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Optimal federal co-regulation of renewable energy deployment

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Abstract

In federal countries the allocation of renewable energy (RE) deployment is simultaneously regulated by national and subnational governments. We analyze the efficiency of federal co-regulation when different types of policy instruments – price and quantity – are assigned to government levels. Using an analytical model with two regulatory levels, we specify conditions that ensure first-best allocation of RE deployment in equilibrium. These efficiency conditions refer to how the financial burden of the national RE support scheme should be shared among subnational jurisdictions. Under realistic assumptions national price-based regulation is efficient if burden shares are proportional to population shares, regardless of the subnational policy instrument. Contrary, under national quantity-based regulation efficiency conditions depend on the subnational policy instrument. 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.

Keywords: multi-level governance, environmental regulation, renewable energies, tender scheme, feed-in tariff, spatial planning
JEL classification: H23, H77, Q48

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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 vast expansion of large-scale renewable energy (RE) plants. To this end, national governments support RE deployment through price incentives implemented via feed-in tariffs (FiT) or 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 municipality 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 expansion, 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 overall efficiency of RE deployment.

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 incentives 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 external cost of large-scale RE plants. These regional externalities are disamenities, like impacts on residents and ecosystems on site (Zerrahn, 2017; Krekel & Zerrahn, 2017; von Möllendorff & Welsch, 2017; Gibbons, 2015). Consequently, subnational governments may have an incentive to underprovide promotion of RE deployment, i.e., to over-restrict 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 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 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 regulators may lead to an inefficient nationwide allocation of RE deployment. Hence, under federal RE regulation there is need for a regulatory design that provides efficient coordination among national and subnational RE policies in the presence of these strategic incentives.[1]

[1]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,

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

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, simultaneously 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 EU state aid law or national laws ensuring equal treatment of subnational 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 layer

(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 layer

(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 refer to how the national subsidy costs should be distributed among subnational jurisdictions (burden shares). With respect to the national layer, we find that national price-based regulation implements efficient RE deployment if burden shares are proportional to population shares regardless of the policy instrument assigned to the subnational layer. In contrast, the assignment of subnational policy instruments is decisive given national quantity-based regulation. 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

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.

quantity-based regulation burden shares should be oriented towards population shares. These findings apply under the realistic assumption that regional disamenities outweigh any possible regional benefits from RE deployment.

Our work contributes to the branch of environmental and fiscal federalism that looks into strategic interaction among governments of different federal layers (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 externalities (private good or egoistic component) (Caplan & Silva, 2011; Meya & Neetzow, 2019). 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 (Silva & Caplan, 1997) and (Caplan & Silva, 1999) analyze the optimal assignment of price and quantity instruments to different governmental layers within a sequential move setting. The authors do not find a strictly superior assignment of instruments to government levels (regulatory design), 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").[2] In (Silva & Caplan, 1997) and (Caplan & Silva, 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. By contrast, in our model, income transfers are exogenously specified in the form of burden shares and we employ the concept of Nash equilibrium in a simultaneous move game since this more adequately represents mutually responding policy adjustments of national and subnational governments. Thereby, we do not highlight one single regulatory design as superior, but specify rules for interregional income transfers which implement efficient co-regulation for each regulatory design.

(Ambec & 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 applies equally whether local regulators use taxes or abatement quotas. Unlike (Ambec & Coria, 2018), we explicitly include an exogenous transfer mechanism which allocates national subsidy costs to subnational juris-

[2] In a similar manner, (Caplan et al., 2000) and (Caplan & Silva, 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.

dictions. 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. (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 assigned to 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 outcome. 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 financing schemes that are commonly in place. 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 & Neetzow, 2019) 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. 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 assigned to the national and state layer – a state's burden share must be equal to its share of marginal benefits from nationwide RE expansion. In contrast, given a national tender scheme states' burden shares must be equal to their shares of first-best nationwide RE expansion (Meya & Neetzow, 2019). We confirm their results within our model which in addition to positive also incorporates negative regional externalities of RE deployment. Most importantly, unlike (Meya & Neetzow, 2019), we allow for a quantity instrument at the subnational layer (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 disamenities from RE deployment predominate over 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 expansion in a nation with a two-level federal system. The nation is composed of n states. A national government exerts nationwide RE policy that is uniformly effective in all states. State governments exert RE policies that are only effective within their respective jurisdictions.

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 electricity produced from RE. 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 national and state policies. In the second stage, after equilibrium policies are implemented, suppliers choose RE deployment. The amount of electricity produced from RE capacities installed in state i is denoted 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, installing and operating RE capacities for power production generates costs for suppliers. Power production costs of generating a certain amount of electricity x_i from RE in state i are denoted by $C_i(x_i)$. Due to geographical characteristics, e.g. wind speed or solar irradiation, productivity of RE plants depends on their location, and consequently power production costs differ across states, $C_j(\cdot) \neq C_i(\cdot)$, $\forall j \neq i$. Within a state, power production 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 (as in Lancker & Quaas, 2019).

Second, since RE plants substitute fossil-fuel based power plants they reduce GHG emissions. These nationwide external benefits from emissions reductions are captured by $B(\cdot)$. Benefits from emissions reductions are the same for residents nationwide.[3] We assume that $B(\cdot)$ depends

[3] We think this simplification is tenable since our analysis aims at explaining subnational policy choices in

on the amount of electricity produced from RE plants installed nationwide, $X \equiv \sum_{i=1}^{n} x_i$, and $\frac{\partial B}{\partial X} > 0$, $\frac{\partial^2 B}{\partial X^2} < 0$.

Third, using RE causes regional external costs to residents living in the same state, denoted by $D_i(\cdot)$. State-specific externalities mainly comprise regional disamenities from RE deployment, like noise or visual impacts through wind power plants (i.a. Zerrahn, 2017). We assume regional disamenities to depend on the amount of electricity produced from RE plants installed in a state, x_i. This is a reasonable assumption as increasing electricity generation requires more capacity and more (and larger) RE plants which cause regional disamenities. There may also be regional external benefits from RE deployment, $D_i(\cdot) < 0$ and $\frac{\partial D_i}{\partial x_i} < 0$, e.g. positive effects on regional GDP and employment. However, since these regional external benefits are relatively small (i.a. Többen, 2017; Ejdemo & Söderholm, 2015; Mauritzen, 2020) we assume that as regional RE expansion increases at some point regional external cost prevail. Formally, we consider $D_i(\cdot)$ to be convex $\frac{\partial^2 D_i}{\partial x_i^2} > 0$ such that $\lim_{x_i \to \infty} D_i(x_i) > 0$ and $\lim_{x_i \to \infty} \frac{\partial D_i}{\partial x_i} > 0$, $\forall i$.

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 expansion, while state governments consider their respective state-specific costs and benefits. Each government cares about the sum of utilities of its citizens and about the profit of its regional supplier, since we assume that each supplier is owned by citizens of the state in which the supplier operates. In other words, governments seek to maximize their corresponding welfare.

National Government

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

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

The first term in (1) 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 (1) comprises all state-specific costs of nationwide RE deployment. For each state, state-specific costs consist of regional external costs 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 the external benefit, 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. With price-based regulation the national government administratively determines the level of p^N. With quantity-based

the presence of national and regional externalities. 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).

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.[4]

State Governments

The welfare function of state i's government is given by:

$$\mathscr{W}_i(x_i, \boldsymbol{x_{-i}}, p^N) = \eta_i B(X) - D_i(x_i) - C_i(x_i) + p^N x_i - \gamma_i \sum_{i=1}^{n} p^N x_i \qquad \forall i \tag{2}$$

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 external costs and benefits, $\eta_i B(X) - D_i(x_i)$. States do not per se internalize benefits for other states arising from RE deployment in their own jurisdiction, but fully take into account the regional external costs. 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. $\sum_{i=1}^{n} \gamma_i \equiv 1$. 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.

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 or, in contrast, state-level price incentives can promote regional RE deployment, e.g., through tax exemptions. Thereby, state governments can reduce (increase) regional RE deployment, e.g., in order to avert (raise) regional disamenities (benefits).

[4]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 (1) 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 (1) is unchanged regardless of the policy instrument applied at the national tier.

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 externalities.

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 layer.[5] 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 single supplier decides on the amount of state-specific power production, x_i. Every supplier chooses the regional RE expansion level x_i in order to maximize its profit. The profit function of the supplier in state i is defined as follows:

$$\pi_i(x_i, p^N) = (p^N + p_i^S)x_i - C_i(x_i) \qquad \forall i \tag{3}$$

The first term in (3) 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 reduces 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.[6]

3 Social Optimum and Policy Constraints

Before analyzing the outcomes of different federal 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.

[5]Formalizing state-specific price incentives as neutral to state welfare implies that we refer to explicit price 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 layer, subnational price incentives are solely applied in few countries (Iglesias et al., 2011; Lienhoop, 2018; Jørgensen et al., 2020).

[6]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. (1) w.r.t. x_i and setting the result equal to zero:

$$\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} = 0 \qquad \forall i \tag{4}$$

By eq. (4), the socially optimal RE expansion level for state i increases with the marginal nationwide benefit of emissions reduction. It falls with the marginal state-specific external cost of RE deployment and the marginal state-specific power production cost of RE deployment.

The social optimum is characterized such that for neither state there is an additional net benefit from 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 (4). To see that, we first define each supplier's deployment decision by differentiating the supplier's profit function (3) w.r.t. x_i:

$$p_i^N = \frac{\partial C_i}{\partial x_i} \qquad \forall i \tag{5}$$

Eq. (5) implicitly defines the supplier's choice for RE deployment in state i. Substituting (5) into (4) defines state-specific remuneration levels that implement the social optimum:

$$p_i^N = \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} \qquad \forall i \tag{6}$$

If eq. (6) is satisfied across all states, suppliers would incorporate nationwide and regional externalities 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 layer, 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 layers of government (federal structure), and a limitation to uniform regulation policies at the national layer (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 assigned to the national and state layer. For each governmental layer we include two possible policy instruments – a price-based instrument and a quantity-based instrument. Table 1 illustrates the composition of the four regulatory designs that are subsequently analyzed. Each regulatory design is composed of a mix of policy instruments across the two federal layers. We label the regulatory designs by abbreviations, e.g. *Price & Quantity*. The first term covers the policy instrument assigned to the national layer, and the second term covers the policy instrument assigned to the state layer.

Table 1 *Regulatory Designs*

National level / State level	price-based instruments (e.g. FiT)	quantity-based instruments (tenders)
price-based instruments (e.g. levies, taxes, subsidies)	*Price & Price* (I)	*Quantity & Price* (III)
quantity-based instruments (spatial planning)	*Price & Quantity* (II)	*Quantity & Quantity* (IV)

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. (4)). We derive the equilibrium outcome 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.

4.1 National Price-Based Regulation

First, we study the two regulatory designs where the national government administratively determines a uniform price level of RE remuneration (I and II).

4.1.1 Regulatory Design I: *Price & Price*

We start with the regulatory design where states implement a price incentive in addition to the national price-based RE support scheme (*Price & Price* regulation). In the first stage of the game, governments at both federal layers simultaneously choose their policy decisions. 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 its nationwide feed-in tariff, p^N. Once all governments have set their policies, in the second stage suppliers decide on RE deployment, $\boldsymbol{x} = (x_1, ..., x_n)$, by maximizing their profits in the context of this regulatory environment.

Following backward induction, in the second stage of the game we define suppliers' RE deployment decisions by differentiating their profit function eq. (3) w.r.t. x_i. It follows that in equilibrium in each state suppliers expand RE satisfying:

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

In each state suppliers expand RE deployment until their marginal power production costs equate the effective net subsidy level.

In the first stage of the game all governments anticipate effects of their own and effects of co-regulating governments according to eq. (7). In Nash equilibrium, each government takes the policy decisions of all other governments as given. We first look at policy decisions at the state layer. State governments take the national policy p^N as given when setting their optimal policies. Using eq. (7), we derive state i's best policy response to p^N by differentiating state i's welfare function eq. (2) w.r.t. p_i^S and setting the result equal to zero, $\frac{\partial \mathscr{W}_i}{\partial p_i^S} = 0$:

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1-\gamma_i)p^N = 0 \qquad \forall i \tag{8}$$

According to eq. (8) each state government only takes into account marginal external benefits and costs that concern its own residents, $\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i}$. Furthermore, each state considers net national subsidies flowing into its own jurisdiction for an additional unit of RE-based electricity produced on site, $(1-\gamma_i)p^N - \frac{\partial C_i}{\partial x_i}$. The latter is composed of marginal net profit of the regional supplier less marginal financing costs of national RE support. To obtain each state's best response policy dependent on the national support level, substitute eq. (7) into eq. (8):

$$p_i^S = \eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \gamma_i p^N \qquad \forall i \tag{9}$$

For the sake of argument, consider for a moment the case without national RE support ($p^N = 0$), which depicts the case of decentralized state-level RE regulation. For this case, eq. (9) tells us that state governments tax regional RE deployment ($p_i^S < 0$), if marginal regional benefits from nationwide RE expansion are smaller than marginal regional external costs, $\eta_i \frac{\partial B}{\partial X} < \frac{\partial D_i}{\partial x_i}$. States subsidize regional RE expansion ($p_i^S > 0$) if in equilibrium $\eta_i \frac{\partial B}{\partial X} > \frac{\partial D_i}{\partial x_i}$.

Now, if the national government promotes RE deployment through prices ($p^N > 0$), the price incentive that a state chooses falls with the national support level, $\frac{\partial p_i^S}{\partial p^N} < 0$, and it also falls with the state's burden share of national subsidy costs, $\frac{\partial p_i^S}{\partial \gamma_i} < 0$. The former originates in the concavity of the state's welfare function meaning that the sum of marginal state-specific costs $\left(\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i}\right)$ rises with the expansion of RE plants. The latter is intuitive as a state has to finance itself an increasing part of the monetary benefit that it is receiving through the national RE support scheme.

