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Abstract

To ensure security of supply in liberalized electricity markets, different types of capacity mechanisms are currently being debated or have recently been implemented in many European countries. The purpose of this study is to analyze the cross-border effects resulting from different choices on capacity mechanisms in neighboring countries. We consider a model with two connected countries that differ in the regulator's choice on capacity mechanism, namely strategic reserves or capacity payments. In both countries, competitive firms invest in generation capacity before selling electricity on the spot market. We characterize market equilibria and find the following main result: While consumers' costs may be the same under both capacity mechanisms in non-connected countries, we show that the different capacity mechanisms in interconnected countries induce redistribution effects. More precisely, we find that consumers' costs are higher in countries in which reserve capacities are procured than in countries in which capacity payments are used to ensure the targeted reliable level of electricity.

Keywords: Electricity Markets, Capacity Mechanisms, Cross-Border Effects

JEL codes: D47, Q41

1 Introduction

Ensuring adequate generation capacity to meet high security of supply targets in liberalized electricity markets is of major concern to many policymakers. To improve security of supply, different forms of capacity mechanisms are currently being debated or have recently been implemented in many European countries. Capacity mechanisms are mainly chosen on a national basis; however, the implementation of

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the Internal Energy Market in Europe has opened up national markets and induced increasing interdependence, allowing for neighboring countries to be affected by such interventions.[1] Therefore, the European Commission (2013) claims: "Any back-up capacity mechanism should not be designed having only the national market in mind but the European perspective."

The need for capacity mechanisms has been controversially discussed in the literature on electricity market regulation.[2] The main arguments for why security of supply may be endangered in liberalized electricity markets are as follows: First, the price-inelasticity of the fluctuating electricity demand may cause blackouts if capacity becomes scarce. Second, the specific price volatility in electricity markets and market rules such as price caps lower the prospect of price signals leading to sufficient investments in capacity. Hence, different capacity mechanisms are intensively discussed to overcome such imperfections in electricity markets.[3] Although capacity mechanisms take many forms, we merge them into two main groups: strategic reserves and capacity payments. Strategic reserves are generation capacities procured and controlled by a regulator and are only used in times of scarcity. This means that strategic reserves are withheld from the market and only used in case of supply shortages or are alternatively bid into the market at a (high) trigger price.[4] Capacity payments are fees that are paid for capacity to ensure sufficient investments. These fees can either be fixed directly by the regulator or be determined in capacity markets in which the target capacity is fixed.[5] In contrast to strategic reserve capacities, these capacities participate in the wholesale market.

The purpose of this paper is to understand the cross-border effects of different capacity mechanisms in neighboring countries. We investigate such effects by considering a model with two countries, interconnected by some given transmission capacity, that are symmetric in the sense that both countries face the same fluctuating price-inelastic electricity demand. Competitive firms can freely enter the market and invest in generation capacities before selling electricity on the spot market. Spot market prices deviate from marginal generation costs only in times of scarcity; how-

[1] In February 2014, the day-ahead market coupling in the North-West region of Europe began covering 75% of the European power market. Since then, 15 European countries have become closely interlinked. See, e.g., Agency for the Cooperation of Energy Regulators (2014).

[2] See, for example, Hogan (2005), Joskow (2008) and Cramton and Stoft (2005).

[3] See, for example, De Vries and Neuhoff (2004), De Vries (2007), Finon and Pignon (2008), Cramton and Stoft (2008) and Cramton and Ockenfels (2012).

[4] Strategic reserves are used, for example, in Sweden and Finland.

[5] Different forms of capacity markets exist. In some capacity markets, the required target capacity is centrally fixed and procured (e.g., by the regulator) in an auction. The uniform auction price then corresponds to the capacity payments. Alternatively, suppliers may be obliged to buy certificates of previously certified generation capacities. In that case, the certificate price corresponds to the capacity payments. Capacity markets are in a planning stage, for example, in Great Britain, Italy and France.

ever scarcity prices are too low to allow for a full recovery of fixed costs of that amount of capacities that is necessary to ensure an exogenously determined reliability level of electricity. To overcome the resulting "missing money problem", one country employs strategic reserves, while the other country uses capacity payments. We find the following main result: Even though in isolation both forms of capacity mechanisms lead to an efficient generation mix and identical costs in both countries, in interconnected countries the different capacity mechanisms result in redistribution effects such that the country with strategic reserves is worse off. More precisely, the consumers' costs are higher in the country with strategic reserves than in the country that uses capacity payments to ensure the capacity target.

The main intuition for this result is as follows: For a fixed target capacity, firms' revenue streams to cover total costs must either come from the capacity mechanism or from the spot market, i.e., any profits that firms earn on the spot market reduce the amount that consumers need to pay via a capacity mechanism. Capacity payments do not limit the participation of firms on the spot markets, while strategic reserves are withheld from the market and only used in times of scarcity. Consider demand realizations such that demand can be satisfied across both countries, but in doing so, some - but not all - capacity from the strategic reserves is required. As a result, prices are high in at least the country with strategic reserves and trigger electricity imports. Hence, a part of the high payments for electricity consumption by the consumers in the country with strategic reserves is not earned by the country's own firms but "leaks" over the other country with capacity payments and contributes to the financing of the other country's firms, hence reducing its consumers' costs.

Investments in capacity in competitive electricity markets and capacity mechanisms have been studied by Joskow and Tirole (2007) and Borenstein and Holland (2005). Joskow and Tirole (2007) discuss optimal prices and investments in electricity systems in which load serving entities can commit to price-contingent rationing contracts with (price-insensitive) retail consumers. They analyze the effects of price caps, capacity obligations and capacity prices in such markets. They find that price caps may lead to underinvestment, while capacity obligations in combination with capacity payments can restore investments. Borenstein and Holland (2005) also analyze investments in markets in which many consumers face flat-rate prices and hence do not react to real-time prices. They discuss the effect of capacity subsidies and demonstrate that they do not lead to the (second-best) market optimum. The effects of capacity mechanisms on the market structure, i.e., on the market shares of dominant and competitive firms, have been discussed by Elberg and Kranz (2014). Similarities to their model are given by the pricing on the spot market and the consideration of free entry in our model; however we only consider competitive firms.

We contribute to this existing literature by analyzing cross-border effects of capacity mechanisms in competitive electricity markets.

The remainder of this paper is structured as follows: In Section 2, we introduce the model. In Section 3 we discuss a simple numerical example to provide some basic intuition for key effects of the model. Cross-border effects of capacity mechanisms on market equilibria and the distribution of costs are discussed in Section 4. In Section 5, we show the robustness of the results for the case of two (base and peak load) technologies. Section 6 concludes. Proofs are relegated to the Appendix.

2 The Model

We consider a model with two countries A and B that are connected by (exogenously) given cross-border transmission capacity $\alpha \geq 0$. In both countries, competitive firms can freely enter the market and invest in generation capacity, anticipating the price-inelastic fluctuating electricity demand, and thereafter compete in the electricity spot market.

Firms in countries A and B build up their capacities $x_A \in [0,1]$ and $x_B \in [0,1]$, respectively. The constant fixed costs per unit of capacity are denoted by $k \in \mathbb{R}^+$, and the variable costs of production are given by $c \in \mathbb{R}^+$.

The electricity demand is given by non-negative random variables D_A and D_B for countries A and B, respectively. The joint electricity demand is given by $D := D_A + D_B$, with the corresponding joint distribution function G and continuously differentiable density function g. We normalize the random variable D to the unit interval and assume that $g(D) > 0$ for all $D \in [0,1]$. One can think of G as the distribution of demand over a large period of time in which spot market competition with given capacities takes place.

Since we want to focus our analysis on the effect of the choice of different capacity mechanisms, we assume that both countries are perfectly symmetric in the sense that they face identical demand for electricity, $D_A = D_B = \frac{D}{2}$, and target the same reliability level of electricity, i.e., the probability that no power outage ("blackout") occurs due to insufficient capacity. In our model, fixing a reliability level is equivalent to fixing the corresponding capacity in the market. Both countries ensure the same capacity level $x_A^T = x_B^T \in \left[0, \frac{1}{2}\right]$. The countries A and B only differ in the choice of capacity mechanism: Strategic reserves are procured in country A, while capacity payments are used in country B to ensure this capacity target.

Strategic reserves are generation capacities procured and controlled by a regulator and are only used in case of scarcity, i.e., when a supply shortage occurs or the spot market price rises above a previously determined trigger price. Strategic reserves are used to fill the gap between the capacity that is built (and participate) in the market x_A and the target capacity x_A^T. In country A, the regulator procures strategic reserves of size x_A^R that satisfy

$$x_A^T = x_A + x_A^R.$$

Capacity payments z are fees that are uniformly paid according to each capacity unit to achieve the capacity target. The regulator in B fixes capacity payments

$$x_B^T = x_B\left(z\right).$$

The total capacity for both countries is then given by $x^T = x_A^T + x_B^T$.

