5}$$

By differentiating eq. (A.1) w.r.t. p^N we know that $\frac{\partial x_i}{\partial p^N} = \frac{1}{\frac{\partial^2 C_i}{\partial x_i^2}}$.

B.2 Equilibrium outcome

Using the national and state governments' reaction functions eq. (B.5) and (B.3) we derive the equilibrium policies. Inserting eq. (B.3) into (B.5) we obtain:

$$
\begin{aligned}
p^N &= \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\left[\eta_i \frac{\partial B}{\partial X} - \gamma_i p^N\right]}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}} \\
\iff \quad p^N &= \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\eta_i \frac{\partial B}{\partial X}}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}} + \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\gamma_i p^N}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}} \\
\iff \quad \left(1 - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\gamma_i}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}}\right) p^N &= \left(1 - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\eta_i}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}}\right) \frac{\partial B}{\partial X} \\
\iff \quad p^N &= \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}(1-\eta_i)}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}(1-\gamma_i)} \frac{\partial B}{\partial X}
\end{aligned}
\tag{B.6}
$$

By substituting eq. (B.6) into (B.3) we obtain:

$$
p_i^S = \eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \gamma_i \frac{\sum_{j=1}^{n} \frac{\partial x_j}{\partial p^N}(1-\eta_j)}{\sum_{j=1}^{n} \frac{\partial x_j}{\partial p^N}(1-\gamma_j)} \frac{\partial B}{\partial X} \qquad \forall i \tag{B.7}
$$

RE deployment in equilibrium is defined by inserting eq. (B.6) and (B.7) into eq. (A.1):

$$
\forall i: \quad \left((1-\gamma_i)\frac{\sum_{j=1}^{n} \frac{\partial x_j}{\partial p^N}(1-\eta_j)}{\sum_{j=1}^{n} \frac{\partial x_j}{\partial p^N}(1-\gamma_j)} + \eta_i\right)\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} = 0. \tag{B.8}
$$

B.3 Proof of Proposition 1

Eq. (B.8) yields the social optimum (cf. eq. (6)) if and only if the first term on the lhs is equal to one, hence, if:

$$
\begin{aligned}
\frac{\sum_{j=1}^{n} \frac{\partial x_j}{\partial p^N}(1-\eta_j)}{\sum_{j=1}^{n} \frac{\partial x_j}{\partial p^N}(1-\gamma_j)} &= \frac{1-\eta_i}{1-\gamma_i} \qquad \forall i \\
\iff \quad \gamma_i &= \eta_i \qquad \forall i
\end{aligned}
\tag{B.9}
$$

Plugging $\gamma_i = \eta_i \ \forall i$ into eq. (B.6) and (B.7) gives the corresponding policy choices:

$$
p^N = \frac{\partial B}{\partial X} \tag{B.10}
$$

$$
p_i^S = -\frac{\partial D_i}{\partial x_i} \qquad \forall i \tag{B.11}
$$

Q.E.D.

Appendix C QP-Regulation

The derivations in this section mostly resemble Meya and Neetzow (2021), pp. 29-31. In the following we assume that $p^M < \bar{p}$.

In contrast to PP-regulation nationwide RE deployment is fixed through the tendering procedure while the support level p^M is endogenous. The national clearing price is implicitly defined by the following two conditions:

$$p^M + p_i^S = \frac{\partial C_i}{\partial x_i} \qquad \forall i \tag{C.1}$$

$$\sum_{i=1}^{n} x_i = \bar{X} \tag{C.2}$$

The national clearing price $p^M(\boldsymbol{x})$ is a function of the level of nationwide RE deployment resp. the tender volume $\bar{X}$ and the allocation of RE deployment across states.

Differentiating eq. (C.1) w.r.t. p^M gives (since $\frac{\partial p_i^S}{\partial p^M} = 0$):

$$\frac{\partial x_i}{\partial p^M} = \frac{1}{\frac{\partial^2 C_i}{\partial x_i^2}} \qquad \forall i \tag{C.3}$$

Eq. (C.1) and (C.2) establish that x_i, $i = 1, ..., n$ depends on the national clearing price, $x_i(p^M)$, and p^M depends on the allocation of RE deployment across states, $p^M(x_1, ..., x_n)$. Differentiating eq. (C.2) w.r.t. x_j and rearranging yields (since $\frac{\partial x_j}{\partial x_j} = 1$ and $\frac{\partial \bar{X}}{\partial x_j} = 0$):

$$1 + \sum_{i \neq j} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial x_j} = 0$$

$$\iff \frac{\partial p^M}{\partial x_j} = -\frac{1}{\sum_{i \neq j} \frac{\partial x_i}{\partial p^M}} \qquad \forall j \tag{C.4}$$

$$\iff \frac{\partial p^M}{\partial x_j} = -\frac{1}{\sum_{i \neq j} \frac{1}{\frac{\partial^2 C_i}{\partial x_i^2}}} \qquad \forall j \tag{C.5}$$

Differentiating eq. (C.2) w.r.t. $\bar{X}$ gives:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} = 1$$

$$\iff \quad \frac{\partial p^M}{\partial \bar{X}} = \frac{1}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M}} \tag{C.6}$$

C.1 Reaction functions

State-level Policy

Note that nationwide RE deployment is fixed to $X = \bar{X}$, thus $\frac{\partial X}{\partial x_i} = 0$. We derive state i's policy choice of p_i^S given the national policy p^M by differentiating state i's welfare function eq. (4) w.r.t. p_i^S and setting the result equal to zero, $\frac{\partial \mathscr{W}_i}{\partial p_i^S} = 0$:

$$\frac{\partial x_i}{\partial p_i^S} \left[-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^M(\boldsymbol{x}) + \frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X}) \right] = 0 \qquad \forall i \tag{C.7}$$

Dividing eq. (C.7) by $\frac{\partial x_i}{\partial p_i^S}$ yields:

$$-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^M(\boldsymbol{x}) + \frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X}) = 0 \qquad \forall i \tag{C.8}$$

Inserting eq. (C.1) into (C.8) and rearranging for p_i^S gives the state government's reaction function as a function of $\bar{X}$:

$$p_i^S = -\frac{\partial D_i}{\partial x_i} + \frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X}) \qquad \forall i \tag{C.9}$$

National Policy

We derive the national government's policy choice of $\bar{X}$ by differentiating the national welfare function given in eq. (3) w.r.t. $\bar{X}$ and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial \bar{X}} = 0$:

$$\frac{\partial B}{\partial X} - \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} \left[\frac{\partial D_i}{\partial x_i} + \frac{\partial C_i}{\partial x_i} \right] = 0 \tag{C.10}$$

$\frac{\partial x_i}{\partial p^M}$ is defined by eq. (C.3) and $\frac{\partial p^M}{\partial \bar{X}}$ is defined by eq. (C.6).

Inserting eq. (A.1) and solving for p^M gives the national government's implicit reaction function for $\bar{X}$ as a function of $p_1^S, ..., p_n^S$:

$$\frac{\partial B}{\partial X} - \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} \left[\frac{\partial D_i}{\partial x_i} + (p^M + p_i^S) \right] = 0$$

$$\iff \frac{\partial B}{\partial X} - \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} p^M - \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} \left[\frac{\partial D_i}{\partial x_i} + p_i^S \right] = 0$$

Since $\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} = 1$ (see eq. (C.6)) we obtain:

$$\iff \quad p^M = \frac{\partial B}{\partial X} - \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} \left[\frac{\partial D_i}{\partial x_i} + p_i^S \right] \tag{C.11}$$

Using eq. (C.6) we can rewrite:

$$\iff \quad p^M = \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \left[\frac{\partial D_i}{\partial x_i} + p_i^S \right]}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M}} \tag{C.12}$$

C.2 Equilibrium outcome

Using the national and state governments' reaction functions we derive the equilibrium policies. Inserting eq. (C.9) into (C.12) we obtain:

$$p^M = \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial x_i} (x_i - \gamma_i \bar{X})}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M}} \tag{C.13}$$

From eq. (C.9) we have:

$$p_i^S = -\frac{\partial D_i}{\partial x_i} + \frac{\partial p^M}{\partial x_i} (x_i - \gamma_i \bar{X}) \qquad \forall i \tag{C.14}$$

RE deployment in equilibrium is defined by inserting eq. (C.13) and (C.14) into eq. (A.1):

$$\forall i: \quad \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} - \frac{\sum_{j=1}^{n} \frac{\partial x_j}{\partial p^M} \frac{\partial p^M}{\partial x_j} (x_j - \gamma_j \bar{X})}{\sum_{j=1}^{n} \frac{\partial x_j}{\partial p^M}} + \frac{\partial p^M}{\partial x_i} (x_i - \gamma_i \bar{X}) = 0. \tag{C.15}$$

From the second term in eq. (C.13) we deduce that the RE deployment levels in states with lower (higher) curvature of RE deployment costs have lower (higher) influence on the clearing price. This is because $\frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial x_i} = -\frac{\frac{\partial x_i}{\partial p^M}}{\sum_{j \neq i} \frac{\partial x_j}{\partial p^M}}$ is large (small) for large (small) $\frac{\partial x_i}{\partial p^M}$ respectively small (large) $\frac{\partial^2 C_i}{\partial x_i^2}$ (see eq. C.3 to C.5).

From the second term in eq. (C.14) we deduce that states with higher (lower) curvature of

RE deployment costs less (more) strongly consider their influence on the clearing price. This is because $\left|\frac{\partial p^M}{\partial x_i}\right| = \frac{1}{\sum_{j\neq i}\frac{1}{\frac{\partial^2 C_j}{\partial x_j^2}}}$ is relatively large (small) for small (large) $\frac{\partial^2 C_i}{\partial x_i^2}$.