For the national government, we derive the equilibrium policy by differentiating the national welfare function eq. (1) w.r.t. p^N, inserting eq. (8) and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial p^N} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \left[(1-\eta_i)\frac{\partial B}{\partial X} - (1-\gamma_i)p^N \right] = 0 \tag{10}$$

Rearranging for p^N yields:

$$p^N = \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}(1-\eta_i)}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}(1-\gamma_i)} \frac{\partial B}{\partial X} \tag{11}$$

As we already know, state governments internalize both private power production costs and external costs occurring within their jurisdictions (see eq. (8)). That is why the national government merely needs to bother about the interregional spillover, $(1-\eta_i)\frac{\partial B}{\partial X}$. Also from eq. (8) we know that states gain net subsidy revenues of $(1-\gamma_i)p^N$ per additional unit of RE deployment. Thus, the national government's rationale is to utilize this influence on state-level policy. At best, the national government incentivizes states such that they strive for the nationally resp. socially optimal RE expansion within their territories. This is achieved only if the state-specific gain from additional RE deployment equals the interregional spillover, $(1-\gamma_i)p^N = (1-\eta_i)\frac{\partial B}{\partial X}$.

If $\gamma_i = \eta_i \ \forall i$, then the national government sets the support level 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 of national subsidy costs is equal to the population share, then the national government's equilibrium policy is $p^N = \frac{\partial B}{\partial X}$. For the case of $\gamma_i = \eta_i \ \forall i$, inserting $p^N = \frac{\partial B}{\partial X}$ into eq. (8) gives eq. (4). Hence, in each state first-best RE deployment is realized. In contrast, first-best RE deployment is not implementable, if for at least one state $\gamma_i \neq \eta_i \ \exists i$, since then some state cannot be incentivized properly given a uniform national subsidy. Only differentiated national regulation would remedy this problem.

Proposition 1. *When both the national and state layer regulate through price 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 A.

Intuitively, if the efficiency condition of Proposition 1 is true, then national and regional interests are perfectly aligned because net marginal benefits from expanding RE 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.[7] If 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 $p^N = \frac{\partial B}{\partial X}$).

Following eq. (11) we see that mainly these opposing drivers of state-level policies affect the policy choice of the national government. The national government, in turn, influences RE allocation not only directly through suppliers' deployment decisions, but also indirectly

[7] 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. (8). The state would choose the same policy as without national RE support.

by affecting state-level co-regulation. Let us refer to these direct and indirect channels as the *marginal quantity effect* of national policy, captured by $\frac{\partial x_i}{\partial p^N}$ (see Appendix A). The marginal quantity effect explains the equilibrium choice of the national support level. If $\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \eta_i \gtreqless \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \gamma_i$, then $p^N \lesseqgtr \frac{\partial B}{\partial X}$. That is, if the marginal quantity effect of national policy correlates stronger with states' population shares than with states' burden shares, the national support level lies below $\frac{\partial B}{\partial X}$, and vice versa. You may see that by considering a single state with a population share of $\hat{\eta}$ and a burden share of $\hat{\gamma}$. To align national and regional interests for this state, according to eq. (8) the level of national RE remuneration must be lower (higher) than $\frac{\partial B}{\partial X}$ if $\hat{\eta} > \hat{\gamma}$ ($\hat{\eta} < \hat{\gamma}$).

4.1.2 Regulatory Design II: *Price & Quantity*

In this section we alter the policy instrument assigned to the state layer. We now assume that state governments regulate RE expansion through quantity caps and do not set price incentives anymore. Again, we first define the supplier's RE deployment decision (second stage) before analyzing the RE policies (first stage).

The supplier's optimization problem is distinct from the one under *Price & Price* regulation on two points. First, remuneration for one unit of RE-based electricity is 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 which limits the maximum amount of RE expansion 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:

$$\forall i: \quad p^N \begin{cases} = \dfrac{\partial C_i}{\partial x_i} \quad \wedge \quad x_i < \bar{x}_i & \text{(12a)} \\ \geq \dfrac{\partial C_i}{\partial x_i} \quad \wedge \quad x_i = \bar{x}_i & \text{(12b)} \end{cases}$$

If the supplier intends to deploy less RE than the corresponding quantity cap allows (see eq. (12a)), the supplier's first-order condition is similar to eq. (7). If the supplier would like to deploy as much as or more RE than the corresponding quantity cap approves (see eq. (12b)), the supplier deploys exactly as much as the quantity cap allows for, $x_i = \bar{x}_i$.

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, $\bar{x}_i = \underset{x_i}{\arg\max}\, \mathscr{W}_i(x_i)$. Taking the first derivative of state i's welfare function (2) w.r.t. x_i and setting the result equal to zero, $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$, implicitly defines $\bar{x}_i$:

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1 - \gamma_i) p^N = 0 \qquad \forall i \tag{13}$$

Eq. (13) is identical to eq. (8). This means that given price-based regulation at the national layer and regardless of the policy instrument assigned to the state layer (price-based or quantity-based regulation) state governments favor the same regional RE expansion, ceteris paribus. Bearing in mind that under *Price & Price* regulation taxing (or subsidizing) regional RE expansion is a zero-sum game for states, this is straightforward.

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. Because if in state i the quantity cap is not binding, then the supplier determines actual RE deployment in state i (according to eq. (12a)). However, if the quantity cap is binding, then the state government determines actual RE deployment in state i (according to eq. (12b)). In the latter case, the supplier aims at deploying at least as much RE as the state's quantity cap allows, $p^N \geq \frac{\partial C_i}{\partial x_i}$ and $x_i = \bar{x}_i$.

The following lemma defines under which condition a state's quantity cap is 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:*

$$\eta_a \frac{\partial B}{\partial X} > \frac{\partial D_a}{\partial x_a} + \gamma_a p^N \qquad a \in \mathcal{A}. \tag{14}$$

Then state a's quantity cap is larger than the level of RE deployment preferred by the supplier. The supplier determines the actual RE expansion level in state a.[8]

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:*

$$\eta_r \frac{\partial B}{\partial X} \leq \frac{\partial D_r}{\partial x_r} + \gamma_r p^N \qquad r \in \mathcal{R}. \tag{15}$$

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 expansion level in state r.

To derive the national government's policy choice we differentiate its welfare function eq. (2) w.r.t. p^N and insert eq. (12a) for ambitious states and eq. (13) for restrictive states to obtain:

$$\sum_{a \in \mathcal{A}} \frac{\partial x_a}{\partial p^N} \left[\frac{\partial B}{\partial X} - \frac{\partial D_a}{\partial x_a} - p^N \right] + \sum_{r \in \mathcal{R}} \frac{\partial x_r}{\partial p^N} \left[(1-\eta_r) \frac{\partial B}{\partial X} - (1-\gamma_r) p^N \right] = 0 \tag{16}$$

Rearranging eq. (16) for p^N gives:

$$p^N = \frac{\sum_{r \in \mathcal{R}} \frac{\partial x_r}{\partial p^N}(1-\eta_r) + \sum_{a \in \mathcal{A}} \frac{\partial x_a}{\partial p^N}}{\sum_{r \in \mathcal{R}} \frac{\partial x_r}{\partial p^N}(1-\gamma_r) + \sum_{a \in \mathcal{A}} \frac{\partial x_a}{\partial p^N}} \frac{\partial B}{\partial X} - \frac{\sum_{a \in \mathcal{A}} \frac{\partial x_a}{\partial p^N} \frac{\partial D_a}{\partial x_a}}{\sum_{r \in \mathcal{R}} \frac{\partial x_r}{\partial p^N}(1-\gamma_r) + \sum_{a \in \mathcal{A}} \frac{\partial x_a}{\partial p^N}} \tag{17}$$

[8]Note that for the same state eq. (15) may apply if values for $p^N, \gamma_1, ..., \gamma_n$ change. The set of states that enact ambitious policies $\mathcal{A}$ is a function of p^N and $\gamma_1, ..., \gamma_n$. Correspondingly, the same applies for the set of states that enact restrictive policies $\mathcal{R}$. Note also that $\mathcal{A} \cup \mathcal{R} = \mathcal{N}$ with $\mathcal{N} = \{1, ..., n\}$ and $\mathcal{A} \cap \mathcal{R} = \emptyset$.

Eq. (17) defines the equilibrium policy of the national government. It also shows that the choice of the national support level depends on how many states implement ambitious resp. restrictive policies in equilibrium. More precisely, with regard to restrictive states the ratio between the correlation of the marginal quantity effect of national policy with states' population shares and the correlation of the marginal quantity effect of national policy with states' burden shares matters, just like under *Price & Price* regulation. Formally, this is the ratio between $\sum_{r=1}^{k} \frac{\partial x_r}{\partial p^N}(1-\eta_r)$ and $\sum_{r=1}^{k} \frac{\partial x_r}{\partial p^N}(1-\gamma_r)$. With regard to ambitious states primarily the level of positive marginal externalities $\frac{\partial D_a}{\partial x_a}$ is decisive. While national RE support is thus depending on how many states enact ambitious resp. restrictive policies, the level of the national RE support itself influences how many states pursue ambitious resp. restrictive policies in the first place (see *Lemma 1*).

We know that with increasing p^N less states enact *ambitious* policies resp. more states enact *restrictive* policies. This follows from differentiating eq. (14) resp. eq. (15) w.r.t. p^N since $\eta_i \frac{\partial^2 B}{\partial X^2}\frac{\partial x_i}{\partial p^N} - \frac{\partial^2 D_i}{\partial x_i^2}\frac{\partial x_i}{\partial p^N} - \gamma_i < 0$. Thus, there exists a national support level $\hat{p}$ such that if $p^N \geq \hat{p}$ then all state governments enact *restrictive* policies (note that $\hat{p}$ is a function of $\gamma_1, ..., \gamma_n$). As p^N rises any state government increases its quantity cap by a smaller amount than the supplier strives for because marginal net state-specific deployment costs keep increasing (i.e. marginal external benefits from RE deployment decline while marginal regional external cost grow). Intuitively, each state demands for a growing compensation for every extra unit of RE deployment.

Figure 1: *Aggregate state-level quantity cap dependent on national price incentive*

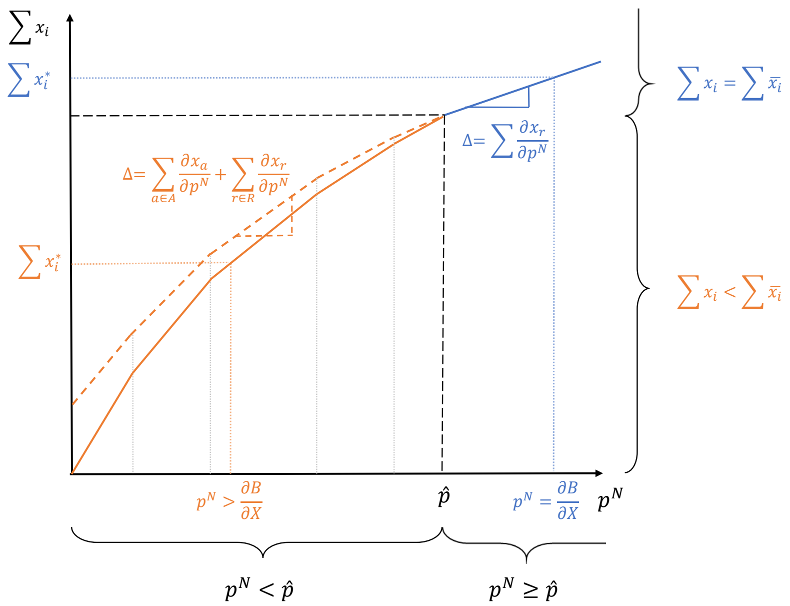


Figure 1 shows this relationship by illustrating the sum of state-level quantity caps dependent on the national support level. Within the left-hand range, i.e. when the national government sets $p^N < \hat{p}$, the aggregate quantity cap (dashed orange line) exceeds aggregate nationwide RE expansion (solid orange line), $\sum_{i=1}^n \bar{x}_i > \sum_{i=1}^n x_i$. Within the right-hand range, i.e. when the national government sets $p^N \geq \hat{p}$, the aggregate quantity cap determines aggregate national RE expansion, $\sum_{i=1}^n \bar{x}_i = \sum_{i=1}^n x_i$.

To analyze national and state-level equilibrium policies, in the following we distinguish between an equilibrium where at least one state government exerts ambitious policy, $p^N < \hat{p}$ (Case A), and an equilibrium where all state governments exert restrictive policies, $p^N \geq \hat{p}$ (Case R).

Case A: $p^N < \hat{p}$

As long as $p^N < \hat{p}$ in equilibrium at least one state government pursues an ambitious RE policy. Contrary to *Price & Price* regulation, the national government now has to care about regional externalities in ambitious states since state-level policies do not effectively steer RE expansion in these states. Without specifying states' burden shares we cannot further characterize the equilibrium. Still, we can draw important conclusions for the most relevant (and realistic) scenario, namely when burden shares are equal to population shares, $\gamma_i = \eta_i \; \forall i$. Furthermore, we introduce the distinction among *type-B nations* and *type-D nations* which simplifies the presentation of our results.

Lemma 2.

*As a **type-B nation** we denote a nation where at the social optimum at least in one state regional benefits of RE deployment outweigh regional disamenities,* $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0 \; \exists j$.[9] *As a **type-D nation** we denote a nation where at the social optimum in all states regional disamenities of RE deployment prevail,* $\frac{\partial D_j(x_j^*)}{\partial x_j} > 0 \; \forall j$.

Using *Lemma 2*, we derive the following result:

Proposition 2a. *If $\gamma_i = \eta_i \; \forall i$, then under Price & Quantity regulation in a type-B nation in equilibrium some states enact ambitious policies such that $\sum_{i=1}^n x_i < \sum_{i=1}^n \bar{x}_i$ and the social optimum is not attainable.*[10]

Proof: See Appendix B.

[9]For example, think of state j for which power production costs are steeply increasing with increasing regional RE expansion, but at the same time state j receives external benefits from regional RE expansion at low levels, including x_j^* (e.g. value-creation effects or green preferences may outweigh any negative externalities for lower levels of RE deployment in that state). Then, from a social welfare (resp. national welfare) perspective, RE expansion in state j should stop at $x_j = x_j^*$, although state j's citizens would experience more positive externalities from further regional RE expansion.