Firms offer electricity on the spot market, knowing the realization of demand. When there is sufficient capacity available to cover the demand, competition drives prices down to marginal costs c. Otherwise, electricity is scarce and the maximum price $\bar{P} > c$ is reached.[6,7] The maximum price $\bar{P}$ refers either to a price cap fixed by a regulator or to the value of lost load (VOLL) that denotes the maximal amount customers are willing to pay for electricity.

Cross-border trading impacts the spot market prices as follows: When the transmission capacity α is non-binding, cross-border trading leads to equal prices in both markets, i.e., either there is sufficient capacity to cover the demand in A and B or scarcity prices occur in both markets. However, if α is a binding restriction, the prices in A and B may differ.

We assume that the trigger price of the strategic reserves equals the maximum price $\bar{P}$, i.e., strategic reserves do not push prices below the maximum price. Strategic reserves are only used if there is not sufficient (generation or transmission) capacity participating in the market to cover demand.

2.1 Spot Market Competition and Investments

We start by analyzing the spot market and its outcome. Since both countries target the same capacity level $x_A^T = x_B^T$, but country A's strategic reserves x_A^R do not participate in the spot market while in B the whole capacity $x_B^T = x_B$ participates, we restrict our attention to the case that $x_A \leq x_B$. The spot market prices behave as

[6] We assume that a partial blackout occurs, if electricity demand exceeds supply. In this case, there will be exactly so many consumers cut off from the electricity supply such that the remaining consumption equals the given supply.

[7] We assume that scarcity prices occur if and only if capacity is equal to or less than demand. One could expect scarcity prices to occur if there is just enough capacity, i.e., ϵ more than needed. However, in this case, the given capacity would change by the constant amount ϵ and our results would be the same.

follows: When demand is less than the domestic firms' capacities in both countries, the spot market prices equal the marginal costs c. Moreover, even if the demand exceeds the domestic firms' capacities in A, the prices equal marginal costs c in both countries if the total capacity of both countries exceeds the total demand D and α is sufficiently large, i.e., $\frac{D}{2} - x_A < \alpha$. In contrast, if the total demand D exceeds the total capacities, the price equals the maximum price $\bar{P}$ in A - and if, in addition, $x_B - \frac{D}{2} \leq \alpha$, the price also rises to $\bar{P}$ in B. Obviously, scarcity prices occur in both countries when the demand exceeds the domestic capacities in both countries. More comprehensively, the spot market prices in A are given by

$$P_A = \begin{cases} \bar{P} & \text{otherwise} \\ c & \text{if } D < x_A + x_B \text{ and } \frac{D}{2} - x_A < \alpha. \end{cases} \tag{1}$$

The spot market prices in B are given by

$$P_B = \begin{cases} \bar{P} & \text{if } D \geq x_A + x_B \text{ and } x_B - \frac{D}{2} \leq \alpha \\ c & \text{otherwise.} \end{cases} \tag{2}$$

We assume that firms in both countries always receive the domestic price for selling electricity, and consumers in both countries always pay the domestic price for electricity consumption. Congestion rents, which occur when a limited α results in price differences between two markets, are shared between (the transmission system operators of) both countries equally.[8] Hence, implicitly, consumers of both countries benefit equally from congestion rents.

To avoid uninteresting case distinctions, we restrict our attention to the case $x_A + x_B \leq 1$. Independent from the realization of demand, it follows from equations (1) and (2) that α is always non-binding if $x_B - x_A \leq 2\alpha$.[9] Hence, dependent on x_A, x_B and α, we distinguish between two possible outcomes for the expected variable spot market profits per capacity unit in both countries:

Case 1. If α is at least sometimes binding, i.e., $x_B - x_A > 2\alpha$, the expected variable spot market profits per capacity unit for firms in A and B differ and are given by

$$\pi_A^S = \left(\bar{P} - c\right)\left[1 - G\left(2x_A + 2\alpha\right)\right] \tag{3}$$

$$\pi_B^S = \left(\bar{P} - c\right)\left[1 - G\left(2x_B - 2\alpha\right)\right], \tag{4}$$

[8] This is basically how congestion rents resulting from market coupling are shared, e.g., in the Central West Europe region, see CWE MC Project Group (2010).

[9] The following relationship holds: $x_A + x_B \leq 2x_A + 2\alpha \Leftrightarrow x_B - x_A \leq 2\alpha \Leftrightarrow 2x_B - 2\alpha \leq x_A + x_B$. If $x_B - x_A \leq 2\alpha$ holds, $P_A(D) = P_B(D)$ for all $D \in [0, 1]$. If $x_B - x_A > 2\alpha$ holds, $P_A = \bar{P}$ if $D \geq 2x_A + 2\alpha$ and $P_B = \bar{P}$ if $D \geq 2x_B - 2\alpha$.

respectively.

Case 2. If α is always non-binding, i.e., $x_B - x_A \leq 2\alpha$, the firms' expected variable spot market profits per capacity unit are the same in both countries A and B and are given by

$$\pi_A^S = \pi_B^S = \left(\bar{P} - c\right)\left[1 - G\left(x_A + x_B\right)\right]. \tag{5}$$

Remark 1. *If α is (sometimes) binding, the expected variable spot market profits per capacity unit are higher in country A than in country B. Moreover, π_A^S is decreasing in α and π_B^S is increasing in α.*

Since we consider competitive markets, firms enter the market until profits are driven down to zero.[10] The firms' zero profit condition in A is then given by

$$0 = k - \pi_A^S. \tag{6}$$

In B the capacity payments z that are paid for each unit of capacity impact the firms' investments. The firms' zero profit condition in B can be written as

$$z = k - \pi_B^S. \tag{7}$$

The strategic reserves are only used in times of scarcity and as mentioned above the trigger price equals the maximum price $\bar{P}$. Hence, the usage policy follows

$$q_A^R = \min\left\{x_A^R, \max\left\{0, \frac{D}{2} - x_A - \alpha, D - x_A - x_B\right\}\right\},$$

where we define q_A^R as the amount of electricity produced by the reserve capacities. Strategic reserves are given by the difference $x_A^R = x_A^T - x_A$, i.e., strategic reserves are capacities that are not worth building in the market because they would earn negative profits. Additional payments are necessary that are born by the consumers, as we discuss below.

To avoid uninteresting case distinctions, we assume that $x^T \geq 2\alpha$.[11] In addition, we make the following

Assumption 1. *The maximum spot market mark-up $\bar{P} - c$ is strictly larger than the fixed costs of capacity k.*

[10] We assume that regulators want to increase the reliability level of electricity, i.e., they choose a target capacity that is at least as large as the capacity that would have been built in the market without any capacity mechanism. To make sure that $x_A^R \geq 0$ and $z \geq 0$, we assume that $\frac{k}{\bar{P}-c} > 1 - G\left(x^T\right)$.

[11] In our model, there is no need to consider transmission capacity that is larger than the maximum generation capacity in one of the two countries.

2.2 Consumers' Costs

The consumers' costs can be split into two parts: First, consumers pay (spot market prices) for their electricity consumption. Second, the consumers have to bear the costs incurred by the capacity mechanisms, i.e., they pay for the reliability level.[12] The consumers' costs CC_A and CC_B in A and B, respectively, are given by

$$CC_A = CC_A^S + CC_A^{SR} \quad \text{and} \quad CC_B = CC_B^S + CC_B^Z, \tag{8}$$

where we define CC_A^S and CC_B^S as the costs incurred on the spot markets, CC_A^{SR} as the strategic reserves' costs and CC_B^Z as the costs arising from capacity payments. While the costs from capacity payments are simply given by

$$CC_B^Z = zx_B,$$

the costs of the strategic reserves depend on the usage of the strategic reserves:

$$CC_A^{SR} = kx_A^R - \left(\bar{P} - c\right) \mathbb{E}\left[q_A^R\left(D, x_A, x_A^R, x_B, \alpha\right)\right].$$

The consumers pay the procurement costs (defined as the fixed costs) of the strategic reserves and the generation costs. At the same time, spot market revenues generated by strategic reserve capacities are used to partially offset these costs and hence benefit the consumers.

Furthermore, congestion rents may benefit consumers by lowering their costs. These rents are shared equally between the two countries. Since we are not interested in the magnitude of consumers' costs but rather in the cost differential between consumers of both countries, we do not specify the congestion rent in our model. In the following, the consumers' costs in both countries are analyzed.

Benchmark: Non-connected countries

In order to compare both capacity mechanisms, let us consider the case in which there does not exist any transmission capacity between A and B, i.e., $\alpha = 0$.

Proposition 1. *The target reliability level is reached by capacity payments and strategic reserves. The consumers' costs are the same for both mechanisms.*

[12] Furthermore, blackout costs occur if sufficient capacity is not available to cover demand. The blackout price is at least as high as the maximum price $\bar{P}$ that occurs on the spot market (and is always finite). However, since both countries have identical demand for electricity and the same reliability level, the blackout costs are the same in both countries. We are not interested in the absolute amount of consumer cost but rather in the cost difference between the two countries; therefore we neglect these costs in our analysis.