C.3 Proof of Proposition 2

To satisfy the condition for first-best RE deployment in all states (cf. eq. (6)) the fourth and fifth term in eq. (C.15) must be equal to zero for all states:

$$\begin{aligned} \frac{\sum_{j=1}^n \frac{\partial x_j}{\partial p^M}\frac{\partial p^M}{\partial x_j}(x_j - \gamma_j \bar{X})}{\sum_{j=1}^n \frac{\partial x_j}{\partial p^M}} &= \frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X}) \quad \forall i \\ \iff \quad \sum_{j=1}^n \frac{\partial x_j}{\partial p^M}\frac{\partial p^M}{\partial x_j}(x_j - \gamma_j \bar{X}) &= \left(\sum_{j=1}^n \frac{\partial x_j}{\partial p^M}\right)\frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X}) \quad \forall i \end{aligned}$$

Given eq. (C.2) this is true if and only if:

$$\iff \quad \gamma_i = \frac{x_i^*}{X^*} \qquad \forall i \tag{C.16}$$

Q.E.D.

C.4 Ceiling Price under QP-Regulation

Assume that $\gamma_i = \eta_i\ \forall i$ and $\gamma_i \neq \frac{x_i^*}{X^*}\ \forall i$. When setting the ceiling price $\bar{p}$ equal to the national price in equilibrium under PP-regulation (according to eq. (B.6)), $\bar{p}$ is binding in equilibrium under QP-regulation if:

$$\begin{aligned} \bar{p} &< \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^n \frac{\partial x_i}{\partial p^M}\frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X})}{\sum_{i=1}^n \frac{\partial x_i}{\partial p^M}} \\ \iff \quad \frac{\sum_{i=1}^n \frac{\partial x_i}{\partial p^N}(1-\eta_i)}{\sum_{i=1}^n \frac{\partial x_i}{\partial p^N}(1-\gamma_i)}\frac{\partial B}{\partial X} &< \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^n \frac{\partial x_i}{\partial p^M}\frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X})}{\sum_{i=1}^n \frac{\partial x_i}{\partial p^M}} \end{aligned}$$

Because $\frac{\sum_{i=1}^n \frac{\partial x_i}{\partial p^N}(1-\eta_i)}{\sum_{i=1}^n \frac{\partial x_i}{\partial p^N}(1-\gamma_i)} = \frac{\partial B}{\partial X}$ and assuming that $\frac{\partial B}{\partial X}$ =const. we rearrange such that:

$$0 < -\frac{\sum_{i=1}^n \frac{\partial x_i}{\partial p^M}\frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X})}{\sum_{i=1}^n \frac{\partial x_i}{\partial p^M}} \tag{C.17}$$

The inequality in eq. (C.17) holds if $\left|\frac{\partial p^M}{\partial x_i}\right|$ and $(x_i - \gamma_i \bar{X})$ are positively correlated respectively if $\frac{\partial^2 C_i}{\partial x_i^2}$ and $(x_i - \gamma_i \bar{X})$ are negatively correlated. The latter in turn requires that $\frac{\partial^2 C_i}{\partial x_i^2}$ and γ_i are positively correlated. This applies if those states bear larger (smaller) burden shares in which RE deployment costs grow much faster (slower).[43]

Appendix D PQ-Regulation

D.1 Reaction functions

State-level Policy

We assume that each state sets its quantity cap equal to its welfare maximizing RE expansion level, hence $\bar{x}_i = \underset{x_i}{\arg\max}\, \mathscr{W}_i(x_i)$. Taking p^N as given, state i's choice is implicitly defined by differentiating state i's welfare function eq. (4) w.r.t. x_i and setting the result equal to zero, $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$:

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1-\gamma_i)p^N = 0 \qquad \forall i \tag{D.1}$$

State-level policy in state i is implicitly defined as a function of the national price incentive, $\bar{x}_i(p^N)$.

D.1.1 Setting binding (restrictive) and non-binding (ambitious) quantity caps

Denote by x_i^{ES} the RE deployment level striven for by electricity suppliers. x_i^{ES} is implicitly defined by $p^N = \frac{\partial C_i}{\partial x_i}\big|_{x_i = x_i^{ES}}$. State governments set binding (restrictive) caps if $x_i^{ES} \geq \bar{x}_i$, and they set non-binding (ambitious) caps if $x_i^{ES} < \bar{x}_i$ with $\bar{x}_i$ implicitly defined through eq. (D.1).

Binding (restrictive) quantity caps

If $x_i^{ES} \geq \bar{x}_i$, then it must be true that $\frac{\partial C_i}{\partial x_i}\big|_{x_i = x_i^{ES}} \geq \frac{\partial C_i}{\partial x_i}\big|_{x_i = \bar{x}_i}$. We derive the condition for

[43] This is also reflected in the Two-State Example in Appendix F. With RE deployment costs specified such that $\frac{\partial^2 C_1}{\partial x_1^2} < \frac{\partial^2 C_2}{\partial x_2^2}$ the ceiling price becomes binding as γ_1 becomes smaller.

binding (restrictive) quantity caps by using eq. (D.1):

$$
\begin{aligned}
& \left.\frac{\partial C_i}{\partial x_i}\right|_{x_i=x_i^{ES}} \geq \left.\frac{\partial C_i}{\partial x_i}\right|_{x_i=\bar{x}_i} && \forall i \\
\iff & \left.\frac{\partial C_i}{\partial x_i}\right|_{x_i=x_i^{ES}} \geq \eta_i \frac{\partial B}{\partial X} - \left.\frac{\partial D_i}{\partial x_i}\right|_{x_i=\bar{x}_i} + (1-\gamma_i)p^N && \forall i \\
\iff & p^N \geq \eta_i \frac{\partial B}{\partial X} - \left.\frac{\partial D_i}{\partial x_i}\right|_{x_i=\bar{x}_i} + (1-\gamma_i)p^N && \forall i \\
\iff & 0 \geq \eta_i \frac{\partial B}{\partial X} - \left.\frac{\partial D_i}{\partial x_i}\right|_{x_i=\bar{x}_i} - \gamma_i p^N && \forall i
\end{aligned} \tag{D.2}
$$

According to eq. (D.2) whether state governments set binding (restrictive) quantity caps depends on their population share η_i and burden share γ_i, on marginal regional cost $\frac{\partial D_i}{\partial x_i}$, on the national price level p^N, and marginal nationwide benefits $\frac{\partial B}{\partial X}$.

If eq. (D.2) applies, then state i sets a binding (restrictive) quantity cap.

Non-binding (ambitious) quantity caps

If $x_i^{ES} < \bar{x}_i$, then it must be true that $\frac{\partial C_i}{\partial x_i}|_{x_i=x_i^{ES}} < \frac{\partial C_i}{\partial x_i}|_{x_i=\bar{x}_i}$. We derive the condition for non-binding (ambitious) quantity caps by using eq. (D.1):

$$
\begin{aligned}
& \left.\frac{\partial C_i}{\partial x_i}\right|_{x_i=x_i^{ES}} < \left.\frac{\partial C_i}{\partial x_i}\right|_{x_i=\bar{x}_i} && \forall i \\
\iff & \left.\frac{\partial C_i}{\partial x_i}\right|_{x_i=x_i^{ES}} < \eta_i \frac{\partial B}{\partial X} - \left.\frac{\partial D_i}{\partial x_i}\right|_{x_i=\bar{x}_i} + (1-\gamma_i)p^N && \forall i \\
\iff & p^N < \eta_i \frac{\partial B}{\partial X} - \left.\frac{\partial D_i}{\partial x_i}\right|_{x_i=\bar{x}_i} + (1-\gamma_i)p^N && \forall i \\
\iff & 0 < \eta_i \frac{\partial B}{\partial X} - \left.\frac{\partial D_i}{\partial x_i}\right|_{x_i=\bar{x}_i} - \gamma_i p^N && \forall i
\end{aligned} \tag{D.3}
$$

According to eq. (D.3) whether state governments set non-binding (ambitious) quantity caps depends on their population share η_i and burden share γ_i, on marginal regional cost $\frac{\partial D_i}{\partial x_i}$, on the national price level p^N, and marginal nationwide benefits $\frac{\partial B}{\partial X}$.

If eq. (D.3) applies, then state i sets a non-binding (ambitious) quantity cap.

States that set binding quantity caps are called *restrictive* and indexed by $r \in \mathcal{R}^{PQ}$ and states that set non-binding quantity caps are called *ambitious* and indexed by $a \in \mathcal{A}^{PQ}$.

Q.E.D.

National Policy

We derive the national government's policy choice of p^N by differentiating the national welfare function given in eq. (3) w.r.t. p^N and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial p^N} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \left[\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} \right] = 0 \tag{D.4}$$

D.2 Equilibrium outcome

Taking other policies as given, the national government soley influences RE deployment in states where the quantity caps are non-binding. Given $\frac{\partial x_r}{\partial p^N} = 0$, $r \in \mathcal{R}^{PQ}$ we insert eq. (A.4a) into (D.4) and solve for p^N:

$$\sum_{a \in \mathcal{A}^{PQ}} \frac{\partial x_a}{\partial p^N} \left[\frac{\partial B}{\partial X} - \frac{\partial D_a}{\partial x_a} - p^N \right] = 0$$

$$\iff \quad p^N = \frac{\partial B}{\partial X} - \frac{\sum_{a \in \mathcal{A}^{PQ}} \frac{\partial x_a}{\partial p^N} \frac{\partial D_a}{\partial x_a}}{\sum_{a \in \mathcal{A}^{PQ}} \frac{\partial x_a}{\partial p^N}} \tag{D.5}$$

For the case that the state-specific quantity cap is non-binding respectively states are *ambitous* it follows from eq. (A.4a), (D.1) and (D.5) that in equilibrium state governments set $\bar{x}_a$ such that

$$\eta_a \frac{\partial B}{\partial X} - \left.\frac{\partial D_a}{\partial x_a}\right|_{x_a = \bar{x}_a} - \gamma_a \left(\frac{\partial B}{\partial X} - \frac{\sum_{\hat{a} \in \mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a} \in \mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}} \right) = 0 \qquad a \in \mathcal{A}^{PQ}$$

$$\iff \quad (\eta_a - \gamma_a) \frac{\partial B}{\partial X} - \left.\frac{\partial D_a}{\partial x_a}\right|_{x_a = \bar{x}_a} + \gamma_a \frac{\sum_{\hat{a} \in \mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a} \in \mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}} = 0 \qquad a \in \mathcal{A}^{PQ} \tag{D.6}$$