[10]If at the social optimum $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$ applies for only one state, then states' burden shares can be adjusted to implement the social optimum (see Appendix B). Regardless of the specification of states' burden shares, if at the social optimum for more than one state $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$, then under *Price & Quantity* regulation the social optimum is not attainable.

Case R: $p^N \geq \hat{p}$

For $p^N \geq \hat{p}$ in equilibrium in every state RE deployment proceeds until the state's quantity cap binds (restrictive policies), the first term in eq. (16) vanishes and we obtain eq. (10). The same equilibrium outcome ensues as under *Price & Price* regulation. Hence, we can state the following:

Proposition 2b. *If $\gamma_i = \eta_i \ \forall i$, then under Price & Quantity regulation in a type-D nation in equilibrium all states enact restrictive policies, $\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} \bar{x}_i$, and the social optimum is implemented.*

Proof: See Appendix B.

Supposing burden shares equal population shares, if for first-best RE deployment in all states marginal regional externalities are negative (type-D nation), then under *Price & Quantity* regulation all states enact restrictive policies in equilibrium. In turn, if all state governments pursue restrictive policies, the efficiency condition is the same as under *Price & Price* regulation (cf. Proposition 1). Different from *Price & Price* regulation under *Price & Quantity* regulation money from national RE support flows into a state solely through the supplier's profit and not additionally through negative state-level price incentives, e.g. taxes. The rationale for the national government is still defined by eq. (10) resp. (16) and its effectiveness in changing regional RE expansion in state i (marginal quantity effect) is still defined by $\frac{\partial x_i}{\partial p^N} = -\frac{1-\gamma_i}{\eta_i \frac{\partial^2 B}{\partial X^2} - \frac{\partial^2 D_i}{\partial x_i^2} - \frac{\partial^2 C_i}{\partial x_i^2}} \ \forall i$.

4.2 National Quantity-Based Regulation

In the following, we turn to regulatory designs where the national government governs nationwide RE deployment through quantity-based regulation (III and IV). Under quantity-based regulation (e.g. tenders) the national government specifies a fixed maximum amount of electricity 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. The national government can set a ceiling price, $\bar{p}$, that limits the level of the clearing price, $p^N \leq \bar{p}$.

4.2.1 Regulatory Design III: *Quantity & Price*

Under *Quantity & Price* regulation state governments co-regulate by price incentives. Since in the second stage suppliers observe national and state-level policies, their RE deployment decisions are again defined similarly to *Price & Price* regulation (see eq. (7)). In contrast to *Price & Price* regulation, the level of national RE support is not determined directly by the national government (resp. in an administrative procedure), but it is determined endogenously through a tendering procedure. This implies that the ceiling price set by the national government is not binding. If the national government would set a binding ceiling price, then the quantity put out to tender would not be auctioned off entirely, $\sum_{i=1}^{n} x_i < \bar{X}$. At the end of this section we analyze under what circumstances the national government rationally opts for a binding ceiling price. For the moment, we assume $p^N < \bar{p}$.

To analyze national and state-level equilibrium policies, we first look at the equilibrium conditions that represent the national tendering procedure (i.e. uniform price auction) and hence determine the level of p^N:

$$p^N + p_i^S = \frac{\partial C_i}{\partial x_i} \qquad \forall i \tag{18}$$

$$\sum_{i=1}^{n} x_i = \bar{X} \tag{19}$$

As under *Price & Price* regulation, eq. (18) defines state-specific RE deployment as a function of national and state-level price incentives, $x_i(p^N, p_i^S)$. Eq. (19) establishes that the entire tender volume $\bar{X}$ is tendered off. Therefore, eq. (19) is also referred to as the *market clearing condition* (Helm, 2003). This means under *Quantity & Price* regulation the national government prescribes the amount of nationwide RE deployment, $\sum_{i=1}^{n} x_i \equiv X$. By eq. (18) this implies that the clearing price p^N rises until eq. (19) is satisfied. Hence, the above equilibrium conditions implicitly define the clearing price as a function of the allocation of regional RE expansion levels across states, $p^N(\boldsymbol{x})$, and also indirectly as a function of the tender volume.

Of course, national and state governments consider this price mechanism when setting their RE policies. We first derive state governments' equilibrium policies. 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^N through increasing or decreasing their state-specific price incentives, p_i^S. By increasing (decreasing) p_i^S state i effectively makes RE deployment in its jurisdiction comparatively cheaper (more expensive) 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, X. As before, we derive state i's equilibrium policy by differentiating eq. (2) w.r.t. p_i^S, setting $\frac{\partial \mathscr{W}_i}{\partial p_i^S} = 0$ and inserting eq. (19):

$$-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^N(\boldsymbol{x}) + \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) = 0 \qquad \forall i \tag{20}$$

Compared to *Price & Price* regulation, state governments still internalize regional externalities from RE deployment within their own jurisdictions (first term of eq. (20)). Each state government also considers marginal profit for its supplier (second and third term). However, under *Quantity & Price* regulation a state cannot influence the nationwide RE expansion level, $\frac{\partial X}{\partial x_i}\frac{\partial x_i}{\partial p_i^S} = 0$. Accordingly, when deciding on its policy, the state government does not care about benefits from emissions reduction, since these are fixed at $\eta_i B(\bar{X})$. Eventually, a state government considers its policy impact on the level of national RE support (last term). Though nationwide RE expansion does not change due to shifts in states' policy choices resp. their RE expansion levels, p^N does change, $\frac{\partial p^N}{\partial x_i} < 0$ (see Appendix C). Whether a state benefits or loses from this change depends on whether RE deployment in a state, x_i, is larger or smaller than the share of nationwide RE deployment that the state is funding, $\gamma_i \bar{X}$.

To obtain state i's equilibrium policy, substitute eq. (18) into (20) to get:

$$p_i^S = -\frac{\partial D_i}{\partial x_i} + \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) \qquad \forall i \tag{21}$$

According to the second term on the *rhs* of eq. (21), if in equilibrium state i finances a share of nationwide RE expansion that is larger (smaller) than the amount of RE expansion 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 regional external cost. 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 cheaper (more expensive) and thus indirectly lowers (enhances) the national clearing price.

For the national government we derive the equilibrium choice by differentiating the national welfare function eq. (1) w.r.t. $\bar{X}$, inserting eq. (20) and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial \bar{X}} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \left[\frac{\partial B}{\partial X} - p^N - \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) \right] = 0 \tag{22}$$

Rearranging eq. (22) for p^N yields:

$$p^N = \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X})}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}} \tag{23}$$

Eq. (23) implies that under *Quantity & Price* 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 marginal quantity effect of national policy $\frac{\partial x_i}{\partial p^N}$ with state-specific incentives to change the national price level by promoting RE deployment within their own state $\frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X})$. 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 expansion. In particular, under *Quantity & Price* regulation the extent of these incentives depends on the ratio of $\frac{x_i}{\gamma_i \bar{X}}$, in contrast to *Price & Price* regulation where it depends on the ratio of $\frac{\eta_i}{\gamma_i}$. This is reflected by the efficiency condition for *Quantity & Price* regulation:

Proposition 3. *Under Quantity & Price regulation the equilibrium outcome is socially optimal, 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 $p^N = \frac{\partial B}{\partial X}$.*
Proof: See Appendix C.

The efficiency condition for *Quantity & Price* 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 regional externalities from RE deployment, and states' strategic incentives to change the clearing price vanish.

This efficiency condition is very distinct from the one derived for *Price & Price* regulation summarized in Proposition 1. Under national *Price* regulation state governments have an incentive to contribute to nationwide RE expansion 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 layer (e.g. FiT) requires states' burden shares to be distributed along states' population shares. In contrast, under *Quantity* regulation at the national layer 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 layer (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 & Neetzow, 2019) 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 of the state-specific effectiveness of national policy.[11]

Eventually, we include the possibility that the national government can set a binding ceiling price. Up to now, we have assumed that the clearing price is competitively determined, $p^N < \bar{p}$, and the national tender volume is entirely tendered off, $\sum_{i=1}^{n} x_i = \bar{X}$. However, if the national government sets a binding ceiling price, $p^N = \bar{p}$, the national tender volume is not fully exploited, $\sum_{i=1}^{n} x_i < \bar{X}$. This implies that the national government effectively resorts to *Price* regulation. National and state-level policy choices are again rationalized as under *Price & Price* regulation (cf. eq. (9) and (11)). Consequently, in equilibrium state governments take national RE support as given, but they can change nationwide RE expansion, $\frac{\partial X}{\partial x_i}\frac{\partial x_i}{\partial p_i^S} > 0$. Accordingly, the underlying incentive structure of state policy is again oriented towards states' population shares. The national government may choose a binding ceiling price – to bring about this de facto regime shift from national *Quantity* to national *Price* regulation – if existing burden shares correspond to population shares. In that case a binding ceiling price may likely induce a rather efficient spatial allocation of RE deployment, as state policies are more properly incentivized. However, this comes at the cost of falling short of the preferred nationwide RE expansion level.

In the next section we show that states' strategic incentives again change with altering the policy instrument assigned to the state layer.

4.2.2 Regulatory Design IV: *Quantity & Quantity*

Under *Quantity & Quantity* regulation the market clearing condition may not apply in equilibrium, namely, when the sum of state-level quantity caps $\sum_{i=1}^{n} \bar{x}_i$ is smaller than the national tender volume $\bar{X}$. To analyze the equilibrium outcome we need to distinguish between an equilibrium where $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$ (Case A), and an equilibrium where $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$ (Case R).

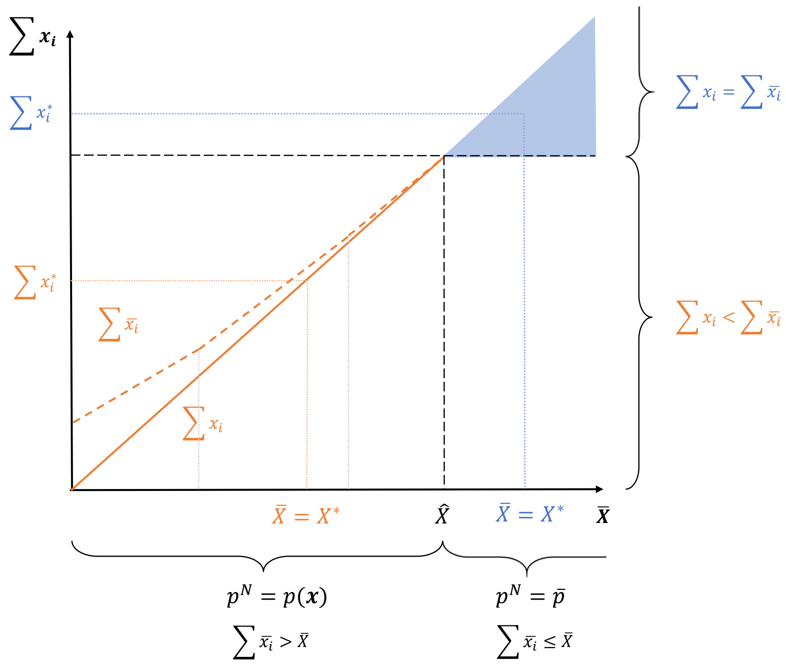
The distinction of Case A and Case R is analogous to the distinction of cases under *Price & Quantity* regulation in Section 4.1.2. In Case A the national tender volume is binding as at least

[11] The latter does not matter in (Meya & Neetzow, 2019) since they make the simplifying assumption – expressed in our model terms – that $\frac{\partial^2 C_i}{\partial x_i^2}$ is identical across all states.

one state exerts ambitious policy by setting a non-binding quantity cap, $x_a < \bar{x_a}$. The market clearing condition applies, $\sum_{i=1}^{n} x_i = \bar{X}$, and thus the clearing price is competitively determined and below the ceiling price, $p^N < \bar{p}$. In Case R the national tender volume is not binding, but each state pursues restrictive policies by setting a binding quantity cap, $x_i = \bar{x_i}\ \forall i$. Notice that in Case R suppliers do not face any competition in the tendering procedure (in the second stage of the game) since all submitted bids are awarded. This means in all states suppliers bid at the ceiling price, $p^N = \bar{p}$, and fully exploit quantity caps, $x_i = \bar{x_i}\ \forall i$.

Whether in equilibrium Case A or Case R applies depends on the choice of the national tender volume $\bar{X}$, and the choice of the ceiling price $\bar{p}$. For the purpose of analysis, we first assume that the national government does not set a binding ceiling price as long as the national tender volume alone is binding, i. e. $\sum_{i=1}^{n} \bar{x_i} > \bar{X}$. This means that the national government allows p^N to be determined competitively through tenders if possible. Then the choice of $\bar{X}$ alone defines whether Case A or Case R applies.

Figure 2: *Aggregate state-level quantity cap dependent on tender volume*



Analogous to *Price & Quantity* regulation, there must exist a threshold level $\hat{X}$ such that in equilibrium $\sum_{i=1}^{n} \bar{x_i} > \bar{X}$ for $\bar{X} \in (0, \hat{X})$, and $\sum_{i=1}^{n} \bar{x_i} \leq \bar{X}$ for $\bar{X} \geq \hat{X}$. This relationship is illustrated in Figure 2. When the national government sets $\bar{X} < \hat{X}$ (left-hand range), the aggregate state-level quantity cap (dashed orange line) exceeds the national tender volume, $\sum_{i=1}^{n} \bar{x_i} > \bar{X}$. Here, nationwide RE deployment is equal to the national tender volume, $\sum_{i=1}^{n} x_i = \bar{X}$ (orange 45° line). When the national government sets $\bar{X} \geq \hat{X}$ (right-hand range), the aggregate state-level quantity cap is smaller or equal to the national tender volume, $\sum_{i=1}^{n} \bar{x_i} \leq \bar{X}$. Now, the level of the ceiling price determines the aggregate state-level quantity cap which lies within the blue area, and nationwide RE expansion is equal to the aggregate state-level quantity cap, $\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} \bar{x_i}$.