The intuition is as follows: In our model with competitive firms and free entry, firms enter the market until profits are driven down to zero. This happens regardless of where the revenue streams come from. Hence, in both countries, the consumers pay the exact amount that is necessary to reach the previously determined capacity level.

3 A Simple Numerical Example

We discuss a simple numerical example in order to highlight some effects resulting from different capacity mechanisms in neighboring countries. Consider the two symmetric countries A and B that are connected by transmission capacity $\alpha = 0.05$. The maximum price for electricity is given by $\bar{P} = 1000$ and the firms can produce electricity at costs $c = 100$. The fixed costs are given by $k = 9$. The regulators of both countries target the same capacity level $x_A^T = x_B^T = 0.5$, i.e., total capacity is given by $x^T = 1$. While the regulator in A procures strategic reserves to reach the capacity target, the regulator in B determines capacity payments that are paid for each unit of capacity.

For the fixed target capacity, firms' revenue streams to cover total costs must either come from the spot market or from the capacity mechanism. In country A, in equilibrium the spot market revenues earned by capacity x_A are exactly as large as the firms' total costs. The costs of the strategic reserves x_A^R are born by the consumers and given by the difference between the sum of procurement (defined by the fixed costs) and generation costs and the spot market revenues. Hence, the higher the spot market revenues of the strategic reserves become, the lower the costs of the strategic reserves will be. In country B, the total costs of capacity $x_B^T = x_B$ are exactly covered by the sum of spot market revenues and capacity payments. Hence, the costs of the capacity mechanisms strongly depend on the variable spot market profits. The firms' variable spot market profits, in turn, depend not only on the domestic electricity demand but also on cross-border transmission capacity between both countries. Let us assume that in A, firms build up capacities $x_A = 0.3$ and hence the regulator procures $x_A^R = 0.2$ as strategic reserves. We split the possible spot market outcomes into three different cases:

- If demand is sufficiently small, i.e., $D < 0.7$, the spot market price equals marginal generation costs in both countries since sufficient generation capacity is built in the market or transmission capacity is available to cover total demand. In these hours, firms in both countries do not earn any profits to cover their fixed costs.

- If $0.7 \leq D < 0.9$, the prices in both countries differ. Suppose demand is given by $D = 0.8$. In country A, the price rises up to $\bar{P}$ and in country B, the price equals marginal generation costs c. To cover the demand in A, the capacities that are built in the market $x_A = 0.3$ are fully utilized, electricity is imported from country B according to the transmission capacity $\alpha = 0.05$ and the strategic reserves are used, which amounts to $q_A^R = 0.05$. Even though consumers pay the high price for $\frac{D}{2} = 0.4$, only $x_A + q_A^R = 0.35$ of A's capacity is used and profits from the high prices. The congestion rent, which results from the electricity import, is shared between both countries equally.[13] Consumers in country A pay $\bar{P}$ for each unit of electricity. However, only a fraction of the corresponding revenues is earned by the country's own firms, allowing for the reduction of ex ante payments for strategic reserve capacities. For the exports from B to A, part of the payments for electricity consumption "leaks" over country B and contributes to the financing of B's firms.

- If $0.9 \leq D < 1$, the maximum price is reached in both countries. Suppose demand is given by $D = 0.95$. In that case, B's total capacities $x_B = 0.5$ are fully utilized, while in A the capacities that are built in the market $x_A = 0.3$ are fully utilized but the strategic reserves do not operate at full capacity, $q_A^R = 0.15$. Although consumers from both countries pay the same for electricity consumption, the costs of the capacity mechanisms are reduced more in B than in A.

Hence, in this example, the consumers' costs are higher in A than in B. So far, we have not proved whether the capacities in A are equilibrium capacities, i.e., we do not know whether $x_A = 0.3$ would have been built in the market for given assumptions on $\bar{P}, c, k$ and α. To solve the problem, one has to specify the distribution of demand. Suppose the demand is beta-distributed, $D \sim Beta\,(2, 5)$; then $x_A^* \approx 0.3$ and $x_A^{R*} \approx 0.2$ are indeed equilibrium outcomes.

In the following section, we determine equilibrium outcomes for any arbitrary choice of $\bar{P}$, c, α, x^T and distribution of demand G. Furthermore, we show that the result from our example always holds, i.e., the consumers' costs for A are always higher than those for B.

4 Cross-Border Effects on Market Equilibria

In this section, we investigate cross-border effects resulting from different capacity mechanisms in the two connected countries. We henceforth assume that $\alpha > 0$. In

[13] If the congestion rent had been completely given to country A, the additional costs on the spot market due to higher prices would equal the cost reduction by the congestion rent.

particular, we are interested in the size of the strategic reserves, the capacity that is built in the market, the amount of capacity payments and the effects on consumers' costs. We can generally establish the following

Proposition 2. *Assume countries A and B use different capacity mechanisms, namely strategic reserves and capacity payments, to ensure the same reliability level. For every given combination of $\bar{P}$, c, k, any distribution of demand G, transmission capacity α and target capacity x^T, a unique market equilibrium exists. The equilibrium capacities x_A^*, x_A^{R*} and capacity payments z^* are characterized as follows:*

(i) If $1-G(2\alpha) > \frac{k}{\bar{P}-c}$ *and* $1-G\left(x^T-2\alpha\right) < \frac{k}{\bar{P}-c}$,

$$x_A^{R*} > 0, \quad x_A^* > 0 \quad \textit{and} \quad z^* > 0.$$

(ii) If $1-G(2\alpha) \leq \frac{k}{\bar{P}-c}$ *and* $2\alpha < \frac{x^T}{2}$,

$$x_A^{R*} = \frac{x^T}{2}, \quad x_A^* = 0 \quad \textit{and} \quad z^* > 0.$$

In (i) and (ii), Case 1 holds; i.e., α is sometimes binding.

(iii) If $1-G\left(\frac{x^T}{2}\right) > \frac{k}{\bar{P}-c}$ *and* $1-G\left(x^T-2\alpha\right) \geq \frac{k}{\bar{P}-c}$,

$$x_A^{R*} > 0, \quad x_A^* > 0 \quad \textit{and} \quad z^* = 0.$$

(iv) If $1-G\left(\frac{x^T}{2}\right) \leq \frac{k}{\bar{P}-c}$ *and* $2\alpha \geq \frac{x^T}{2}$,

$$x_A^{R*} = \frac{x^T}{2}, \quad x_A^* = 0 \quad \textit{and} \quad z^* > 0.$$

In (iii) and (iv), Case 2 holds; i.e., α is always non-binding.[14]

Let us first discuss (*i*) and (*ii*), i.e., the cases in which the transmission capacity α is binding. Depending on whether or not $\mathbb{P}(D > 2\alpha) > \frac{k}{\bar{P}-c}$, the equilibrium capacities in A that are built in the market are either positive or zero. The threshold value $\frac{k}{\bar{P}-c}$ can be interpreted as a measure of how severe the missing money problem is: The higher the difference between the maximum spot market mark-up $\bar{P}-c$ and the fixed costs k is, the less severe the missing money problem becomes (for a given capacity target x^T). Given the distribution of demand G and transmission capacity α, a lower threshold value leads to an equilibrium in which (positive) capacities

[14]See the proof of Proposition 2 for the equilibrium capacities in the Appendix.

are built in the market in A. In contrast, if the difference between the maximum spot market mark-up and the fixed costs is sufficiently small, all capacities in A are procured as strategic reserves. In cases (iii) and (iv), the arguments are similar. The difference in these cases is that the capacity level x^T, instead of the transmission capacity α, is crucial. Depending on whether or not the probability of demand exceeding A's target capacity is greater than the threshold value, capacity that is built in the market is positive or zero.

The intuition of this proposition is as follows: The amount of capacity that is built in A depends on the value of the spot market mark-up relative to the fixed costs and on the frequency in which high prices occur. If the maximum spot market mark-up is relatively high, sufficient variable spot market profits can be earned in peak price periods to cover the fixed costs of capacities and therefore, (positive) capacities are built in A.

Note that for case (iii) in which α is always non-binding and thus the spot market prices are always the same in both countries, some capacities are procured as strategic reserves in A, while the capacity payments in B are zero. This means that only consumers in A pay for the capacity mechanism while consumers from both countries benefit from the same reliability level and pay exactly the same amount for electricity consumption. In the following, we investigate the redistribution effects that are induced by different capacity mechanisms.