For the case that the state-specific quantity cap is binding respectively states are *restrictive* it follows from eq. (A.4b), (D.1) and (D.5) that in equilibrium state government set $\bar{x}_r$ such that

$$\eta_r \frac{\partial B}{\partial X} - \frac{\partial D_r}{\partial x_r} - \frac{\partial C_r}{\partial x_r} + (1 - \gamma_r) \left(\frac{\partial B}{\partial X} - \frac{\sum_{\hat{a} \in \mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a} \in \mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}} \right) = 0 \qquad r \in \mathcal{R}^{PQ}$$

$$\iff \quad (1 + \eta_r - \gamma_r) \frac{\partial B}{\partial X} - \frac{\partial D_r}{\partial x_r} - \frac{\partial C_r}{\partial x_r} - (1 - \gamma_r) \frac{\sum_{\hat{a} \in \mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a} \in \mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}} = 0 \qquad r \in \mathcal{R}^{PQ} \tag{D.7}$$

RE deployment in equilibrium follows from inserting eq. (D.5) into eq. (A.4a) and from (D.7):

$$\frac{\partial B}{\partial X} - \frac{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}\frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}} - \frac{\partial C_a}{\partial x_a} = 0 \qquad a \in \mathcal{A}^{PQ} \tag{D.8}$$

$$(1+\eta_r-\gamma_r)\frac{\partial B}{\partial X} - \frac{\partial D_r}{\partial x_r} - \frac{\partial C_r}{\partial x_r} - (1-\gamma_r)\frac{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}\frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}} = 0 \qquad r \in \mathcal{R}^{PQ} \tag{D.9}$$

D.3 Proof of Proposition 3

From $x_a < \bar{x_a}$ it follows that $\frac{\partial D_a}{\partial x_a} < \frac{\partial D_a}{\partial x_a}\big|_{x_a=\bar{x_a}}$. Therefore aggregating eq. (D.6) across all ambitious states we derive:

$$\sum_{a\in\mathcal{A}^{PQ}} \frac{\partial D_a}{\partial x_a}\bigg|_{x_a=\bar{x_a}} = \sum_{a\in\mathcal{A}^{PQ}} (\eta_a-\gamma_a)\frac{\partial B}{\partial X} + \sum_{a\in\mathcal{A}^{PQ}} \gamma_a \frac{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}\frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}} > \sum_{a\in\mathcal{A}^{PQ}} \frac{\partial D_a}{\partial x_a}\,.$$

Assuming that $\forall i : \eta_i = \gamma_i$ we obtain:

$$\begin{aligned} &\sum_{a\in\mathcal{A}^{PQ}} \gamma_a \frac{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}\frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}} > \sum_{a\in\mathcal{A}^{PQ}} \frac{\partial D_a}{\partial x_a} \\ \iff &\sum_{a\in\mathcal{A}^{PQ}} \gamma_a \sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N}\frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}} > \sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial p^N} \sum_{a\in\mathcal{A}^{PQ}} \frac{\partial D_a}{\partial x_a}\,. \end{aligned} \tag{D.10}$$

From eq. (D.10) follows by contradiction that there are no *ambitious* states if $\forall i : \frac{\partial D_i}{\partial x_i} > 0$ and $\gamma_i = \eta_i$ for all states. In other words, all states are *restrictive* if $\forall i : \frac{\partial D_i}{\partial x_i} > 0$ and $\gamma_i = \eta_i$ for all states. Consequently, the last term in eq. (D.5) as well as in eq. (D.9) drops out, and the equilibrium outcome implements the social optimum.

Q.E.D.

On the contrary, given $\forall i : \frac{\partial D_i}{\partial x_i} < 0$ and $\gamma_i = \eta_i$ for all states, according to eq. (D.10) it is possible that all states set non-binding quantity caps. Then the equilibrium outcome is equal to the outcome when the national government alone steers through uniform RE subsidies.

D.4 Adjusted Burden Shares under PQ-regulation

From eq. (D.8) we see that the social optimum can only be reached if all *ambitious* states have identical regional cost functions and marginal regional costs are not correlated with the curvatare of RE deployment costs. Given this special case burden shares of restrictive states can be adjusted such that the social optimum is implemented in equilibrium. Combining eq. (6) and (D.9) gives the optimal adjusted burden shares:

$$(\eta_r - \gamma_r)\frac{\partial B}{\partial X} = (1-\gamma_r)\,\frac{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}\frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}} \qquad r\in\mathcal{R}^{PQ}$$

$$\iff \quad \gamma_r = \frac{\eta_r\frac{\partial B}{\partial X} - \frac{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}\frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}}}{\frac{\partial B}{\partial X} - \frac{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}\frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{PQ}}\frac{\partial x_a}{\partial p^N}}} \qquad r\in\mathcal{R}^{PQ} \tag{D.11}$$

The second term in the nominator and denominator in eq. (D.11) is equal to $\frac{\partial D_a}{\partial x_a}\big|_{x_a=x_a^*}$ since we assumed all *ambitious* states to be homogenous with regard to their regional costs. Burden shares are adjusted such that they are higher than the population share for *restrictive* states $\gamma_r > \eta_r$, $r\in\mathcal{R}^{PQ}$.[44]

Appendix E QQ-Regulation

The national ceiling price $\bar{p}$ comes into force if $\sum_{i=1}^{n}\bar{x}_i \leq \bar{X}$. Otherwise the national clearing price p^N from the tendering procedure applies. The national clearing price is implicitly defined by the following conditions:

$$\forall i: \quad p^M \begin{cases} = \dfrac{\partial C_i}{\partial x_i} & \text{and} \quad x_i < \bar{x}_i \qquad \text{(E.1a)} \\ \geq \dfrac{\partial C_i}{\partial x_i} & \text{and} \quad x_i = \bar{x}_i \qquad \text{(E.1b)} \end{cases}$$

$$\sum_{i=1}^{n} x_i = \bar{X} \tag{E.2}$$

The national clearing price $p^M(\boldsymbol{x})$ is a function of the level of nationwide RE deployment resp. the tender volume $\bar{X}$ and the allocation of RE deployment across states $\boldsymbol{x} = (x_1, ..., x_n)$.

[44]By assuming all *ambitious* states to be homogenous with regard to their regional costs, it follows that $\frac{\partial D_a}{\partial x_a}\big|_{x_a=x_a^*} < 0$ from eq. (D.3) and (D.11).

From eq. (E.1a) and (E.1b) we get:

$$\frac{\partial x_a}{\partial p^M} = \frac{1}{\frac{\partial^2 C_a}{\partial x_a^2}} \tag{E.3}$$

$$\frac{\partial x_r}{\partial p^M} = 0 \tag{E.4}$$

Differentiating eq. (E.2) w.r.t. x_j and using eq. (E.3) and (E.4) yields:

$$\begin{aligned}
& 1 + \sum_{i \neq j} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial x_j} = 0 \\
\iff \quad & \frac{\partial p^M}{\partial x_j} = -\frac{1}{\sum_{i \neq j} \frac{\partial x_i}{\partial p^M}} \qquad \forall j \\
\iff \quad & \frac{\partial p^M}{\partial x_j} = -\frac{1}{\sum_{a \in \mathcal{A}^{-j}} \frac{1}{\frac{\partial^2 C_a}{\partial x_a^2}}} \qquad \forall j \\
& \text{with} \quad \mathcal{A}^{-j} = \mathcal{A} \setminus \{j\}
\end{aligned} \tag{E.5}$$

In contrast to QP regulation $\frac{\partial p^M}{\partial x_i}$ is state-specific as it differs across ambitious states.

Differentiating eq. (E.2) w.r.t. $\bar{X}$ gives:

$$\begin{aligned}
& \frac{\partial p^M}{\partial x_i} = \frac{1}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M}} \qquad \forall i \\
\iff \quad & \frac{\partial p^M}{\partial \bar{X}} = \frac{1}{\sum_{a \in \mathcal{A}} \frac{1}{\frac{\partial^2 C_a}{\partial x_a^2}}}
\end{aligned} \tag{E.6}$$

E.1 Reaction functions

State-level Policy

We derive state i's implicit reaction function by differentiating eq. (4) w.r.t. x_i and setting $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$:

$$-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^M(\boldsymbol{x}) + \frac{\partial p^M}{\partial x_i}(x_i - \gamma_i \bar{X}) = 0 \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i > \bar{X} \tag{E.7}$$

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1 - \gamma_i)\bar{p} = 0 \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i \leq \bar{X} \tag{E.8}$$

E.1.1 Setting binding (restrictive) and non-binding (ambitious) quantity caps

Denote by x_i^{ES} the RE deployment level striven for by electricity suppliers. x_i^{ES} is implicitly defined by $p^M = \frac{\partial C_i}{\partial x_i}\big|_{x_i = x_i^{ES}}$. State governments set binding (restrictive) caps if $x_i^{ES} \geq \bar{x}_i$, and they set non-binding (ambitious) caps if $x_i^{ES} < \bar{x}_i$ with $\bar{x}_i$ implicitly defined through eq. (D.1).

Binding (restrictive) quantity caps

If $x_i^{ES} \geq \bar{x}_i$, then it must be true that $\frac{\partial C_i}{\partial x_i}\big|_{x_i=x_i^{ES}} \geq \frac{\partial C_i}{\partial x_i}\big|_{x_i=\bar{x}_i}$. We derive the condition for binding (restrictive) quantity caps by using eq. (E.7):

$$\begin{aligned}
& \frac{\partial C_i}{\partial x_i}\bigg|_{x_i=x_i^{ES}} \geq \frac{\partial C_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} && \forall i \\
\iff \quad & \frac{\partial C_i}{\partial x_i}\bigg|_{x_i=x_i^{ES}} \geq -\frac{\partial D_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} + p^M + \frac{\partial p^M}{\partial x_i}\bigg|_{x_i=\bar{x}_i}(\bar{x}_i - \gamma_i \bar{X}) && \forall i \\
\iff \quad & p^M \geq -\frac{\partial D_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} + p^M + \frac{\partial p^M}{\partial x_i}\bigg|_{x_i=\bar{x}_i}(\bar{x}_i - \gamma_i \bar{X}) && \forall i \\
\iff \quad & 0 \geq -\frac{\partial D_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} + \frac{\partial p^M}{\partial x_i}\bigg|_{x_i=\bar{x}_i}(\bar{x}_i - \gamma_i \bar{X}) && \forall i \qquad \text{(E.9)}
\end{aligned}$$

According to eq. (E.9) whether state governments set binding (restrictive) quantity caps depends on marginal regional cost $\frac{\partial D_i}{\partial x_i}$, their burden share γ_i, and the quantity cap level $\bar{x}_i$.

