Equilibrium supply security in a multinational electricity market with renewable production*

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Abstract

An increasing reliance on variable renewable energy has raised concern about system ability to continuously satisfy electricity demand. This paper examines countries' unilateral incentives to achieve supply security through capacity reserves and market integration in a multinational electricity market. Capacity reserves protect consumers against blackouts and extreme prices, but distort the market. Market integration reduces supply imbalances, but requires network investment. Equilibrium capacity reserves can be too high or low, but network investment is always insufficient relative to the total welfare maximizing level. Capacity reserves are smaller when there are financial markets or when aimed at solving domestic supply constraints.

Key words: Capacity mechanism, decentralized policy making, multinational electricity market, network investment, security of supply.

JEL codes: D24; H23; L94; Q48

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1 Introduction

Support schemes to increase the production of energy from renewable sources are common in many parts of the world as part of a policy to reduce greenhouse gas emissions and energy import dependence.[1] Subsidization of renewable electricity often has sparked investments predominantly in solar and wind power.[2] The output fluctuations inherent to solar and wind power have subsequently raised concern about the ability to continuously satisfy demand in a market that relies on such intermittent electricity production.

In circumstances of a substantial shortfall of renewable output, the system operator may be forced to disconnect consumers from the grid in order to maintain system stability. Such rolling blackouts (curtailment) represent the most dramatic manifestation of supply shortage, but scarcity affects consumers negatively also in less extreme circumstances. Price insensitive short-run demand for electricity and capacity constraints in production and transmission imply that the market-clearing spot price of electricity can be very high in event the market is supply constrained even if not on the verge of collapse. The tolerance for blackouts and extreme prices is very limited in advanced economies. A key feature of a viable electricity market based upon renewable electricity production therefore is to maintain a *security of supply*, i.e. ensure that there is adequate generation capacity to satisfy demand at acceptable consumer prices.[3]

There are two main ways how countries can achieve supply security. The first is to keep capacity reserves as backup in event of supply shortages in the spot market.[4] Reserves often are procured by the use of capacity mechanisms such as auctions for generation capacity. Typical mechanisms address the problem of blackouts by requiring that available production capacity has a sufficient reserve margin to prevent the loss of load probability from exceeding some target level.[5] They limit consumer price exposure by establishing trigger levels in the spot market above which capacity reserves are activated.[6]

[1] See, for instance, the EU Renewables Directive (2009/28/EC) for a formulation of such objectives.

[2] Germany is a leading example of a country that has started a transition to an electricity market based on renewables. Approximately one fourth of the country's annual electricity production came from renewable sources in 2014 compared to 6% at the turn of the millennium. Two-thirds of this increase can be attributed to solar and wind power. The data were retrieved from www.iea.org/statistics/ November 4, 2016.

[3] The Union of the Electricity Industry in Europe defines security of electricity supply as (Eurelectric, 2006, p.15) "the ability of the electrical power system to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner." This definition appears to encompass curtailment alone, but in the subsequent discussion Eurelectric emphasizes that "energy prices can also have an influence on security of supply. For instance, if electricity prices were to rise enduringly to levels which were not affordable for a substantial portion of customers (households and industry), there would be an impact on security of supply." Oren (2005) similarly views capacity reserves as an insurance both against curtailment and high prices.

[4] Such capacity is sometimes known as a *strategic reserve*; see, for instance, Erbach (2017).

[5] The loss of load probability is the likelihood that available production capacity is insufficient to cover demand within a given period. For instance, ERCOT (Texas) and PJM (North-East USA) apply the same "one day in ten years" loss of load criterion for reserve margins. France and Great Britain use a very similar criterion.

[6] See Neuhoff et al. (2016) for a characterization of common mechanisms. Trigger prices often are explicit. For instance, NEM (Eastern and Southern Australia) and PJM define a specific price cap in the short-term market for situations of supply scarcity. Columbia and New England instead use capacity mechanisms based upon the more unusual reliability options. Producers are then forced to issue call options for the contracted capacity reserve at some regulated strike price and pay consumers the difference between the spot price and the strike price. By way of construction, consumers *de facto* pay the minimum of the strike price and the spot price for their electricity (Cramton et al., 2013). Trigger prices can also be implicit. In Sweden, for instance, the system operator until recently activated the capacity reserve whenever demand in the spot market exceeded supply at the maximal offer

The second solution is to increase network capacity and thereby improve the flow of electricity across the market. Better market integration reduces the likelihood of supply shortage and lowers market prices by allowing demand and supply fluctuations in different parts of the network to offset one another. Network expansion is regulated and undertaken by the network owner.

In a multinational electricity market, the price effects associated with capacity reserves and network investment propagate through to surrounding countries. Decisions at the national level concerning security of supply therefore run the risk of impairing the overall market performance insofar as local policy makers fail to fully account for the effects of their decisions. The concerns expressed by the European Commission (2015, p.10) in the recent framework strategy for an Energy Union about "divergent national market arrangements" and a necessity to ensure that "capacity mechanisms and support for renewable electricity are fully in line with existing rules and do not distort the internal energy market" bear testimony to this perception.

Scope The purpose of this paper is to contribute to our understanding of the incentives for introducing capacity reserves in markets with intermittent renewable electricity generation. It emphasizes the implications of and consequences for market integration by couching the problem in a multinational electricity market setting. A main objective is to identify and account for foreign external effects and assess the overall welfare consequences of decentralized policy making associated with security of supply problems.

Analysis Section 2 builds a model of an electricity market in which supply shortages arise with positive probability in the short-term (spot) market because renewable production is stochastic, thermal capacity available to the market is limited, and short-term demand is independent of the spot price of electricity. If there exists no market-clearing spot price, then consumption and production must be balanced by the system operator (SO) to uphold system stability. Curtailing consumption is politically unacceptable.[7] Instead, the SO maintains enough reserve capacity to cover excess demand. The size of the capacity reserve depends on market design, specifically a spot price cap applied during supply shortage. A larger cap increases the expected spot price, drives up market-based investment in thermal capacity and reduces long-term demand. The capacity reserve required to uphold system stability therefore is smaller when the price cap is larger. Conversely, a larger capacity reserve renders a relatively smaller price cap sufficient to generate enough market-based investment in thermal capacity to cover excess demand.

Capacity reserves can improve social welfare by protecting consumers from curtailment and high spot prices if the market cannot diversify away all risks associated with supply shortages. But as capacity reserves are purchased outside the spot market, they interfere with long-run

price. The capacity reserve was then supplied to cover excess demand at this offer price. Then the spot price of electricity can never exceed the short-term marginal production cost of the most expensive unit in the market if the spot market is otherwise competitive. As of 2018, the Swedish system operator is instead supposed to bid in its capacity reserve at the spot market bid cap in scarcity situations.

[7] Curtailment happens very infrequently in restructured electricity markets. A sector inquiry found one single instance of consumers being disconnected across the EU over a five year period. This happened during a heat wave in Poland in August 2015 (European Commission, 2016). One explanation could be strict reliability criteria; see footnote 4. For simplicity, the model assumes a target level of curtailment equal to zero.

efficiency by driving a wedge between the marginal cost of supplying electricity and the marginal utility of consuming it. The socially optimal level of the capacity reserve equates the marginal benefit of improved security of supply with the distortions to consumption and market-based investment resulting from a downward distortion in the long-run (expected) price of electricity.

I then expand the model to consider two countries connected by a cross-border transmission line that permits electricity to flow freely between them. Countries are symmetric except for an imperfect correlation of renewable electricity production that reduces the probability of a supply shortage in an integrated market. This *portfolio effect of renewable electricity* reduces the marginal social benefit of capacity reserves. Capacity reserves can also be allocated across borders when markets are integrated. This *pooling effect of capacity reserves* reduces the marginal social cost of capacity reserves. I provide conditions for when the portfolio effect dominates (is dominated by) the pooling effect and the socially optimal level of capacity reserves smaller (larger) in a perfectly integrated electricity market than when electricity markets are national.

Instead of assuming that capacity reserves are chosen centrally to maximize total welfare, I let domestic policy makers unilaterally choose capacity reserves to maximize domestic welfare.[8] Although policy makers disregard the effects abroad, there need not be any welfare loss associated with decentralized policy making. If market integration is perfect and capacity reserves efficiently deployed, then domestic welfare depends on the average capacity reserve of the two countries and is proportional to total welfare. Decision makers then effectively internalize all externalities of the domestic capacity reserve, and the social optimum represents a Nash equilibrium.

Section 3 considers partial market integration, measured here in terms of network reliability. The two countries are perfectly integrated with positive probability, but purely national otherwise. Capacity reserves are distorted in equilibrium compared to the jointly welfare maximizing level, but the direction and magnitude depends on the portfolio and pooling effects. A large portfolio effect means that an increase in the domestic capacity reserve only has a small positive effect on foreign supply security compared to the marginal market distortion abroad. This creates a negative net foreign externality that causes capacity reserves to be excessive in equilibrium. Conversely, equilibrium capacity reserves are too small if the pooling effect dominates.

Section 4 endogenizes market integration by allowing investment in network reliability, either at the central level to maximize total welfare, or at the national level. An increase in the capacity reserve decreases (increases) the marginal value of market integration if the foreign externality is negative (positive) and thereby reduces (increases) network investment. This strategic substitutability (complementarity) between capacity reserves and market integration causes network reliability to be unambiguously downward distorted compared to the total welfare maximizing level because the capacity reserve is too large (small) from a social point of view under a negative (positive) foreign externality. Decentralized network investment exacerbates this underinvestment problem further because domestic policy makers ignore the positive effects abroad of improved market integration.

[8] This is really a model of market integration between jurisdictions, where each jurisdiction unilaterally decides on policy. In the present context, these jurisdictions are countries, but one could equally well assume them to be states, such as in the U.S.

An alternative to hedging spot prices through capacity reserves would be for consumers worried about prices to sign financial contracts. Section 5 shows that the socially optimal capacity reserve is close to zero if consumers can purchase call options in a competitive financial market that renders the equilibrium option price equal to the expected option payment. But if sellers of such contracts cannot diversify away all risk, for instance because they are liquidity constrained, then capacity reserves can be welfare improving even under financial contracting.[9] Individual consumers always prefer to hedge through a capacity reserve because capacity payments are distributed across all consumers, whereas the financial contract is a private cost. A policy maker who attached more weight to specific consumer interests would then have an incentive to introduce capacity reserves even if inefficient.

I consider in Section 6 the effect of defining supply shortage at the national level instead of at the aggregate level, and requiring that capacity reserves be directed towards solving domestic capacity problems. The resulting dispatch of the capacity reserve then is inefficient, which makes market-based outcomes comparatively more attractive from an efficiency viewpoint. This reduces the socially optimal and equilibrium capacity reserve.

Section 7 concludes with a discussion of policy implications.

Related literature This paper is one of only a few to consider endogenous capacity reserves. An explanation for the lack of research can be that standard economic theory posits that specific measures to achieve supply security are unnecessary. A competitive "energy-only" market—where customers only pay for the amount of energy they consume and generators only are paid for the amount of energy they produce—is sufficient. Price hikes in times of scarcity will create just enough rent to render the socially optimal investments in thermal capacity profitable on market-based terms (Hogan, 2005; Oren, 2005 and Joskow, 2007).

The efficiency of an energy-only market arises under ideal market conditions where demand is price sensitive enough always to deliver some, possibly very high, price that clears the market. It is arguable whether current electricity markets fit this description, not least because many households are on contracts that do not incite them to respond to short-term price signals. Cramton and Stoft (2006) and Cramton et al. (2013) argue that appropriately designed capacity mechanisms are an efficient way of resolving associated supply constraints.

Joskow and Tirole (2007) show in their seminal contribution that price insensitive short-term demand alone is insufficient to vindicate capacity mechanisms on efficiency grounds. Instead, capacity obligations have the potential to improve efficiency if curtailment is inefficient or if price signals are distorted, for example as a result of market power or because of regulatory intervention. Joskow and Tirole (2007) explore in detail capacity obligations in relation to imperfect competition. Creti and Fabra (2007) and Schwenen (2014) illustrate in a similar vein

[9] An illustrative example is the California electricity market at the turn of the millennium. The price hedge then consisted of a regulated retail price with retailers carrying the full spot price risk. As a consequence, all three investor-owned retailers ran into serious financial difficulties as spot prices soared to record levels in the summer of 2000. One of them went bankrupt; see Wolak (2003) for a discussion of the famous California electricity crisis. Under a system of reliability options, producers carry the spot price risk, unless they themselves manage to hedge this risk. Neuhoff et al. (2016) discuss the distribution of risks associated with such reliability options.

how capacity reserves mitigate strategic withholding of production from the spot market.

There can be reasons for introducing capacity mechanisms also in a competitive market. Efficiency requires a price cap set at the perceived cost of involuntary rationing, the *value of lost load* (VOLL), which renders consumers indifferent between being rationed or not in scarcity situations (Stoft, 2002). The applicability of such a policy can be disputed, not only because VOLL is difficult to estimate correctly, but also because it may be politically infeasible to permit the electricity price to increase by a factor of 100 or more above its normal level to achieve VOLL (Cramton et al., 2013). Firms may then question the credibility of VOLL pricing, in which case the desired investments will not come about (Joskow and Tirole, 2007). This is the well-known *missing money* problem in electricity markets; see e.g. Joskow (2007) and Hogan (2013). This paper endogenously derives the optimal capacity reserve (and price cap) as a trade-off between protecting consumers against high prices and distorting the spot market.[10] Framing the problem in a competitive electricity market setting facilitates the analysis of decentralized policy making and the interaction between capacity reserves and market integration in a multinational electricity market, issues that so far have received little attention in the literature.[11]

2 Capacity reserves in national or perfectly integrated markets

There are two countries, identical in terms of consumer preferences, income and production technologies. The benchmark model encompasses two polar degrees of market structure, $M = N, I$. Index N refers to the case of purely national electricity markets, meaning there is no electricity trade between the two countries. Instead, there are transmission lines with sufficient capacity to guarantee a free flow of electricity and equalize prices across the two countries in the second case of perfect market integration, indexed by I. I consider the intermediary case of partial market integration in Section 3.