Redistribution Effects

The effects of different capacity mechanisms in two connected countries on consumers' costs can be characterized as follows:

Proposition 3. *Assume the regulator in A procures strategic reserves x_A^R while the regulator in B uses capacity payments z to ensure a total capacity level $x_A^T = x_B^T$. If $\alpha > 0$, the expected consumers' costs are higher in A than in B, i.e., $CC_A > CC_B$.*

Intuition for why the consumers' costs in A are higher than in B: Given a fixed capacity target x_B^T, higher expected variable profits π_B^S lead to a reduction of capacity payments z and vice versa. That is, firms in B earn profits if $P = \bar{P}$, and the amount of capacity payments is reduced exactly by the amount of profits that firms earn during these peak price periods. Accordingly, the capacity payment costs for consumers in B are reduced. Similarly, the strategic reserve costs for consumers in A are reduced by the amount of profits of the strategic reserves. Since both countries have the same amount of capacity and, in country A a part of its capacities are procured as strategic reserves, peak price periods occur either in both countries or only in country A. If the peak price occurs only in country A, electricity is imported from country B according to the transmission capacity α and congestion rents are split equally, i.e., country B benefits from the congestion rents that are paid by A's consumers. If peak prices occur, in both countries which is, e.g., the case if α is non-binding, the capacities x_A and x_B are both fully utilized. However, if demand is less than total capacity $x^T = x_A^T + x_B^T$, the strategic reserves x_A^R by definition do not operate at full capacity. It follows that the average utilization of capacity in B is higher than in A during peak price periods. If α is non-binding, consumers in both countries pay the same for electricity consumption. Consumers in B benefit from peak prices due to reduced capacity payments, while the costs of the strategic reserves in A decrease to a lesser extent. Hence, on average, the consumers' costs in A are higher than in B.

This intuition is quite robust: Even if we had an elastic electricity demand the expected variable spot market profits per capacity unit would be higher in the country with capacity payments than in the country with strategic reserves during peak price periods. This intuition also holds true if demand for electricity varies between both countries. If prices are high the strategic reserves is still the last resort that is used to cover demand. This negatively impacts the consumer costs of the country with strategic reserves.

Remark 2. *Proposition 3 shows that different capacity mechanisms in two connected countries induce redistribution effects and hence impact the welfare of each country. However, total welfare does not change: Regardless of whether both countries choose strategic reserves, capacity payments, or one chooses capacity payments and the other procures strategic reserves, the total welfare remains the same.*

5 Base and Peak Load Technologies

This section studies the robustness of our results regarding the redistribution effects of different capacity mechanisms for the case of two technologies. Firms in both countries A and B invest in two different technologies $x_A, x_B \in [0,1]$ and $x_A^1, x_B^1 \in [0,1]$, i.e., base and peak load technologies, respectively. The investment and marginal generation costs are denoted by $k, c \in \mathbb{R}^+$ and $k^1, c^1 \in \mathbb{R}^+$ for base load (BL) and peak load (PL) technologies, respectively. Base load technologies are characterized by higher fixed costs and lower marginal generation costs compared to peak load technologies, i.e., $k > k^1$ and $c < c^1$. Investments into a generation mix are reasonable due to the fluctuating demand: While base load capacities produce relatively cheaply but have to run many hours to cover the high investment costs, peak load capacities are cheap to build but have high marginal generation costs and hence operate only in times of high demand. To avoid uninteresting case distinctions, we restrict our attention to the case in which it is worth investing in both technologies and henceforth make the following

Assumption 2. *The maximum spot market mark-up $\bar{P}-c^1$ is strictly larger than the fixed costs of the peak load capacity k^1, and the difference in marginal generation costs c^1-c of both technologies is strictly larger than the difference in fixed costs $k-k^1$. In order to ensure that it is reasonable to invest in a generation mix, $\frac{k-k^1}{c^1-c} > \frac{k^1}{\bar{P}-c}$ must hold.*

In this extension, we restrict our analysis to the case in which the transmission capacity α is sufficiently large such that it is always non-binding.

We start by characterizing the spot market and its outcome. Firms offer electricity on the spot market knowing the realized demand. When there is sufficient base load capacity available to cover demand, competition drives prices down to marginal costs c. Correspondingly, when demand exceeds the base load capacity but is less than the sum of the base and peak capacities, the price $c^1 > c$ is reached. If capacity is scarce, the maximum price $\bar{P} > c^1$ occurs. Since we assume that there is sufficient transmission capacity α, the spot market prices are always the same in both markets and characterized by

$$P_A = P_B = \begin{cases} c & \text{if } D < x_A + x_B \\ c^1 & \text{if } x_A + x_B \leq D < x_A + x_B + x_A^1 + x_B^1 \\ \bar{P} & \text{otherwise.} \end{cases} \tag{9}$$

The spot market profits per capacity unit for base and peak load capacities are then given by

$$\begin{aligned} \pi^s_{BL_A} = \pi^s_{BL_B} &= \left(\bar{P}-c\right) - \left(\bar{P}-c_1\right) G\left(x_A + x_B + x_A^1 + x_B^1\right) - \left(c_1 - c\right) G\left(x_B + x_A\right) \\ \pi^s_{PL_A} = \pi^s_{PL_B} &= \left(\bar{P}-c_1\right)\left(1 - G\left(x_A + x_B + x_A^1 + x_B^1\right)\right), \end{aligned}$$

respectively.

As in the main model, we assume that both countries encourage the same capacity level $x_A^T = x_B^T \in \left[0, \frac{1}{2}\right]$, and total capacity is given by $x^T = x_A^T + x_B^T$. The regulator in A procures strategic reserves $x_A^R \geq 0$, while the regulator in B fixes capacity payments $z \geq 0$ to ensure the capacity level.[15] The total capacities in A and B are

[15] We assume that the regulators want to increase the reliability level of electricity, i.e., they choose a target capacity that is at least as large as the capacity that would have been built in the market without any capacity mechanism. To make sure that $x_A^R \geq 0$ and $z \geq 0$, we assume that $\frac{k^1}{\bar{P}-c^1} > 1 - G\left(x^T\right)$.

then given by

$$x_A^T = x_A + x_A^1 + x_A^R \quad \text{and} \quad x_B^T = x_B(z) + x_B^1(z).$$

Since we consider competitive markets, firms enter the market until profits are driven down to zero. The firms' zero profit conditions in A for base and peak load technologies are given by

$$\begin{aligned} 0 &= k - \pi_{BL_A}^s \\ 0 &= k^1 - \pi_{PL_A}^s, \end{aligned}$$

respectively. The firms' zero profit conditions in B for base load and peak load technologies are given by

$$\begin{aligned} 0 &= k - \pi_{BL_B}^s - z \\ 0 &= k^1 - \pi_{PL_B}^s - z, \end{aligned}$$

respectively.

Benchmark: One capacity mechanism for both countries

In order to compare both capacity mechanisms, let us consider the case in which regulators of both countries choose the same capacity mechanism.

Proposition 4. *Assume the regulators choose the same capacity mechanism. Both capacity mechanisms are efficient in the sense that they ensure the target capacity level with minimal costs. The total equilibrium base load capacity is given by*

$$x_A^* + x_B^* = G^{-1}\left(1 - \frac{k - k^1}{c^1 - c}\right).$$

The consumers' costs are the same for both mechanisms.

Interestingly, the equilibrium base load capacity $x_A^* + x_B^*$ neither depends on the target capacity level x^T, nor on the choice of capacity mechanism, nor on the maximum price $\bar{P}$.[16] The efficient amount of base load capacity is solely determined by the relation between fixed costs and variable generation costs between base and peak load technologies. The reason is as follows: Since we assume that it is worth it to invest in both technologies (by Assumption 2), peak load capacity is needed

[16] Zoettl (2011) analyzes the impact of reduced scarcity prices on investment incentives in electricity markets with imperfect competition. In this model, the chosen limit on prices also leaves the amount of base load technology unchanged.

that operates so infrequently that its fixed cost advantage over base load capacity dominates the disadvantage of higher generation costs. If the regulators want to increase the reliability level of electricity and fix a capacity target $x^T = x_A^T + x_B^T$, the additional capacity units are used even less and hence peak load capacities are built to reach the target. This holds for both mechanisms. Since the total capacity is fixed and the firms' profits are zero, the consumers' costs remain the same.

Cross-border effects of capacity mechanisms in neighboring countries

From now on, we investigate cross-border effects resulting from different capacity mechanisms in the two fully connected countries. We can establish the following

Proposition 5. *Assume the regulator in A procures strategic reserves x_A^R, while the regulator in B uses capacity payments z to ensure the capacity level $x_A^T = x_B^T$, and both countries are fully connected. The equilibrium capacities are characterized as follows:*

(i) If $1 - G\left(\frac{x^T}{2}\right) > \frac{k^1}{\bar{P}-c^1}$,

$$x_A^{R*} > 0, \quad x_A^* + x_A^{1*} > 0 \quad \textit{and} \quad z^* = 0.$$

(ii) If $1 - G\left(\frac{x^T}{2}\right) \leq \frac{k^1}{\bar{P}-c^1}$,

$$x_A^{R*} = \frac{x^T}{2}, \quad x_A^* = x_A^{1*} = 0 \quad \textit{and} \quad z^* > 0.$$

In (i) and (ii), the total base load capacity is independent of the total capacity level x^T and the maximum price $\bar{P}$ and is given by $x_A^* + x_B^* = G^{-1}\left(1 - \frac{k-k^1}{c^1-c}\right)$.