If eq. (E.9) applies, then state i sets a binding (restrictive) quantity cap.

Non-binding (ambitious) quantity caps

If $x_i^{ES} < \bar{x}_i$, then it must be true that $\frac{\partial C_i}{\partial x_i}\big|_{x_i=x_i^{ES}} < \frac{\partial C_i}{\partial x_i}\big|_{x_i=\bar{x}_i}$. We derive the condition for non-binding (ambitious) quantity caps by using eq. (E.7):

$$\begin{aligned}
& \frac{\partial C_i}{\partial x_i}\bigg|_{x_i=x_i^{ES}} < \frac{\partial C_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} && \forall i \\
\iff \quad & \frac{\partial C_i}{\partial x_i}\bigg|_{x_i=x_i^{ES}} < -\frac{\partial D_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} + p^M + \frac{\partial p^M}{\partial x_i}(\bar{x}_i - \gamma_i \bar{X}) && \forall i \\
\iff \quad & p^M < -\frac{\partial D_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} + p^M + \frac{\partial p^M}{\partial x_i}(\bar{x}_i - \gamma_i \bar{X}) && \forall i \\
\iff \quad & 0 < -\frac{\partial D_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} + \frac{\partial p^M}{\partial x_i}(\bar{x}_i - \gamma_i \bar{X}) && \forall i \qquad \text{(E.10)}
\end{aligned}$$

A marginal change of the quantity cap $\bar{x}_i$ does not change the clearing price since the quantity cap is not binding. From $x_i^{ES} < \bar{x}_i$ follows that $\frac{\partial p^M}{\partial x_i}\big|_{x_i=\bar{x}_i} = 0$.

$$\iff \quad 0 < -\frac{\partial D_i}{\partial x_i}\bigg|_{x_i=\bar{x}_i} \qquad \forall i \qquad \text{(E.11)}$$

According to eq. (E.11) whether state governments set binding (restrictive) quantity caps depends on marginal disamenities function $\frac{\partial D_i}{\partial x_i}$ only.

If eq. (E.11) applies, then state i sets a non-binding (ambitious) quantity cap. According to eq. (E.11) this can only be true for states with marginal regional benefits $\frac{\partial D_i}{\partial x_i} < 0$.

States that set binding quantity caps are called *restrictive* and indexed by $r \in \mathcal{R}^{QQ}$ and states that set non-binding quantity caps are called *ambitious* and indexed by $a \in \mathcal{A}^{QQ}$.

Q.E.D.

National Policy

We derive the national government's policy choice of $\bar{X}$ by differentiating the national welfare function eq. (3) w.r.t. $\bar{X}$ and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial \bar{X}} = 0$:

$$\frac{\partial B}{\partial X} - \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} \left[\frac{\partial D_i}{\partial x_i} + \frac{\partial C_i}{\partial x_i} \right] = 0 \tag{E.12}$$

We derive the national government's policy choice of $\bar{p}$ by differentiating the national welfare function eq. (3) w.r.t. $\bar{p}$ and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial \bar{p}} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial \bar{p}} \left[\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} \right] = 0 \tag{E.13}$$

E.2 Equilibrium outcome

Taking other policies as given, by setting $\bar{X}$ the national government soley influences RE deployment in states where the quantity caps are not binding. Given $\frac{\partial \bar{x}_r}{\partial p^M} = \frac{\partial x_r}{\partial p^M} = 0$, $r \in \mathcal{R}^{QQ}$ and substituting eq. (E.1a) we obtain:

$$\begin{aligned} & \frac{\partial B}{\partial X} - \sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} \left[\frac{\partial D_a}{\partial x_a} + p^M \right] = 0 \\ \iff & \frac{\partial B}{\partial X} - \sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} p^M - \sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} \frac{\partial D_a}{\partial x_a} = 0 \end{aligned}$$

Using eq. (E.6) and since $\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial p^M}{\partial \bar{X}} = 1$ we obtain:

$$p^M = \frac{\partial B}{\partial X} - \frac{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial D_a}{\partial x_a}}{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M}} \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i > \bar{X} \tag{E.14}$$

The ceiling price $\bar{p}$ is derived analogous to PQ-regulation:

$$\bar{p} = \frac{\partial B}{\partial X} - \frac{\sum_{a\in\mathcal{A}^{PQ}} \frac{\partial x_a}{\partial \bar{p}} \frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{PQ}} \frac{\partial x_a}{\partial \bar{p}}} \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i \leq \bar{X} \tag{E.15}$$

For the case that $p^M = \frac{\partial C_a}{\partial x_a}$ and $x_a < \bar{x_a}$, $a \in \mathcal{A}^{QQ}$ it is recalled that changing $\bar{x_a}$ does not change actual RE deployment x_a such that $\frac{\partial p^M}{\partial x_a} = 0$. Inserting this into eq. (E.7) and using eq. (E.15) in (E.8) defines the equilibrium choice of $\bar{x_a}$ for the case that $x_a < \bar{x_a}$:

$$-\frac{\partial D_a}{\partial x_a}\bigg|_{x_a=\bar{x_a}} = 0 \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i > \bar{X} \tag{E.16}$$

$$(\eta_a - \gamma_a)\frac{\partial B}{\partial X} - \frac{\partial D_a}{\partial x_a}\bigg|_{x_a=\bar{x_a}} - \gamma_a \frac{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial \bar{p}} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial \bar{p}}} = 0 \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i \leq \bar{X} \tag{E.17}$$

For the case that $p^M \geq \frac{\partial C_r}{\partial x_r}$ and $x_r = \bar{x_r}$, $r \in \mathcal{R}^{QQ}$ it is recalled that changing $\bar{x_r}$ translates into an one-by-one change in actual RE deployment $\frac{\partial x_r}{\partial \bar{x_r}} = 1$ and that $\frac{\partial p^M}{\partial x_r} < 0$. Inserting eq. (E.14) into (E.7) and (E.15) into (E.8) defines the equilibrium choice of $\bar{x_r}$ for the case that $x_r < \bar{x_r}$:

$$\frac{\partial B}{\partial X} - \frac{\partial D_r}{\partial x_r} - \frac{\partial C_r}{\partial x_r} - \frac{\sum_{\hat{a}\in\mathcal{A}^{QQ}} \frac{\partial x_{\hat{a}}}{\partial p^M} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{QQ}} \frac{\partial x_{\hat{a}}}{\partial p^M}} + \frac{\partial p^M}{\partial x_r}(x_r - \gamma_r \bar{X}) = 0 \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i > \bar{X} \tag{E.18}$$

$$(1 + \eta_r - \gamma_r)\frac{\partial B}{\partial X} - \frac{\partial D_r}{\partial x_r} - \frac{\partial C_r}{\partial x_r} - (1 - \gamma_r)\frac{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial \bar{p}} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial \bar{p}}} = 0 \quad \text{if} \quad \sum_{i=1}^{n} \bar{x}_i \leq \bar{X} \tag{E.19}$$

In the equilibrium where $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$ RE deployment follows from inserting eq. (E.14) into eq. (E.1a) and from (E.18):

$$\frac{\partial B}{\partial X} - \frac{\sum_{\hat{a}\in\mathcal{A}^{QQ}} \frac{\partial x_{\hat{a}}}{\partial p^M} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{QQ}} \frac{\partial x_{\hat{a}}}{\partial p^M}} - \frac{\partial C_a}{\partial x_a} = 0 \qquad a \in \mathcal{A}^{QQ} \tag{E.20}$$

$$\frac{\partial B}{\partial X} - \frac{\partial D_r}{\partial x_r} - \frac{\partial C_r}{\partial x_r} - \frac{\sum_{a\in\mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M}} + \frac{\partial p^M}{\partial x_r}(x_r - \gamma_r \bar{X}) = 0 \qquad r \in \mathcal{R}^{QQ} \tag{E.21}$$

In the equilibrium where $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$ RE deployment is identical to under PQ-regulation:

$$\frac{\partial B}{\partial X} - \frac{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial \bar{p}} \frac{\partial D_{\hat{a}}}{\partial x_{\hat{a}}}}{\sum_{\hat{a}\in\mathcal{A}^{PQ}} \frac{\partial x_{\hat{a}}}{\partial \bar{p}}} - \frac{\partial C_a}{\partial x_a} = 0 \qquad a \in \mathcal{A}^{PQ} \tag{E.22}$$

$$(1 + \eta_r - \gamma_r)\frac{\partial B}{\partial X} - \frac{\partial D_r}{\partial x_r} - \frac{\partial C_r}{\partial x_r} - (1 - \gamma_r)\frac{\sum_{a\in\mathcal{A}^{PQ}} \frac{\partial x_a}{\partial \bar{p}} \frac{\partial D_a}{\partial x_a}}{\sum_{a\in\mathcal{A}^{PQ}} \frac{\partial x_a}{\partial \bar{p}}} = 0 \qquad r \in \mathcal{R}^{PQ} \tag{E.23}$$

Following eq. (E.20) to (E.23) there can be two Nash equilibria: first, one where $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$, and second, one where $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$.

E.3 Proof of Proposition 4

In a *type-D* nation where $\forall i : \frac{\partial D_i}{\partial x_i} > 0$ there is no market clearing equilibrium with $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$ and $\sum_{i=1}^{n} x_i = \bar{X}$. The proof is by contradiction:

Given $\forall i : \frac{\partial D_i}{\partial x_i} > 0$ if $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$ and $\sum_{i=1}^{n} x_i = \bar{X}$ by eq. (E.16) there are no *ambitious* states such that $\bar{x_a} > x_a$. If there are no states where $\bar{x_a} > x_a$, then $\sum_{i=1}^{n} \bar{x}_i$ cannot exceed $\bar{X} = \sum_{i=1}^{n} x_i$.

Q.E.D.