Before analyzing the two cases, note that the suppliers' deployment decisions are analogous to those under *Price & Quantity* regulation. That is, suppliers either expand RE deployment until marginal power production cost equate national RE support (see eq. (24a)), which is true given *ambitious* state policy. Or, suppliers expand RE deployment until the quantity cap is exploited (see eq. (24b)), which is true given *restrictive* state policy:

$$\forall i: \quad p^N \begin{cases} = \dfrac{\partial C_i}{\partial x_i} & \text{if} \quad x_i < \bar{x}_i \qquad (24a) \\ \geq \dfrac{\partial C_i}{\partial x_i} & \text{if} \quad x_i = \bar{x}_i \qquad (24b) \end{cases}$$

Case A: $\bar{X} < \hat{X}$

If in equilibrium the sum of states' quantity caps exceeds the national tender volume, $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$, then national RE support resp. the clearing price p^N is competitively determined through the tendering procedure.[12] Actual nationwide RE deployment is fixed to $X = \bar{X}$ and thus $\frac{\partial X}{\partial \bar{x}_i} = 0$. We derive state i's equilibrium policy $\bar{x}_i$ by differentiating eq. (2) w.r.t. x_i and setting $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$:

$$-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^N(\boldsymbol{x}) + \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) = 0 \qquad \forall i \tag{25}$$

As eq. (25) depicts, in Case A state governments' policy choices are identically rationalized as under *Quantity & Price* regulation (cf. eq. (20)). For restrictive states, where $\bar{x}_r = x_r$ and $p^N \geq \frac{\partial C_r}{\partial x_r}$, an increase of the quantity cap leads to a decrease in the national clearing price $\frac{\partial p^N}{\partial x_r} < 0$. By expanding its quantity cap a restrictive state lowers the clearing price because additional RE deployment with marginal power production cost below the clearing price level is unlocked to participate in national tenders. For ambitious states, where $\bar{x}_a > x_a$ and $p^N = \frac{\partial C_a}{\partial x_a}$, an increase of the quantity cap effectively does neither change regional RE deployment nor the national clearing price $\frac{\partial p^N}{\partial x_a} = 0$. Accordingly, ambitious states choose $\bar{x}_a$ such that $\frac{\partial D_a(\bar{x}_a)}{\partial x_a} = 0$. In the equilibrium of Case A at least one ambitious state sets a non-binding quantity cap $x_j < \bar{x}_j$ such that $p^N = \frac{\partial C_j(x_j)}{\partial x_j}$. Therefore, eq. (25) implicitly excludes an equilibrium if in all states marginal external regional costs are always positive, $\frac{\partial D_i}{\partial x_i} > 0 \ \forall i$, because then no state would set a non-binding quantity cap. Note that from eq. (25) we also derive that in equilibrium $0 < \sum_{i=1}^{n} \frac{\partial \bar{x}_i}{\partial \bar{X}} < 1$. Thus, increasing $\bar{X}$ must lead to $\sum_{i=1}^{n} \bar{x}_i = \bar{X}$ at some level of $\bar{X}$ (see Figure 2).[13]

For the national government we derive the equilibrium choice $\bar{X}$ by differentiating the national welfare function eq. (1) w.r.t. X, inserting (25) for restrictive states and eq. (24a) for

[12] Further below, we also analyze the possibility that the national government chooses a binding ceiling price, though tenders would competitively determine a clearing price for the preferred amount of nationwide RE expansion.

[13] See Appendix D. Note that the threshold level $\hat{X}$ varies with the exogenous parameters including states' burden shares. Think of Figure 2 as illustrating $\hat{X}$ given a certain burden sharing, e.g. $\gamma_i = \frac{x_i^*}{X^*} \ \forall i$ or $\gamma_i = \eta_i \ \forall i$.

ambitious states and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial X} = 0$:

$$\sum_{r\in\mathcal{R}} \frac{\partial x_r}{\partial p^N}\left[\frac{\partial B}{\partial X} - p^N - \frac{\partial p^N}{\partial x_r}(x_r - \gamma_r \bar{X})\right] + \sum_{a\in\mathcal{A}} \frac{\partial x_a}{\partial p^N}\left[\frac{\partial B}{\partial X} - \frac{\partial D_a}{\partial x_a} - p^N\right] = 0 \tag{26}$$

Rearranging eq. (26) shows that the national government chooses $\bar{X}$ such that the clearing price settles at:

$$p^N = \frac{\partial B}{\partial X} - \frac{\sum_{r\in\mathcal{R}} \frac{\partial x_r}{\partial p^N}\frac{\partial p^N}{\partial x_r}(x_r - \gamma_r \bar{X}) + \sum_{a\in\mathcal{A}} \frac{\partial x_a}{\partial p^N}\frac{\partial D_a}{\partial x_a}}{\sum_{r\in\mathcal{R}} \frac{\partial x_r}{\partial p^N} + \sum_{a\in\mathcal{A}} \frac{\partial x_a}{\partial p^N}} \tag{27}$$

If in equilibrium the clearing price is competitively determined, on the one hand, the national RE support under *Quantity & Quantity* regulation is similarly defined to national RE support under *Quantity & Price* regulation (cf. eq. (23)). On the other hand, the level of national RE support adjusts to regional externalities in ambitious states like under *Price & Quantity* regulation (cf. eq. (17)).

Case R: $\bar{X} > \hat{X}$

If in equilibrium all state governments establish an aggregate quantity cap as large as or less than the national tender volume, $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$, then the clearing price is no longer competitively determined. $\bar{X}$ is not binding, but instead all state-level quantity caps are binding, $x_i = \bar{x}_i \; \forall i$. Thereby, in the second stage of the game the aggregate demand for national subsidies is constrained to be equal to or lower than the supply offered through the national tender volume. Hence, suppliers are always rewarded within the tendering procedure, and therefore they bid at the ceiling price. The clearing price being equal to the ceiling price, $p^N = \bar{p}$, eventually implies that the level of $\sum_{i=1}^{n} \bar{x}_i$ resp. $\sum_{i=1}^{n} x_i$ only depends on the level of $\bar{p}$.

State governments anticipate that in equilibrium $p^N = \bar{p}$ which is effectively equivalent to an administratively fixed national price incentive (as under *Price* regulation at the national layer). State governments also anticipate that altering quantity caps changes nationwide RE deployment, $\frac{\partial X}{\partial \bar{x}_i} = 1$. Given this, deriving state i's equilibrium policy $\bar{x}_i$ by differentiating eq. (2) w.r.t. x_i and setting $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$, we arrive at the same state-level policy choices as in the presence of solely restrictive state policies under *Price & Quantity* regulation (see eq. (13)). The national government's choice of the ceiling price is consequently identical to the choice of national RE support under *Price & Quantity* regulation (see eq. (11)).

In a type-B nation the social optimum can neither ensue in an equilibrium of Case A nor in an equilibrium of Case R. This is for the same reason as under *Price & Quantity* regulation (see Section 4.1.2). In a type-D nation the social optimum can only ensue in an equilibrium of Case R. Since in Case R *Quantity & Quantity* regulation de facto resembles *Price & Quantity* regulation, efficiency condition and equilibrium policies are also the same.

Proposition 4. *Under Quantity & Quantity regulation the social optimum is only attainable in a type-D nation. Here, Quantity & Quantity regulation is efficient, if and only if the states'* *burden shares are defined by* $\gamma_i = \eta_i \; \forall i$. *The equilibrium policies are* $\bar{X} \geq X^*$ *and* $\bar{x}_i = x_i^* \; \forall i$, *and the clearing price is equal to the ceiling price,* $p^N = \bar{p} = \frac{\partial B}{\partial X}$.[14]

Proof: See Appendix D.

Finally, we consider the strategic use of the ceiling price given that a formal shift to price-based regulation is precluded (analogous to our analysis in Section 4.2.1). So far, we assumed that the national government solely sets a binding ceiling price in conjunction with those levels of the national tender volume for which no competition among suppliers ensues, $\bar{X} \geq \hat{X}$ (right-hand range in Figure 2). Of course, the national government may also set a binding ceiling price in combination with a level of the national tender volume that would otherwise allow for a competitive determination of the national clearing price, $\bar{X} < \hat{X}$ (left-hand range in Figure 2). Regarding the latter, setting a binding ceiling price means that the tender volume is not binding anymore, $\sum_{i=1}^{n} x_i < \bar{X}$, and the national government de facto exerts *Price* regulation.

This may be reasonable, although nationwide RE deployment is reduced below a preferred expansion level. For example, assume that states' burden shares are in fact specified by $\gamma_i = \eta_i \; \forall i$ and that $X^* < \hat{X}$ (hence the social optimum is not attainable). Furthermore, assume that a competitively determined clearing price would settle at $p^N > \frac{\partial B}{\partial X}$. In this case, it may be reasonable that the national government chooses $\bar{p} = \frac{\partial B}{\partial X}$ because then the binding ceiling price would at least induce first-best RE expansion levels in all restrictive states. Still, some states would enact ambitious policies and within their jurisdictions RE deployment would be inefficiently low. However, in total the national welfare loss due to inefficiently low nationwide RE deployment may be outweighed by welfare gains due to more efficient spatial allocation of RE deployment.

In other words, there is a trade-off for the national government between setting a binding ceiling price or not that depends on states' actual burden shares: an inefficiently low level of nationwide RE expansion that is spatially rather efficiently allocated *versus* an efficiently high level of nationwide RE expansion that is spatially inefficiently allocated. The degree of spatial efficiency depends on states' actual burden shares and how these burden shares shape incentives for state-level policies in Case A and Case R. For example, if states' actual burden shares are roughly specified by $\gamma_i = \frac{x_i^*}{X^*} \; \forall i$, then the national government more likely restrains from setting a binding ceiling price since under competitive tenders ($X^* < \hat{X}$) this burden sharing at least induces restrictive states to implement quite efficient expansion levels.

[14]With regard to Figure 2, the social optimum is attainable as long as $X^* \geq \hat{X}$. Note that the level of $\hat{X}$ is depending on $\gamma_1, ...\gamma_n$. Therefore, to be precise the social optimum is attainable, if $X^* \geq \hat{X}$ for $\gamma_i = \eta_i \; \forall i$. If at the social optimum for only one state $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$, then analogous to *Price & Quantity* regulation the social optimum is still attainable, and then it is implemented through adjusted burden shares as shown in Appendix D. The social optimum is not attainable if $X^* < \hat{X}$ and $|N_a| > 1$ with $N_a = \{i | \frac{\partial D_i(x_i^*)}{\partial x_i} < 0\}$.

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 always attainable under all regulatory designs. In fact, it is crucial whether at the social optimum for at least one state additional regional RE deployment provides regional benefits (type-B nation), or conversely, whether all states experience only regional disamenities from RE deployment (type-D nation). In a type-B nation the social optimum is only attainable under regulatory designs I and III where price instruments are assigned to the state layer. In a type-D nation the social optimum is attainable under all four regulatory designs.

Table 2 *Efficiency conditions dependent on regulatory design and type of nation*

State layer \ National layer	Price	Quantity	
Price	$\gamma_i^* = \eta_i$	$\gamma_i^* = \frac{x_i^*}{X^*}$	type-B nation
	$\gamma_i^* = \eta_i$	$\gamma_i^* = \frac{x_i^*}{X^*}$	type-D nation
Quantity	social optimum not attainable		type-B nation
	$\gamma_i^* = \eta_i$	$\gamma_i^* = \eta_i$	type-D nation

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 $\boldsymbol{\gamma}^*$. In a type-B nation specification of efficient burden shares varies with the policy instrument at the national layer. If a price instrument is assigned to the national layer, then states' burden shares must equate states' population shares, $\gamma_i^* = \eta_i \ \forall i$. If a quantity instrument is assigned to the national layer, then states' burden shares should equate states' first-best deployment shares, $\gamma_i^* = \frac{x_i^*}{X^*} \ \forall i$. The latter also holds for a type-D nation. In contrast, for all other regulatory designs in a type-D nation states' burden shares should again equate states' population shares, $\gamma_i^* = \eta_i \ \forall i$.

These diverging efficiency conditions result from diverging incentives for states' policy choices under the different regulatory designs. Under national *Price* regulation states act according to the same incentives, no matter which policy instrument is assigned to the state layer (states' first-order conditions are identical, cf. eq. (8) and (13)). Merely the channel through which states benefit from national support payments alters with the state-level policy instrument.

Under state-level *Price* regulation states are compensated for their regional disamenities through public revenues collected via negative price incentives such as state-specific levies or taxes. Under state-level *Quantity* regulation states are compensated through higher profits for electricity suppliers via national RE remunerations exceeding marginal power production costs. Under both regulatory designs 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.[15]

Under national *Quantity* regulation incentives for states may vary with the policy instrument assigned to the state layer. Under state-level *Price* regulation state policies only affect the level of national RE support but not the level of nationwide RE expansion. Accordingly, states consider whether they benefit or lose from a change in the national support level. For each state this, in turn, depends on the ratio of RE deployment in a state's jurisdiction compared to nationwide RE deployment. Therefore, efficient burden sharing is oriented towards this ratio. Under state-level *Quantity* regulation in Case A (restrictive) states equally affect the national support level and face similar incentives. However, in Case R under state-level *Quantity* regulation states act according to the same incentives as under national *Price* regulation. Here, efficient burden sharing is thus oriented towards states' population shares. Consequently, under national *Quantity* regulation shifting from state-level *Price* to *Quantity* regulation may change incentives for states' policy choices. In fact, in a type-D nation shifting from state-level *Price* to *Quantity* regulation always changes efficiency conditions from oriented towards RE deployment shares to oriented towards population shares (bottom row in Table 2).

5 Discussion

In the following we deduce several policy implications from our main results that are particularly important for regime shifts, meaning changes in policy instruments assigned to the national or state layer. Subsequently, we discuss limitations of our model and point out to areas of further research.