As in Proposition 4, the total equilibrium base load capacity is independent of the choice of capacity mechanism: It is exactly equal to the amount of base load capacity that would have been built in the market without any capacity mechanism. However, the amount of peak load capacity depends on the target capacity level. Depending on whether or not $\mathbb{P}\left(D > \frac{x^T}{2}\right) > \frac{k^1}{\bar{P}-c^1}$, the equilibrium capacities in A that are built in the market are positive or zero. The threshold value $\frac{k^1}{\bar{P}-c^1}$ indicates how severe the missing money problem is, i.e., the maximum spot market mark-up $\bar{P} - c^1$ relative to the fixed costs of the peak capacity k^1 is crucial for the amount of capacity that is procured as strategic reserves. Given the distribution of demand and the target capacity x^T, a higher threshold value leads to the case in which the whole capacity in A has to be procured as strategic reserves.

Note, that in case (ii), each unit of the total base load capacity receives capacity payments. In both cases, only peak load capacity is procured as strategic reserve. The redistribution effects that are induced by the choice of different capacity mechanisms in connected countries can be characterized as follows:

Proposition 6. *Assume the regulator in A procures strategic reserves x_A^R, while the regulator in B uses capacity payments z to ensure the capacity level $x_A^T = x_B^T$, and both countries are fully connected. The expected consumers' costs are higher in A than in B.*

The intuition for this result is similar to that in the case of one technology: In peak price periods, the total capacity $x_B^T = x_B + x_B^1$ and the capacities x_A, x_A^1 that are built in the market are fully utilized. However, if demand is less than total capacity, the strategic reserves x_A^R do not operate at full capacity in these periods. Even though the electricity consumption costs are equal, firms' expected variable spot market profits per capacity unit are higher in B than in A. Hence, the consumers' costs from strategic reserves are higher than capacity payment costs.

Corollary 1. *Regardless of whether regulators of both countries choose strategic reserves, capacity payments or one chooses capacity payments and the other procures strategic reserves, the joint welfare remains the same.*

6 Conclusion

It has been the purpose of this study to understand the cross-border effects of different capacity mechanisms in neighboring countries. For our analysis, we have chosen a model with two symmetric countries that are connected by some given transmission capacity. Both countries only differ in their regulator's choice of capacity mechanisms, namely strategic reserves or capacity payments. In both countries, competitive firms can freely enter the market and invest in generation capacities before selling electricity on the spot market, which is characterized by fluctuating price-inelastic electricity demand. We have characterized different market equilibria and found the following main result: Even if both forms of capacity mechanisms lead to an efficient generation mix and induce the same consumer costs in non-connected countries, different capacity mechanisms lead to redistribution effects for interconnected countries. The country with strategic reserves is worse off; more precisely, the consumers' costs are higher in the country with strategic reserves than in the country with capacity payments. We have shown that this result holds robustly for the case of two technologies.

The main effect that drives this result comes from the fact that strategic reserves are used only if electricity import is limited by transmission capacity or no sufficient (other) capacities are available. Hence, in times of scarcity when demand is less than total capacity, part of the high payments for electricity consumption in the country with strategic reserves are not earned by the country's own firms but "leaks" over to the country with capacity payments and implicitly benefits its consumers. In our model, we have chosen completely symmetric countries in order to point out the effects resulting from different capacity mechanisms. However, this effect should have more general implications: First, even if we had an elastic electricity demand or demand varied between both countries, the average capacity utilization during peak price periods in which the transmission capacity is non-binding would be higher for the country with capacity payments than in the country with strategic reserves. Second, even if the maximum price varied between the two countries and was, e.g., lower in the country with capacity payments, the consumers who pay capacity payments would benefit from the fact that strategic reserves are only used as a last resort.

The result we established may be informative for the policy debate surrounding the design of capacity mechanisms and the effects for the internal market in Europe. In this discussion, one should take into account that such policy interventions may lead to redistribution effects. Redistribution may affect the choice of capacity mechanism as well as the cooperation between different countries. It is clear that cross-border trading can be beneficial for the countries involved and reduce consumers' costs, e.g., through increased competition or a better technology mix that lowers the costs of production. However, the cross-border effects resulting from the choice of different capacity mechanisms can induce negative welfare effects for individual countries, as shown in our analysis.

In our analysis, we have chosen a theoretical model to investigate the cross-border effects of different capacity mechanisms in neighboring countries to clearly point out the factors that drive these effects. Further research could quantify the equilibrium investments and the redistribution effects for an existing market. This would be very interesting in light of the recently introduced market coupling in the North-West region of Europe and the different capacity mechanisms that are currently being implemented.

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Appendix

The Appendix contains all proofs of the paper.

Proof of Proposition 1.
From equation (6) follows that the firms' zero profit condition in A is given by

$$0 = \left(\bar{P} - c\right)\left(1 - G\left(2x_A\right)\right) - k.$$

The unique equilibrium capacity is then given by $x_A^* = \frac{1}{2}G^{-1}\left(1 - \frac{k}{\bar{P}-c}\right)$ since x_{A}^* is the unique solution of the firms' zero profit condition and $x_A^* > 0$. The target capacity is given by $x_A^T = \frac{x^T}{2}$. The difference $x_A^T - x_A^* = x_A^{R*}$ determines the reserve capacity. The electricity consumption costs are given by

$$CC_A^S = c\int_0^{2x_A^*} \frac{D}{2} g\left(D\right)dD + \bar{P}\left(\int_{2x_A^*}^{x^T} \frac{D}{2} g\left(D\right)dD + \frac{x^T}{2}\left(1 - G\left(x^T\right)\right)\right). \quad (10)$$

The costs from the strategic reserves are given by

$$CC_A^{SR} = kx_A^{R*} - \left(\bar{P} - c\right)\left(\int_{2x_A^*}^{x^T}\left(\frac{D}{2} - x_A^*\right)g\left(D\right)dD + x_A^R\left(1 - G\left(x^T\right)\right)\right). \quad (11)$$

The consumers' costs are given by $CC_A = CC_A^S + CC_A^{SR}$. Plugging x_A^* into equations (10) and (11) leads to

$$CC_A = c\left(\int_0^{x^T} \frac{D}{2} g\left(D\right)dD + \frac{x^T}{2}\left(1 - G\left(x^T\right)\right)\right) + k\frac{x^T}{2}.$$

Let us consider country B. For a given capacity level $x_B^T = \frac{x^T}{2}$, we can argue from equation (7) that the capacity payments are given by

$$z = k - \left(\bar{P} - c\right)\left(1 - G\left(x^T\right)\right).$$

The electricity consumption costs are given by

$$CC_B^S = \frac{c}{2}\int_0^{x^T} Dg\left(D\right)dD + \bar{P}\frac{x^T}{2}\left(1 - G\left(x^T\right)\right).$$

The capacity payment costs are given by

$$CC_B^Z = zx_B = \left(k - \left(\bar{P} - c\right)\left(1 - G\left(x^T\right)\right)\right)\frac{x^T}{2}.$$

The consumers' costs are given by $CC_B = CC_B^S + CC_B^Z$. Summing up leads to

$$CC_B = \frac{c}{2}\left(\int_0^{x^T} Dg\left(D\right)dD + x^T\left(1 - G\left(x^T\right)\right)\right) + k\frac{x^T}{2}.$$

Hence, we have shown that $CC_A = CC_B$ holds.

Proof of Proposition 2.

For the proof of Proposition 2, we show first the following

Lemma. *For every choice of $\bar{P}$, c, k, G, α and x^T, one and only one of the following conditions holds:*

(i) $1 - G\left(2\alpha\right) > \frac{k}{\bar{P}-c}$ *and* $1 - G\left(x^T - 2\alpha\right) < \frac{k}{\bar{P}-c}$

(ii) $1 - G\left(2\alpha\right) \leq \frac{k}{\bar{P}-c}$ *and* $2\alpha < \frac{x^T}{2}$

(iii) $1 - G\left(\frac{x^T}{2}\right) > \frac{k}{\bar{P}-c}$ *and* $1 - G\left(x^T - 2\alpha\right) \geq \frac{k}{\bar{P}-c}$

(iv) $1 - G\left(\frac{x^T}{2}\right) \leq \frac{k}{\bar{P}-c}$ *and* $2\alpha \geq \frac{x^T}{2}$.