In a price taking equilibrium there may be some states enacting ambitious policies. For this equilibrium it is possible that $\sum_{i=1}^{n} \bar{x}_i \geq \bar{X} > \sum_{i=1}^{n} x_i$ or that $\bar{X} \geq \sum_{i=1}^{n} \bar{x}_i > \sum_{i=1}^{n} x_i$. In the former equilibrium the ceiling price is binding because the national government chooses a low level. In the latter equilibrium the ceiling price is binding because there is no competition in the tenders.

E.4 Adjusted burden shares under QQ-regulation

In the *market clearing equilibrium* efficient burden shares for restrictive states are lower than their RE deployment share of nationwide optimal RE deloyment $\gamma_r < \frac{x_r^*}{X^*}$. This follows from inserting eq. (6) into eq. (E.21):

$$\frac{\partial p^M}{\partial x_r}(x_r^* - \gamma_r X^*) = \frac{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial D_a}{\partial x_a}}{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M}} \qquad r \in \mathcal{R}^{QQ}$$

$$\iff \quad \gamma_r = \frac{x_r^*}{X^*} - \frac{1}{\frac{\partial p^M}{\partial x_r} X^*} \frac{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M} \frac{\partial D_a}{\partial x_a}}{\sum_{a \in \mathcal{A}^{QQ}} \frac{\partial x_a}{\partial p^M}} \qquad r \in \mathcal{R}^{QQ} \tag{E.24}$$

Marginal regional costs in ambitious states are negative (see Appendix E.1.1) and thereby the second term in eq. (E.24) is positive. Analogous to PQ-regulation these adjusted burden shares are efficient, only if all ambitious states have identical disamenity functions (see Appendix D.4).

In the *fixed price equilibrium* efficient burden shares for restrictive states are likely higher than their population share $\gamma_r > \eta_i$. This follows from inserting eq. (6) into eq. (E.23). See Appendix D.4.

E.5 Comparison of burden share bias under QP- and QQ-regulation

For the case that $x_r = \bar{x_r}$ the *burden share bias* is stronger under QQ-regulation than under QP-regulation. This follows from comparing eq. (C.5) and (E.5):

$$-\frac{1}{\sum_{j\neq i}\frac{1}{\frac{\partial^2 C_j}{\partial x_j^2}}} > -\frac{1}{\sum_{a\in\mathcal{A}^{-i}}\frac{1}{\frac{\partial^2 C_a}{\partial x_a^2}}} \qquad \forall i \tag{E.25}$$

$$\text{with} \quad \mathcal{A}^{-i} = \mathcal{A}\setminus\{i\}$$

Under QQ-regulation $\frac{\partial p^M}{\partial x_r}$ is in absolute terms always larger than under QP-regulation. Thus, states with higher (lower) burden shares have stronger strategic incentives to increase (decrease) their quantity cap under QQ-regulation compared to QP-regulation.

E.6 Stability of the market clearing equilibrium under QQ-regulation

If $\sum_{i=1}^n \bar{x}_i = \bar{X} + \epsilon$, then for small enough ϵ by their choice of $\bar{x}_i$ states can decide whether $\sum_{i=1}^n \bar{x}_i$ is larger versus equal to or smaller than $\bar{X}$. When facing this choice state governments consider the jump in the national subsidy from p^M to $\bar{p}$ as soon as $\sum_{i=1}^n \bar{x}_i$ falls below $\bar{X}$, or vice versa.

Let us denote by $\bar{x_i}^0$ the threshold such that $\bar{x_i}^0 = \bar{X} - \sum_{j\neq i}\bar{x}_j$ given the quantity caps of all other states. Also, in the *market clearing equilibrium* where $\sum_{i=1}^n \bar{x}_i > \bar{X}$ let us denote states' quantity caps by $\bar{x_i}^M$. By changing its quantity cap by $\triangle\bar{x}_i = \bar{x_i}^0 - \bar{x_i}^M = -\epsilon < 0$ state i can achieve that $\sum_{i=1}^n \bar{x}_i$ falls at $\bar{X}$. With this change in $\bar{x}_i$ at the same time the national subsidy level jumps from the clearing price to the ceiling price denoted by $\triangle p = \bar{p} - p^M > 0$. To define when state i prefers $\bar{x_i}^0$ over $\bar{x_i}^M$ we calculate the total differential of state welfare (eq. (4)) for changing the quantity cap by $\triangle\bar{x}_i$ at $\bar{x_i}^M$. For $\triangle\bar{x}_i \left.\frac{dW_i}{dx_i}\right|_{x_i=\bar{x_i}^M}$ we obtain:

$$\triangle\bar{x}_i\left(-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^M + \triangle p\right) + \triangle p(\bar{x_i}^M - \gamma_i\bar{X}) \lesseqgtr 0 \tag{E.26}$$

Note that by changing a state's quantity cap by $\triangle\bar{x}_i = -\epsilon$ nationwide RE deployment remains the same $\sum_{i=1}^{n} x_i = \bar{X}$. Since at $x_i = \bar{x}_i{}^M$ eq. (E.7) applies we can rewrite eq. (E.26) as:

$$\begin{aligned} &\triangle\bar{x}_i\triangle p - \triangle\bar{x}_i\frac{\partial p^M}{\partial x_i}(\bar{x}_i{}^M - \gamma_i\bar{X}) + \triangle p(\bar{x}_i{}^M - \gamma_i\bar{X}) \lesseqgtr 0 \\ \iff\quad &\triangle\bar{x}_i\triangle p + \left(\triangle p - \triangle\bar{x}_i\frac{\partial p^M}{\partial x_i}\right)(\bar{x}_i{}^M - \gamma_i\bar{X}) \lesseqgtr 0 \\ \iff\quad &\left(\triangle p - \triangle\bar{x}_i\frac{\partial p^M}{\partial x_i}\right)(\bar{x}_i{}^M - \gamma_i\bar{X}) \lesseqgtr -\triangle\bar{x}_i\triangle p \end{aligned} \tag{E.27}$$

The *rhs* of eq. (E.27) is positive, and it is larger the larger are the change in the quantity cap and the change in the national price level. The sign and magnitude of the *lhs* of eq. (E.27) depends on the equilibrium level of RE deployment $\bar{x}_i{}^M$, since the discrete jump from clearing price to ceiling price is at least as large as the hypothetical price change of the clearing price $\triangle p \geq \triangle\bar{x}_i\frac{\partial p^M}{\partial x_i}$. The *lhs* is positive if in equilibrium state i's share in nationwide RE deployment is above its burden share $\frac{\bar{x}_i{}^M}{\bar{X}} > \gamma_i$. Hence, the *lhs* of eq. (E.27) is increasing in $\bar{x}_i{}^M$.[45]

From eq. (E.27) follows that in the market clearing equilibrium (when $\sum_{i=1}^{n}\bar{x}_i > \bar{X}$) states with a high quantity cap $\bar{x}_i{}^M$ have an incentive to cut their quantity cap and jump to $\bar{x}_i{}^0$ if their share in nationwide RE deployment $\bar{x}_i{}^M$ is high enough to satisfy eq. (E.27). Graphically, the total differential of changing $\bar{x}_i$ by $\triangle\bar{x}_i$ is exemplarily depicted in Figure 2.

[Input: Figure 2]

The option for states with $\bar{x}_i{}^M >> \gamma_i\bar{X}$ to jump to a higher welfare level by cutting their quantity caps can destabilize the market clearing equilibrium under QQ-regulation, and may make the occurrence of a fixed price euilibrium more likely. States which have considerably higher RE deployment shares than their burden shares in the market clearing equilibrium $\frac{\bar{x}_i{}^M}{\bar{X}} >> \gamma_i$ may benefit by inducing a jump to the ceiling price because this generates a high additional inflow of national RE support (depicted by I in Figure 2) while additional financing costs of national RE support are small (depicted by III).

Analogously, a fixed price equilibrium can be destabilized by the option for states with $\bar{x}_i{}^F << \gamma_i\bar{X}$ to jump to a higher welfare level by expanding their quantity caps such that $\sum_{i=1}^{n}\bar{x}_i = \bar{X} + \epsilon$ and national RE support falls from $\bar{p}$ to p^M. Hence, both the market clearing equilibrium and the fixed price equilibrium are the more stable the closer states' RE deployment shares reflect their burden shares.

[45] Rearranging eq. (E.26) yields: $-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^M + \frac{\triangle p}{\triangle\bar{x}_i}(\bar{x}_i{}^M - \gamma_i\bar{X}) + \triangle p \lesseqgtr 0$. For $\triangle\bar{x}_i$, $\triangle p \longrightarrow 0$ eq. (E.27) converges to eq. (E.7). However, though $\triangle\bar{x}_i$ is assumed to be small, $\triangle p$ depicts a discrete jump in the national subsidy level. Therefore, $\left|\frac{\triangle p}{\triangle\bar{x}_i}\right|$ in eq. (E.27) is at least as large as $\left|\frac{\partial p}{\partial x_i}\right|$ in eq. (E.7).

Appendix F Stylized Two-States Example

F.1 Two-states example of a type-D nation

We calibrate a numerical example of a nation composed of two states that roughly resembles regional features of Germany. Splitting Germany in a Northern *state 1* and a Southern *state 2* we specify benefit and cost parameters as depicted in Table 4. We graphically present equilibrium outcomes for national policy and national welfare depending on the specification of states' burden shares γ_1 respectively $\gamma_2 = 1 - \gamma_1$.

[Input: Table 4]

PQ-Regulation: For this calibration we find that under PQ-regulation for all constellations with $\gamma_1 < 0.1$, in equilibrium the national government sets a price below the marginal nationwide benefit from emissions reductions, $p^N < 0.2$. Thereby national policy accounts for disamenities from RE deployment in state 1 (see Figure 3a). State 1 enacts ambitious policy resp. sets a non-binding quantity cap while state 2 enacts restrictive policy resp. sets a binding quantity cap. For $\gamma_1 \geq 0.1$ both states enact restrictive policies and the national government sets the national price equal to the marginal nationwide benefit from emissions reductions, $p^N = 0.2$. National welfare is maximized at $\gamma_1 = 0.6$ (see Figure 3b), namely, if the efficiency condition of Proposition 3 is satisfied, $\gamma_i = \eta_i \; \forall i$. For comparison, we also depict equilibrium outcomes under PP-regulation. Under PP-regulation the national price is increasing in γ_1, but national welfare is also maximized at $\gamma_1 = \eta_1$ (see Figure 3).