2.1 The model

Demand There are two types of representative consumers: households and an electricity intensive industry. Households pay the expected (long-run) wholesale price of electricity $E[\tilde{p}]$. Their consumption q_h therefore is independent of short-term price fluctuations and chosen to maximize quasi-linear utility $u(q_h) + q_0$ subject to the budget constraint $E[\tilde{p}]q_h + q_0 + T \leq Y_0$, where q_0 is a numeraire good, T is a fixed fee, and Y_0 represents income. Let $u(\cdot)$ be twice continuously differentiable, strictly increasing in the relevant domain and strictly concave, and assume that income Y_0 is large enough that the demand for both goods is strictly positive.[12]

A representative energy intensive industry pays the short-run price $\tilde{p}$ and converts each MWh

[10] Joskow and Tirole (2007) discuss capacity reserves in relation to an exogenous price cap in the spot market.

[11] Meyer and Gore (2015) simulate within a two-country numerical model the cross-border effects of capacity mechanisms, but assume that their size is exogenously given.

[12] Electricity is an input factor in the production of energy services ultimately demanded by households, such as heating and cooling. The long-run demand for electricity depends on the substitutability of electricity for other inputs and the cost of improving energy efficiency. Changes in relative prices and support systems cause long-run demand for electricity to be price elastic even if perhaps demand for energy services varies little over time.

of electricity one-for-one into a good sold in the international market at price $\phi > 0$ net of other variable operating costs. Energy intensive industries depend on stable production conditions to run efficiently and therefore cannot respond to short-term price increases by reducing electricity consumption. Hence, I assume that the industry has inelastic demand for $q_n \geq 0$ MWh electricity independently of $\tilde{p}$. In particular, the industry suffers an operating loss if $\tilde{p} > \phi$. Its surplus equals $q_n(\phi - \tilde{p} - B(\tilde{p} - \phi))$. The term $B(\cdot)$ represents a shadow cost of the loss that is continuously differentiable, increasing and convex for all $\tilde{p} > \phi$, with $B(\tilde{p} - \phi) = B'(0) = 0$ for all $\tilde{p} \leq \phi$. The asymmetry between profits and losses could stem for instance from liquidity constraints or from profit taxes that treat operating gains and losses asymmetrically, i.e. losses are not fully deductible. $B(\cdot)$ represents a negative externality that creates a demand for capacity reserves to reduce price risk. One would expect the industry also to hedge risk in the financial market or through long-term contracts. I consider financial contracting in Section 5. For now, note that the analysis under financial contracting is qualitatively the same as below and in Sections 3 and 4 under the assumption of risk aversion on both the buyer and the seller side, as in the seminal contribution by Bessembinder and Lemmon (2002). The assumption that only household demand is long-run price sensitive is for simplicity.

Supply Electricity is competitively supplied in the short and the long-run. Let $c(x)$ be the variable cost (fuel cost, variable O&M) of producing the xth MWh of thermal electricity in the country, a cost that is strictly increasing, convex and continuously differentiable. There is also a capital cost of installing thermal capacity that for simplicity is assumed to be constant and equal to $\delta > 0$ per MWe.

Renewable output $(r_1, r_2) \in [0, \bar{r}]^2$ in the two countries is intermittent (stochastic) and jointly distributed with cumulative distribution function $F(r_1, r_2)$ and density $f(r_1, r_2)$. Renewable production is symmetric, meaning $f(r_1, r_2) = f(r_2, r_1)$ in the entire domain. The marginal density function $f_N(r) = \int_0^{\bar{r}} f(r, \tilde{r}) d\tilde{r}$ and cumulative distribution function $F_N(r) = \int_0^r f_N(\tilde{r}) d\tilde{r}$ identify the stochastic properties of renewable production in each country in the case of national electricity markets. The cumulative distribution function

$$F_I(r) = \begin{cases} \int_0^{2r} F_N(2r - \tilde{r}) f_N(\tilde{r}) d\tilde{r} & \text{for } r \in [0, \bar{r}/2] \\ 1 - \int_{2r-\bar{r}}^{\bar{r}} (1 - F_N(2r - \tilde{r})) f_N(\tilde{r}) d\tilde{r} & \text{for } r \in [\bar{r}/2, \bar{r}] \end{cases}$$

of the average renewable output $r = \frac{r_1 + r_2}{2}$ and the associated density function $f_I(r) = F_I'(r)$ identify the relevant stochastic properties of renewable production in the case of perfectly integrated electricity markets. Renewable electricity production has zero marginal production cost. The capacity is politically determined, so I treat it as exogenous throughout. Gains from electricity trade arise in a perfectly integrated market even if countries are ex ante symmetric insofar as renewable outputs r_1 and r_2 are imperfectly correlated.

Short-run equilibrium Assume that the market-based thermal capacity x (i.e. excluding any capacity reserve) is the same in both countries. The equilibrium price of electricity then is implicitly defined by the market-clearing condition $c^{-1}(\tilde{p}) + r = q_h + q_n = q$ if renewable output is large enough, where r indicates the renewable output in the representative country when electricity markets are national. If $x < q$, then there is no market clearing price for low realizations of renewable output. I assume that the wholesale price is set at a price cap $\bar{p}$ if the market fails to clear. Hence,

$$\tilde{p}(q-r) = \begin{cases} c(q-r) & \forall r \geq q-x \\ \bar{p} & \forall r < q-x, \end{cases} \tag{1}$$

identifies the short-term price of electricity.[13] The price cap $\bar{p}$ is endogenous, but has no implications in the short-run besides redistributing income between consumers and electricity producers. Its importance will be apparent through its effects on long-run demand and investment in thermal capacity.

Long-run equilibrium The long-run household demand $D_M(\bar{p})$ and the market-based investment level $X_M(\bar{p})$ in thermal capacity depend on the market structure $M = N, I$ because the relevant distribution of renewable output does so. The point at which the marginal utility of electricity consumption equals the expected price defines the equilibrium household demand:

$$u'(D_M) = \int_{D_M+q_n-X_M}^{\overline{r}} c(D_M + q_n - r)dF_M(r) + \bar{p}F_M(D_M + q_n - X_M). \tag{2}$$

The corresponding market-based investment level in thermal capacity equates the expected scarcity rent of the marginal capacity with the marginal capital cost:

$$(\bar{p} - c(X_M))F_M(D_M + q_n - X_M) = \delta. \tag{3}$$

Demand is decreasing and market-based thermal investment is increasing in the price cap $\bar{p}$; see Appendix A.1.

Capacity reserves For any price cap $\bar{p}$, the market-based supply of thermal capacity is insufficient to cover demand for low realizations of renewable output, i.e. whenever $r + X_M(\bar{p}) < D_M(\bar{p}) + q_n$. The system operator then can either activate capacity reserves to maintain system stability or, if that option has been exhausted, disconnect consumers. If system balance were to be attained entirely by curtailment, this would yield a disconnection (loss of load) probability equal to $F_M(D_M(\bar{p}) + q_n - X_M(\bar{p})) > 0$. I assume that it is politically unacceptable for system operators to deliberately disconnect consumers. The remaining solution then is to procure enough capacity reserves that curtailment will not occur.

If electricity markets are purely national, then $\bar{p}_N = \bar{P}_N(k)$ given by

$$X_N(\bar{P}_N) + k = D_N(\bar{P}_N) + q_n$$

[13] The discontinuity of the short term price at $r = q - x$ creates some uninteresting technical problems. The findings in the main text are limit results of a perturbed model where the wholesale price is continuous in r; see Appendix A.1 for the details.

represents the smallest price cap that would generate precisely enough market-based investment to ensure that total thermal capacity equals total demand given the national capacity reserve k. For any price cap above $\bar{P}_N(k)$, there would be overinvestment and under-utilization of the capacity reserve. Conversely, there would not be enough capacity in the market to cover demand in all possible contingencies for a price cap below $\bar{P}_N(k)$.

Denote by $k = \frac{k_1+k_2}{2}$ the average capacity reserve under perfect market integration, where (k_1, k_2) are the capacity reserves in the two countries. The price cap $\bar{p}_I = \bar{P}_I(k)$ defined by

$$X_I(\bar{P}_I) + k = D_I(\bar{P}_I) + q_n$$

is the smallest one required to generate enough market-based investment to ensure security of supply in the integrated market given the average capacity reserve k.[14,15] I assume that the activated capacity reserve is divided equally among the two countries under scarcity, i.e. whenever $r = \frac{r_1+r_2}{2} < k$. This allocation rule is ex post efficient here because it equates the marginal thermal costs across the two countries. The price cap is smaller when the capacity reserve is larger under both market structures $M = N, I$:

$$\bar{P}'_M(k) = \frac{1}{D'_M(\bar{P}_M(k)) - X'_M(\bar{P}_M(k))} < 0.$$

For future reference, let

$$\bar{k}_M = D_M(\phi) + q_n - X_M(\phi) > 0 \tag{4}$$

be the minimal capacity reserve necessary to fully protect the electricity intensive industry from losses under market structure M.

Most wholesale electricity markets feature a *bid cap* above which the market participants cannot submit bids or offers. In some markets, this bid cap is set at VOLL.[16] The price cap analyzed in this paper is the one implied by the target loss of load probability (which is zero) and the size of the capacity reserve, and can be substantially smaller than the bid cap. Hence, situations may occur in which capacity reserves are activated at prices below VOLL and without there being any substantial risk of rolling blackouts.[17]

[14] In the present context, the price cap $\bar{P}_M(k)$ is implicitly defined by the size of the capacity reserve. Alternatively, one can consider an explicit price cap $\bar{p}$ and an implied capacity reserve $K_M(\bar{p}) = D_M(\bar{p}) + q_n - X_M(\bar{p})$. The two approaches are formally equivalent in a national electricity market, but may have different implications in an integrated market because of strategic interaction between policy makers.

[15] One could also specify a target loss of load of load probability $\theta \geq 0$. Within this more general framework, $X_M(\bar{\mathcal{P}}_M) + k + F_M^{-1}(\theta) = D_M(\bar{\mathcal{P}}_M) + q_n$ characterizes the price cap $\bar{\mathcal{P}}_M(k, \theta)$ that for a capacity reserve k yields precisely enough market-based investment in thermal capacity to generate a loss of load probability θ under market structure M. Actual θs are very small. For instance, an annual loss of load probability of 0.1 days implies $\theta < 0.0003$. For simplicity, I let $\theta = 0$, such that $\bar{P}_M(k) = \bar{\mathcal{P}}_M(k, 0)$.

[16] Examples include ERCOT (Texas) and NEM (Eastern and Southern Australia).

[17] Sweden is an illustrative case in point. It has not experienced even a single hour of curtailment since liberalization of its electricity market in 1996. Nor did the electricity price ever hit the bid cap of 2000 Euro/MWh during this period. Yet, the system operator has intervened on a number of occasions, most recently during the cold winter of 2009-10. This pattern is consistent with security of supply being defined also in terms of avoiding very high prices instead of only averting curtailment. Naturally, there have been several uncontrolled blackouts

For renewable output $r \geq k$, there is enough thermal output offered at market terms to clear the market at the short-term marginal cost. If renewable output falls below the critical level $r < k$, then it becomes necessary to invoke some of the capacity reserve to avoid curtailment. In this case, the capacity reserve is bid into the market at the price cap. Therefore

$$p_M(r,k) = \begin{cases} c(x_M(k) + k - r) & \forall r \geq k \\ \bar{P}_M(k) & \forall r < k \end{cases} \tag{5}$$

characterizes the short-term price of electricity, where $x_M(k) = X_M(\bar{P}_M(k))$ is the market-based thermal capacity, and r and k represent country averages under perfect market integration.

Henceforth, I make the simplifying assumption that

$$c(x_M(k)) < \phi \ \forall k > 0. \tag{6}$$

By this assumption, the electricity intensive industry earns an operating profit under normal market conditions, i.e. as long as the market clears at the marginal thermal production cost. The industry runs into profitability problems only in situations of supply scarcity.

Domestic welfare The revenue generated in the market is insufficient to ensure supply security on market-based terms. Additional capacity payments must therefore be put in place in order to ensure the profitability to investors of providing the required capacity reserves. As the industry's marginal utility of income is larger than that of the households, it is socially optimal that households finance the entire capacity payment $T_M(k)$ in this model (which is also technically convenient and politically plausible). Letting $q_M(k) = D_M(\bar{P}_M(k)) + q_n$ denote consumption in the representative country as a function of the (average) capacity reserve k, the expected consumer surplus becomes

$$u(q_M(k) - q_n) + q_n\phi - \int_0^{\bar{r}} p_M(r,k) dF_M(r) q_M(k) - T_M(k) - q_n B(\bar{P}_M(k) - \phi) F_M(k).$$

The first two terms are the gross utilities of electricity consumption for the two consumer types. The third term is the expected wholesale cost of electricity, the fourth is the capacity payment. The final term is the expected shadow cost of the industry loss. The optimal capacity reserve features a trade-off between insurance and efficiency, but is nonetheless different from a standard moral hazard problem: it is the electricity intensive industry that is exposed to price risk, but the households that pay the insurance in terms of the capacity payment.