Proof. First, we show that only one of the four conditions can hold: Obviously, only one of the conditions (i) and (ii), one of the conditions (i) and (iii), one of the conditions (ii) and (iv), as well as only one of the conditions (iii) and (iv) can hold. Hence, we have to show that only one of the conditions (i) and (iv) as well as only one of the conditions (ii) and (iii) can hold: From (i) follows that $1 - G\left(2\alpha\right) > \frac{k}{\bar{P}-c} > 1 - G\left(x^T - 2\alpha\right) \Rightarrow x^T - 2\alpha > 2\alpha \Rightarrow \frac{x^T}{2} > 2\alpha$. Hence, (iv) does not hold. From (iv) follows that $1 - \frac{k}{\bar{P}-c} \leq G\left(\frac{x^T}{2}\right) \leq G\left(2\alpha\right) \Rightarrow 1 - G\left(2\alpha\right) \leq \frac{k}{\bar{P}-c}$. Hence, (i) does not hold. From (ii) follows that $G\left(\frac{x^T}{2}\right) > G\left(2\alpha\right) \geq 1 - \frac{k}{\bar{P}-c} \Rightarrow \frac{k}{\bar{P}-c} \geq 1 - G\left(\frac{x^T}{2}\right)$. Hence, (iii) does not hold. From (iii) follows that $G\left(\frac{x^T}{2}\right) < 1 - \frac{k}{\bar{P}-c}$. If, in addition, $1 - \frac{k}{\bar{P}-c} \leq G\left(2\alpha\right)$ holds, $2\alpha < \frac{x^T}{2}$ can not hold. Hence, (ii) does not hold. Thus, we have shown that only one of the four conditions above can hold.

Second, we prove that always one of the four conditions holds by showing that no further cases exist. By considering all possible combinations of (a), (b), (c) and (d)

(a) $1 - G\left(2\alpha\right) > (\leq) \dfrac{k}{\bar{P} - c}$, (b) $1 - G\left(\dfrac{x^T}{2}\right) > (\leq) \dfrac{k}{\bar{P} - c}$,

(c) $1 - G\left(x^T - 2\alpha\right) < (\geq) \dfrac{k}{\bar{P} - c}$, (d) $2\alpha < (\geq) \dfrac{x^T}{2}$

it follows directly that in 14 out of these 16 cases, either (i), (ii), (iii) or (iv) occurs. We only have to analyze the following two cases:

$$\begin{aligned}
I \quad &: \quad \text{(a) } 1-G\left(2\alpha\right) > \frac{k}{\bar{P}-c}, \qquad && \text{(b) } 1-G\left(\frac{x^T}{2}\right) \leq \frac{k}{\bar{P}-c}, \\
& \quad\ \ \text{(c) } 1-G\left(x^T-2\alpha\right) \geq \frac{k}{\bar{P}-c}, && \text{(d) } 2\alpha < \frac{x^T}{2}. \\
II \quad &: \quad \text{(a) } 1-G\left(2\alpha\right) \leq \frac{k}{\bar{P}-c}, && \text{(b) } 1-G\left(\frac{x^T}{2}\right) > \frac{k}{\bar{P}-c}, \\
& \quad\ \ \text{(c) } 1-G\left(x^T-2\alpha\right) < \frac{k}{\bar{P}-c}, && \text{(d) } 2\alpha \geq \frac{x^T}{2}.
\end{aligned}$$

In case I, the conditions (a), (c) and (d) lead to

$$G\left(\frac{x^T}{2}\right) = G\left(x^T-2\alpha-\left(\frac{x^T}{2}-2\alpha\right)\right) < G\left(x^T-2\alpha\right) \leq 1-\frac{k}{\bar{P}-c}.$$

This is a contradiction to (b). Hence, case I does not occur. In case II, the conditions (a), (b) and (c) lead to

$$1-\frac{k}{\bar{P}-c} > G\left(\frac{x^T}{2}\right) = G\left(x^T-2\alpha-\left(\frac{x^T}{2}-2\alpha\right)\right) > G\left(x^T-2\alpha\right).$$

This is a contradiction to (c). Hence, case II can not occur. Therefore, we have shown that for any choice of $\bar{P}$, c, k, G, α and x^T, exactly one of the conditions (i), (ii), (iii) or (iv) occurs.

From the lemma above, we can argue that if we find for each of the four cases (i)-(iv) unique equilibrium capacities, then there always exists an equilibrium that is unique for given $\bar{P}$,k, c, G, α and x^T. The firms' capacity in equilibrium has to fulfill one of the following two conditions: (I) The firms' capacity in equilibrium is positive and their profits are zero. (II) The firms' capacity is zero and the profits are negative or zero.

Case (i): $1-G\left(x^T-2\alpha\right) < \frac{k}{\bar{P}-c}$ and $1-G\left(2\alpha\right) > \frac{k}{\bar{P}-c}$. The unique equilibrium capacity x_A^* that is built in the market in A and the capacity payments z^* that are paid in B are given by

$$x_A^* = \frac{1}{2}G^{-1}\left(1-\frac{k}{\bar{P}-c}\right)-\alpha \quad \text{and} \quad z^* = k-\left(\bar{P}-c\right)\left(1-G\left(x^T-2\alpha\right)\right),$$

for the following reasons: (1.) $z^*>0$, (2.) $x_A^*>0$, (3.) z^* and x_A^* are the unique solutions for the firms' zero profit conditions

$$\begin{aligned}
0 &= \left(\bar{P}-c\right)\left(1-G\left(2x_A+2\alpha\right)\right)-k, \\
0 &= \left(\bar{P}-c\right)\left(1-G\left(x^T-2\alpha\right)\right)+z-k,
\end{aligned}$$

and (4.) $x_B^*-x_A^*=\frac{x^T}{2}-\frac{1}{2}G^{-1}\left(1-\frac{k}{\bar{P}-c}\right)-\alpha>2\alpha$.

Case (ii): $2\alpha<\frac{x^T}{2}$ and $1-G\left(2\alpha\right)\leq\frac{k}{\bar{P}-c}$. These inequalities lead to

$$1-\frac{k}{\bar{P}-c}\leq G\left(2\alpha\right)\leq G\left(\frac{x^T}{2}\right)=G\left(x^T-2\alpha-\left(\frac{x^T}{2}-2\alpha\right)\right)<G\left(x^T-2\alpha\right),$$

i.e., $1-\frac{k}{\bar{P}-c}<G\left(x^T-2\alpha\right)$. The unique equilibrium capacity x_A^* and capacity payments z^* are then given by

$$x_A^*=0 \quad \text{and} \quad z^*=k-\left(\bar{P}-c\right)\left(1-G\left(x^T-2\alpha\right)\right),$$

for the following reasons: (1.) $z^*>0$, (2.) $x_A^*=0$,(3.) the profits for x_A^* are negative or zero

$$\left(\bar{P}-c\right)\left(1-G\left(2\alpha\right)\right)-k\leq\left(\bar{P}-c\right)\left(1-\left(1-\frac{k}{\bar{P}-c}\right)\right)-k=0,$$

and z^* is the unique solution for the zero profit condition of B's firms

$$0=\left(\bar{P}-c\right)\left(1-G\left(x^T-2\alpha\right)\right)+z-k,$$

and (4.) $x_B^*-x_A^*=\frac{x^T}{2}>2\alpha$. The total capacity $x_A^T=\frac{x^T}{2}$ is procured as strategic reserve.

Case (iii): $1-G\left(x^T-2\alpha\right)\geq\frac{k}{\bar{P}-c}$ and $1-G\left(\frac{x^T}{2}\right)>\frac{k}{\bar{P}-c}$. The unique equilibrium capacity x_A^* and capacity payments z^* are then given by

$$x_A^*=G^{-1}\left(1-\frac{k}{\bar{P}-c}\right)-\frac{x^T}{2} \quad \text{and} \quad z^*=0,$$

for the following reasons: (1.) $z^*=0$, (2.) $x_A^*>0$, (3.) z^* and x_A^* are the unique solutions for the firms' zero profit conditions

$$\begin{aligned}
0 &= \left(\bar{P}-c\right)\left(1-G\left(x_A+\frac{x^T}{2}\right)\right)-k \\
0 &= \left(\bar{P}-c\right)\left(1-G\left(x_A+\frac{x^T}{2}\right)\right)+z-k,
\end{aligned}$$

and (4.) $x_B^* - x_A^* = x^T - G^{-1}\left(1 - \frac{k}{\bar{P}-c}\right) \leq 2\alpha$.