[Input: Figure 3]

QP-Regulation: We find that under QP-regulation for all constellations with $\gamma_1 \leq 0.712$ (indicated by the vertical gray dashed line), the national government sets a ceiling price that will bind in equilibrium (solid orange line in Figure 4a). As long as $\gamma_1 \leq 0.712$ setting a ceiling price is welfare enhancing in comparison to leaving the clearing price unconstrained (solid orange line lies above the dotted blue line in Figure 4b). This means that the national government de facto exerts price-based regulation. In turn, for all constellations with $\gamma_1 > 0.712$ the national government does not set a binding ceiling price (solid orange line in Figure 4a) because the clearing price implements a welfare superior allocation of RE deployment in comparison to setting a binding ceiling price (solid blue line lies above the dotted orange line in Figure 4b). Under QP-regulation national welfare is maximized in a market clearing equilibrium if $\gamma_1 = \frac{x_1^*}{X^*} = 0.864$. National welfare is maximized in a fixed price equilirbium if $\gamma_1 = \eta_1 = 0.6$.

[Input: Figure 4]

QQ-Regulation: Under QQ-regulation it follows from Proposition 4 that for a type-D nation the equilibrium outcome is identical to the equilibrium outcome under PQ-regulation.

F.2 Two-states example of a type-B nation

In comparison to the example above which depicts a type-D nation we change the disamenity function of *state 1* in order to illustrate an example of a type-B nation. We add a constant marginal regional benefit $\hat{d}_1$ in state 1 (see Table 5) in order to also incorporate positive regional effects of RE deployment (e.g. regional economies). All other parameters remain the same.

[Input: Table 5]

PQ-Regulation For this stylized type-B nation we find that under PQ-regulation for all constellations with $\gamma_1 < 0.625$ (right gray vertical dashed line), the national government sets a price above the marginal nationwide benefit from emissions reductions, $p^N = 0.213$ (according to eq. (21), see Figure 5a). State 1 enacts ambitious policy resp. sets a non-binding quantity cap, while state 2 enacts restrictive policy resp. sets a binding quantity cap. For $\gamma_1 \geq 0.625$ both states enact restrictive policies and the national government sets the national price equal to the marginal nationwide benefit from emissions reductions $p^N = 0.2$. National welfare is maximized at $\gamma_1 = 0.5625$ (see Figure 5b). This highlights that for adjusted burden shares (according to Appendix D.4) the social optimum can be implemented under PQ-regulation in a type-B nation. As mentioned before, this is only true for the particular case that all ambitious states are homogeneous in their disamenities. This applies to the stylized example at hand because there is only one ambitious state. In contrast, under PP-regulation the social optimum is implemented in equilibrium if $\gamma_i = \eta_i \; \forall i$ (cf. Proposition 1) is satisfied, here if $\gamma_1 = 0.6$.

[Input: Figure 5]

QQ-Regulation We find that under QQ-regulation for all constellations with $\gamma_1 \leq 0.705$ (gray vertical dashed line), the national government sets a ceiling price that binds in equilibrium (solid red line in Figure 6a). That is, a fixed price equilibrium ensues which is identical to the equilibrium outcome under PQ-regulation (cf. red lines in Figure 5 and 6). For $0 \leq \gamma_1 \leq 0.625$ the sum of states' quantity caps exceeds the national tender volume $\sum_{i=1}^{2} \bar{x}_i > \bar{X}$, but the national ceiling price is set to $p^N = 0.213$ such that in state 1 suppliers do not expand RE deployment to reach the quantity cap $x_1 < \bar{x}_1$ and therefore $\sum_{i=1}^{2} x_i < \bar{X}$. In turn, for $0.625 < \gamma_1 \leq 0.705$ suppliers do exploit the whole quantity cap in state 1 $x_1 = \bar{x}_1$ (and in state 2 as well), and the ceiling price is binding to avoid an infinitely high bidding price in tenders, because $\sum_{i=1}^{2} \bar{x}_i \leq \bar{X}$. For constellations with $\gamma_1 > 0.705$ the national government sets a ceiling price above the clearing price $p^M < \bar{p}$ such that a market clearing equilibrium ensues with $\sum_{i=1}^{2} \bar{x}_i > \bar{X}$ and $\sum_{i=1}^{2} x_i = \bar{X}$. The latter is socially optimal if $\gamma_1 = 0.967$, hence if the restrictive state 2 has a burden share such that $\gamma_2 < \frac{x_2^*}{X^*}$ (according to Appendix E.4). Note that state 2 enacts restrictive policies for all possible constellations of burden shares, whereas state 1 enacts ambitious policies both in the fixed price equilibrium for $0 \leq \gamma_1 \leq 0.625$ and in the market clearing equilibrium for $0.705 \leq \gamma_1 \leq 1$. For comparison, Figure 6 also shows equilibrium outcomes under QP-regulation (solid blue line). Here the social optimum is implemented in equilibrium, if $\gamma_1 = 0.910$, i.e. $\gamma_1 = \frac{x_1^*}{X^*}$

[Input: Figure 6]

Appendix G Simulation of First-best Wind Power Deployment in Germany

In Germany there are 16 states (*Bundesländer*), $i = 1, ..., 16$. For each state we calibrate the state-specific disamenity function $D_i(x_i)$ as well as the power production cost function $C_i(x_i)$. We assume quadratic cost and benefit functions.

We abstract from possible positive regional effects of wind power deployment and solely consider regional costs of wind power deployment, $D_i(x_i) \geq 0$ for $x_i \in [0, \infty)$. We assume $D_i(x_i)$ to be of the form:

$$D_i(x_i) = \frac{1}{2}\delta_i x_i^2 \tag{G.1}$$

We assume $C_i(x_i)$ to be of the form:

$$C_i(x_i) = \zeta_{1,i} x_i + \frac{1}{2}\zeta_{2,i} x_i^2 \tag{G.2}$$

x_i represents the total amount of electricity produced from wind power in state i in unit kWh. $\zeta_{1,i}$ has unit $\frac{€}{kWh}$ and $\zeta_{2,i}$ and δ_i have unit $\frac{€}{kWh^2}$.

To calibrate eq. (G.1) and (G.2), we use data from Tafarte and Lehmann (2019). They provide cost values for 106,497 potential wind turbine sites in Germany.[46] For each potential site they provide values on annual power production costs and annual disamenity costs for all surrounding respectively affected households. Based on this data, we estimate $\zeta_{1,i}$ and $\zeta_{2,i}$, and δ_i.[47] Table 6 presents the estimates.

[Input: Table 6]

Based on the estimated parameters in Table 6, we calculate states' first-best wind power deployment levels $\boldsymbol{x}^* = x_1^*, ..., x_{16}^*$ according to eq. (6). Hereto, we assume that the marginal nationwide benefit $\frac{\partial B}{\partial X}$ from substituting 1 kWh from fossil-based power production by 1 kWh

[46] The potential wind turbine sites satisfy the very minimum legal and technical requirements, e.g. minimum distances to settlements (following from immission control requirements, not from minimum distances choices by state governments), or areas technically unsuitable for the construction of wind turbines.

[47] Precisely, to estimate eq. (G.1) for each German state, we first sorted wind turbine sites in ascending order with respect to their annual disamenity costs (ADC). Second, we generated the cumulated sum of ADC for all wind turbine sites (such that for the first site ADC and cumulated ADC are identical and for the last site cumulated ADC are equal to the sum of ADC across all sites), and we generated the cumulated sum of annual electricity production (AEP). Third, we ran a linear regression of cumulated ADC on cumulated AEP to obtain estimates for δ_i, $i = 1, ..., 16$. To estimate eq. (G.2), we proceeded analogously with annual power production costs of wind turbine sites. We used the *lm*-command in R.

from wind power deployment is linearly decreasing in X. Implicitly, we thus assume that the most harmful fossil sources are replaced first (e.g. lignite). We use data on power production from 2019 in order to parameterize the nationwide benefit function $B(\cdot)$. In 2019, power production from fossil sources was equal to 241 TWh and power production from wind power was equal to 114 TWh (German Environment Agency, 2021).[48] We assume that power production from wind power replaces power production from fossil sources. Hence, we also assume that fossil-based power production would amount to 355 TWh (= 241 TWh + 114 TWh), if nationwide power production from wind power was equal to zero, i.e. $X = 0\ TWh$. On average, lignite plants list highest in CO_2 emission intensity of power production ($1,135\ gCO_2/kWh$) and gas plants record lowest ($409\ gCO_2/kWh$) (German Environment Agency, 2021, p. 16). The assumptions that emission intensity of substituted fossil power plants is linearly decreasing and that social cost of carbon (SCC) amount to 195 €$/tCO_2$ or equivalently 0.000195 €$/gCO_2$ (German Environment Agency, 2020, p. 26) are represented by the following equations:

$$B(0\ \text{TWh}) = 0\ \text{€}, \tag{G.3}$$

$$\left.\frac{\partial B}{\partial X}\right|_{X=0\ \text{TWh}} = 0.000195\ \text{€}/gCO_2 \times 1,135\ gCO_2/kWh, \tag{G.4}$$

$$\left.\frac{\partial B}{\partial X}\right|_{X=355\ \text{TWh}} = 0.000195\ \text{€}/gCO_2 \times 409\ gCO_2/kWh \tag{G.5}$$

We assume $B(X)$ to be of the form:

$$B = \beta_1\ X - \frac{1}{2}\beta_2\ X^2 \tag{G.6}$$

The parameter values result from eq. (G.3) to (G.6):

$$\beta_1 = 0.000195\ \text{€}/gCO_2 \times 1,135\ gCO_2/kWh = 0.22133\ \text{€}/kWh \tag{G.7}$$

$$\beta_2 = \frac{0.000195\ \text{€}/gCO_2 \times (1,135 - 409)\ gCO_2/kWh}{355 \times 10^9\ kWh} = 3.988 \times 10^{-13}\ \text{€}/kWh^2 \tag{G.8}$$

Simulating first-best wind power deployment for Germany gives the nationwide socially optimal wind power production of $X^* = 318.715\ TWh$.[49] This corresponds to a marginal benefit of

[48] Lignite power plants produced 103 TWh, hard coal power plants produced 52 TWh, gas power plants produced 82 TWh, and oil-fired power plants produced 4 TWh (German Environment Agency, 2021, p. 28).