The expected surplus of the electricity producers is the expected wholesale revenue plus the capacity payment, minus the expected variable thermal cost and the capital cost:

$$\int_0^{\bar{r}} p_M(r,k) dF_M(r) q_M(k) + T_M(k) - \int_0^{\bar{r}} \int_0^{q_M(k)-r} c(\tilde{r}) d\tilde{r} dF_M(r) - \delta q_M(k).$$

Domestic welfare is the sum of consumer and producer surplus. Symmetry, full price equal-

in Sweden, the most severe of which was the consequence of Hurricane Gudrun in 2005.

ization and efficient dispatch of the capacity reserve imply that domestic welfare is the same in both countries under perfect market integration and a function of the average capacity reserve k. Hence, the domestic welfare in the representative country becomes

$$W_M(k) = u(q_M(k) - q_n) + q_n\phi - \int_0^{\overline{r}} \int_0^{q_M(k)-r} c(\tilde{r})d\tilde{r}dF_M(r) - \delta q_M(k) - q_n B(\bar{P}_M(k) - \phi)F_M(k)$$

for market structures $M = N, I$. The wholesale cost and the capacity payment represent pure redistribution and therefore vanish from the welfare expression.[18]

Policy makers choose capacity reserves non-cooperatively to maximize domestic welfare, taking the capacity reserve in the other country as given. I assume throughout that the problem of optimizing the capacity reserve is well-behaved under both market structures:[19]

$$\begin{array}{l} W_N''(k) < 0 \ \forall k \in (0, 2\max\{\bar{k}_N; \bar{k}_I\}], \\ W_I''(k) < 0 \ \forall k \in (0, \max\{\bar{k}_N; \bar{k}_I\}], \\ \lim_{k\to 0} W_M'(k) > 0,\ M = N, I. \end{array} \tag{7}$$

2.2 The socially optimal capacity reserve

By differentiating $W_M(k)$, we first note that a larger capacity reserve interferes with market prices by driving a wedge between the marginal utility of consumption (the expected spot price) and the marginal cost of thermal investment (the expected spot price plus capacity payment):

$$\begin{aligned} -\psi_M(k)q_M'(k) = & \ [u'(q_M(k) - q_n) - \textstyle\int_0^{\overline{r}} c(q_M(k) - r)dF_M(r) - \delta]q_M'(k) \\ = & \ -\textstyle\int_0^k [c(q_M(k) - r) - c(q_M(k) - k)]dF_M(r)q_M'(k) < 0. \end{aligned} \tag{8}$$

Instead of under-consuming relative to the competitive equilibrium, as would be the case under imperfect competition, households are over-consuming under the capacity mechanism. This marginal distortion calls for reducing the capacity reserve. Next, an increase in the capacity reserve also affects the exposure of the electricity intensive-industry to price risk. The first term in the marginal expected security of supply,

$$SS_M(k, \phi) = -q_n B'(\bar{P}_M(k) - \phi)F_M(k)\bar{P}_M'(k) - q_n B(\bar{P}_M(k) - \phi)f_M(k)q_M'(k), \tag{9}$$

measures the direct benefit of the reduction in the maximal spot price. But a larger capacity reserve crowds out market-based investment in thermal capacity, which increases the probability of a supply shortage in the spot market and that the spot price jumps to the price cap $\bar{P}_M(k)$.

[18] Appendix A.2 derives the least cost capacity payments under both market structures. The design of the mechanism should not matter for the results. Let the capacity reserve be those units that receive capacity payments in equilibrium. If the tendering process for capacity is competitive, then all units in the reserve have variable production costs above $c(x_M(k))$ by the assumption they all have the same capital cost δ. Therefore, it is unprofitable to bid in any part of the capacity reserve into the spot market unless there is a scarcity situation ($r < k$). It does not matter whether this capacity is reserved only for scarcity situations (a strategic reserve) or not (as in other types of mechanisms).

[19] Appendix A.3 shows that assumption (7) is satisfied for $\bar{k}_N$ and $\bar{k}_I$ sufficiently small under reasonable assumptions on $f_M(\cdot)$, $B(\cdot)$ and $u(\cdot)$.

This effect is the second term in (9); see Appendix A.3 for the details. Just like the associated price reduction can cause a firm's total revenue to fall if output is large, crowding out can cause security of supply to fall if the capacity reserve is large. In such a case, the policy maker can both increase security of supply and market efficiency by reducing the capacity reserve. Hence (the proof is in Appendix A.4):

Proposition 1 *The socially optimal capacity reserve $k_M^{fb} \in (0, \bar{k}_M)$ under market structure $M = N, I$ entails a trade-off between the marginal benefit of increased security of supply against the marginal cost of distorting consumption and investment:*

$$SS_M(k_M^{fb}, \phi) = \psi_M(k_M^{fb}) q_M'(k_M^{fb}). \tag{10}$$

The social optimum can be implemented as a pay-off dominant Nash equilibrium.

The assumption that capacity reserves are set by policy makers in each country in a decentralized and non-cooperative manner does not necessarily represent any large source of inefficiency. Domestic welfare depends on the average capacity reserve $k = (k_1 + k_2)/2$ if capacity reserves are allocated in an ex post efficient manner and the market is perfectly integrated. Domestic welfare is proportional to total welfare under symmetry. Then it is optimal for the home country to choose k_M^{fb} if the foreign country has done so. Each country *de facto* internalizes the welfare effect abroad in their choice of capacity reserve.

Comparative statics The trade-off facing policy makers is qualitatively the same independently of whether electricity markets are purely national of perfectly integrated. However, the magnitudes of the marginal effects differ between the two market structures. A fully integrated electricity market allows for a more efficient use of a given total capacity reserve $k_1 + k_2$ because reserves can be activated in such a manner as to increase efficiency by equalizing marginal thermal production costs across countries. This *pooling effect of capacity reserves* can be represented as the ratio of the expected cost distortion under market integration over the expected cost distortion when markets are national,

$$\frac{\psi_I(k)}{\psi_N(k)}, \tag{11}$$

and tends to increase the socially optimal capacity reserve under full market integration relative to the case when electricity markets are national.

The probability of a shortage of renewable electricity is relatively small under market integration because of trade and the imperfect correlation of renewable output. This *portfolio effect of renewable electricity* can be represented as the adjusted probability that the capacity reserve is invoked under market integration relative to the adjusted probability that it is invoked in the national market,

$$\frac{F_I(k)\frac{B'(\bar{P}_I(k)-\phi)}{D_I'(\bar{P}_I(k))} + B(\bar{P}_I(k) - \phi) f_I(k)}{F_N(k)\frac{B'(\bar{P}_N(k)-\phi)}{D_N'(\bar{P}_N(k))} + B(\bar{P}_N(k) - \phi) f_N(k)}, \tag{12}$$

and tends to reduce the socially optimal capacity reserve under full market integration relative to the case when electricity markets are national.[20] The net effect of market integration on capacity reserves depends on the relative magnitudes of the two effects (the proof is in Appendix A.5):

Proposition 2 *The socially optimal capacity reserve is larger under perfect market integration compared to the case when electricity markets are national ($k_I^{fb} > k_N^{fb}$) if the pooling effect of capacity reserves dominates the portfolio effect of renewable electricity:*

$$\frac{\psi_I(k)}{\psi_N(k)} < \frac{F_I(k)\frac{B'(\bar{P}_I(k)-\phi)}{D_I'(\bar{P}_I(k))} + B(\bar{P}_I(k)-\phi)f_I(k)}{F_N(k)\frac{B'(\bar{P}_N(k)-\phi)}{D_N'(\bar{P}_N(k))} + B(\bar{P}_N(k)-\phi)f_N(k)}, \; k \in \{k_N^{fb}, k_I^{fb}\}. \tag{13}$$

The opposite result holds if the inequality is reversed so that the portfolio effect dominates.

3 Capacity reserves in partially integrated markets

The analysis has so far relied on assumptions that markets either are purely national or perfectly integrated. This section allows markets to be partially integrated in the sense that trade flows are sometimes restricted.

3.1 Model extension

The analysis of electricity markets under transmission constraints is notoriously difficult when there is strategic interaction among players (policy makers in the present context). In particular, optimal behavior is discontinuous at trading volumes around which the constraint is just binding; see Holmberg and Philpott (2012) and references therein. To maintain tractability of the model while still capturing the flavor of network constraints, I assume that the transmission network has enough installed capacity to handle all trade flows, but the network breaks down with probability $1-\sigma \in (0,1)$. If this happens, then markets become completely separated and thus purely national. Instead, the market is fully integrated if the transmission network operates at full capacity. The parameter σ is a measure of market integration under this simplified structure. While a gross simplification, there is a grain of truth to this way of modeling networks because transmission capacity sometimes is reduced for scheduled or unscheduled maintenance reasons.

I also make a small reinterpretation of the time frame of the model. The analysis in Section 2 was cast in terms of the long-term problem of ensuring enough thermal investment to cover demand while simultaneously avoiding price spikes. Many countries in the EU actually are in a situation of overcapacity (European Commission, 2016). Instead, renewable production has driven prices down so far that the expected market revenue is insufficient to cover the fixed costs of keeping thermal capacity available for the spot market. Assume now that δ is the fixed cost of maintaining a unit of thermal capacity in operation mode and $c(\cdot)$ its variable production cost. Consider the problem of keeping enough thermal capacity online to ensure supply security.

[20] If, for instance $c(x) = cx$ and (r_1, r_2) are stochastically independent with distribution $F_N(r) = \frac{r}{\bar{r}}$, then $\frac{\psi_I(k)}{\psi_N(k)} = \frac{2}{3}\frac{2k}{\bar{r}}$ and $\frac{F_I(k)}{F_N(k)} = \frac{2k}{\bar{r}}$ are both below unity for $k \leq \bar{k}_M \leq \frac{\bar{r}}{2}$.

The timing of the game is as follows. The policy makers in the two countries procure capacity reserves (k_1, k_2) in the first stage. Network reliability is realized, after which markets are either perfectly integrated or national. Consumers decide how much electricity to purchase and power producers how much thermal capacity to make available to the short-term market depending on the market structure $M = N, I$. Finally, renewable output is realized in the two countries. The wholesale market clears all prices if renewable output and transmission capacity are sufficient to handle the net flow of electricity between markets. If not, capacity reserves are activated in one or both markets.[21,22] Expected welfare in country i is the weighted average

$$W(k_i, k_j) = \sigma W_I(k) + (1-\sigma)W_N(k_i) \tag{14}$$

under this structure, where $k = (k_1+k_2)/2$ is the average capacity reserve. The expected welfare in the representative country equals $W(k,k)$ under symmetric capacity reserves, $k_1 = k_2 = k$.

3.2 Equilibrium capacity reserves

Consider the social optimum as a benchmark. The first-best optimal capacity reserve $k^{fb}(\sigma)$ is symmetric and trades-off the marginal effect in the integrated market against the marginal effect when markets are national:

$$\sigma W_I'(k^{fb}) + (1-\sigma)W_N'(k^{fb}) = 0. \tag{15}$$

Now let policy makers in each country set their capacity reserves non-cooperatively to maximize domestic welfare $W(k_i, k_j)$. The first-order condition becomes

$$\frac{\partial W(k_i, k^*)}{\partial k_i}|_{k_i=k^*} = \tfrac{1}{2}\sigma W_I'(k^*) + (1-\sigma)W_N'(k^*) = 0 \tag{16}$$

in symmetric equilibrium, $k_1^* = k_2^* = k^*(\sigma)$. An electricity market with zero or full integration delivers an efficient outcome in this model, but the market with partial integration does not. A comparison of equilibrium condition (16) with the optimality condition (15) traces the inefficiency of decentralized policy making down to the failure of policy makers to take into account the marginal effect $\sigma W_I'(k)/2$ abroad of expanding the capacity reserve at home. However, capacity reserves can be upward or downward distorted under partial market integration.

To evaluate the effects of decentralized policy making, consider the symmetric capacity reserve $k_1 = k_2 = \kappa(t, \sigma)$ implicitly defined by the solution to

$$\tfrac{1+t}{2}\sigma W_I'(\kappa) + (1-\sigma)W_N'(\kappa) = 0. \tag{17}$$

[21] An alternative timing would be to assume that consumers and power producers make their choices prior to the revelation of market structure. Demand and thermal supply in each country would then depend on the full range of price caps $(\bar{p}_{N1}, \bar{p}_{N2}, \bar{p}_I)$. The trade-off facing policy makers would remain qualitatively intact, but the analysis of decentralized policy making would be obscured by an intractability of second-order conditions.

[22] One could also maintain a long-term framework and assume that network owners with probability σ make an incremental investment to remove bottlenecks. I endogenize σ in Section 4.

The parameter t measures the degree to which policy makers internalize the externality abroad of changes in the domestic capacity reserve. Policy makers internalize the full effect if $t = 1$, in which case the first-best solution obtains: $\kappa(1,\sigma) = k^{fb}(\sigma)$. The non-cooperative solution obtains when policy makers do not internalize any of the effects abroad: $\kappa(0,\sigma) = k^*(\sigma)$.

The difference between the socially optimal capacity reserve and the equilibrium solution is

$$k^{fb} - k^* = \int_0^1 \frac{\partial \kappa(t,\sigma)}{\partial t} dt = \int_0^1 \frac{\sigma W_I'(\kappa(t,\sigma))}{-[(1+t)\sigma W_I''(\kappa(t,\sigma)) + 2(1-\sigma) W_N''(\kappa(t,\sigma))]} dt. \tag{18}$$

The denominator of (18) is strictly positive by assumption (7). Hence, decentralized policy making leads to downward (upward) distortions in the equilibrium capacity reserve if the foreign externality is positive (negative), which is very intuitive. The sign of the externality in turn depends on the relative strengths of the marginal effects of market integration:

Lemma 1 *The foreign externality is positive [negative] if the pooling effect of capacity reserves is stronger [weaker] than the portfolio effect of renewable electricity ($\sigma W_I'(\kappa(t,\sigma)) > [<] 0$ for all $t \in [0,1]$ and $\sigma \in (0,1]$ if inequality (13) is satisfied [violated]).*

Proof. Assume that $(t,\sigma) \in [0,1] \times (0,1]$. Strict quasi-concavity of $W_I(k)$ and $W_N(k)$ imply $\frac{1+t}{2}\sigma W_I'(k) + (1-\sigma) W_N'(k) > (<) 0$ for all $k < \min\{k_N^{fb}; k_I^{fb}\}$ ($k > \max\{k_N^{fb}; k_I^{fb}\}$). Hence, $\kappa(t,\sigma) \in [\min\{k_N^{fb}; k_I^{fb}\}, \max\{k_N^{fb}; k_I^{fb}\}]$. If inequality (13) is satisfied [violated], then $\kappa(t,\sigma) \in [k_N^{fb}, k_I^{fb}]$ [$\kappa(t,\sigma) \in [k_I^{fb}, k_N^{fb}]$] by Proposition 2. Strict quasi-concavity of $W_I(k)$ then implies $W_I'(\kappa(t,\sigma)) > [<] 0$ if inequality (13) is satisfied [violated]. ■

A marginal increase in the domestic capacity reserve increases the security of supply even abroad in an integrated market, but the lower price cap exacerbates consumption and investment distortions abroad. The marginal distortion of an increase in the capacity reserve is small (large) in magnitude compared to the supply security effect if the pooling effect is strong (weak). The foreign externality is positive (negative) in this case. Hence (the proof is in Appendix A.6):

Proposition 3 *The symmetric equilibrium capacity reserve $k^*(\sigma) \in [\min\{k_N^{fb}; k_I^{fb}\}, \max\{k_N^{fb}; k_I^{fb}\}]$ solves*

$$\tfrac{1}{2}\sigma SS_I(k^*,\phi) + (1-\sigma) SS_N(k^*,\phi) = \tfrac{1}{2}\sigma \psi_I(k^*) q_I'(k^*) + (1-\sigma)\psi_N(k^*) q_N'(k^*) \tag{19}$$

when electricity markets are partially integrated. The equilibrium capacity reserve is downward [upward] distorted if the pooling effect of capacity reserves dominates [is dominated by] the portfolio effect of renewable electricity ($k^*(\sigma) < [>] k^{fb}(\sigma)$ if inequality (13) is satisfied [violated]).