Case (iv): $2\alpha \geq \frac{x^T}{2}$ and $1 - G\left(\frac{x^T}{2}\right) \leq \frac{k}{\bar{P}-c}$. The unique equilibrium capacity x_A^* and capacity payments z^* are then given by

$$x_A^* = 0 \text{ and } z^* = k - \left(\bar{P} - c\right)\left(1 - G\left(\frac{x^T}{2}\right)\right),$$

for the following reasons: (1.) $z^* \geq 0$, (2.) $x_A^* = 0$, (3.) the profits for x_A^* are negative or zero

$$\left(\bar{P} - c\right)\left(1 - G\left(\frac{x^T}{2}\right)\right) - k \leq \left(\bar{P} - c\right)\left(\frac{k}{\bar{P} - c}\right) - k = 0,$$

and x_A^* and z^* are the unique solution for the zero profit condition of B's firms

$$0 = \left(\bar{P} - c\right)\left(1 - G\left(\frac{x^T}{2}\right)\right) + z - k,$$

and (4.) $x_B^* - x_A^* = \frac{x^T}{2} \leq 2\alpha$. The total capacity x_A^T is procured as strategic reserve. Hence, we have proven Proposition 2.

Proof of Proposition 3.

The consumers' costs are given by equation (8).

Case 1: Let us first consider the case in which α is sometimes binding and in which the expected variable spot market profits per capacity unit in A and B are given by equations (4) and (4). The electricity consumption costs in A and B are then given by

$$CC_A^S = c\int_0^{2x_A+2\alpha} \frac{D}{2} g\left(D\right) dD + \bar{P}\left(\int_{2x_A+2\alpha}^{x^T} \frac{D}{2} g\left(D\right) dD + \frac{x^T}{2}\left(1 - G\left(x^T\right)\right)\right)$$

and

$$CC_B^S = c\int_0^{2x_B-2\alpha} \frac{D}{2} g\left(D\right) dD + \bar{P}\left(\int_{2x_B-2\alpha}^{x^T} \frac{D}{2} g\left(D\right) dD + \frac{x^T}{2}\left(1 - G\left(x^T\right)\right)\right),$$

respectively. The costs from the strategic reserves are given by

$$\begin{aligned} CC_A^{SR} &= kx_A^R - \left(\bar{P}-c\right)\int_{2x_A+2\alpha}^{x^T-2\alpha}\left(\frac{D}{2}-x_A-\alpha\right)g\left(D\right)dD \\ &\quad -\left(\bar{P}-c\right)\int_{x^T-2\alpha}^{x^T}\left(D-x_A-\frac{x^T}{2}\right)g\left(D\right)dD \\ &\quad -\left(\bar{P}-c\right)x_A^R\left(1-G\left(x_T\right)\right). \end{aligned}$$

The capacity payment costs are given by

$$CC_B^Z = zx_B = \left[k-\left(\bar{P}-c\right)\left(1-G\left(x^T-2\alpha\right)\right)\right]\frac{x^T}{2}.$$

The difference in consumers' costs is given by:

$$\begin{aligned} CC_A - CC_B &= CC_A^S - CC_B^S + CC_A^{SR} - CC_B^Z \\ &= \left(\bar{P}-c\right)\int_{2x_A+2\alpha}^{x^T-2\alpha}\frac{D}{2}g\left(D\right)dD + \left(k-\left(\bar{P}-c\right)\left(1-G\left(x_T\right)\right)\right)x_A^R \\ &\quad -\left(\bar{P}-c\right)\int_{2x_A+2\alpha}^{x^T-2\alpha}\left(\frac{D}{2}-x_A-\alpha\right)g\left(D\right)dD \\ &\quad -\left(\bar{P}-c\right)\int_{x^T-2\alpha}^{x^T}\left(D-x_A-\frac{x^T}{2}\right)g\left(D\right)dD \\ &\quad -\left[k-\left(\bar{P}-c\right)\left(1-G\left(x^T-2\alpha\right)\right)\right]\frac{x^T}{2} \\ &> \left(k-\left(\bar{P}-c\right)\left(1-G\left(x_T\right)\right)\right)x_A^R \\ &\quad +\left(\bar{P}-c\right)\left(x_A+\alpha\right)\left(G\left(x^T-2\alpha\right)-G\left(2x_A+2\alpha\right)\right) \\ &\quad -\left(\bar{P}-c\right)\left(x^T-x_A-\frac{x^T}{2}\right)\left(G\left(x^T\right)-G\left(x^T-2\alpha\right)\right) \\ &\quad -\left[k-\left(\bar{P}-c\right)\left(1-G\left(x^T-2\alpha\right)\right)\right]\frac{x^T}{2} \\ &= \left(\bar{P}-c\right)\left(\alpha G\left(x^T-2\alpha\right)-\left(x_A+\alpha\right)G\left(2x_A+2\alpha\right)+x_A\right)-kx_A \end{aligned}$$

and the inequality holds due to $\int_{x^T-2\alpha}^{x^T} Dg\left(D\right)dD < x^T\left(G\left(x^T\right)-G\left(x^T-2\alpha\right)\right)$.

If $1-G\left(2\alpha\right) > \frac{k}{\bar{P}-c}$ and $1-G\left(x^T-2\alpha\right) < \frac{k}{\bar{P}-c}$, A's equilibrium capacity x_A^* is given by $x_A^* = \frac{1}{2}G^{-1}\left(1-\frac{k}{\bar{P}-c}\right)-\alpha$ (see proof of Proposition 2). Using $1-\frac{k}{\bar{P}-c} < G\left(x^T-2\alpha\right)$ and plugging x_A^* into the inequality leads to

$$\begin{aligned} CC_A - CC_B &> \left(\bar{P}-c\right)\left(\alpha G\left(x^T-2\alpha\right)-\left(x_A+\alpha\right)G\left(2x_A+2\alpha\right)+x_A\right)-kx_A \\ &> \left(\bar{P}-c\right)\left(x_A+\alpha\right)\left(1-G\left(2x_A+2\alpha\right)\right)-\left(x_A+\alpha\right)k \\ &= 0. \end{aligned}$$

If $1 - G(2\alpha) \leq \frac{k}{\bar{P}-c}$ and $2\alpha < \frac{x^T}{2}$, A's equilibrium capacity is given by $x_A^* = 0$. Plugging x_A^* into the inequality leads to

$$\begin{aligned}
CC_A - CC_B &> \left(\bar{P} - c\right)\left(\alpha G\left(x^T - 2\alpha\right) - \left(x_A + \alpha\right) G\left(2x_A + 2\alpha\right) + x_A\right) - kx_A \\
&= \left(\bar{P} - c\right)\alpha\left(G\left(x^T - 2\alpha\right) - G\left(2x_A + 2\alpha\right)\right) \\
&> 0.
\end{aligned}$$

Hence, we have proven that in cases (i) and (ii) of Proposition 2, $CC_A > CC_B$ holds.

Case 2: Let us consider the case in which α is always non-binding and in which the expected variable spot market profits per capacity unit in A and B are given by equation (5). The electricity consumption costs in A and B are the same, and we only have to analyze the difference between CC_A^{SR} and CC_B^{Z}. The costs from the strategic reserves are given by

$$CC_A^{SR} = kx_A^R - \left(\bar{P} - c\right)\left(\int_{x_A + x_B}^{x^T} \left(D - x_A - x_B\right) g\left(D\right) dD + x_A^R\left(1 - G\left(x^T\right)\right)\right).$$

The capacity payment costs are given by

$$CC_B^Z = zx_B = \left[k - \left(\bar{P} - c\right)\left(1 - G\left(x_A + x_B\right)\right)\right]\frac{x^T}{2}.$$

Let us show that $CC_A^{SR} > CC_B^Z$:

$$\begin{aligned}
& CC_B^Z - CC_A^{SR} \\
= \; & kx_A \\
& - \left(\bar{P} - c\right)\left(x_A + x^T G\left(x^T\right) - \left(x^T + x_A\right) G\left(x_A + \frac{x^T}{2}\right)\right) \\
& - \left(\bar{P} - c\right)\left(-\int_{x_A + \frac{x^T}{2}}^{x^T} Dg\left(D\right) dD\right) \\
> \; & \left(k - \left(\bar{P} - c\right)\left(1 - G\left(x_A + \frac{x^T}{2}\right)\right)\right) x_A
\end{aligned}$$

and the inequality holds due to $\int_{x_A + \frac{x^T}{2}}^{x^T} Dg\left(D\right) dD < x^T\left(G\left(x^T\right) - G\left(x_A + \frac{x^T}{2}\right)\right)$.

If $1 - G\left(\frac{x^T}{2}\right) > \frac{k}{\bar{P}-c}$ and $1 - G\left(x^T - 2\alpha\right) \geq \frac{k}{\bar{P}-c}$, the capacity payments are zero and

$$z^* = k - \left(\bar{P} - c\right)\left(1 - G\left(x_A + \frac{x^T}{2}\right)\right) = 0$$

holds (see proof of Proposition 2). Hence, $CC_B^Z - CC_A^{SR} > 0$.

If $1-G\left(\frac{x^T}{2}\right) \leq \frac{k}{\bar{P}-c}$ and $2\alpha \geq \frac{x^T}{2}$, equilibrium capacity in A is given by $x_A^* = 0$. Thus, $CC_B^Z - CC_A^{SR} > 0$.

Proof of Proposition 4.