Policy Implications

In the following, it is especially instructive to evaluate some real world examples against the background of our model results. Firstly, we look at levy-based financing schemes that are widely observed in practice. In the beginning most national support schemes were set up as feed-in tariffs (national *Price* regulation) and financed through levies imposed on the electricity price paid by all (or most) electricity consumers (Council of European Energy Regulators,

[15] Precisely, efficiency conditions may differ, but only for the special case where $\frac{\partial D_i(x_i^*)}{\partial x_i} < 0$ is true for exactly one state. See Appendix B for the adjusted efficiency conditions in this case. Of course, the above applies for type-D nations, i.e. if the social optimum is also attainable under *Price & Quantity* regulation.

2018).[16] Effectively, a levy-based system establishes that the share of national subsidy costs borne by a subnational jurisdiction (e.g. state) closely corresponds to its population share. For example, in Germany burden shares of the *Bundesländer* (German states) almost reflect their population shares (see Table 3). Based on our results and referring to countries where regional externalities of RE deployment are mostly negative (as in type-D nations), we conclude that the implementation of levy-based financing schemes together with a regulatory design of national *Price* regulation yields efficient federal co-regulation. This holds regardless of the policy instrument assigned to the subnational layer.

Secondly, we look at national quantity-based regulation that gains currency as recently many countries, including various EU member states, have shifted national support from *Price* to *Quantity* regulation (REN21, 2019; Council of European Energy Regulators, 2018).[17] From our results we know that a shift from national *Price* to national *Quantity* regulation requires to reconfigure burden shares along regional shares of first-best RE deployment if subnational authorities (e.g. states) regulate through price incentives. Our analysis shows that such national policy reforms imply that federal co-regulation becomes inefficient if levy-funding continues to be proportional to population shares. In these cases another financing scheme needs to distribute burden shares along first-best RE deployment shares.

For Germany (where this regime shift took place in 2017) we find significant differences among states' population shares and states' first-best RE deployment shares (see Table 3), indicating to possible inefficiencies if burden shares are not adjusted. Our results regarding a switch from *Price & Price* regulation to *Quantity & Price* regulation confirm the findings by (Meya & Neetzow, 2019) who analyze the reaction of state policies caused by such a regime shift. States with a higher (lower) actual burden share than their first-best RE deployment share set inefficiently high (low) state-specific price incentives. Accordingly, for example Baden-Wuerttemberg (BW) would set too high price incentives, whereas Mecklenburg-Western Pomerania (MWP) would set too low price incentives.[18]

[16] 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.

[17] 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).

[18] The results by (Meya & Neetzow, 2019) rest upon the assumption that spatial allocation of nationwide RE deployment matters for marginal benefits from emissions reduction. In our model terms, (Meya & Neetzow, 2019) assume that benefits from emissions reduction are state-specific, $B_i(\cdot)$, and that $\frac{\partial^2 B_j}{\partial X \partial x_i} \leq 0$, $j \neq i$. Our model refrains from this assumption such that additional RE deployment in any location generates the same marginal nationwide benefit. While we abstract from state-specific benefits of nationwide emissions reduction, $B(\cdot)$, and (Meya & Neetzow, 2019) take this into account, $B_i(\cdot)$. While they assume that $\frac{\partial^2 C_i}{\partial x_i^2} = c \; \forall i$, we allow

Table 3 *Comparison of actual and efficient burden shares of the German states (Bundesländer) in the case of onshore wind energy deployment*

State	Actual Population Share η	Actual Burden Share γ	Simulated First-Best Expansion Share $\frac{x^*}{X^*}$
BW	0.1333	0.1430	0.0000
BY	0.1575	0.1588	0.0151
BE	0.0439	0.0245	0.0000
BB	0.0303	0.0310	0.2020
HB	0.0082	0.0091	0.0000
HH	0.0222	0.0229	0.0000
HE	0.0755	0.0750	0.0286
MWP	0.0194	0.0145	0.3128
NN	0.0962	0.1035	0.1868
NRW	0.2160	0.2230	0.0047
RP	0.0492	0.0532	0.0098
SL	0.0119	0.0171	0.0000
SN	0.0491	0.0433	0.0419
ST	0.0266	0.0310	0.1214
SH	0.0349	0.0241	0.0409
TH	0.0258	0.0261	0.0361

Notes: See Appendix E.

However, these results only hold as long as subnational governments regulate through price incentives, but the result changes if they co-regulate by quantity caps. In fact, like in Germany, it is more common that subnational governments regulate through quantity-based approaches, i.e. spatial planning, than through price incentives (Keenleyside et al., 2009; Pettersson et al., 2010; Power & Cowell, 2012). So thirdly, we show that eventual welfare implications crucially depend on whether subnational governments co-regulate by price or quantity instruments. Under certain conditions levy-based funding schemes remain efficient even after a national regime shift: in type-D nations a shift from national price-based regulation (*Price & Quantity*) to national quantity-based regulation (*Quantity & Quantity*) does not call for reconfigured burden sharing. Countries like Germany may reasonably be seen as type-D nations since here a growing number of local conflicts related to the deployment of large-scale RE plants indicates to predominantly negative externalities (e.g. noise impacts, landscape degradation, threats to protected species). In general, empirical evidence indicates to minor positive regional externalities from RE deploy-

for $\frac{\partial^2 C_i}{\partial x_i^2} \neq \frac{\partial^2 C_i}{\partial x_i^2}$ $\forall i, j$. In addition, our model recognizes the interplay of state-specific effectiveness of national policy $\frac{\partial x_i}{\partial p^N}$ and state-specific policy incentives $\frac{\partial p^N}{\partial x_i}$.

ment that unlikely offset regional disamenities (Brown et al., 2012; Többen, 2017; Mauritzen, 2020). For these type-D nations funding schemes should continue to distribute states' burden shares along states' population shares.

Fourthly, our findings square with the development of submitted bids and clearing prices in tender rounds for wind energy deployment in Germany since 2017. Supposing that in Germany regional disamenities from RE deployment prevail $\left(\frac{\partial D_i}{\partial x_i} \geq 0 \; \forall i\right)$, our model results suggest that in equilibrium we would find $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$, meaning that German states (*Bundesländer*) provide less building land for RE deployment than is promoted by national tenders (see Case R in Section 4.2.2). As we explained before, then the clearing price settles at the level of the ceiling price because suppliers face no competition in national tenders. Indeed, since 2018 underprovision of available construction sites and a clearing price in national tenders that reaches the ceiling price level are observed for wind energy deployment (Meier et al., 2019; German Environment Agency, 2019).[19] Moreover, following the implications of our model, German federal co-regulation of onshore wind energy deployment could be considered as efficiently coordinated among federal layers if the national government would set the efficient tender volume and ceiling price. Of course, the observed development of wind energy expansion in Germany also originates in other factors, e.g. legal complaints against approvals for wind energy deployment (Grashof et al., 2020), and evidently nationwide onshore wind energy expansion falls short of a socially optimal level when merely 1 GW is installed in 2019.[20]

We have thus demonstrated that in type-D nations like Germany a national regime shift does not change the efficiency condition. In contrast, in type-B nations where subnational entities receive regional benefits from RE deployment (even at the social optimum $\frac{\partial D_i(x_j^*)}{\partial x_j} < 0 \; \exists j$) a shift from national price-based to national quantity-based regulation may indeed call for readjusted burden shares (see Case A in Section 4.2.2). Incentives for subnational governments are no longer oriented towards population shares but towards RE deployment shares. Although the social optimum is not attainable, adjusting burden shares may improve coordination among national and subnational governments. If burden shares cannot be modified (e.g. due to constitutional constraints), the national government may also choose a binding ceiling price in order to render spatial RE allocation more efficiently. As explained in Section 4.2.2, this would improve the coordination with subnational policies but would come at cost of an inefficiently low nationwide

[19] Although the German tender scheme is designed as a pay-as-you-bid auction, average winning bids have reached the ceiling price quasi in all auction rounds since the beginning of 2018 (Federal Network Agency, 2020).

[20] Furthermore, state-level policies might be too restrictive. This might be reasoned by the problem to provide (local) citizen-based RE projects (e.g. cooperatives) to have a fair chance in national tenders. Whereas in the case of cooperatives remuneration payments benefit people on site, main shares of remunerations may flow to other regions when non-local suppliers realize RE projects. With respect to our model this translates to a modified assumption that allows for suppliers to deploy RE in other states and to spatially disentangle profits and RE deployment. In fact, in Germany and other countries this is an upcoming argument for the assignment of a price instrument to the subnational layer, because contrary to spatial planning price-based regulation can still compensate subnational jurisdictions for their regional disamenities (see e.g. Kerr, Johnson, & Weir, 2017; Jørgensen et al., 2020).

RE expansion level.

Lastly, since in many countries a switch from quantity-based to price-based regulation at the subnational layer is discussed, we point out to its policy implications. For example, in Germany a (at least partial) shift from subnational *Quantity* to *Price* regulation is foreseeable as the public debate on compensation schemes for communities with large-scale wind power and PV deployment goes on. In other countries some forms of subnational price instruments are already established (Rodi, 2017; Kerr et al., 2017; Jørgensen et al., 2020). In most countries a subnational regime shift would occur under national quantity-based regulation (i.e. tender schemes) and given predominantly negative regional externalities (type-D nations). In this context, we emphasize that a subnational shift from quantity-based to price-based regulation does alter incentives for subnational RE policies, such that subnational governments become concerned about their RE deployment shares. Furthermore, in type-B nations this subnational regime shift could increase national welfare, if at the same time the financing scheme is modified such that burden shares are oriented towards first-best RE deployment shares. Depending on which subnational tier holds regulatory power (e.g. state or community level), burden shares of course would need to be tailored to the respective jurisdictions.

Generally, it should be noted that what we refer to as 'states' within the model equivalently applies to other subnational entities like provinces or municipalities. For some countries, referring to lower subnational layers 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 energy areas (Lauf et al., 2020). Hence, our results are similarly applicable to federal co-regulation that is carried on by a national and a regional (or local) layer, and implications from our model generally pertain to RE policies in federally structured countries.

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 at the national and state layer. Consequently, information asymmetry among national and subnational policymakers is not taken into account. A more realistic setting would include that policymakers on lower federal layers are better informed about regional external costs and benefits than policymakers on higher federal layers. In fact, this is a standard argument of the fiscal federalism literature in favor of subsidiarity (Oates, 1999). If information about regional costs and benefits is not (perfectly) available at the national layer, our results imply that those regulatory designs are favorable where no information about subnational preferences is needed to design national policies efficiently. This is true for regulatory designs where efficient burden shares are equal to population shares (see Table 2). As population shares are common knowledge and given that the national government is enabled to control burden shares, it could still implement the social optimum under information asymmetry. In contrast, under *Quantity & Price* regulation the condition on efficient burden sharing relies on information about regional external costs (as knowledge about the first-best allocation of RE deployment is required). In this case, an imperfectly informed national government would be unable to implement the first-best allocation. In this regard, regulatory designs with state-level spatial planning are (in the case of type-D nations) less demanding with respect to information requirements than *Quantity & Price* regulation.

Another simplification based on the assumption of perfect information concerns the advantages and disadvantages of price and quantity instruments. As power production costs are actually private information of suppliers, neither public actors (exactly) know them, nor is every supplier perfectly informed about power production costs of competing suppliers. In point of fact, recently observed regime shifts to national tender schemes are mainly motivated by the objective to elicit information on true power production costs (Gephart et al., 2017; Grashof et al., 2020). In our setting this advantageous feature of market-based quantity instruments is not reflected. Simultaneously possible merits of price instruments, like strengthening small (community-owned) and more risk-averse suppliers, are neither recognized. The focus of this work was rather upon the strategic interactions of governmental actors.

Secondly, we assume that there is a single electricity supplier in each state and that its economic activities are limited to the respective state. We thereby abstract from competition among suppliers for building land. Although sites for RE plants are coveted, many suppliers acquire sites in a first-come-first-serve manner rather than in competition with other opponents. Commonly, suppliers already sign land-use contracts with landowners and secure construction permits issued by regional authorities before other parties enter the stage. Nonetheless, the assumption of one supplier per jurisdiction implies that subsidies completely benefit the corresponding jurisdiction – either via profits of the regional supplier, or via subnational levies on regional RE deployment. In reality, of course, often suppliers from other jurisdictions own RE plants such that national remunerations for RE deployment do not fully flow into the jurisdiction where RE 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.[21]

Thirdly, we model national and subnational RE policies in a simplified manner. We assume national policy to be spatially uniform. In practice, national governments mainly steer spatial allocation of RE deployment through financial incentives, e.g. national support schemes. If a national government can spatially differentiate RE remuneration, the first-best allocation would be always implemented in a perfect information setting. However, even though national support schemes partly include elements of spatial differentiation[22], the latter is often restricted because national subsidy policies (must) pursue further policy goals like cost-effectiveness and competitiveness[23]. Naturally, the toolbox of national governments contains more instruments like rules

[21]This design option intends to accrue national RE remunerations for RE deployment to residents.

[22]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).

[23]Among others, these are prescribed for EU member states in the EU Renewable Energy Directive, see

of planning law, building law, energy law, etc. Through these channels a national government additionally sets the scope for subsequent governmental layers and constrains their policy discretion. However, such complementary regulation generally imposes uniform requirements on subnational decision-making.

With regard to subnational policy instruments, within our model we obviously simplify elaborate spatial planning procedures when expressing them by means of expansion limits (*quantity caps*). Yet, this formalization captures the essential feature of spatial planning policy, namely the provision of building area for large-scale RE (Keenleyside et al., 2009; Pettersson et al., 2010; Power & Cowell, 2012). If, as seen for example for Germany, regional authorities enact restrictive policies, then the provision of available sites already determines actual regional RE deployment (Meier et al., 2019). To put it in model terms, since regional disamenities dominate regional benefits, subnational governments set binding quantity caps and suppliers fully exploit regional RE expansion possibilities. Admittedly, soft policy measures by subnational governments may ease or hamper RE deployment for suppliers by supporting planning or approval procedures, and may be better formalized by means of subnational implicit price incentives. But within our model[24] subnational price incentives do not reflect these transaction costs imposed through subnational planning or permission requirements. In contrast, within our model subnational price incentives spend or generate public revenues of subnational jurisdictions. Therefore, within our model setup we shall think of subnational prices as explicit levies or taxes on RE deployment. In fact, there are some variants of such price instruments (e.g. in Germany, Denmark, or Spain), though up to date they rarely take actual steering effect on location decisions for RE deployment (Iglesias et al., 2011; Jørgensen et al., 2020).