4 Network investment to increase market integration

Network owners typically earn their income from buying electricity at a low price in one area and selling it at a higher price in another when network constraints prevent the market from clearing at a single price. The market generates no such *congestion rent* here. Either the transmission network is fully operational, in which case the market is integrated and there are no price differences, or the network is completely down, in which case the countries do not trade. As is particularly visible in the present context, the market generally provides insufficient incentives for improving network reliability. To account for the "missing money" problem in network investment, I assume that the transmission networks are regulated. I consider both the case when regulation of network investment is centralized and when network investment is decentralized to the individual countries along with the choice of capacity reserves.

4.1 Centralized network investment

Total reliability σ_I is chosen to maximize the expected total welfare

$$\sigma_I W_I(k) + (1-\sigma_I) W_N(k) - C(\sqrt{\sigma_I})$$

of the two countries, taking capacity reserves as given and symmetric, $k_1 = k_2 = k$, and subject to the twice continuously differentiable, increasing and strictly convex cost function $C(\cdot)$, where assumptions that $\frac{C''(y)y}{C'(y)} > 1$ for all $y > 0$, $\lim_{y\to 0} C'(y)/y < W_I(k_N^{fb}) - W_N(k_N^{fb})$ and $C'(1)/2 > W_I(k_I^{fb}) - W_N(k_I^{fb})$ ensure existence of an interior solution. The optimal degree $R_I(k)$ of network reliability trades off the marginal value of market integration against marginal network cost:

$$W_I(k) - W_N(k) = \frac{C'(\sqrt{R_I})}{2\sqrt{R_I}}.$$

Countries choose capacity reserves to maximize domestic welfare subject to network reliability σ_I and the capacity reserve abroad. Then $\sigma_I = R_I(\kappa(t, \sigma_I))$ characterizes the equilibrium degree of market integration $\sigma_I(t)$ as a function of the degree t to which policy makers internalize the foreign externality of capacity reserves. The first-best solution satisfies $\sigma^{fb} = \sigma_I(1)$, and the equilibrium solution is $\sigma_I^* = \sigma_I(0)$. Hence,

$$\sigma^{fb} - \sigma_I^* = \int_0^1 \sigma_I'(t)dt = \int_0^1 \frac{R_I'(\kappa(t,\sigma_I(t)))\partial\kappa(t,\sigma_I(t))/\partial t}{1 - R_I'(\kappa(t,\sigma_I(t)))\partial\kappa(t,\sigma_I(t))/\partial\sigma} dt$$

measures the effect on market integration of decentralizing the choice of capacity reserves under centralized network regulation. The denominator of the fraction is positive in stable equilibrium (Dixit, 1986). By

$$R_I'(\kappa) = \frac{(1+t)\sigma_I + 2(1-\sigma_I)}{1-\sigma_I} \frac{2\sigma_I^{\frac{3}{2}} W_I'(\kappa)}{C''(\sqrt{\sigma_I})\sqrt{\sigma_I} - C'(\sqrt{\sigma_I})},$$

an increase in the capacity reserve tends to increase the marginal value of market integration and drive up network investment if the foreign externality is positive. Capacity reserves and market integration are strategic complements in this case. Instead, capacity reserves and market integration are strategic substitutes if the foreign externality is negative. Whether equilibrium capacity reserves are above or below the social optimum under decentralized policy making also depends on the magnitudes of the two effects of market integration, see (18). Multiplying the two effects yields

$$R_I'(\kappa)\frac{\partial \kappa}{\partial t} = \frac{2\sigma_I^{\frac{5}{2}}\frac{(1+t)\sigma_I+2(1-\sigma_I)}{1-\sigma_I}}{C''(\sqrt{\sigma_I})\sqrt{\sigma_I}-C'(\sqrt{\sigma_I})}\frac{(W_I'(\kappa))^2}{-[(1+t)\sigma_I W_I''(\kappa(t,\sigma))+2(1-\sigma_I)W_N''(\kappa)]} > 0,$$

and we get the following result:

Proposition 4 *Market integration is downward distorted if network investment is centralized and countries choose capacity reserves non-cooperatively ($\sigma_I^* < \sigma^{fb}$ in stable equilibrium).*

A decentralized choice of capacity reserves at the individual country level has an unambiguous effect on market integration, despite the ambiguous effect on capacity reserves. Capacity reserves are downward distorted if the pooling effect of capacity reserves is comparatively strong, which in turn leads to a downward distortion of network investment by strategic complementarity. Instead, capacity reserves are upward distorted if the portfolio effect of renewable electricity is comparatively strong, which again leads to a downward distortion of network investment, this time by strategic substitutability.

4.2 Decentralized network investment

Building new cross-border transmission capacity requires coordination across countries, but they can unilaterally decide how much to spend on maintaining the part of the network that is located domestically. To account for decentralized decisions, let the two countries invest in domestic network reliability (y_1, y_2) non-cooperatively. If network reliability is stochastically independent across the two countries, then the total network reliability is $y_1 y_2$.

Country i's welfare function

$$y_1 y_2 W_I(k) + (1 - y_1 y_2) W_N(k_i) - C(y_i)$$

is not necessarily quasi-concave in the domestic policy variables (k_i, y_i) although it is quasi-concave in each of the two arguments k_i and y_i. To circumvent existence problems caused by non-concavity, I assume that k_i and y_i are decentralized to different policy makers in country i and chosen independently of one another. Any Nash equilibrium under a coordinated choice of (k_i, y_i) is contained in the set of Nash equilibria under a non-cooperative choice of k_i and y_i.

The total network reliability $R_N(k) = y_N^2(k)$ under decentralized network investment is characterized by the solution to

$$W_I(k) - W_N(k) = \frac{C'(\sqrt{R_N})}{\sqrt{R_N}}$$

in interior symmetric equilibrium for a symmetric capacity reserve $k_1 = k_2 = k$.[23] The equilibrium degree of market integration $\sigma_N(t)$ under decentralized network investment is implicitly

[23] Observe that $y_1 = y_2 = 0$ constitutes a Nash equilibrium under decentralized network investment because network reliability is zero independently of y_i if $y_j = 0$. More interesting is the case of positive market integration.

characterized by the solution to $\sigma_N = R_N(\kappa(t, \sigma_N))$ as a function of the degree t to which policy makers internalize the foreign externality of capacity reserves.

By following the same procedure as in the case of centralized network investment, it is easy to verify that market integration is smaller when domestic policy makers fail to internalize the external effects of capacity reserves compared to the case when all such effects are internalized: $\sigma_N^* < \sigma_N(1)$. The next question is whether decentralized network investment further accentuates those distortions, i.e. whether $\sigma_N^* < \sigma_I^*$. To analyze this question, define $R(k, \tau)$ by

$$W_I(k) - W_N(k) = \frac{C'(\sqrt{R})}{(1+\tau)\sqrt{R}}$$

and $\sigma(t, \tau)$ by $\sigma = R(\kappa(t, \sigma), \tau)$. By construction, $\sigma_I^* = \sigma(0, 1)$ and $\sigma_N^* = \sigma(0, 0)$, so that the difference in network reliability between the two regimes becomes:

$$\sigma_I^* - \sigma_N^* = \int_0^1 \frac{\partial \sigma(0, \tau)}{\partial \tau} d\tau = \int_0^1 \frac{\partial R(\kappa(t, \sigma), \tau)/\partial \tau}{1 - (\partial R(\kappa(t, \sigma), \tau)/\partial k)\partial \kappa(t, \sigma)/\partial \sigma} d\tau.$$

The denominator is positive in stable equilibrium, so that the effect on market integration is determined by the direct effect:

$$\frac{\partial R(\kappa, \tau)}{\partial \tau} = \frac{1}{1+\tau} \frac{2\sigma C'(\sigma^{\frac{1}{2}})}{C''(\sqrt{\sigma})\sqrt{\sigma} - C'(\sqrt{\sigma})} > 0,$$

and it follows that:

Proposition 5 *Market integration is further downward distorted if both network investment and capacity reserves are decided non-cooperatively by the two countries compared to the case when network investment is centralized ($\sigma_N^* < \sigma_I^* < \sigma^{fb}$ in stable equilibrium).*

Domestic investment in network reliability has positive effects abroad because of improved market integration. A country concerned entirely with the maximization of domestic surplus neglects these positive external effects, which causes the total network reliability to be smaller under decentralized than centralized network investment. Hence, the welfare distortions associated with decentralized decision making are additive in this model.

5 Financial markets

An alternative to hedging price risk through a capacity market would be through a financial market. This section investigates how financial markets interact with the socially optimal capacity reserves and those that would arise in equilibrium.

5.1 Model extension

Let the industry in country i purchase q_n call options for one MWh each with strike price s. Assume that the financial market is perfectly competitive and that realized gains and losses are treated symmetrically in the financial market; the seller is risk neutral and can clear any losses one for one against other profits. The equilibrium option price $v(k_i, k_j, s)$ in country i then simply equals the expected option payment:

$$v(k_i, k_j, s) = \sigma \int_0^{\bar{r}} \max\{p_I(r, k) - s; 0\} dF_I(r) + (1 - \sigma) \int_0^{\bar{r}} \max\{p_N(r, k_i) - s; 0\} dF_N(r)$$

under partial market integration ($\sigma \in [0, 1]$ and exogenous).

Financial contracting leaves the profit of the power producers unaffected. The expected welfare in country i thus becomes

$$W(k_i, k_j, s) = \sigma W_I(k, s) + (1 - \sigma) W_N(k_i, s) - q_n v(k_i, k_j, s),$$

where the domestic welfare under market structure M is given by

$$W_M(k, s) = u(q_M(k) - q_n) + q_n \phi - \int_0^{\bar{r}} \int_0^{q_M(k)-r} c(\tilde{r}) d\tilde{r} dF_M(r) - \delta q_M(k) - q_n \int_0^{\bar{r}} B(\min\{p_M(r, k); s\} - \phi) dF_M(r)$$

gross of the option cost $q_n v(k_i, k_j, s)$.[24] The expected welfare in the representative country equals $W(k, s) = W(k, k, s)$ under symmetric capacity reserves, $k_1 = k_2 = k$.

5.2 Equilibrium capacity reserves vs. the social optimum

Assume that the capacity reserves are symmetric and so small that the option is in the money when renewable resources are scarce under both market structures, i.e. $\bar{P}_I(k) > s$ and $\bar{P}_N(k) > s$. We can then write the welfare effect of an increase in the capacity reserve as:

$$\begin{aligned} \frac{\partial W(k, s)}{\partial k} = & -q_n B(s - \phi)[\sigma f_I(k) q_I'(k) + (1 - \sigma) f_N(k) q_N'(k)] \\ & -\sigma \psi_I(k) q_I'(k) - (1 - \sigma) \psi_N(k) q_N'(k). \end{aligned} \tag{20}$$

The sum of the two terms on the second row is the marginal expected distortion of consumption and investment in a partially integrated market. The term on the first row is the marginal price effect. It is zero if the strike price is below the industry's break-even price so that the financial market already offers complete insurance ($B(s - \phi) = 0$ for all $s \leq \phi$). It is *strictly negative* when the firm is exposed to price risk ($s > \phi$). Recall that the welfare benefit of an increase in the capacity reserve works through the reduction in the maximal price, $\bar{P}_M'(k) < 0$, when there are no financial contracts; see Proposition 1. This benefit vanishes under option contracting because then it is the strike price s that marks the maximal price for the electricity intensive industry. The remaining effect of the capacity reserve is to crowd out market-based investment in thermal capacity, which increases the probability of a supply shortage in the short-term market.

[24] It would be appropriate to denote the shadow cost $B(\min\{p_M(r, k); s\} + v(k_i, k_j, s) - \phi)$ under financial contracting because the electricity intensive industry turns an operating profit if and only if $\phi \geq \min\{p_M(r, k); s\} + v(k_i, k_j, s)$. However, the options are purchased prior to the resolution of any uncertainty and therefore represents a sunk cost at the production stage. To avoid uninteresting complications, I assume that only the variable part of the profit represents a shadow cost to the firm.

Crowding-out represents the first term in (20) above. Hence (the proof is in Appendix A.7):

Proposition 6 *Assume that consumers can hedge risk by purchasing call options in a competitive financial market that renders the equilibrium option price equal to the expected option payment. The socially optimal capacity reserve $k^{fb}(\sigma, s)$ is zero for any degree of market integration $\sigma \in [0, 1]$ and any option strike price $s < \infty$. The social optimum can be implemented as a pay-off dominant Nash equilibrium.*

Financial markets remove the scope for capacity reserves because they distort prices and investments without providing any hedging benefits beyond what can be achieved through financial contracting. The efficiency of energy-only markets does not hinge upon financial markets being able to hedge all consumers' price risk ($s \leq \phi$). All that matters is that the price risk is bounded ($s < \infty$). The expected shadow cost of losses is driven to zero as capacity reserves become small because the probability $F_M(k)$ of supply shortage vanishes. It is not necessary to disconnect any consumers because all necessary capacity is supplied on market-based terms.

There are no inefficiencies associated with decentralized policy making, not even under incomplete market integration. No country has anything to gain by unilaterally introducing a capacity market in an energy-only market with financial contracting because there are no domestic hedging benefits to be achieved, only distortions.

Proposition 6 points to at least two reasons why countries would introduce capacity markets in a market with financial contracting. Domestic policy makers could have other objectives than to maximize the sum of domestic consumer and producer surplus. If, for example, the expected profit of the energy intensive industry weighs more heavily than the other groups in the economy, a motive for introducing a capacity mechanism would be to push down the expected option payment and thereby reduce the cost to the industry of financial contracting.