[49] Though our estimate for a socially optimal amount of wind power production is based on a coarse approximation, recent studies expect future onshore wind power deployment to range from 204 TWh in 2030 to 413 TWh in 2050 (Fraunhofer ISI, 2021).

$\frac{\partial B}{\partial X}\big|_{X=X^*} = 0.094$ €$/kWh$. Of course, the level of SCC is uncertain and possibly different from 195 €$/tCO_2$. However, the relative distribution of wind power deployment across German states, as presented in Table 6, remains nearly similar for other levels of SCC.

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Tables

Table 1 ***Overview of Regulatory Designs***

State level \ National level	**price**-based (e.g. FiT)	**quantity**-based (i.e. tenders)
price-based (e.g. levies, taxes, subsidies)	***PP-regulation*** p^N & p_i^S 4.1.1	***QP-regulation*** $\bar{X}, \bar{p}$ & $\bar{x}_i$ 4.1.2
quantity-based (i.e. spatial planning)	***PQ-regulation*** p^N & p_i^S 4.2.1	***QQ-regulation*** $\bar{X}, \bar{p}$ & $\bar{x}_i$ 4.2.2

Table 2 ***Overview of Efficiency Conditions***

<table>
<tr><th>State level \ National level</th><th>price-based
(e.g. FiT)</th><th>quantity-based
(i.e. tenders)</th></tr>
<tr><td>price-based
(e.g. levies, taxes, subsidies)</td><td>$\gamma_i^* = \eta_i$</td><td>$\gamma_i^* = \frac{x_i^*}{X^*}$</td></tr>
<tr><td>quantity-based
(i.e. spatial planning)</td><td colspan="2">for type-B nations:
social optimum not attainable[50]

for type-D nations:
$\gamma_i^* = \eta_i$</td></tr>
</table>

Table 3 ***Burden Sharing among German States***

State	Actual Population Share η	Actual Burden Share γ	Simulated First-Best Deployment Share $\frac{x^*}{X^*}$
BW	0.1333	0.1430	0.0094
BY	0.1575	0.1588	0.0224
BE	0.0439	0.0245	0.0000
BB	0.0303	0.0310	0.2138
HB	0.0082	0.0091	0.0000
HH	0.0222	0.0229	0.0000
HE	0.0755	0.0750	0.0303
MWP	0.0194	0.0145	0.2868
NN	0.0962	0.1035	0.1617
NRW	0.2160	0.2230	0.0061
RP	0.0492	0.0532	0.0119
SL	0.0119	0.0171	0.0001
SN	0.0491	0.0433	0.0344
ST	0.0266	0.0310	0.1483
SH	0.0349	0.0241	0.0364
TH	0.0258	0.0261	0.0382

Notes: *Actual burden shares of German states report the share of national support payments for wind power financed by each state. Simulated first-best deployment shares report the share of the amount of electricity produced from wind power in each state. Data on actual burden shares was taken from the latest published report of the German Association of Energy and Water Industries (2017). First-best deployment shares of wind power deployment were simulated with data by Tafarte and Lehmann (2019). The simulation only includes benefits from emissions reductions, power production costs and regional costs of wind turbines, but does not include potential positive regional effects. For more details see Appendix G.*

Table 4 ***Parameters of Numerical Calibration***

Benefits/Costs	Model notation	Calibration
burden shares	γ_1, γ_2	$\gamma_1, \gamma_2 \in [0,1]$ and $\gamma_2 = 1 - \gamma_1$
population shares	η_1, η_2	0.6, 0.4
nationwide benefits from emissions reduction	$\frac{\partial B}{\partial X} = b\ X$	$b = 0.2$ €$/kWh^2$
disamenities from RE deployment in state 1	$\frac{\partial D_1}{\partial x_1} = d_1\ x_1$	$d_1 = 2 \times 10^{-13}$ €$/kWh^2$
disamenities from RE deployment in state 2	$\frac{\partial D_2}{\partial x_2} = d_2\ x_2$	$d_2 = 3 \times 10^{-12}$ €$/kWh^2$
RE deployment costs in state 1	$\frac{\partial C_1}{\partial x_1} = c_1\ x_1$	$c_1 = 4 \times 10^{-13}$ €$/kWh^2$
RE deployment costs in state 2	$\frac{\partial C_2}{\partial x_2} = c_2\ x_2$	$c_2 = 8 \times 10^{-13}$ €$/kWh^2$

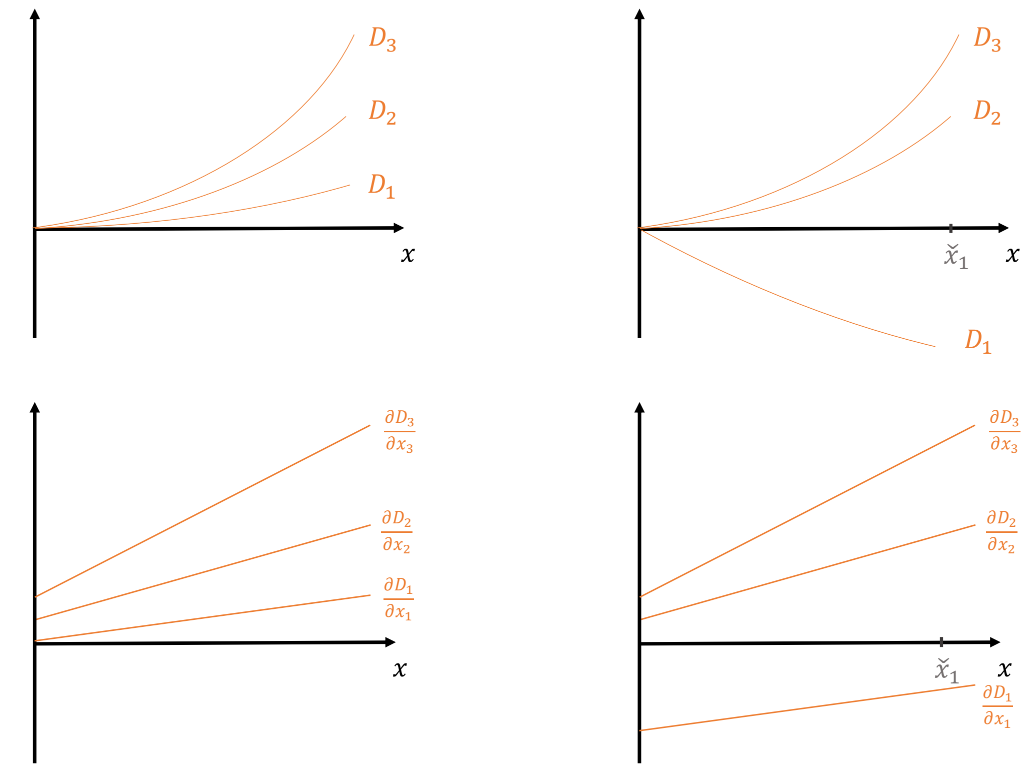
Table 5 ***Parameters of Numerical Calibration – Type-B nation***

Benefit/Costs	Model notation	Calibration
disamenities from RE deployment in state 1	$\frac{\partial D_1}{\partial x_1} = \hat{d}_1 + d_1\ x_1$	$\hat{d}_1 = -0.12$ €$/kWh,\ d_1 = 2 \times 10^{-13}$ €$/kWh^2$

Table 6 ***Estimated Cost Parameters and Simulated First-Best Deployment Levels***

State	**Regional Costs** δ_i	**Power Production Costs** $\zeta_{1,i}$	$\zeta_{2,i}$	**First-Best** x_i^* (in TWh)
Baden-Wuerttemberg	4.47×10^{-12}	9.24×10^{-13}	0.062	2.99
Bavaria	2.29×10^{-12}	6.67×10^{-13}	0.052	7.141
Berlin	5.14×10^{-8}	3.86×10^{-10}	0.06	0
Brandenburg	2.19×10^{-13}	1.35×10^{-13}	0.046	68.154
Bremen	7.86×10^{-9}	1.32×10^{-11}	0.051	0
Hamburg	5.53×10^{-8}	0	0.057	0
Hesse	2.02×10^{-12}	4.79×10^{-13}	0.046	9.649
Mecklenburg-Vorpommern	2.15×10^{-13}	7.09×10^{-14}	0.042	91.413
Lower Saxony	4.20×10^{-13}	1.06×10^{-13}	0.04	51.523
North Rhine-Westfalia	1.05×10^{-11}	7.66×10^{-13}	0.05	1.956
Rhineland-Palatinate	4.68×10^{-12}	1.26×10^{-12}	0.049	3.808
Saarland	3.28×10^{-10}	2.41×10^{-11}	0.068	0.037
Saxony	1.98×10^{-12}	5.76×10^{-13}	0.038	10.979
Saxony-Anhalt	3.94×10^{-13}	8.45×10^{-14}	0.049	47.281
Schleswig-Holstein	1.96×10^{-12}	3.38×10^{-13}	0.041	11.601
Thuringia	1.59×10^{-12}	3.94×10^{-13}	0.046	12.181

Figures



(a) Type-D nation

(b) Type-B nation

Figure 1: *Illustrative examples for type-D and type-B nations each with three states.*