Fourthly, 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 & Neetzow, 2019)), our main messages change only in the sense that population shares need to be complemented by region-specific benefits. More importantly, results may be substantially altered if the assumed shape of subutility functions fails to reflect reality. Marginal benefits from emissions reductions may possibly not decrease monotonically because RE-based electricity production does not necessarily substitute those fossil-based electricity producers which are most CO_2-intensive. Whether CO_2-intensive power plants are actually the first to be crowded out is rather determined by the merit order of power plants, i.e. marginal power production costs of fossil electricity producers. Likewise, functions of regional disamenities may exhibit kinks at certain thresholds. We also supposed that the site with lowest power production cost concurrently exhibits lowest regional disamenities, such that marginal regional disamenities and marginal power production cost are monotonically increasing in each jurisdiction. This relationship is more likely, the smaller is

(European Union, 2018).

[24]This is also true for the model setup in (Williams III, 2012) and in (Meya & Neetzow, 2019).

the considered administrative unit, and thus must be taken into account especially at the state or province level. Regarding our numerical example of the first-best allocation of wind energy deployment in Germany, we find that deviations from this assumed relationship are negligible for the level of the *Bundesländer*.

Fifthly, we abstract from the complex process of policy formation in a multi-level system where national policy is often influenced by political actors of all federal layers. National legislation may demand 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 exertion of influence is also restricted by constitutional division of competences or majority rules. For example 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.[25] Our static framework also simplifies the dynamics of a socio-technical transformation process. Policy setting of national and subnational governments takes place within longer time frames. Changes in the national support level or in the regional provision of RE expansion areas are made at larger time intervals. Still, we think that analyzing the Nash equilibrium of a simultaneous move game of federal co-regulation may adequately represent successive and mutually responding policy adjustments of national and subnational governments.

Finally, within our model the regulatory design of federal co-regulation, including the assignment 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 a constant across time and countries (Council of European Energy Regulators, 2018). Therefore, when making their policy choices on prices or quantities, governments of all federal layers may regard the financing scheme, respectively subnational burden sharing, as at least temporarily given. If the national government can decide on subnational burden sharing, our analysis shows that current financing schemes are likely well chosen. If, realistically, the national government can choose between price-based and quantity-based instruments, our results reveal that the optimal choice depends on instruments applied at the subnational layer. For subnational layers the assumption of assigned policy instruments may be valid, depending on the competences (and policy fields) that are constitutionally designated to them. Certainly, this endogeneity of the regulatory design as well as implications of instrument choices for distributive issues among regions need further research.

[25] Furthermore, in particular a transition to a RE-based electricity sector needs sufficient stakeholder support, and therefore offers many opportunities for stakeholder groups to shape regulation policies in their interests. Hence, RE policy has to take into account the potential redistribution of resources among interest groups (Gawel et al., 2017; del Río & Labandeira, 2009). Apart from "rent management" within RE policy (Schmitz et al., 2013), also policy choices as well as the choice of regulatory instruments can be ascribed to rent-seeking behavior of different interest groups (Kirchgässner & Schneider, 2003).

6 Conclusion

What combination of policy instruments should be assigned to different federal layers to attain an efficient allocation of RE deployment? We answer this question by using a simple two-level regulation model of federal RE policies. We analyze strategic interactions between national and subnational RE regulation under different combinations of price and quantity instruments. Our analysis extends the existing (theoretical) literature on federal RE regulation by including subnational quantity-based regulation, i.e. spatial planning. The focus on spatial planning is crucial as it is the standard policy instrument of subnational regulation of RE deployment. Since subnational governments effectively pick siting areas for RE deployment, we formalize spatial planing policies through 'quantity caps' that implement an upper limit on regional RE deployment.

Efficiency of federal co-regulation hinges upon how the financial burden of the national RE support scheme is shared among subnational jurisdictions. Under realistic assumptions national price-based regulation is efficient if burden shares of subnational jurisdictions are proportional to their population shares. This holds regardless of the subnational policy instrument. Contrary, under national quantity-based regulation efficient burden sharing depends on the policy instrument assigned to the subnational layer. Given subnational price-based combined with national quantity-based regulation burden shares should be oriented towards first-best RE deployment shares. Given subnational quantity-based combined with national quantity-based regulation burden shares should be oriented towards population shares. These findings apply under the realistic assumption that regional disamenities outweigh regional benefits from RE deployment. As an example, we show that for Germany the assignment of the subnational policy instrument substantially alters the efficient specification of subnational burden sharing.

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. To quote only two, the application of price-based versus quantity-based instruments affects the cost-effectiveness of RE support schemes (Gephart et al., 2017) as well as the plurality of actors (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 a significant 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 by RE in state i
$\bar{x_i}$	state-level quantity cap
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
$\bar{p}$	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 by RE in state i
$D_i(x_i)$	Net regional external costs (and benefits) of RE deployment in state i
$B(X)$	Nationwide benefit from nationwide RE deployment

Appendix A *Price & Price* regulation

In the first stage, national and state-level governments decide on their policy choices. In the second stage, in each state the supplier decides on its RE deployment given the policy choices. We solve each regulation outcome by backward induction. First, we derive the first-order conditions for all electricity suppliers. Second, we derive the equilibrium strategies of national and state-level governments.

Electricity Suppliers

Each supplier's optimization problem is defined as:

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

Each supplier chooses RE deployment according to:

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

RE deployment in state i is implicitly defined as a function of national and state-level price incentives, $x_i(p^N, p_i^S)$.

State-level Policy

Taking p^N as given, the marginal change in x_i caused by a marginal increase in state i's price incentive is defined by $\frac{\partial x_i}{\partial p_i^S} = \frac{1}{\frac{\partial^2 C_i}{\partial x_i^2}}$ $\forall i$. We derive state i's policy choice of p_i^S given the national policy p^N by differentiating state i's welfare function eq. (2) w.r.t. p_i^S and setting the result equal to zero, $\frac{\partial \mathscr{W}_i}{\partial p_i^S} = 0$:

$$\frac{\partial x_i}{\partial p_i^S}\left[\eta_i \frac{\partial B}{\partial X}\frac{\partial X}{\partial x_i} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1-\gamma_i)p^N\right] = 0 \qquad \forall i \tag{A.3}$$

Note that $\frac{\partial X}{\partial x_i} = 1\ \forall i$. Dividing eq. (A.3) by $\frac{\partial x_i}{\partial p_i^S}$ gives eq. (8):

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1-\gamma_i)p^N = 0 \qquad \forall i \tag{A.4}$$

National Policy

Differentiating eq. (A.4) w.r.t. p^N gives $\frac{\partial x_i}{\partial p^N} = -\frac{1-\gamma_i}{\eta_i \frac{\partial^2 B}{\partial X^2} - \frac{\partial^2 D_i}{\partial x_i^2} - \frac{\partial^2 C_i}{\partial x_i^2}}\ \forall i$.

We derive the national government's policy choice of p^N by differentiating the national welfare function eq. 1 w.r.t. p^N and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial p^N} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\left[\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i}\right] = 0 \tag{A.5}$$

By substituting eq. (A.4) we obtain eq. (10):

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\left[(1-\eta_i)\frac{\partial B}{\partial X} - (1-\gamma_i)p^N\right] = 0 \tag{A.6}$$

Solving for p^N:

$$p^N = \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}(1-\eta_i)}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}(1-\gamma_i)} \frac{\partial B}{\partial X} \tag{A.7}$$

Proof of Proposition 1

Plugging $\gamma_i = \eta_i\ \forall i$ into eq. (A.7) gives the national government's policy choice of p^N:

$$p^N = \frac{\partial B}{\partial X} \tag{A.8}$$

Plugging $\gamma_i = \eta_i\ \forall i$ and eq. (A.8) into eq. (A.4) gives the state governments' policy choices of $p_1^S, ..., p_n^S$:

$$p_i^S = -\frac{\partial D_i}{\partial x_i} \qquad \forall i \tag{A.9}$$

Substituting eq. (A.8) and eq. (A.9) into eq. (A.2) yields the social optimum, (cf. eq. (4). *Q.E.D.*

Appendix B *Price & Quantity* regulation

Electricity Suppliers

The electricity supplier's optimization problem is defined as:

$$\underset{x_i}{max}\ \pi_i(x_i) = p^N x_i + C_i(x_i) \quad s.t. \quad x_i \leq \bar{x}_i \qquad \forall i \tag{B.1}$$

Each electricity supplier chooses x_i according to:

$$\forall i: \quad p^N \begin{cases} = \dfrac{\partial C_i}{\partial x_i} \quad \wedge \quad x_i < \bar{x}_i & \text{(B.2a)} \\ \geq \dfrac{\partial C_i}{\partial x_i} \quad \wedge \quad x_i = \bar{x}_i & \text{(B.2b)} \end{cases}$$

RE deployment in state i is implicitly defined as a function of either the national price incentive, $x_i(p^N)$, or the state-level quantity cap, $x_i(\bar{x}_i)$.

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. (2) w.r.t. x_i and setting the result equal to zero, $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$:

$$\eta_i \frac{\partial B}{\partial X}\frac{\partial X}{\partial x_i} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1-\gamma_i)p^N = 0 \qquad \forall i \tag{B.3}$$

State-level policy in state i is implicitly defined as a function of the national price incentive, $\bar{x}_i(p^N)$. State governments prefer the same RE deployment as under *Price & Price* regulation (cf. eq. (8)). Differentiating eq. (B.3) w.r.t. p^N and rearranging gives:

$$\frac{\partial \bar{x}_i}{\partial p^N} = -\frac{1-\gamma_i}{\eta_i \frac{\partial^2 B}{\partial X^2} - \frac{\partial^2 D_i}{\partial x_i^2} - \frac{\partial^2 C_i}{\partial x_i^2}} \tag{B.4}$$

Proof of *Lemma 1*

Denote by x_i^{ES} the RE deployment level striven for by suppliers, $p^N = \frac{\partial C_i}{\partial x_i}\big|_{x_i = x_i^{ES}}$. If in the second stage the electricity supplier chooses to deploy less RE than state i's quantity cap allows, hence if $x_i^{ES} < \bar{x}_i$ and equivalently $\frac{\partial C_i}{\partial x_i}\big|_{x_i = x_i^{ES}} < \frac{\partial C_i}{\partial x_i}\big|_{x_i = \bar{x}_i}$, then this implies that state i prefers more RE deployment than is realized by the electricity supplier. In this case we say state i pursues an *ambitious* policy.

If the electricity supplier in state i exhausts the quantity cap, hence if $x_i^{ES} \geq \bar{x}_i$, then it must be true that $\frac{\partial C_i}{\partial x_i}\big|_{x_i = x_i^{ES}} \geq \frac{\partial C_i}{\partial x_i}\big|_{x_i = \bar{x}_i}$. The latter inequality means that the electricity supplier strives for at least as much RE deployment in state i as state i's government favors. In that case we say state i pursues a *restrictive* policy.

We define that state governments pursue *ambitious* or *restrictive* policies in equilibrium by rewriting eq. (B.3) as:

$$\frac{\partial C_i}{\partial x_i} = \eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} + (1-\gamma_i)p^N \qquad \forall i \tag{B.5}$$

First, it follows that $\frac{\partial C_i}{\partial x_i}\big|_{x_i=x_i^{ES}} < \frac{\partial C_i}{\partial x_i}\big|_{x_i=\bar{x}_i}$ if at $x_i = \bar{x}_i$:

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \gamma_i \; p^N > 0 \tag{B.6}$$

If $\frac{\partial C_i}{\partial x_i}\big|_{x_i=x_i^{ES}} < \frac{\partial C_i}{\partial x_i}\big|_{x_i=\bar{x}_i}$ resp. if eq. (B.6) applies in equilibrium, then state i pursues an *ambitious* policy.

Second, it follows that $\frac{\partial C_i}{\partial x_i}\big|_{x_i=x_i^{ES}} \geq \frac{\partial C_i}{\partial x_i}\big|_{x_i=\bar{x}_i}$ if at $x_i = \bar{x}_i$:

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \gamma_i \; p^N \leq 0 \tag{B.7}$$

Hence, if eq. (B.7) applies in equilibrium, then state i pursues a *restrictive* policy.

States that choose *restrictive* policies in equilibrium are indexed by r and states that choose *ambitious* policies in equilibrium are indexed by a. The above definitions are summarized in *Lemma 1*.

With increasing p^N less states enact *ambitious* policies resp. more states enact *restrictive* policies. This can be seen by differentiating the *lhs* of eq. (B.6) resp. (B.7) w.r.t. p^N which gives $\eta_i \frac{\partial^2 B}{\partial X^2}\frac{\partial x_i}{\partial p^N} - \frac{\partial^2 D_i}{\partial x_i^2}\frac{\partial x_i}{\partial p^N} - \gamma_i < 0$. Thus, the set of states that enact *ambitious* policies, denoted by $\mathcal{A}$, resp. the set of states that enact *restrictive* policies, denoted by $\mathcal{R}$, is a function of p^N. Furthermore, for each specification of states' burden shares $\gamma_1, ..., \gamma_n$ there exists a national support level $\hat{p}$ such that, if $p^N \geq \hat{p}$, then all state governments enact *restrictive* policies.