An efficiency argument in favour of capacity markets arises in an imperfect financial market unable to hedge all risk. There could for instance be volume risk, which I have ignored by assuming constant demand q_n. But there could also be remaining price risk. Assume that the sellers of financial contracts cannot diversify away all risk. To facilitate comparison with the analysis in Section 3, assume that $B(\cdot)$ now denotes the shadow cost of losses faced by the *sellers* of the option contracts, whereas $\tilde{B}(\cdot)$ represents the industry's shadow cost.[25] In a competitive financial market, the option price equals the expected option payment plus the risk correction:

$$v(k, k, s) = \sigma \int_0^{\bar{r}} B(\max\{p_I(r, k) - s; 0\}) dF_I(r) + (1 - \sigma) \int_0^{\bar{r}} B(\max\{p_N(r, k) - s; 0\}) dF_N(r).$$

The option price will be very high in an energy-only market if $B(\cdot)$ is large for large option payments, even if the financial market is competitive and despite the option payment being bounded in expectation.[26] Capacity reserves again improve performance in the financial market by limiting market participants' exposure to price spikes. The welfare effect of a small increase

[25] Now there is risk aversion both on the seller and buyer side. A sufficient condition for gains from trade in the financial markets given $s > \phi$ is $\tilde{B}(\tilde{p} - \phi) - \tilde{B}(s - \phi) > B(\tilde{p} - s)$ for all $\tilde{p} > s$.

[26] It is easy to verify that $\lim_{k \to 0} v(k, k, s) \leq \sigma \lim_{k \to 0} u'(q_I(k) - q_n) + (1 - \sigma) \lim_{k \to 0} u'(q_N(k) - q_n) < \infty$.

in the capacity reserve equals

$$\frac{\partial W(k,s)}{\partial k} = \sigma SS_I(k,s) + (1-\sigma)SS_N(k,s)$$
$$-\sigma[\psi_I(k) + q_n\tilde{B}(s-\phi)f_I(k)]q_I'(k) - (1-\sigma)[\psi_N(k) + q_n\tilde{B}(s-\phi)f_N(k)]q_N'(k).$$

This trade-off is qualitatively similar to the one that arises with consumer risk aversion, but no financial markets. A minor difference is that the reference price now equals the strike price s instead of the industry break-even price ϕ. If $s = \phi$, then the solution is exactly the same as in Proposition 3. Hence, it is only under strong assumptions about the financial market in terms of competitiveness and the diversifiability of risk that the need for capacity reserves vanishes.

6 National allocation rules for capacity reserves

I have so far assumed that all available capacity reserves are used in an efficient manner under market integration, independently of where the market is constrained the most. In this section, I instead assume that countries are responsible for handling their own supply problems separately. This change is of no consequence in a situation with national markets, because then there would be no flow of electricity between the countries anyway. For illustration, consider therefore the opposite polar case of perfect market integration.

In a perfectly integrated market, total consumption q and market-based investment $x < q$ are identical in the two countries independently of the how supply constraints are handled because all consumers and producers face identical prices. There is enough thermal capacity to clear the market if and only if $r \geq q - x$. In the opposite case of a supply constrained market, I define the national supply constraint in country i as

$$\begin{array}{ll} \max\{q - x - r_i; 0\} & \text{if } r < q - x \text{ and } r_j < q - x \\ 2(q-x) - r_1 - r_2 & \text{if } r < q - x \text{ and } r_j \geq q - x. \end{array}$$

Country i faces a national supply constraint only if the domestic market-based supply is insufficient to cover the domestic demand: $x + r_i < q$. If this situation occurs also in country j, then the domestic excess demand defines the national supply constraint in both countries. If instead country j has excess supply, $x + r_j \geq q$, then the national supply constraint in country i is the difference between the domestic excess demand and net imports.

The price cap $\bar{P}_I(k)$ of Section 2 was defined to generate precisely enough market-based thermal investment $x_I(k)$ to cover residual demand $q_I(k) - k$ in the worst case scenario without renewable production anywhere and if the two countries have the same capacity reserve, $k_1 = k_2 = k$. If the two countries have chosen different capacity reserves, $k_1 \neq k_2$, then $\bar{P}_I(k)$ is still necessary and sufficient to ensure the security of supply in both markets if now $k = \min\{k_1; k_2\}$.

The symmetry of demand and market-based thermal investment implies that total thermal output only depends on $k = \min\{k_1; k_2\}$ even if $k_1 \neq k_2$. In this case, there is excess thermal capacity $k_i - \min\{k_1; k_2\}$ in one country. Importantly, the thermal production

$$\begin{array}{ll} q_I(k) - r_i & \text{if } r_i < k \text{ and } r_j < k \\ 2q_I(k) - x_I(k) - r_i - r_j & \text{if } r < k \text{ and } r_j \geq k \\ x_I(k) & \text{if } r < k \text{ and } r_i \geq k \end{array}$$

in country i displays more variability under a national supply constraint than under an aggregate supply constraint where thermal production equals $q_I(k) - r$. This variability implies an inefficiency because of the convexity of the thermal production cost. The welfare in the representative country can then be written as

$$W_{Inat}(k) = W_I(k) - \Omega_I(k)$$

for symmetric capacity reserves $k_1 = k_2 = k$, where $\Omega_I(k)$ represents the production inefficiency associated with the national supply constraint, and $\Omega_I'(k) = \omega_I(k)q_I'(k) > 0$ is the corresponding marginal production inefficiency; see equations (33) and (34) in Appendix A.8 for a characterization and a proof of the following:

Proposition 7 *Assume that electricity markets are perfectly integrated, but supply constraints are defined at the national level. Any constrained socially optimal capacity reserve satisfies* $k_I^{sb} < k_I^{fb}$ *and is characterized by:*

$$SS_I(k_I^{sb}, \phi) = [\psi_I(k_I^{sb}) + \omega_I(k_I^{sb})]q_I'(k_I^{sb}). \tag{21}$$

The constrained social optimum can be implemented as a pay-off dominant Nash equilibrium.

National allocation rules imply that the socially optimal capacity reserve k_I^{sb} falls below the level k_I^{fb} that would arise under an efficient dispatch of capacity reserves because the marginal distortion associated with a capacity reserve is larger in the former case. However, there are no particular distortions associated with decentralized policy making in the perfectly integrated market. Symmetry across countries and the fact that the price cap $\bar{P}_I(k)$ is determined by the minimal capacity reserve $k = \min\{k_1; k_2\}$ imply that each country internalizes all welfare effects by the unilaterally optimal choice of capacity reserve.

7 Policy discussion

This paper has studied countries' unilateral incentives for increasing security of supply by means of capacity reserves and network investment in a two-country model of interconnected electricity markets with fluctuating renewable production. Capacity reserves offer consumers protection against price spikes and running blackouts in situations of renewable production shortfalls, but also distort long-run investment and consumption decisions in the market. Network reinforcements reduce national supply constraints, but are costly.

A first finding is that a non-cooperative choice of capacity reserves not necessarily is inefficient. National policy makers effectively internalize the foreign externalities if countries are symmetric, perfectly integrated, and capacity reserves are deployed in an efficient matter. Hence, necessary conditions for inefficient policy making are country asymmetries and/or imperfectly integrated markets. This paper emphasizes distortions associated with market integration.

Equilibrium capacity reserves can be too large or too small in an imperfectly integrated market depending on the relative magnitude of two cross-border externalities. On the one hand, a larger foreign capacity reserve benefits the home country by improving supply security in the entire market. Free-riding on foreign capacity reserves tends to generate capacity reserves that are too small. On the other hand, a larger domestic capacity reserve exacerbates consumption and investment distortions abroad. Such international spill-overs cause excessive capacity reserves. Because of these ambiguous effects, it is impossible to make general recommendations about whether countries should be encouraged to increase domestic capacity reserves or discouraged from doing so. The net effect depends quantitatively on the strength of a portfolio effect of renewable electricity relative to a pooling effect of capacity reserves.

Network underinvestment is a pervasive problem. First of all, congestion rent is an inappropriate measure of the social value of network reinforcements to increase system reliability. For instance, congestion rents are always zero in the present model independently of network reliability. Hence, the optimal level of network investment cannot be decided on the basis of market signals alone. Centralizing the choice of network investment improves matters because of the positive foreign externalities associated with improved market integration. However, even a regulation that causes network owners to invest in order to maximize total welfare is insufficient if countries choose capacity reserves non-cooperatively. In light of this finding, the current EU guidelines for cross-border interconnections subject to which (European Union, 2013, p.44) "[t]he costs for the development, construction, operation and maintenance of projects of common interest should in general be fully borne by the users of the infrastructure" are likely to be suboptimal from a social welfare perspective. One way to reduce the inefficiency of domestically chosen capacity reserves is to establish a regulation that induces network investors to attach a stronger weight to the marginal value of increased market integration relative to the cost of improving the network and thus to *overinvest* all else equal. This suggests that users should either pay in excess of the full network costs, or network investment should be subsidized at central EU level to offset the distortions associated with capacity reserves.

A major benefit of capacity reserves is to shelter consumers against short-term price spikes in the market. This benefit is reduced if consumers also can hedge price risk in a financial market. Financial contracting thus reduces the need for capacity mechanisms. Put differently, a larger share of the thermal investment necessary to ensure security of supply can be left to the market if consumers have the possibility to insure themselves against the price spikes necessary to accomplish this investment. In fact, the optimal capacity reserve is close to zero in the limit when the financial market is efficient and able to absorb all price risk.[27] A fundamental

[27] See Galetovic et al. (2015) for a quantitative analysis of energy-only versus markets with capacity reserves and the role of financial markets in bridging the gap between the two.

property of an efficient market design therefore is the development of an efficient financial market (European Commission, 2016). However, this market is more likely to develop if capacity reserves are in place to protect market participants against extreme prices. Consequently, capacity and financial markets are not necessarily substitutes for one another.

The socially optimal and equilibrium capacity reserves are smaller when reserves are deployed solely to resolve domestic supply constraints, because the marginal thermal production cost associated with capacity reserves then is larger than necessary. A national perspective on supply constraints therefore transforms into larger than necessary price spikes to ensure the security of supply in an integrated electricity market with large shares of renewable production. A multinational approach to capacity mechanisms would increase efficiency and the security of supply. An example of such an approach would be a market in which domestic capacity reserves can be invoked to relieve supply security problems abroad.[28]

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Appendices

A.1 The continuous price extension

Let the wholesale price be defined by

$$\tilde{p}(q-r) = \begin{cases} c(q-r) & \forall r \geq q-x \\ \hat{p}(q-r) & \forall r \in ((q-x)(1-\varepsilon), q-x) \\ \bar{p} & \forall r \leq (q-x)(1-\varepsilon). \end{cases}$$

The only difference between this price and (1) in the main text is the inclusion of the twice continuously differentiable and increasing function $\hat{p}(\cdot)$ in a small interval $r \in ((q-x)(1-\varepsilon), q-x)$. Let $\hat{p}(x) = c(x)$ and $\hat{p}(q\varepsilon + x(1-\varepsilon)) = \bar{p}$. The purpose is to avoid uninteresting and complicating discontinuities around the point of full capacity utilization, $r = q - x$. All results in the main text are limiting results for $\varepsilon \to 0$.

The optimality conditions

$$u'(D_M) = \int_{(D_M+q_n-X_M)(1-\varepsilon)}^{\overline{r}} \tilde{p}(D_M + q_n - r)dF_M(r) + \bar{p}F_M((D_M + q_n - X_M)(1 - \varepsilon)), \quad (22)$$

$$\int_{(D_M+q_n-X_M)(1-\varepsilon)}^{D_M+q_n-X_M} (\hat{p}(D_M + q_n - r) - \bar{p})dF_M(r) + (\bar{p} - c(X_M))F_M(D_M + q_n - X_M) = \delta \quad (23)$$

jointly define the equilibrium household demand $D_M(\bar{p})$ and market-based investment $X_M(\bar{p})$. Straightforward differentiation of the two conditions yields:

$$D'_M(\bar{p}) = \frac{F_M((D_M+q_n-X_M)(1-\varepsilon))}{u''(D_M)-\int_{(D_M+q_n-X_M)(1-\varepsilon)}^{\overline{r}} \tilde{p}'(D_M+q_n-r)dF_M(r)} < 0,$$

$$X'_M(\bar{p}) = \frac{u''(D_M)-\int_{D_M+q_n-X_M}^{\overline{r}} c'(D_M+q_n-r)dF_M(r)}{c'(X_M)F_M(D_M+q_n-X_M)} D'_M(\bar{p}) > 0.$$

Combine the two market-clearing conditions to get

$$u'(D_M) = \int_{D_M+q_n-X_M}^{\overline{r}} c(D_M + q_n - r)dF_M(r) + c(X_M)F_M(D_M + q_n - X_M) + \delta.$$

The demand in the energy-only market, $\lim_{\bar{p}\to\infty} D_M(\bar{p}) = D_M^\infty > 0$, is the solution to

$$u'(D_M^\infty) = \int_0^{\overline{r}} c(D_M^\infty + q_n - r)dF_M(r) + \delta,$$

whereas the market-based investment level satisfies $X_M^\infty = \lim_{\bar{p}\to\infty} X_M(\bar{p}) = D_M^\infty + q_n < \infty$.

By the definitions of $\bar{P}_M(k)$ and $x_M(k)$ in the main text, I can then solve for the short-term price as a function of k:

$$p_M(r,k) = \begin{cases} c(x_M(k) + k - r) & \forall r \geq k \\ \hat{p}(x_M(k) + k - r) & \forall r \in (k(1-\varepsilon), k) \\ \bar{P}_M(k) & \forall r \leq k(1-\varepsilon) \end{cases} \quad (24)$$

Straightforward differentiation of $q_M(k) = D_M(\bar{P}_M(k)) + q_n$ yields

$$q'_M(k) = \frac{c'(x_M(k))F_M(k)}{c'(x_M(k))F_M(k) + \int_k^{\overline{r}} c'(q_M(k) - r)dF_M(r) - u''(q_M(k) - q_n)} \in (0,1). \quad (25)$$

A.2 Capacity payments

The activated capacity reserve is sold in the wholesale market at the price cap. Then

$$T_N(k) = \int_0^k [\int_0^{k-r} c(x_N(k) + z)dz - p_N(r,k)(k - r)]dF_N(r) + \delta k$$

represents the minimal capacity payment necessary to procure the desired capacity reserve k and ensure supply security at the price cap $\bar{P}_N(k)$ when electricity markets are national.