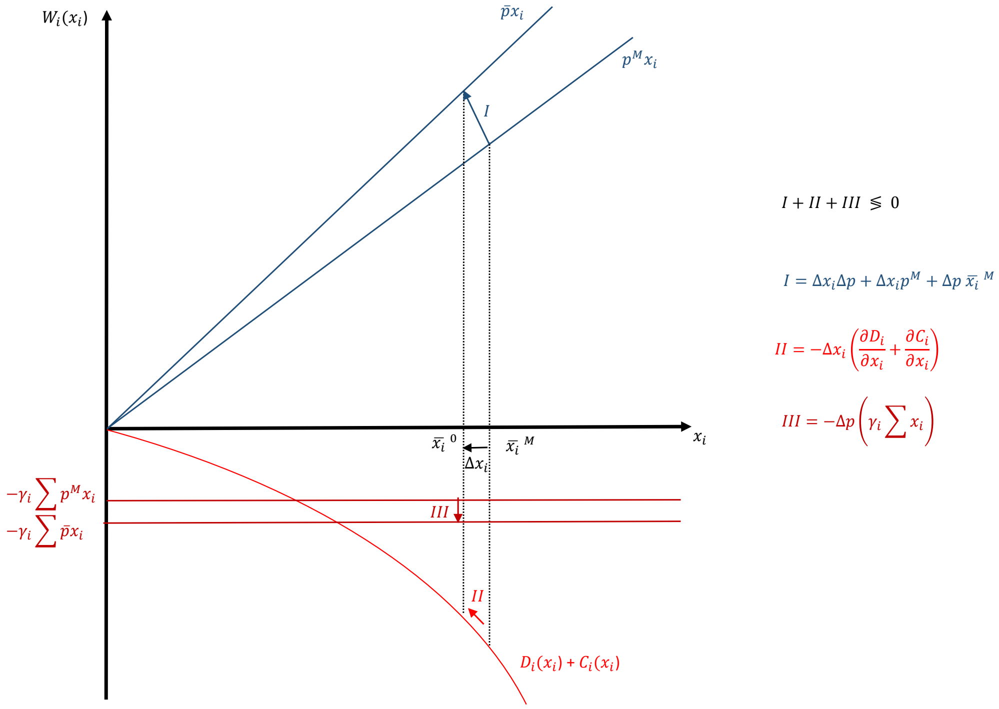
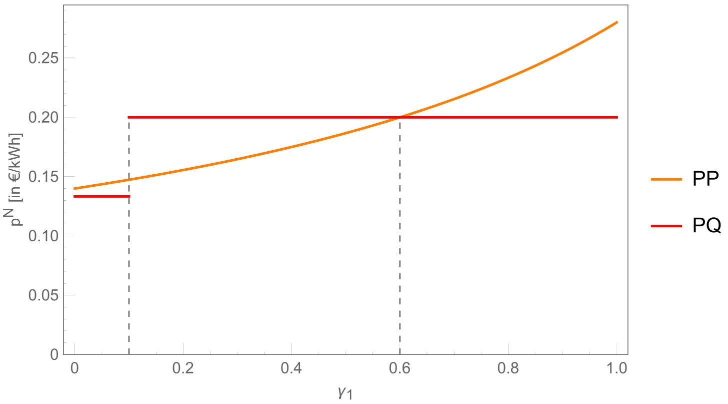
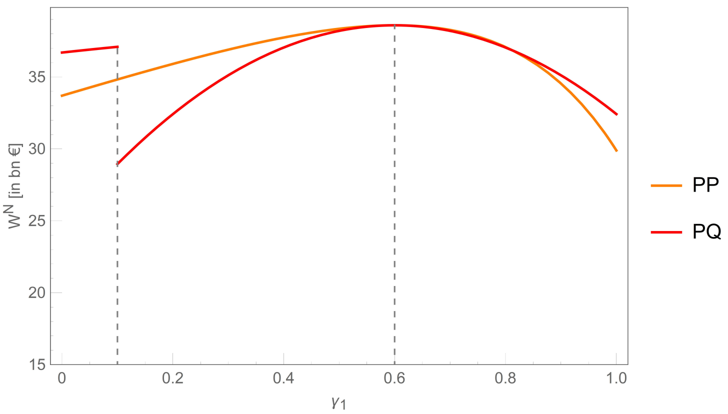


Figure 2: *Total Differential*

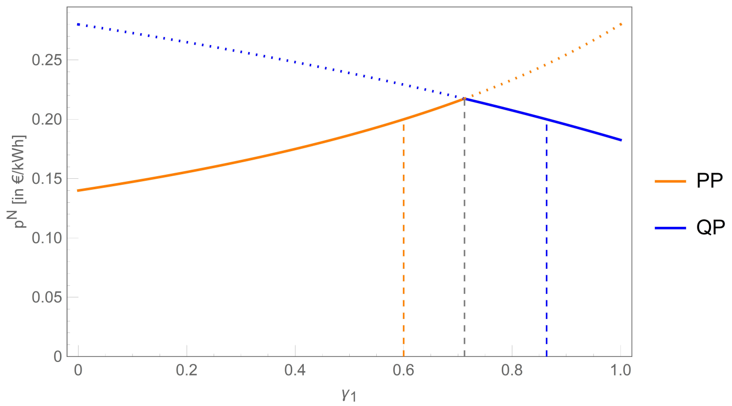


(a) National Price as a function of State 1's Burden Share

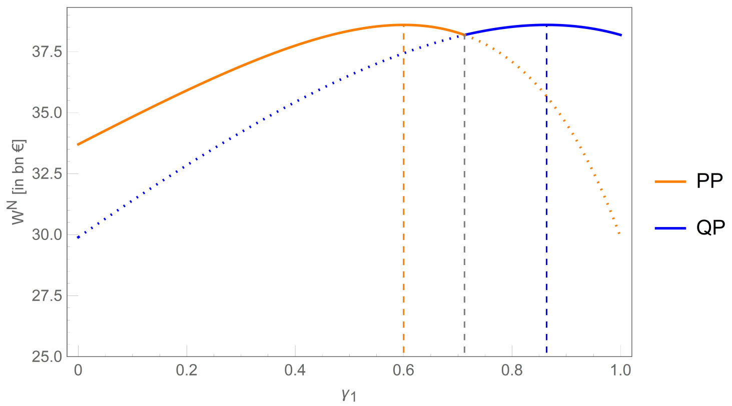


(b) National Welfare as a function of State 1's Burden Share

Figure 3: *Equilibrium Outcomes under PP- and PQ-regulation in a Type-D nation*

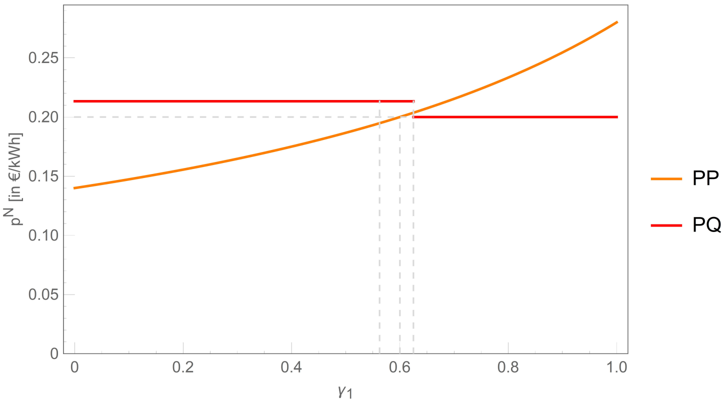


(a) National Price as a function of State 1's Burden Share

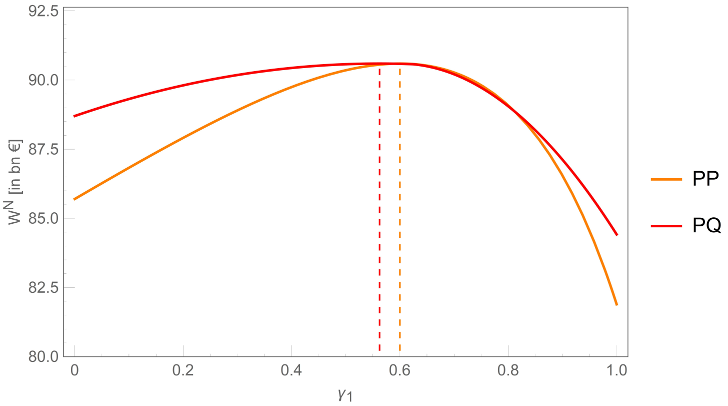


(b) National Welfare as a function of State 1's Burden Share

Figure 4: *Equilibrium Outcomes under PP- and QP-regulation in a Type-D nation*

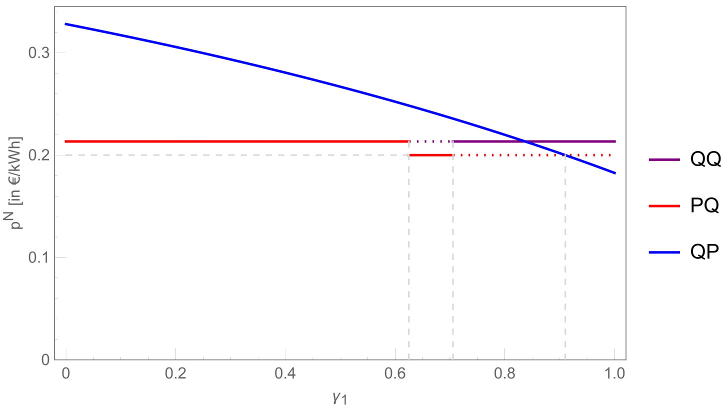


(a) National Price as a function of State 1's Burden Share

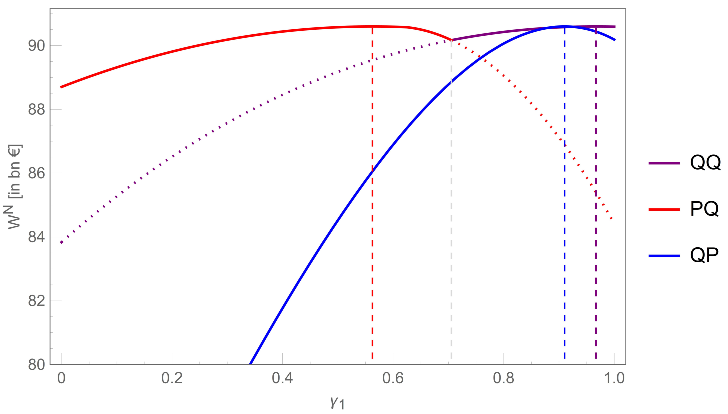


(b) National Welfare as a function of State 1's Burden Share

Figure 5: *Equilibrium Outcomes under PP- and PQ-regulation in a Type-B nation*



(a) National Price as a function of State 1's Burden Share



(b) National Welfare as a function of State 1's Burden Share

Figure 6: *Equilibrium Outcomes under PQ-, QP- and QQ-regulation in a Type-B nation*