National Policy

We derive the national government's policy choice of p^N by differentiating the national welfare function eq. (1) w.r.t. p^N and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial p^N} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}\left[\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i}\right] = 0 \tag{B.8}$$

By substituting eq. (B.2a) and (B.3) into (B.8) we obtain eq. (16):

$$\sum_{a\in\mathcal{A}} \frac{\partial x_a}{\partial p^N}\left[\frac{\partial B}{\partial X} - \frac{\partial D_a}{\partial x_a} - p^N\right] + \sum_{r\in\mathcal{R}} \frac{\partial x_r}{\partial p^N}\left[(1-\eta_r)\frac{\partial B}{\partial X} - (1-\gamma_r)p^N\right] = 0 \tag{B.9}$$

Solving for p^N gives eq. (17):

$$p^N = \frac{\sum_{r\in\mathcal{R}} \frac{\partial x_r}{\partial p^N}(1-\eta_r) + \sum_{a\in\mathcal{A}} \frac{\partial x_a}{\partial p^N}}{\sum_{r\in\mathcal{R}} \frac{\partial x_r}{\partial p^N}(1-\gamma_r) + \sum_{a\in\mathcal{A}} \frac{\partial x_a}{\partial p^N}}\frac{\partial B}{\partial X} - \frac{\sum_{a\in\mathcal{A}} \frac{\partial x_a}{\partial p^N}\frac{\partial D_a}{\partial x_a}}{\sum_{r\in\mathcal{R}} \frac{\partial x_r}{\partial p^N}(1-\gamma_r) + \sum_{a\in\mathcal{A}} \frac{\partial x_a}{\partial p^N}} \tag{B.10}$$

Proof of Proposition 2a and Proposition 2b

We first show that given $\gamma_i = \eta_i \; \forall i$, if at the social optimum $\frac{\partial D_i(x_i^*)}{\partial x_i} > 0 \; \forall i$, then all states enact restrictive policies and first-best RE allocation is implemented: Suppose that the national government sets $p^N = \frac{\partial B(X^*)}{\partial X}$. Given $\gamma_i = \eta_i \; \forall i$, according to eq. (B.3) all state governments set $\bar{x}_i = x_i^* \; \forall i$. This implies that according to eq. (B.7) all states enact restrictive policies and hence $x_i = x_i^* \; \forall i$. Since in this way the social optimum is implemented, the national government does not change its policy choice $p^N = \frac{\partial B(X^*)}{\partial X}$ in the first place.

Second, we show that given $\gamma_i = \eta_i \; \forall i$, if at the social optimum $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0 \; \exists j$, then at least one state enacts ambitious policies (see Case A) and the social optimum is not implemented: Suppose that at the social optimum for only one state j we have $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$, and for all other states we have $\frac{\partial D_i(x_i^*)}{\partial x_i} > 0 \; \forall i \neq j$. For $p^N = \frac{\partial B(X^*)}{\partial X}$ the latter states would implement first-best RE deployment within their states (see paragraph above). According to eq. (B.3) state j's government would set $\bar{x}_j = x_j^*$, but since at the social optimum $\frac{\partial C_j(x_j^*)}{\partial x_j} = \frac{\partial B(X^*)}{\partial X} - \frac{\partial D_j(x_j^*)}{\partial x_j}$ it would follow that $x_j < x_j^*$. Therefore, by slightly increasing p^N within the range of $\frac{\partial B(X^*)}{\partial X} < p^N < \frac{\partial B(X^*)}{\partial X} - \frac{\partial D_j(x_j^*)}{\partial x_j}$ the national government could increase national welfare. Then according to eq. (B.3) state governments set $\bar{x}_i > x_i^* \; \forall i \neq j$, thus $x_i > x_i^* \; \forall i \neq j$ and $x_j < x_j^*$. The social optimum is not implemented.

Third, we show that if at the social optimum for only one state $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$ applies, then *Price & Quantity* regulation can still implement the social optimum: Suppose that $\gamma_i = \eta_i \; \forall i$. To implement first-best RE deployment in state j the national government must set $p^N = \frac{\partial B(X^*)}{\partial X} - \frac{\partial D_j(x_j^*)}{\partial x_j} = \frac{\partial C_j(x_j^*)}{\partial x_j}$ (since state j enacts an ambitious policy, see previous paragraph). Therefore, burden shares of all other (restrictive) states need to be adjusted to this level of p^N. In equilibrium state-specific RE deployment are determined through $p^N = \frac{\partial C_j(x_j^*)}{\partial x_j}$ in state j and through eq. (B.3) in all other states. Combining the latter two equations and rewriting gives:

$$\frac{1}{1-\gamma_i}\left[\frac{\partial C_i}{\partial x_i} - \eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i}\right] = \frac{\partial C_j}{\partial x_j} \qquad \forall i \neq j \tag{B.11}$$

Plugging the condition for the social optimum eq. (4) into (B.11) leads to an adjusted efficiency condition:

$$\gamma_i = \frac{\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_j}{\partial x_j}}{\frac{\partial B}{\partial X} - \frac{\partial D_j}{\partial x_j}} \qquad \forall i \neq j \tag{B.12}$$

In comparison to Proposition 1, the burden shares of restrictive states are adjusted according to the marginal regional externality in the ambitious state at the social optimum, $\frac{\partial D_j(x_j^*)}{\partial x_j}$. Since $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$, and the adjusted efficient burden shares of restrictive states are higher, $\gamma_i > \eta_i \; \forall i \neq j$, the adjusted efficient burden share of the ambitious state is lower, $\gamma_j < \eta_j$, and p^N is higher, $p^N > \frac{\partial B(X^*)}{\partial X}$, compared to Proposition 1. By configuring burden shares according to eq. (B.12) the social optimum is implemented in equilibrium. However, this is only true if at the social optimum $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$ solely applies for one state. If the latter applies for more than one state, the social optimum is not attainable under *Price & Quantity* regulation. If for more than one state $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$, then by eq. (B.11) this would require that at the social optimum we would have $\frac{\partial C_{j'}}{\partial x_{j'}} = \frac{\partial C_{j''}}{\partial x_{j''}} \; \forall j', j''$ for all states where $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$. That is only true by chance. Precisely, at the same time, for all states where $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$ applies, we would also need $\frac{\partial D_{j'}}{\partial x_{j'}} = \frac{\partial D_{j''}}{\partial x_{j''}} \; \forall j', j''$.

Q.E.D.

Appendix C *Quantity & Price* regulation

The derivations in this section mostly resemble (Meya & Neetzow, 2019), pp. 29-31. In the following we assume that $\bar{p} > p^N$.

Electricity Suppliers

The suppliers' optimization problem is the same as under *Price & Price* regulation. In contrast to *Price & Price* regulation nationwide RE expansion is fixed through the tendering procedure while the support level p^N is endogenous. The equilibrium is defined as follows:

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

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

According to eq. (C.1) regional RE deployment depends on p^N and p_i^S, hence $x_i(p^N, p_i^S)$. The above equilibrium conditions implicitly define the clearing price as a function of the allocation of RE deployment across states, $p^N(\boldsymbol{x})$. Accordingly, the clearing price also depends on the level of nationwide RE deployment resp. the tender volume, $\bar{X}$.

Differentiating eq. (C.1) w.r.t. p^N leads to (in equilibrium $\frac{\partial p_i^S}{\partial p^N} = 0$):

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

Differentiating eq. (C.2) w.r.t. x_i and rearranging yields:

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

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

Differentiating eq. (C.1) w.r.t. $\bar{X}$ gives:

$$\frac{\partial p^N}{\partial \bar{X}} = \frac{1}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}} \qquad \forall i \tag{C.5}$$

State-level Policy

Given the national policy choice $\bar{X}$, nationwide RE expansion is fixed to $X = \bar{X}$ and thus $\frac{\partial X}{\partial x_i} = 0$. We derive state i's equilibrium policy by differentiating eq. (2) w.r.t. p_i^S and setting $\frac{\partial \mathscr{W}_i}{\partial p_i^S} = 0$:

$$\frac{\partial x_i}{\partial p_i^S} \left[-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^N(\boldsymbol{x}) + \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) \right] = 0 \qquad \forall i \tag{C.6}$$

Dividing eq. (C.6) by $\frac{\partial x_i}{\partial p_i^S}$ yields eq. (20):

$$-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^N(\boldsymbol{x}) + \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) = 0 \qquad \forall i \tag{C.7}$$

Rearranging eq. (C.7) for p_i^S yields:

$$p_i^S = -\frac{\partial D_i}{\partial x_i} + \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) \qquad \forall i \tag{C.8}$$

$\frac{\partial p^N}{\partial x_i}$ is defined by eq. (C.4).

National Policy

We derive the national government's equilibrium choice of $\bar{X}$ by differentiating the national welfare function eq. (1) w.r.t. $\bar{X}$ and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial \bar{X}} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \frac{\partial p^N}{\partial \bar{X}} \left[\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} \right] = 0 \tag{C.9}$$

$\frac{\partial x_i}{\partial p^N}$ is defined by eq. (C.3) and $\frac{\partial p^N}{\partial \bar{X}}$ is defined by eq. (C.5).
Dividing by $\frac{\partial p^N}{\partial \bar{X}}$ and substituting eq. (C.7) into (C.9) we obtain:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \left[\frac{\partial B}{\partial X} - p^N - \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) \right] = 0 \tag{C.10}$$

$$\iff \quad \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \left[\frac{\partial B}{\partial X} - p^N \right] - \sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) = 0 \tag{C.11}$$

$$\iff \quad p^N = \frac{\partial B}{\partial X} - \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N} \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X})}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}} \tag{C.12}$$

Proof of Proposition 3

Plugging eq. (C.8) and (C.12) into (C.1) and rearranging gives:

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

If for all states the *rhs* of eq. (C.13) is equal to zero, then *Quantity & Price* regulation implements the social optimum (cf. eq. (4)). The former is true, if and only if for all states we have $x_i^* = \gamma_i \bar{X}$. In combination with eq. (C.2) this results in the efficiency condition of Proposition 3:

$$\gamma_i = \frac{x_i^*}{X^*} \qquad \forall i \tag{C.14}$$

Q.E.D.

Appendix D *Quantity & Quantity* regulation

Electricity Suppliers

The suppliers' optimization problem is analogous to the one under *Price & Quantity* regulation:

$$\underset{x_i}{max} \; \pi_i(x_i) = p^N x_i + C_i(x_i) \quad s.t. \quad x_i \leq \bar{x}_i \qquad \forall i \tag{D.1}$$

Each supplier chooses x_i according to:

$$\forall i: \quad p^N \begin{cases} = \dfrac{\partial C_i}{\partial x_i} & \text{if} \quad x_i < \bar{x}_i \qquad \text{(D.2a)} \\ \geq \dfrac{\partial C_i}{\partial x_i} & \text{if} \quad x_i = \bar{x}_i \qquad \text{(D.2b)} \end{cases}$$

RE deployment in state i is implicitly defined as a function of either the national clearing price, $x_i(p^N)$ as depicted by eq. (D.2a), or the state-level quantity cap, $x_i(\bar{x}_i)$ as depicted by eq. (D.2b).

Distinction of Equilibrium Cases

To analyze national and state policies we distinguish between two types of equilibrium that are feasible. The two types are characterized by the relation of $\sum_{i=1}^{n} \bar{x}_i$ and $\bar{X}$.

Case A: $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$

If the sum of state-level quantity caps exceeds the national tender volume, $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$, then the clearing price is competitively determined. Electricity suppliers bid at their marginal power production costs to get awarded in the tendering process. If in equilibrium $\sum_{i=1}^{n} \bar{x}_i > \bar{X}$, this implies that at least in one state the quantity cap is non-binding, $x_a < \bar{x}_a$, that is at least for one supplier eq. (D.2a) applies. Further, the market clearing condition is met in equilibrium:

$$\sum_{i=1}^{n} x_i = \bar{X} \tag{D.3}$$

State-level Policy

Given the national policy choice $\bar{X}$, nationwide RE deployment is fixed to $X = \bar{X}$ and thus $\frac{\partial X}{\partial x_i} = 0$. We derive state i's equilibrium policy by differentiating eq. (2) w.r.t. x_i and setting $\frac{\partial \mathscr{W}_i}{\partial x_i} = 0$:

$$-\frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + p^N(\boldsymbol{x}) + \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) = 0 \qquad \forall i \tag{D.4}$$

In equilibrium for states where the quantity cap is not binding, $x_a < \bar{x}_a$ (ambitious states) and hence $\frac{\partial C_a(x_a)}{\partial x_a} = p^N$, it follows that $\frac{\partial p^N}{\partial x_a} = 0$. Therefore, ambitious states set $\bar{x}_a$ such that $\frac{\partial D_a(\bar{x}_a)}{\partial x_a} = 0$. In equilibrium for states where the quantity cap is binding, $x_r = \bar{x}_r$ (restrictive states) and hence $\frac{\partial C_r}{\partial x_r} \leq p^N$, it follows that $\frac{\partial p^N}{\partial x_r} < 0$.
Differentiating eq. (D.2a) w.r.t. p^N we obtain:

$$\frac{\partial x_a}{\partial p^N} = \frac{1}{\frac{\partial^2 C_a}{\partial x_a^2}} \qquad a \in \mathcal{A} \tag{D.5}$$

Differentiating eq. (D.4) w.r.t. p^N for restrictive states we obtain:

$$\frac{\partial x_r}{\partial p^N} = \frac{1}{\frac{\partial^2 D_i}{\partial x_i^2} + \frac{\partial^2 C_i}{\partial x_i^2} - \frac{\partial p^N}{\partial x_r}} \tag{D.6}$$

Differentiating $\sum_{i=1}^{n} x_i = \bar{X}$ w.r.t. $\bar{X}$ gives:

$$\frac{\partial p^N}{\partial \bar{X}} = \frac{1}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial p^N}} \tag{D.7}$$

Differentiating $\sum_{i=1}^{n} x_i = \bar{X}$ w.r.t. x_r gives (where $x_r = \bar{x}_r$ in equilibrium):

$$
\begin{aligned}
& 1 + \sum_{j \neq r} \frac{\partial x_j}{\partial p^N} \frac{\partial p^N}{\partial x_r} = 0 \\
\iff \quad & \frac{\partial p^N}{\partial x_r} = -\frac{1}{\sum_{j \neq r}^{n} \frac{\partial x_j}{\partial p^N}}
\end{aligned} \tag{D.8}
$$