The minimal capacity payment necessary to implement a capacity reserve of k in both countries under perfect market integration is given by

$$T_I(k) = \int_{\max\{2k-\bar{r};0\}}^{\min\{2k;\bar{r}\}} \int_0^{2k-r_2} [\int_0^{k-r} c(x_I(k)+z)dz - p_I(r,k)(k-r)]dF(r_1,r_2)$$
$$+ \int_0^{\max\{2k-\bar{r};0\}} \int_0^{\bar{r}} [\int_0^{k-r} c(x_I(k)+z)dz - p_I(r,k)(k-r)]dF(r_1,r_2) + \delta k.$$

The renewable output in country 2 is large enough to clear the market independently of renewable output in country 1 if $r_2 \geq \min\{2k;\bar{r}\}$. At the other extreme, the capacity reserve in country 1 is always activated independently of domestic renewable production if $r_2 < \max\{2k-\bar{r};0\}$. This possibility is captured by the first term on the second row above. In the intermediate case, $\max\{2k-\bar{r};0\} \leq r_2 < \min\{2k;\bar{r}\}$, the capacity reserve in country 1 is activated if and only if the domestic renewable output is too small: $r_1 < 2k - r_2$. This case represents the term on the first row above.

A.3 Regularity assumptions

This appendix derives sufficient conditions for assumption (7) to hold.

Deriving the marginal security of supply. Let $\rho_M(k,\phi)$ defined by $p_M(\rho_M,k) = \phi$ for $k < \bar{k}_M$ and by $\rho_M(k,\phi) = 0$ for $k > \bar{k}_M$ be the threshold level of renewable output below which the wholesale price rises above ϕ. By the definition of $\bar{k}_M$ in (4) and assumption (6), it follows that $\rho_M(k,\phi) \in (k(1-\varepsilon), k)$ if $k < \bar{k}_M$. The expected shadow cost $A_M(k)$ of operating losses is characterized by

$$A_M(k) = \int_{k(1-\varepsilon)}^{\rho_M(k,\phi)} B(\hat{p}(q_M(k)-r)-\phi)dF_M(r) + B(\bar{P}_M(k)-\phi)F_M(k(1-\varepsilon))$$

for $k < \bar{k}_M$ and by $A_M(k) = 0$ for $k \geq \bar{k}_M$. The shadow cost is continuous because $\rho_M(\bar{k}_M,\phi) = \bar{k}_M(1-\varepsilon)$ and $B(0) = 0$ imply $\lim_{k\uparrow\bar{k}_M} A_M(k) = 0$. If $k < \bar{k}_M$, then

$$A'_M(k) = q'_M(k)\int_{k(1-\varepsilon)}^{\rho_M(k,\phi)} B'(\hat{p}(q_M(k)-r)-\phi)\hat{p}'(q_M(k)-r)dF_M(r)+B'(\bar{P}_M(k)-\phi)F_M(k(1-\varepsilon))\bar{P}'_M(k).$$

Using the following integration by parts

$$\int_{k(1-\varepsilon)}^{\rho_M(k,\phi)} B'(\hat{p}(q_M(k)-r)-\phi)\hat{p}'(q_M(k)-r)dF_M(r)$$
$$= \int_{k(1-\varepsilon)}^{\rho_M(k,\phi)} B(\hat{p}(q_M(k)-r)-\phi)f'_M(r) + B(\bar{P}_M(k)-\phi)f_M(k(1-\varepsilon))$$

I obtain

$$\begin{aligned} A'_M(k) = {} & B'(\bar{P}_M(k)-\phi)F_M(k(1-\varepsilon))\bar{P}'_M(k) + q'_M(k)B(\bar{P}_M(k)-\phi)f_M(k(1-\varepsilon)) \\ + {} & q'_M(k)\textstyle\int_{k(1-\varepsilon)}^{\rho_M(k,\phi)} B(\hat{p}(q_M(k)-r)-\phi)f'_M(r)dr. \end{aligned} \tag{26}$$

Observe that $\lim_{k\uparrow\bar{k}_M} A'_M(k) = 0$ by the additional assumption that $B'(0) = 0$. Hence, $A_M(k)$ is continuously differentiable in k. Furthermore, the term on the second row converges to zero as $\varepsilon \to 0$ because $\rho_M(k,\phi) \in (k(1-\varepsilon), k)$. Hence, the marginal benefit of hedging price spikes, $-q_n A'_M(k)$, can be written approximately as (9) for ε close to zero.

Marginal domestic welfare. The next task is to evaluate $\lim_{k\to 0} W'_M(k) = -q_n \lim_{k\to 0} A'_M(k) - \lim_{k\to 0} \psi_M(k) q'_M(k)$. To this end, I make the following assumptions beyond those specified in the main body of the text: $f_M(\cdot)$ is bounded and twice continuously differentiable, with $f'_M(\cdot)$ and $f''_M(\cdot)$ bounded for $M = N, I$. Furthermore,

$$\begin{array}{l} f'_M(k) \geq 0 \ \forall k \text{ sufficiently close to zero, } \lim_{k\to 0} \frac{F_M(k)}{f_M(k(1-\varepsilon))} = 0, \\ \lim_{\tilde{p}\to\infty} B(\tilde{p}-\phi) = \infty, \ \lim_{\tilde{p}\to\infty} \frac{B'(\tilde{p}-\phi)}{B(\tilde{p}-\phi)} > 0. \end{array} \tag{27}$$

Rewrite $-A'_M(k)$ as:

$$\begin{array}{l} -A'_M(k) = \frac{q'_M(k)}{F_M(k)} B(\bar{P}_M(k)-\phi) f_M(k(1-\varepsilon)) \\ \quad \times [\frac{B'(\bar{P}_M(k)-\phi)}{B(\bar{P}_M(k)-\phi)} \frac{F_M(k(1-\varepsilon))}{-D'_M(\bar{P}_M(k))} \frac{F_M(k)}{f_M(k(1-\varepsilon))} - f_M(\rho_M(k,\phi)) \frac{F_M(k)}{f_M(k(1-\varepsilon))}] \\ \quad + q'_M(k) \int_{k(1-\varepsilon)}^{\rho_M(k,\phi)} [B(\bar{P}_M(k)-\phi) - B(\hat{p}(q_M(k)-r)-\phi)] f'_M(r) dr. \end{array} \tag{28}$$

The term on the third row of (28) is non-negative for all k sufficiently close to zero by the assumption that $f'_M(r) \geq 0$ for all r sufficiently close to zero. Consider next the terms inside the square brackets on the second row of (28). The second term is negative, but vanishes in the limit as $k \to 0$ by the assumption that $f_M(r)$ is bounded and $\lim_{k\to 0} \frac{F_M(k)}{f_M(k(1-\varepsilon))} = 0$. To evaluate the first term inside the square brackets, observe that

$$\begin{aligned} \frac{F_M(k(1-\varepsilon))}{-D'_M(\bar{P}_M(k))} &= \int_k^{\bar{r}} c'(q_M(k)-r) dF_M(r) + \int_{k(1-\varepsilon)}^k \hat{p}(q_M(k)-r) f'_M(r) dr - u''(q_M(k)-q_n) \\ &\quad + \bar{P}_M(k) f_M(k(1-\varepsilon)) - c(x_M(k)) f_M(k) \end{aligned}$$

after an integration by parts. Multiplying this expression by $F_M(k)/f_M(k(1-\varepsilon))$ and substituting in the optimality condition (23) for market-based investment yields

$$\begin{aligned} \frac{F_M(k(1-\varepsilon))}{-D'_M(\bar{P}_M(k))} \frac{F_M(k)}{f_M(k(1-\varepsilon))} &= [\int_k^{\bar{r}} c'(q_M(k)-r) dF_M(r) - u''(q_M(k)-q_n)] \frac{F_M(k)}{f_M(k(1-\varepsilon))} \\ &\quad + \int_{k(1-\varepsilon)}^k [\hat{p}(q_M(k)-r) - c(x_M(k)] f'_M(r) dr \frac{F_M(k)}{f_M(k(1-\varepsilon))} \\ &\quad + \int_{k(1-\varepsilon)}^k (\bar{P}_M(k) - \hat{p}(q_M(k)-r)) dF_M(r) + \delta \end{aligned}$$

after simplification. The term on the first row is positive, the term on the second row is non-negative for k sufficiently close to zero by the assumption that $f'_M(r) \geq 0$ for all r sufficiently close to zero. The first term on the third row is also positive. It then follows that

$$\frac{F_M(k(1-\varepsilon))}{-D'_M(\bar{P}_M(k))} \frac{F_M(k)}{f_M(k(1-\varepsilon))} > \delta \tag{29}$$

for all k sufficiently close to zero. By the additional assumption that $\lim_{\tilde{p}\to\infty} \frac{B'(\tilde{p}-\phi)}{B(\tilde{p}-\phi)} > 0$, it follows that the term inside the square brackets on the second row of (28) is strictly positive and bounded away from zero for all k sufficiently close to zero. Finally, evaluate the terms on the first row of (28). From (25), it follows directly that

$$\lim_{k\to 0} \frac{q'_M(k)}{F_M(k)} = \frac{c'(K_M^\infty)}{\int_0^{\overline{r}} c'(D_M^\infty + q_n - r)dF_M(r) - u''(D_M^\infty)} > 0 \tag{30}$$

and bounded from above. By way of the optimality condition (23) for market-based investment, it follows that $\bar{P}_M(k) > \frac{\delta}{F_M(k)} + c(x_M(k))$. Monotonicity of B then implies

$$\begin{aligned}\lim_{k\to 0} B(\bar{P}_M(k) - \phi)F_M(k) &\geq \lim_{k\to 0} B(\frac{\delta}{F_M(k)} + c(x_M(k)) - \phi)F_M(k) \\ &= \delta \lim_{k\to 0} B'(\frac{\delta}{F_M(k)} + c(x_M(k)) - \phi) > 0,\end{aligned}$$

where I have used L'Hôpital's rule to get the second result. Hence,

$$\lim_{k\to 0} B(\bar{P}_M(k) - \phi))f_M(k(1-\varepsilon)) = \lim_{k\to 0} B(\bar{P}_M(k) - \phi))F_M(k)\frac{f_M(k(1-\varepsilon))}{F_M(k)} = \infty.$$

To conclude, $\lim_{k\to 0} W'_M(k) = -q_n \lim_{k\to 0} A'_M(k) = \infty$ under the additional assumptions (27).

Concavity of the domestic welfare function. The final task is to evaluate $W''_M(k)$. In doing so, I will make the following assumptions additional to (27):

$$\begin{aligned}&u'''(q_n) \geq 0, \\ &f''_M(k) \geq 0 \ \forall k \text{ sufficiently close to zero, } \lim_{k\to 0} \frac{F_M(k(1-\varepsilon))f_M(k)}{f_M(k(1-\varepsilon))F_M(k)} < \infty, \\ &\lim_{\tilde{p}\to\infty} B'(\tilde{p}-\phi) = \infty, \ \lim_{\tilde{p}\to\infty} \frac{B''(\tilde{p}-\phi)}{B'(\tilde{p}-\phi)} > 0 \text{ and sufficiently large.}\end{aligned} \tag{31}$$

Straightforward differentiation yields

$$\begin{aligned}A''_M(k) \;=\; & B'(\bar{P}_M(k) - \phi)\frac{F_M(k(1-\varepsilon))}{D'_M(\bar{P}_M(k))}[\frac{B''(\bar{P}_M(k) - \phi)}{B'(\bar{P}_M(k) - \phi)} q'_M(k)\bar{P}'_M(k) + q''_M(k)] \\ & + q'_M(k)B'(\bar{P}_M(k) - \phi)[\frac{d}{dk}\frac{F_M(k(1-\varepsilon))}{D'_M(\bar{P}_M(k))} + f_M(k(1-\varepsilon))\bar{P}'_M(k)] \\ & + B(\bar{P}_M(k) - \phi)[q''_M(k)f_M(k(1-\varepsilon)) + (q'_M(k))^2 f'_M(k(1-\varepsilon))] \\ & + \int_{k(1-\varepsilon)}^{\rho_M(k,\phi)} B(\hat{p}(q_M(k) - r) - \phi)[q''_M(k)f'_M(r) + (q'_M(k))^2 f''_M(r)]dr.\end{aligned}$$

after using an integration by parts similar to the above and collecting terms.

Next, substitute

$$\begin{aligned} & \frac{1}{q'_M(k)}[\frac{d}{dk}\frac{F_M(k(1-\varepsilon))}{D'_M(\bar{P}_M(k))} + f_M(k(1-\varepsilon))\bar{P}'_M(k)] \\ = \; & u'''(q_M(k)-q_n) + c'(x_M(k))f_M(k) + \textstyle\int_{k(1-\varepsilon)}^{k}[\bar{P}_M(k) - \hat{p}(q_M(k)-r)]f''_M(r)dr \\ & -\textstyle\int_k^{\bar{r}} c''(q_M(k)-r)dF_M(r) - [\bar{P}_M(k) - c(x_M(k))]f'_M(k) \end{aligned}$$

into $A''_M(k)$ above to get

$$\begin{aligned} A''_M(k) \;=\; & B'(\bar{P}_M(k)-\phi)F_M(k(1-\varepsilon))(\bar{P}'_M(k))^2\left\{\frac{B''(\bar{P}_M(k)-\phi)}{B'(\bar{P}_M(k)-\phi)} + \frac{q''_M(k)}{q'_M(k)\bar{P}'_M(k)}\right. \\ & \left. - \frac{(D'_M(\bar{P}_M(k)))^2}{F_M(k(1-\varepsilon))}(\bar{P}_M(k) - c(x_M(k)))[\frac{\int_k^{\bar{r}} c''(q_M(k)-r)dF_M(r)}{\bar{P}_M(k) - c(x_M(k))} + f'_M(k)]\right\} \\ & +(q'_M(k))^2 B'(\bar{P}_M(k)-\phi)[u'''(q_M(k)-q_n) \\ & +c'(x_M(k))f_M(k) + \textstyle\int_{k(1-\varepsilon)}^{k}(\bar{P}_M(k) - \hat{p}(q_M(k)-r))f''_M(r)dr] \\ & +B(\bar{P}_M(k)-\phi)[q''_M(k)f_M(k(1-\varepsilon)) + (q'_M(k))^2 f'_M(k(1-\varepsilon))] \\ & +\int_{k(1-\varepsilon)}^{\rho_M(k,\phi)} B(\hat{p}(q_M(k)-r)-\phi)[q''_M(k)f'_M(r) + (q'_M(k))^2 f''_M(r)]dr. \end{aligned}$$