We define $x := x_A + x_B$ and $x^1 := x_A^1 + x_B^1$. If both regulators choose strategic reserves to ensure the target capacity level, the equilibrium capacities are given by $x^* = G^{-1}\left(1 - \frac{k-k^1}{c^1-c}\right)$ and $x^{1*} = G^{-1}\left(1 - \frac{k^1}{\bar{P}-c^1}\right) - x^*$ since both capacities are positive and the following zero profit conditions of both technologies are fulfilled:

$$\begin{aligned} BL: \quad & 0 = \left(\bar{P} - c\right) - \left(\bar{P} - c^1\right) G\left(x + x^1\right) - \left(c^1 - c\right) G\left(x\right) - k \\ PL: \quad & 0 = \left(\bar{P} - c^1\right)\left(1 - G\left(x + x^1\right)\right) - k^1. \end{aligned}$$

The strategic reserves are then given by

$$x^R = x^T - G^{-1}\left(1 - \frac{k^1}{\bar{P} - c^1}\right).$$

If both regulators choose capacity payments, the equilibrium capacities are given by $x^* = G^{-1}\left(1 - \frac{k-k^1}{c^1-c}\right)$ and $x^{1*} = G^{-1}\left(1 - \frac{k^1-z}{\bar{P}-c^1}\right) - x^*$ since both capacities are positive and the following zero profit conditions of both technologies are fulfilled:

$$\begin{aligned} BL: \quad & z = k - \left(\bar{P} - c\right) + \left(\bar{P} - c^1\right) G\left(x + x^1\right) + \left(c^1 - c\right) G\left(x\right) \\ PL: \quad & z = k^1 - \left(\bar{P} - c^1\right)\left(1 - G\left(x + x^1\right)\right). \end{aligned}$$

The capacity payments are given by $z^* = k^1 - \left(\bar{P} - c^1\right)\left(1 - G\left(x^T\right)\right)$. Since the equilibrium capacities are the same for both mechanisms it follows directly that the consumers' costs are the same for both mechanisms.

Proof of Proposition 5.

The firms' capacity in equilibrium has to fulfill one of the following two conditions: (I) The firms' capacitiy in equilibrium is positive and their profits are zero. (II) The firms' capacity is zero and the profits are negative or zero.

If $1 - G\left(\frac{x^T}{2}\right) > \frac{k^1}{\bar{P}-c^1}$, each vector $x^* = \left(x_A, x_B, x_A^1, x_B^1\right)$ with $x_A > 0$, $x_B > 0$, $x_A^1 > 0$ and $x_B^1 > 0$ for which $x_A + x_B = G^{-1}\left(1 - \frac{k-k^1}{c^1-c}\right)$, $x_A^1 + x_B^1 = G^{-1}\left(1 - \frac{k^1}{\bar{P}-c^1}\right) - G^{-1}\left(1 - \frac{k-k^1}{c^1-c}\right)$ and $x_B + x_B^1 = \frac{x^T}{2}$ holds constitute a market equilibrium in which $z^* = 0$ holds. The reason is that all capacities are positive and the following zero profit conditions of both technologies in both countries are fulfilled:

$$\begin{aligned}
BL_B: \quad 0 &= \left(\bar{P}-c\right)-\left(\bar{P}-c^1\right)G\left(x_A+x_B+x_A^1+x_B^1\right) \\
&\quad -\left(c^1-c\right)G\left(x_B+x_A\right)+z-k \\
PL_B: \quad 0 &= \left(\bar{P}-c^1\right)\left(1-G\left(x_A+x_B+x_A^1+x_B^1\right)\right)+z-k^1 \\
BL_A: \quad 0 &= \left(\bar{P}-c\right)-\left(\bar{P}-c^1\right)G\left(x_A+x_B+x_A^1+x_B^1\right) \\
&\quad -\left(c^1-c\right)G\left(x_B+x_A\right)-k \\
PL_A: \quad 0 &= \left(\bar{P}-c^1\right)\left(1-G\left(x_A+x_B+x_A^1+x_B^1\right)\right)-k^1.
\end{aligned}$$

Furthermore, the following combinations of x_A, x_B, x_A^1, x_B^1 constitute market equilibria in which $z^*=0$ holds:

$$\begin{aligned}
I: x_B^* &= \frac{x^T}{2}-G^{-1}\left(1-\frac{k^1}{\bar{P}-c^1}\right)+G^{-1}\left(1-\frac{k-k^1}{c^1-c}\right), \\
x_B^{1*} &= G^{-1}\left(1-\frac{k^1}{\bar{P}-c^1}\right)-G^{-1}\left(1-\frac{k-k^1}{c^1-c}\right), \\
x_A^* &= G^{-1}\left(1-\frac{k^1}{\bar{P}-c^1}\right)-\frac{x^T}{2}, \\
x_A^{1*} &= 0 \\
II: x_B^* &= G^{-1}\left(1-\frac{k-k^1}{c^1-c}\right), \\
x_B^{1*} &= \frac{x^T}{2}-G^{-1}\left(1-\frac{k-k^1}{c^1-c}\right) \\
x_A^* &= 0, \\
x_A^{1*} &= G^{-1}\left(1-\frac{k^1}{\bar{P}-c^1}\right)-\frac{x^T}{2} \\
III: x_B^* &= \frac{x^T}{2}, \\
x_B^{1*} &= 0 \\
x_A^* &= G^{-1}\left(1-\frac{k-k^1}{c^1-c}\right)-\frac{x^T}{2}, \\
x_A^{1*} &= G^{-1}\left(1-\frac{k^1}{\bar{P}-c^1}\right)-G^{-1}\left(1-\frac{k-k^1}{c^1-c}\right) \\
IV: x_B^* &= 0, \\
x_B^{1*} &= \frac{x^T}{2} \\
x_A^* &= G^{-1}\left(1-\frac{k-k^1}{c^1-c}\right), \\
x_A^{1*} &= G^{-1}\left(1-\frac{k^1}{\bar{P}-c^1}\right)-G^{-1}\left(1-\frac{k-k^1}{c^1-c}\right)-\frac{x^T}{2}.
\end{aligned}$$

The reason is that the capacities are either positive and the zero profit conditions are fulfilled, or they are zero and the profits are zero or negative for these capacities. The strategic reserves are given by $x_A^{R*} = x^T - x_A^* > 0$.

If $1 - G\left(\frac{x^T}{2}\right) \leq \frac{k^1}{\bar{P}-c^1}$, the unique market equilibrium is given by

$$x_B^* = G^{-1}\left(1 - \frac{k - k^1}{c^1 - c}\right),\ x_B^{1*} = G^{-1}\left(1 - \frac{k^1 - z}{\bar{P} - c^1}\right) - G^{-1}\left(1 - \frac{k - k^1}{c^1 - c}\right),$$
$$x_A^* = 0,\ x_A^{1*} = 0$$

and

$$z^* = k_1 - \left(\bar{P} - c^1\right)\left(1 - G\left(\frac{x^T}{2}\right)\right),$$

since x_B^* and x_B^{1*} fulfill the zero profits conditions and the profits for $x_A^* = x_A^{1*} = 0$ are zero or negative. By checking the equilibrium conditions for all other combinations of (a), (b), (c) and (d),

$$\text{(a) } x_B > (=)\,0, \quad \text{(b) } x_B^1 > (=)\,0, \quad \text{(c) } x_A > (=)\,0, \quad \text{(d) } x_A^1 > (=)\,0,$$

we find that no further equilibrium exists.

Proof of Proposition 6.

If $z = 0$ and $x_A^R > 0$, the consumers' costs are obviously higher in A than in B. When the equilibrium capacities and capacity payments are given by $x_A^{*1} = x_A^* = 0$ and $z^* = k_1 - \left(\bar{P} - c\right)\left(1 - G\left(\frac{x^T}{2}\right)\right)$, the costs from the strategic reserves are given by

$$CC_A^{SR} = k^1 \frac{x^T}{2} - \left(\bar{P} - c\right)\left(\int_{x_B^1 + x_B}^{x^T}\left(D - \frac{x^T}{2}\right) g\left(D\right) dD + \frac{x^T}{2}\left(1 - G\left(x^T\right)\right)\right).$$

The capacity payment costs are given by

$$CC_B^Z = z x_B = \left[k^1 - \left(\bar{P} - c\right)\left(1 - G\left(\frac{x^T}{2}\right)\right)\right]\frac{x^T}{2}.$$

The difference is given by

$$CC_B^Z - CC_A^{SR} = \left(\bar{P} - c\right)\left(x^T\left(G\left(x^T\right) - G\left(\frac{x^T}{2}\right)\right) - \int_{\frac{x^T}{2}}^{x^T} Dg\left(D\right) dD\right),$$

which is positive since $x^T \int_{\frac{x^T}{2}}^{x^T} g\left(D\right) dD > \int_{\frac{x^T}{2}}^{x^T} Dg\left(D\right) dD$.