Since in equilibrium the effect of changing x_r on all other policy variables is of second order $\left(\frac{\partial \bar{x}_j}{\partial p^N} \frac{p^N}{x_r} = 0\right)$, from eq. (D.8) we obtain:

$$
\frac{\partial p^N}{\partial x_r} = -\frac{1}{\sum_{a \in A} \frac{\partial x_a}{\partial p^N}} \tag{D.9}
$$

Differentiating eq. (D.4) w.r.t. $\bar{X}$ gives:

$$
\frac{\partial \bar{x}_i}{\partial \bar{X}} = \frac{-\gamma_i \frac{\partial p^N}{\partial x_i}}{\frac{\partial^2 D_i}{\partial x_i^2} + \frac{\partial^2 C_i}{\partial x_i^2} - \frac{\partial p^N}{\partial x_i}} \tag{D.10}
$$

We see that $0 < \frac{\partial \bar{x}_i}{\partial \bar{X}} < \gamma_i \; \forall i$. Summing up $\frac{\partial \bar{x}_i}{\partial \bar{X}}$ over all states, we obtain:

$$
\sum_{i=1}^{n} \frac{\partial \bar{x}_i}{\partial \bar{X}} < 1 \tag{D.11}
$$

National Policy

We derive the national government's choice of $\bar{X}$ by differentiating the national welfare function eq. (1) w.r.t. $\bar{X}$ and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial \bar{X}} = 0$:

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

Dividing by $\frac{\partial p^N}{\partial \bar{X}}$ and inserting eq. (D.4) for restrictive states and eq. (D.2a) for ambitious states into eq. (D.12) we obtain eq. (26):

$$
\sum_{r \in \mathcal{R}} \frac{\partial x_r}{\partial p^N} \left[\frac{\partial B}{\partial X} - p^N - \frac{\partial p^N}{\partial x_r} (x_r - \gamma_r \bar{X}) \right] + \sum_{a \in \mathcal{A}} \frac{\partial x_a}{\partial p^N} \left[\frac{\partial B}{\partial X} - \frac{\partial D_a}{\partial x_a} - p^N \right] = 0 \tag{D.13}
$$

Solving for p^N yields eq. (27):

$$
p^N = \frac{\partial B}{\partial X} - \frac{\sum_{r \in \mathcal{R}} \frac{\partial x_r}{\partial p^N} \frac{\partial p^N}{\partial x_r} (x_r - \gamma_r \bar{X}) + \sum_{a \in \mathcal{A}} \frac{\partial x_a}{\partial p^N} \frac{\partial D_a}{\partial x_a}}{\sum_{r \in \mathcal{R}} \frac{\partial x_r}{\partial p^N} + \sum_{a \in \mathcal{A}} \frac{\partial x_a}{\partial p^N}} \tag{D.14}
$$

Case B: $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$

If the sum of state-level quantity caps does not exceed the national tender volume, $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$, then all suppliers bid the ceiling price knowing that they are always awarded in the tendering process. Hence, the clearing price is equal to the ceiling price, $p^N = \bar{p}$. In all states suppliers expand as much RE deployment as is possible, $x_i = \bar{x}_i$, such that eq. (D.2b) applies for all states. The market clearing condition need not be satisfied:

$$\sum_{i=1}^{n} x_i \leq \bar{X} \tag{D.15}$$

State-level Policy

Note that in this case nationwide RE deployment depends on the sum of state-level quantity caps, $X = \sum_{i=1}^{n} \bar{x}_i$, and thus $\frac{\partial X}{\partial \bar{x}_i} = 1$. All state governments anticipate that national RE support is effectively fixed at $p^N = \bar{p}$. Given the national policy choice of $\bar{p}$ and $\bar{X}$, we derive state i's equilibrium policy by differentiating eq. (2) w.r.t. x_i and setting $\frac{\partial \mathscr{W}_i}{\partial \bar{x}_i} = 0$:

$$\eta_i \frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} + (1 - \gamma_i)\bar{p} = 0 \qquad \forall i \tag{D.16}$$

National Policy

Since we look at an equilibrium with $\sum_{i=1}^{n} \bar{x}_i \leq \bar{X}$, that is the national tender volume is not binding but each state's quantity cap is binding, the choice of $\bar{X}$ is by assumption arbitrary. The national government chooses $\bar{X} \geq \sum_{i=1}^{n} \bar{x}_i$. We derive the national government's choice of $\bar{p}$ by differentiating the national welfare function eq. (1) w.r.t. $\bar{p}$ and setting the result equal to zero, $\frac{\partial \mathscr{W}}{\partial \bar{p}} = 0$:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial \bar{p}} \left[\frac{\partial B}{\partial X} - \frac{\partial D_i}{\partial x_i} - \frac{\partial C_i}{\partial x_i} \right] = 0 \tag{D.17}$$

Substituting eq. (D.16) into (D.17) we obtain:

$$\sum_{i=1}^{n} \frac{\partial x_i}{\partial \bar{p}} \left[(1 - \eta_i) \frac{\partial B}{\partial X} - (1 - \gamma_i)\bar{p} \right] = 0 \tag{D.18}$$

Solving for $\bar{p}$:

$$\bar{p} = \frac{\sum_{i=1}^{n} \frac{\partial x_i}{\partial \bar{p}} (1 - \eta_i)}{\sum_{i=1}^{n} \frac{\partial x_i}{\partial \bar{p}} (1 - \gamma_i)} \frac{\partial B}{\partial X} \tag{D.19}$$

Proof of Proposition 4

Given that at the social optimum $\frac{\partial D_i(x_i^*)}{\partial x_i} \geq 0 \; \forall i$, under *Quantity & Quantity* regulation the socially optimal equilibrium implies that all states exert restrictive policies, $\bar{x}_i = x_i^* \; \forall i$. National and state-level policies are defined as in Case R by eq. (D.16) and (D.19). These are identical to eq. (A.4) and (A.7) such that the efficiency condition of Proposition 1 applies. The national tender volume must not bind such that the national government chooses $\bar{X} \geq X^*$.

Precisely, if at the social optimum for only one state $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$ applies, then *Quantity & Quantity* regulation can still implement the social optimum: Suppose that $\gamma_i = \frac{x_i^*}{X^*} \; \forall i$ and that the national government sets $\bar{X} = X^*$. According to eq. (D.4) for $p^N = \frac{\partial B(X^*)}{\partial X}$ all states would implement first-best RE deployment, except for state j where $x_j < \bar{x}_j = x_j^*$ would ensue (see

Case A). Since at this point the market is not cleared, $\sum_{i=1}^{n} x_i < \bar{X} = X^*$, the clearing price would rise until $\sum_{i=1}^{n} x_i = \bar{X} = X^*$. As a result states enlarge their quantity caps such that $\sum_{i=1}^{n} \bar{x}_i > X^* \; \forall i$. To achieve first-best RE deployment in state j the clearing price must satisfy $p^N = \frac{\partial B(X^*)}{\partial X} - \frac{\partial D_j(x_j^*)}{\partial x_j} = \frac{\partial C_j(x_j^*)}{\partial x_j}$. Therefore, burden shares of all other (restrictive) states need to be adjusted to this level of p^N. State-specific RE deployment in equilibrium is determined through $p^N = \frac{\partial C_j(x_j^*)}{\partial x_j}$ in state j and through eq. (D.4) in all other states. Combining these two equations and rewriting gives:

$$\frac{\partial D_i}{\partial x_i} + \frac{\partial C_i}{\partial x_i} - \frac{\partial p^N}{\partial x_i}(x_i - \gamma_i \bar{X}) = \frac{\partial C_j}{\partial x_j} \qquad \forall i \neq j \tag{D.20}$$

Plugging the condition for the social optimum eq. (4) into (D.20) leads to an adjusted efficiency condition:

$$\gamma_i = \frac{x_i^*}{X^*} - \frac{\frac{\partial D_j(x_j^*)}{\partial x_j}}{\frac{\partial^2 C_j}{\partial x_j^2} X^*} \qquad \forall i \neq j \tag{D.21}$$

In comparison to Proposition 3, the burden shares of restrictive states are adjusted according to the marginal regional externality in the ambitious state at the social optimum $\frac{\partial D_j(x_j^*)}{\partial x_j}$. Since $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$, the adjusted efficient burden shares of restrictive states are higher, $\gamma_i > \frac{x_i^*}{X^*} \; \forall i \neq j$, and the adjusted efficient burden share of the ambitious state is lower, $\gamma_j < \frac{x_j^*}{X^*}$, and p^N is higher, $p^N > \frac{\partial B(X^*)}{\partial X}$ compared to Proposition 3. By configuring burden shares according to eq. (D.21) the social optimum is implemented in equilibrium. However, this is only true if at the social optimum $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$ solely applies for one state. If the latter applies for more than one state, the social optimum is not attainable under *Price & Quantity* regulation. If for more than one state $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$, then by eq. (D.20) this would require that at the social optimum we would have $\frac{\partial C_{j'}}{\partial x_{j'}} = \frac{\partial C_{j''}}{\partial x_{j''}} \; \forall j', j''$ for all states where $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$. That is only true by chance. Precisely, at the same time for all states where $\frac{\partial D_j(x_j^*)}{\partial x_j} < 0$ applies we would also need $\frac{\partial D_{j'}}{\partial x_{j'}} = \frac{\partial D_{j''}}{\partial x_{j''}} \; \forall j', j''$.

Appendix E Simulation of First-best RE Deployment in Germany

We assume quadratic cost and benefit functions for our numerical example. To generate the state-specific external cost (disamenities) functions, we assume $D_i(x_i)$ to be of the form:

$$D_i = \delta_i x_i^2 \tag{E.1}$$

To generate the state-specific power production cost functions, we assume $C_i(x_i)$ to be of the form:

$$C_i = \zeta_i^1 x_i + \zeta_i^2 x_i^2 \tag{E.2}$$

x_i represents the total amount of electricity produced from wind energy in state i in unit kWh. D_i and C_i represent total costs of wind energy deployment in state i in unit €.

We use data on the amount of power production (x_i), the annual residential costs (D_i) and the annual power production costs (C_i) at 106,000 potential wind turbine sites in Germany from (Tafarte et al., 2019). Taking the first derivative of eq. (E.1) and (E.2) w.r.t. x_i, we estimate δ_i respectively ζ_i^1 and ζ_i^2 by running a simple linear regression analysis in R (using the *lm*-command). Table 4 presents the results.

Table 4 *State-specific power production costs and residential costs of onshore wind energy deployment in Germany*

State	External Costs δ_i	Power Production Costs ζ_i^1	ζ_i^2	First-Best x_i^* (in TWh)
Baden-Wuerttemberg	4.47×10^{-12}	0.062	9.24×10^{-13}	1.677
Bavaria	2.29×10^{-12}	0.052	6.67×10^{-13}	4.748
Berlin	5.14×10^{-8}	0.06	3.86×10^{-10}	0
Brandenburg	2.19×10^{-13}	0.046	1.35×10^{-13}	48.154
Bremen	7.86×10^{-9}	0.051	1.32×10^{-11}	0.002
Hamburg	5.53×10^{-8}	0.057	0	0
Hesse	2.02×10^{-12}	0.046	4.79×10^{-13}	6.817
Mecklenburg-Vorpommern	2.15×10^{-13}	0.042	7.09×10^{-14}	66.641
Lower Saxony	4.20×10^{-13}	0.04	1.06×10^{-13}	38.076
North Rhine-Westfalia	1.05×10^{-11}	0.05	7.66×10^{-13}	1.33
Rhineland-Palatinate	4.68×10^{-12}	0.049	1.26×10^{-12}	2.617
Saarland	3.28×10^{-10}	0.068	2.41×10^{-11}	0.017
Saxony	1.98×10^{-12}	0.038	5.76×10^{-13}	8.215
Saxony-Anhalt	3.94×10^{-13}	0.049	8.45×10^{-14}	32.485
Schleswig-Holstein	1.96×10^{-12}	0.041	3.38×10^{-13}	8.517
Thuringia	1.59×10^{-12}	0.046	3.94×10^{-13}	8.607

Based on these estimations, we calculate states' first-best RE deployment levels $\boldsymbol{x}^*$ following eq. (4). Hereto, we assume that the marginal nationwide benefit $\frac{\partial B}{\partial X}$ from substituting one kWh from fossil power production by one kWh from wind energy deployment is linearly decreasing in X. Implicitly, we thus assume that the most harmful fossil sources are replaced first (e.g. lignite). In 2019 German fossil power plants produced 243 TWh of electricity. On average, lignite plants list highest in CO_2 emission intensity of power production ($1,137\ gCO_2/kWh$) and gas plants record lowest ($399\ gCO_2/kWh$) (German Environment Agency, 2020, p. 16). Assuming emission intensity of substituted power plants is linearly decreasing and social cost of carbon (SCC) amount to 180 €$/tCO_2$ or equivalently 0.00018 €$/gCO_2$ (German Environment Agency, 2020, p. 26), the benefit function is specified as follows:

$$B = \beta^1\ X - \frac{1}{2}\beta^2\ X^2 \tag{E.3}$$

where the parameters are calculated by:

$$\beta^1 = 0.00018 \text{ €}/gCO_2 \times 1,137 \ gCO_2/kWh = 0.20466 \text{ €}/kWh \tag{E.4}$$

$$\beta^2 = \frac{0.00018 \text{ €}/gCO_2 \times (1,137 - 399) \ gCO_2/kWh}{243 \times 10^9 \ kWh} = 5.467 \times 10^{-13} \text{ €}/kWh^2 \tag{E.5}$$

Simulating first-best wind energy deployment for Germany gives the nationwide socially optimal power production of $X^* = 227.903 \ TWh$ (see Table 4). This corresponds to a marginal benefit of $\frac{\partial B(X^*)}{\partial X} = 0.20466$ €$/kWh$. Of course, the level of SCC is uncertain and possibly below 180 €$/tCO_2$. However, the relative distribution of RE deployment across the German states presented in Table 3 and 4 remains similar.

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