Consider first the properties of $q''_M(k)$. By differentiating (25) and rearranging terms:

$$\begin{aligned} \frac{q''_M(k)}{q'_M(k)}\frac{F_M(k)}{f_M(k)} \;=\; & 1 - \frac{q'_M(k)}{F_M(k)}\frac{F_M(k)}{f_M(k)}(1-q'_M(k))c''(x_M(k))\frac{\int_k^{\bar{r}} c'(q_M(k)-r)dF_M(r) - u''(q_M(k)-q_n)}{c'(x_M(k))^2} \\ & + \frac{q'_M(k)}{F_M(k)}\frac{F_M(k)}{f_M(k)}q'_M(k)\frac{u'''(q_M(k)-q_n) - \int_k^{\bar{r}} c''(q_M(k)-r)dF_M(r)}{c'(x_M(k))} \end{aligned}$$

The right-hand side of this expression converges to 1 by the assumptions that $f'_M(k) \geq 0 \; \forall k$ sufficiently close to zero and $\lim_{k\to 0}\frac{F_M(k)}{f_M(k(1-\varepsilon))} = 0$. Hence, $q''_M(k) > 0$ for all k sufficiently close to zero. This result plus the assumptions that $u''' \geq 0$, $f'_M(k) \geq 0$ and $f''_M(k) \geq 0$ for all k sufficiently close to zero imply that the final four rows of $A''_M(k)$ above all are positive for k sufficiently close to zero. The next expression to evaluate is the one in curly brackets in $A''_M(k)$. By expanding:

$$\frac{q''_M(k)}{q'_M(k)\bar{P}'_M(k)} = \underbrace{\frac{q''_M(k)}{q'_M(k)}\frac{F_M(k)}{f_M(k)}}_{i}\underbrace{\frac{D'_M(\bar{P}_M(k))}{F_M(k(1-\varepsilon))}\frac{f_M(k(1-\varepsilon))}{F_M(k)}}_{ii}\underbrace{\frac{F_M(k)}{q'_M(k)}}_{iii}\underbrace{\frac{F_M(k(1-\varepsilon))f_M(k)}{f_M(k(1-\varepsilon))F_M(k)}}_{iv}.$$

Term i converges to 1, term ii satisfies

$$\lim_{k\to 0}\frac{D'_M(\bar{P}_M(k))}{F_M(k(1-\varepsilon))}\frac{f_M(k(1-\varepsilon))}{F_M(k)} \in [-\frac{1}{\delta}, 0) \tag{32}$$

by (29), term iii is bounded from above by (30), and term iv is bounded from above by assumption (31). Hence, $\lim_{k\to 0}\frac{q''_M(k)}{q'_M(k)\bar{P}'_M(k)}$ is bounded from below and dominated by $\frac{B''(\bar{P}_M(k)-\phi)}{B'(\bar{P}_M(k)-\phi)}$

for k sufficiently close to zero if $\lim_{\tilde{p}\to\infty}\frac{B''(\tilde{p}-\phi)}{B'(\tilde{p}-\phi)}$ is sufficiently large. By expanding the next expression, I obtain

$$\begin{aligned}
& \lim_{k\to 0}\frac{(D'_M(\bar{P}_M(k)))^2}{F_M(k(1-\varepsilon))}(\bar{P}_M(k)-c(x_M(k))) \\
\leq\ & \lim_{k\to 0}\frac{(\bar{P}_M(k)-c(x_M(k)))F_M(k(1-\varepsilon))}{\delta^2}\lim_{k\to 0}\frac{F_M(k)}{f_M(k(1-\varepsilon))}
\end{aligned}$$

by (32). Using again the optimality condition (23) for market-based investment,

$$\begin{aligned}
& (\bar{P}_M(k)-c(x_M(k)))F_M(k(1-\varepsilon)) \\
=\ & \delta-\textstyle\int_{k(1-\varepsilon)}^{k}[\hat{p}(q_M(k)-r)-c(x_M(k))]dF_M(r)<\delta,
\end{aligned}$$

Hence,

$$\lim_{k\to 0}\frac{(D'_M(\bar{P}_M(k)))^2}{F_M(k(1-\varepsilon))}(\bar{P}_M(k)-c(x_M(k)))=0.$$

It follows that the term in curly brackets of $A''_M(k)$ is strictly positive and bounded away from zero for all k sufficiently close to zero. By using the optimality condition (23) for market-based investment one final time, I obtain

$$\begin{aligned}
& -\frac{F_M(k)}{q'_M(k)}\frac{F_M(k(1-\varepsilon))}{f_M(k(1-\varepsilon))}\bar{P}'_M(k) \\
=\ & \delta+\frac{F_M(k)}{f_M(k(1-\varepsilon))}[\textstyle\int_k^{\bar{r}}c'(q_M-r)dF_M(r)-u''(q_M-q_n)]dF_M(r) \\
& +\textstyle\int_{k(1-\varepsilon)}^{k}[\frac{F_M(k)}{f_M(k(1-\varepsilon))}(\hat{p}(q_M-r)-c(x_M))f'_M(r)+(\bar{P}_M(k)-\hat{p}(q_M-r))f_M(r)]dr
\end{aligned}$$

so that

$$\lim_{k\to 0}(\frac{F_M(k(1-\varepsilon))}{f_M(k(1-\varepsilon))}\bar{P}'_M(k))^2\geq\frac{(\delta c'(K_M^\infty))^2}{[\int_0^{\bar{r}}c'(D_M^\infty+q_n-r)dF_M(r)-u''(D_M^\infty)]^2}>0.$$

Hence,

$$\begin{aligned}
& \lim_{k\to 0}B'(\bar{P}_M(k)-\phi)F_M(k(1-\varepsilon))(\bar{P}'_M(k))^2 \\
\geq\ & \lim_{k\to 0}B'(\bar{P}_M(k)-\phi)F_M(k)\frac{(\delta c'(K_M^\infty))^2\lim_{k\to 0}(\frac{f_M(k(1-\varepsilon))}{F_M(k(1-\varepsilon))}\frac{f_M(k(1-\varepsilon))}{F_M(k(1-\varepsilon))})}{[\int_k^{\bar{r}}c'(D_M^\infty+q_n-r)dF_M(r)-u''(D_M^\infty)]^2}
\end{aligned}$$

The proof that $\lim_{k\to 0}B'(\bar{P}_M(k)-\phi)F_M(k)>0$ and bounded away from zero is identical to the proof that $\lim_{k\to 0}B(\bar{P}_M(k)-\phi)F_M(k)>0$ and bounded from zero and therefore omitted.

To summarize these findings, assumptions (31) and (32) jointly imply that $\lim_{k\to 0}A''_M(k)\to\infty$ and $q''_M(k)>0$ for all k sufficiently close to zero. Next

$$\psi'_M(k)=\int_0^k[c'(q_M(k)-r)q'_M(k)+c'(q_M(k)-k)(1-q'_M(k))]dF_M(r)>0$$

because $q'_M(k) \in (0,1)$; see equation (25) in Appendix A.1. It then follows that

$$W''_M(k) = -[q_n A''_M(k) + \psi'_M(k) q'_M(k) + \psi_M(k) q''_M(k)] < 0$$

for all k sufficiently close to zero. By continuity, therefore, $W_N(k)$ is strictly concave in the domain $(0, 2\max\{\bar{k}_N; \bar{k}_I\})$, and $W_I(k)$ is strictly concave in the domain $(0, \max\{\bar{k}_N; \bar{k}_I\})$ unless $\bar{k}_N$ and $\bar{k}_I$ are large, in which case the second-derivatives of $W_N(k)$ and $W_I(k)$ are indeterminate for large enough values of k.

A.4 Proof of Proposition 1

Existence and uniqueness Continuity of $W_M(k)$ in k and compactness of the domain, $k \in [0, \bar{r}]$ imply that a social optimum k_M^{fb} exists. Any socially optimal capacity reserve k_M^{fb} is positive by the assumption that $W'_M(k) > 0$ for all k sufficiently close to zero. It is also the case that $k_M^{fb} \leq \bar{k}_M$ because $\bar{P}_M(k) < \phi$ for all $k > \bar{k}_M$ and any capacity reserve above $\bar{k}_M$ therefore would serve only to distort consumption and investment further without providing any additional insurance benefits. In fact, $k_M^{fb} < \bar{k}_M$ because

$$\lim_{k \uparrow \bar{k}_M} W'_M(k) = -\psi_M(\bar{k}_M) q'_M(\bar{k}_M) < 0,$$

see (26). Strict concavity of $W_M(k)$ in the domain $(0, \bar{k}_M)$ implies that the first-order condition $W'_M(k_M^{fb}) = 0$ uniquely characterizes the socially optimal capacity reserve, which is approximately equal to (10) for ε close to zero.

Implementation. This is trivial when electricity markets are national because then there is no strategic interaction between the policy makers in the two countries. In the case of perfect market integration, expected welfare in country i equals $W_I(\frac{k_i + k_I^{fb}}{2}) \leq W_I(k_I^{fb})$ for all $k_i \neq k_I^{fb}$, where the inequality follows from global optimality of k_I^{fb}. Hence, choosing a capacity reserve of $k_i = k_I^{fb}$ is a best-reply for country i to the choice of capacity reserve $k_j = k_I^{fb}$ in country $j \neq i$. There could be multiple Nash equilibria, but the one in which both countries choose k_I^{fb} is pay-off dominant because national welfare in both countries is proportional to aggregate welfare, which is maximized at k_I^{fb}.■

A.5 Proof of Proposition 2

Observe that

$$\begin{aligned}
\frac{W'_I(k)}{q'_I(k) q_n} &= \frac{\psi_I(k)}{\psi_N(k)} \frac{W'_M(k)}{q'_N(k) q_n} + \psi_I(k) H(k) \\
&\quad + B'(\bar{P}_I(k) - \phi) \frac{F_I(k) - F_I(k(1-\varepsilon))}{D'_I(\bar{P}_I(k))} - \frac{\psi_I(k)}{\psi_N(k)} B'(\bar{P}_N(k) - \phi) \frac{F_N(k) - F_N(k(1-\varepsilon))}{D'_N(\bar{P}_N(k))} \\
&\quad + B(\bar{P}_I(k) - \phi)(f_I(k) - f_I(k(1-\varepsilon))) - \frac{\psi_I(k)}{\psi_N(k)} B(\bar{P}_N(k) - \phi)(f_N(k) - f_N(k(1-\varepsilon))) \\
&\quad - \int_{k(1-\varepsilon)}^{\rho_I(k,\phi)} B(\hat{p}(q_I(k) - r) - \phi) f'_I(r) dr + \frac{\psi_I(k)}{\psi_N(k)} \int_{k(1-\varepsilon)}^{\rho_N(k,\phi)} B(\hat{p}(q_N(k) - r) - \phi) f'_N(r) dr\}
\end{aligned}$$

for $k < \min\{\bar{k}_N; \bar{k}_I\}$, where

$$\begin{aligned} H(k) &= \frac{1}{\psi_N(k)}[B'(\bar{P}_N(k)-\phi)\frac{F_N(k)}{D'_N(\bar{P}_N(k))} + B(\bar{P}_N(k)-\phi)f_N(k)] \\ &\quad -\frac{1}{\psi_I(k)}[B'(\bar{P}_I(k)-\phi)\frac{F_I(k)}{D'_I(\bar{P}_I(k))} + B(\bar{P}_I(k)-\phi)f_I(k)]. \end{aligned}$$

$H(k_N^{fb}) > 0$ and $H(k_I^{fb}) > 0$ if inequality (13) is satisfied, whereas the terms on the last three rows of the above expression are negligible for ε sufficiently close to zero. Assume first that $\bar{k}_I \leq \bar{k}_N$. As $W_I'(k_I^{fb}) = 0$, it follows from the above expression that $W_N'(k_I^{fb}) < 0$. Strict quasi-concavity of W_N then implies $k_N^{fb} < k_I^{fb}$. Assume next that $\bar{k}_N \leq \bar{k}_I$. As $W_N'(k_N^{fb}) = 0$, it follows that $W_I'(k_N^{fb}) > 0$. Strict quasi-concavity of W_I then implies $k_I^{fb} > k_N^{fb}$. All inequalities are reversed if inequality (13) is reversed.■

A.6 Proof of Proposition 3

Uniqueness Let $Z(k,t,\sigma) = \frac{1+t}{2}\sigma W_I'(k) + (1-\sigma)W_N'(k)$. We already know from Lemma 1 that any solution $Z(\kappa,t,\sigma) = 0$ must satisfy $\kappa(t,\sigma) \in [\min\{k_N^{fb}; k_I^{fb}\}, \max\{k_N^{fb}; k_I^{fb}\}]$ and that there exists at least one such solution $\kappa(t,\sigma)$ for every $(t,\sigma) \in [0,1]^2$. Strict concavity of $W_I(k)$ and $W_N(k)$ in the domain $[\min\{k_N^{fb}; k_I^{fb}\}, \max\{k_N^{fb}; k_I^{fb}\}]$ imply that $\kappa(t,\sigma)$ is unique. In particular, there exists a unique symmetric equilibrium candidate $k^*(\sigma) = \kappa(0,\sigma)$ which is, moreover, contained in $[\min\{k_N^{fb}; k_I^{fb}\}, \max\{k_N^{fb}; k_I^{fb}\}]$.

Existence Assume that $k_j = k^*(\sigma)$, and consider country i's incentive to deviate from $k^*(\sigma)$. It can never be optimal for i to deviate to $k_i > 2\max\{\bar{k}_N(\phi); \bar{k}_I(\phi)\} - k^*(\sigma)$ because then $\frac{k_i+k^*(\sigma)}{2} > \bar{k}_I$ and $k_i > \bar{k}_N$ so that $\bar{P}_I(\frac{k_i+k^*(\sigma)}{2}) < \phi$ and $\bar{P}_N(k_i) < \phi$. In this case, country i only distorts investment and consumption at home without offering any additional insurance benefits to the domestic industry. Next,

$$\frac{\partial^2 W(k_i,k^*)}{\partial k_i^2} = \tfrac{1}{4}\sigma W_I''(\tfrac{k_i+k^*(\sigma)}{2}) + (1-\sigma)W_N''(k_i) < 0$$

for all $k_i \in (0, 2\max\{\bar{k}_N; \bar{k}_I\} - k^*(\sigma)]$ by assumption (7), and $k^*(\sigma) \in (0, 2\max\{\bar{k}_N; \bar{k}_I\} - k^*(\sigma)]$ imply that $k_i = k^*(\sigma)$ is country i's unique best-reply to $k_j = k^*(\sigma)$.

Characterization The first-order condition $Z(\kappa,0,\sigma) = 0$ uniquely characterizes the symmetric equilibrium $k^*(\sigma) = \kappa(0,\sigma)$, which is approximately equal to (19) for ε close to zero. The comparative statics follow directly from (18) and Lemma 1.■

A.7 Proof of Proposition 6

The social optimum The expected welfare in country i can equivalently be written as

$$\begin{aligned} W(k_i,k_j,s) &= \hat{W}(k_i,k_j) - q_n\sigma \int_0^{\rho_I(k,\phi)} B(\min\{p_I(r,k); s\} - \phi)dF_I(r) \\ &\quad -q_n(1-\sigma)\int_0^{\rho_N(k_i,\phi)} B(\min\{p_N(r,k_i); s\} - \phi)dF_N(r), \end{aligned}$$

where

$$\begin{aligned}\hat{W}(k_i,k_j) &= \sigma[u(q_I(k)-q_n)+q_n\phi-\int_0^{\bar{r}} p_I(r,k)dF_I(r)q_I(k)+\Pi_I(k)] \\ &\quad +(1-\sigma)[u(q_N(k_i)-q_n)+q_n\phi-\int_0^{\bar{r}} p_N(r,k_i)dF_N(r)q_N(k_i)+\Pi_N(k_i)]\end{aligned}$$

denotes the expected welfare gross of the expected shadow cost of losses. At symmetric capacity reserves $k_1 = k_2 = k$:

$$\hat{W}(k,k) \geq W(k,k,s) \geq \hat{W}(k,k) - q_n B(s-\phi)[\sigma F_I(\rho_I(k,\phi)) + (1-\sigma)F_N(\rho_N(k,\phi))]$$

where the first inequality follows from $B(\min\{p_M(r,k);s\}-\phi) \geq 0$ for all r, and the second from $B(s-\phi) \geq B(\min\{p_M(r,k);s\}-\phi)$ for all r. $\rho_M(k,\phi) \leq k$ yields

$$\begin{aligned}W(0,0,s) &= \hat{W}(0,0) = \sigma[u(D_I^{\infty})+q_n\phi-\int_0^{\bar{r}}\int_0^{D_I^{\infty}+q_n-r} c(\tilde{r})d\tilde{r}dF_I(r)-\delta(D_I^{\infty}+q_n)] \\ &\quad +(1-\sigma)[u(D_N^{\infty})+q_n\phi-\int_0^{\bar{r}}\int_0^{D_N^{\infty}+q_n-r} c(\tilde{r})d\tilde{r}dF_N(r)-\delta(D_N^{\infty}+q_n)]\end{aligned}$$

independently of s. Next,

$$\begin{aligned}W(0,0,s)-W(k_i,k_j,s) &= \hat{W}(0,0)-\hat{W}(k_i,k_j)+q_n\sigma\int_0^{\rho_I(k,\phi)} B(\min\{p_I(r,k);s\}-\phi)dF_I(r) \\ &\quad +q_n(1-\sigma)\int_0^{\rho_N(k_i,\phi)} B(\min\{p_N(r,k_i);s\}-\phi)dF_N(r)\end{aligned}$$

is non-negative for all (k_i,k_j) because the shadow cost is non-negative and

$$\frac{\partial \hat{W}(k_i,k_j)}{\partial k_i} = -\frac{\sigma}{2}\psi_I(k)q_I'(k)-(1-\sigma)\psi_N(k)q_N'(k_i) < 0, \quad \frac{\partial \hat{W}(k_i,k_j)}{\partial k_j} = -\frac{\sigma}{2}\psi_I(k)q_I'(k) \leq 0$$

imply $\hat{W}(0,0) \geq \hat{W}(k_i,k_j)$ for all (k_i,k_j). $W(0,0,s) \geq W(k_i,k_j,s)$ for all (k_i,k_j) implies that $k_1^{fb}(\sigma,s) = k_2^{fb}(\sigma,s) = k^{fb}(\sigma,s) = 0$ is the social optimum.

Implementation $W(0,0,s) \geq W(k_i,0,s)$ for all $k_i > 0$ implies that $k_1^*(\sigma,s) = k_2^*(\sigma,s) = 0$ can be sustained as a Nash equilibrium when the two countries choose capacity reserves non-cooperatively to maximize domestic welfare. The equilibrium is pay-off dominant by symmetry and the fact that zero capacity reserves is the first-best social optimum.

Characterization For completeness, I replicate the marginal welfare expression (20) for $s > \phi$. Assume that $k_1 = k_2 = k$ is sufficiently small that $\bar{P}_I(k) > s$ and $\bar{P}_N(k) > s$. Straightforward differentiation of $W(k,s)$ yields

$$\begin{aligned}\frac{\partial W(k,s)}{\partial k} &= -\sigma q_I'(k)[q_n \int_{\rho_I(k,s)}^{\rho_I(k,\phi)} B'(\hat{p}(q_I(k)-r)-\phi)\hat{p}'(q_I(k)-r)dF_I(r)+\psi_I(k)] \\ &\quad -(1-\sigma)q_N'(k)[q_n \int_{\rho_N(k,s)}^{\rho_N(k,\phi)} B'(\hat{p}(q_N(k)-r)-\phi)\hat{p}'(q_N(k)-r)dF_N(r)+\psi_N(k)],\end{aligned}$$

which is strictly negative. An integration by parts yields

$$\begin{aligned}&\int_{\rho_M(k,s)}^{\rho_M(k,\phi)} B'(\hat{p}(q_M(k)-r)-\phi)\hat{p}'(q_M(k)-r)dF_M(r) \\ =& \int_{\rho_M(k,s)}^{\rho_M(k,\phi)} B(\hat{p}(q_M(k)-r)-\phi)f_M'(r)dr + B(s-\phi)f_M(\rho_M(k,s)) \\ \approx& \; B(s-\phi)f_M(k)\end{aligned}$$

for ε close to zero. The approximation holds because $k(1-\varepsilon) < \rho_M(k,s) < \rho_M(k,\phi) < k$ for $\bar{P}_M(k) > s > \phi$ implies $\rho_M(k,\phi) \to \rho_M(k,s) \to k$ as $\varepsilon \to 0$. Substituting $B(s-\phi)f_M(\rho_M(k,s))$ into $\partial W(k,s)/\partial k$ above produces (20).■

A.8 Proof of Proposition 7

I first characterize the difference between the thermal production cost under a national versus an aggregate supply constraint:

$$\begin{aligned}\Omega_I(k) = &\int_k^{\min\{2k;\bar{r}\}} \int_0^{2k-r_j} \Omega_{1I}(k,r)dF(r_i,r_j) + \int_{\max\{2k-\bar{r};0\}}^{k} \int_k^{2k-r_j} \Omega_{1I}(k,r)dF(r_i,r_j) \\ &+ \int_0^{\max\{2k-\bar{r};0\}} \int_k^{\bar{r}} \Omega_{1I}(k,r)dF(r_i,r_j) + \int_0^k \int_0^k \Omega_{2I}(k,r_i,r_j)dF(r_i,r_j)\end{aligned} \tag{33}$$

for $k = k_1 = k_2$ in an integrated market, where

$$\begin{aligned}\Omega_{1I}(k,r) &= \tfrac{1}{2}\int_0^{2q_I(k)-x_I(k)-2r} c(z)dz + \tfrac{1}{2}\int_0^{x_I(k)} c(z)dz - \int_0^{q_I(k)-r} c(z)dz \\ \Omega_{2I}(k,r_i,r_j) &= \tfrac{1}{2}\int_0^{q_I(k)-r_i} c(z)dz + \tfrac{1}{2}\int_0^{q_I(k)-r_j} c(z)dz - \int_0^{q_I(k)-r} c(z)dz.\end{aligned} \tag{34}$$

The rules for resolving supply constraints matter if and only if $r_j < \min\{2k;\bar{r}\}$ and $r_i < 2k - r_j$ because the market clears supply and demand and delivers efficient dispatch $q_I(k) - r$ of the thermal production in both countries in the other events. The first three expressions in $\Omega_I(k)$ cover a situation with an aggregate supply constraint $r < k$, but either $r_1 \geq k$ or $r_2 \geq k$, so that only the capacity reserve in one country is activated. The final expression identifies the situation with a national supply constraint in both countries. The two expressions $\Omega_{1I}(k)$ and $\Omega_{2I}(k)$ are strictly positive by $c'(z) > 0$ and

$$\tfrac{1}{2}(2q_I(k) - x_I(k) - 2r) + \tfrac{1}{2}x_I(k) = q_I(k) - r = \tfrac{1}{2}(q_I(k) - r_i) + \tfrac{1}{2}(q_I(k) - r_j). \tag{35}$$

The cost distortion is strictly increasing in k: $\Omega_I'(k) = \omega_I(k)q_I'(k) > 0$ for $k \in (0,\bar{r})$ because

$q_I'(k) > 0$ and

$$\omega_I(k) = \int_k^{\min\{2k;\bar{r}\}} \int_0^{2k-r_j} \frac{\partial\Omega_{1I}(k,r)}{\partial k} \frac{1}{q_I'(k)} dF(r_i,r_j) + \int_{\max\{2k-\bar{r};0\}}^{k} \int_k^{2k-r_j} \frac{\partial\Omega_{1I}(k,r)}{\partial k} \frac{1}{q_I'(k)} dF(r_i,r_j)$$
$$+ \int_0^{\max\{2k-\bar{r};0\}} \int_k^{\bar{r}} \frac{\partial\Omega_{1I}(k,r)}{\partial k} \frac{1}{q_I'(k)} dF(r_i,r_j) + \int_0^k \int_0^k \frac{\partial\Omega_{2I}(k,r_i,r_j)}{\partial k} \frac{1}{q_I'(k)} dF(r_i,r_j) \tag{36}$$

is strictly positive for $k \in (0,\bar{r})$. To see this second result, note that

$$\frac{\partial\Omega_{2I}(k,r_i,r_j)}{\partial k} \frac{1}{q_I'(k)} = \frac{1}{2}c(q_I(k) - r_i) + \frac{1}{2}c(q_I(k) - r_j) - c(q_I(k) - r)$$

and the first row of

$$\begin{aligned} \frac{\partial\Omega_{1I}(k,r)}{\partial k} \frac{1}{q_I'(k)} &= \frac{1}{2}c(2q_I(k) - x_I(k) - 2r) + \frac{1}{2}c(x_I(k)) - c(q_I(k) - r) \\ &\quad + \frac{1}{2}[c(x_I(k) + 2(k-r)) - c(x_I(k))](1 - \frac{K_I'(\bar{p}_I)}{D_I'(\bar{p}_I)}) \end{aligned}$$

are both non-negative by weak convexity of $c(z)$ and (35). The expression on the second row of $\frac{\partial\Omega_{1I}}{\partial k}\frac{1}{q_I'}$ is strictly positive for all $r < k$ because $c'(z) > 0$ and

$$1 - \frac{K_I'(\bar{p}_I)}{D_I'(\bar{p}_I)} = 1 + \frac{\int_k^{\bar{r}} c'(q_I(k) - r) dF_I(r) - u''(q_I(k) - q_n)}{c'(x_I(k)) F_I(k)} > 0.$$

The marginal cost distortion converges to zero as k becomes small: $\lim_{k\to 0} \Omega_I'(k) = 0$. To see this, note that (30) implies $\lim_{k\to 0} q_I'(k) = 0$ and $\lim_{k\to 0}(1 - \frac{K_I'(\bar{p}_I)}{D_I'(\bar{p}_I)})q_I'(k) = 1$. Hence, $\lim_{k\to 0} \frac{\partial\Omega_{1I}(k,r)}{\partial k} = 0$ and $\lim_{k\to 0} \frac{\partial\Omega_{2I}(k,r_i,r_j)}{\partial k} = 0$.

Social optimum A constrained social optimum k_I^{sb} exists by continuity of $W_{Inat}(k)$ in k and compactness of the domain: $k \in [0,\bar{r}]$. Any socially optimal capacity reserve satisfies $k_I^{sb} \leq \bar{k}_I$ because a capacity reserve above $\bar{k}_I$ would distort consumption and investment without providing any additional insurance benefits. I next show that $k_I^{sb} > 0$. $W_{Inat}(k) = W_I(k) - \Omega_I(k)$ implies

$$W_{Inat}'(k) = -q_n \int_0^{\bar{r}} B'(p_I(r,k) - \phi) \frac{\partial p_I(r,k)}{\partial k} dF_I(r) - (\psi_I(k) + \omega_I(k)) q_I'(k) \tag{37}$$

by the definition (36) of $\omega_I(k)$. $W_I'(k) > 0$ for all $k > 0$, but sufficiently close to zero by assumption (8), and because $\lim_{k\to 0} \Omega_I'(k) = 0$, it follows that $W_{Inat}'(k) > 0$ for all $k > 0$, but sufficiently close to zero. Hence, a symmetric capacity reserve is a social optimum only if $W_{Inat}'(k_I^{sb}) = 0$, which is approximately equal to (21) for ε close to zero.

Comparative statics Strict quasi-concavity of $W_I(k)$, and $W_I'(k_I^{sb}) = W_{Inat}'(k_I^{sb}) + \Omega_I'(k_I^{sb}) = \Omega_I'(k_I^{sb}) > 0$ imply $k_I^{fb} > k_I^{sb}$.

Implementation The expected welfare in country i equals

$$W_{Inat}(k_i, k_I^{sb}) = W_{Inat}(\min\{k_i; k_I^{sb}\}) - \delta(k_i - \min\{k_i; k_I^{sb}\})$$

for $k_j = k_I^{sb}$. Hence,

$$W_{Inat}(k_I^{sb}, k_I^{sb}) - W_{Inat}(k_i, k_I^{sb}) = W_{Inat}(k_I^{sb}) - W_{Inat}(k_i) \geq 0$$

for all $k_i < k_I^{sb}$ because k_I^{sb} maximizes $W_{Inat}(k)$. Furthermore,

$$W_{Inat}(k_I^{sb}, k_I^{sb}) - W_{Inat}(k_i, k_I^{sb}) = \delta(k_i - k_I^{sb}) > 0$$

for $k_i > k_I^{sb}$. Hence, $k_i = k_I^{sb}$ is a best-reply to $k_j = k_I^{sb}$. The equilibrium is pay-off dominant by symmetry and the assumption that k_I^{sb} is constrained socially optimal under a national supply constraint.■