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“A multi-regional model of electric resource adequacy”

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Abstract

The paper analyzes the determinants of optimal electric capacity and contrasts these with the requirements typically applied in a multi-regional model. We first analyze the relationship between usual reliability criteria such as the value of lost load and the targeted probability of failure, on the one hand, and the conditions that define optimal level of capacity on the other. Secondly, we characterize the social gains from energy trading between two interconnected regions that differ in terms of technologies or demand. Market mechanisms are sufficient to reach the first best allocation, irrespective of the correlation between national demand levels, provided that firms have no market power and fully internalize the value of lost load due to power rationing when supplies are inadequate. Thirdly, we explain the impact of various compensation mechanisms such as capacity payments when producers face a regulatory capacity constraint.

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1 Introduction

1.1 Lack of demand response

The impossibility of storing electric power on a large scale means that consumption and production must be balanced at every moment or power shortages will occur. Typically consumers do not pay real-time prices, and so the optimal probability of a curtailment or an outage will not be zero. This paper examines the question of how market-based balancing - meaning that all wholesale buyers and sellers respond in real-time to price changes and price adjusts instantaneously to maintain equilibrium - will compare with their optimal levels. The paper examines how market mechanisms may not result in optimal capacity, also due to coordination malfunctions across jurisdictions, when suppliers fail to internalize consumer costs of power outages. We explore the impact of various types of corrective regulatory intervention. In practice, regulators and system operators do not rely on extreme price spikes accompanied by intermittent curtailments to incentivize investment. In what follows we find conditions under which the capacity planning mechanisms used in practice, such as capacity markets and credits, can approximate optimal outcomes.

It is most commonly the case that consumers pay time-invariant prices, producers have to provide whatever quantity consumers demand, which is random, and options for storing electricity are very limited. These features of energy markets have two implications. The first is that an installed capacity which adequately ensures a reliable energy supply means that there will be idle capacity, except when demand is near its peak. The second is that any efficient balancing process requires regulation or centralized planning.

Continuous consumption of a non-storable product and lack of real-time metering mean that most consumers cannot effectively respond when shortages are developing and wholesale prices are peaking. Unless price-responsive demand is a large share of the load, price spikes alone cannot be relied upon for system balancing. Furthermore, unless a market is served by a single supplier not connected to any other regions, there will be efficiency gains from coordinating the balancing needs among the suppliers across regions. And when a downstream energy market is served by multiple retailers, the provisions any one retailer makes to ensure reliable supplies for its customers affects the reliability of the entire grid. This paper identifies the conditions that determine optimal capacity, and then compares these conditions with different approaches for ensuring resource adequacy, including energy-only markets and auctioning of capacity credits.

In what follows, we focus on the case of two regions, in which the entire demand is price inelastic, but varies with non-price variables, such as weather conditions. Leaving some - possibly a very small amount of - demand unserved with a positive probability will be optimal whenever the consumer losses from doing so are less than the cost of covering the entire demand. However, public authorities and private firms can have divergent evaluations of the value of unserved demand, leading to divergent views on what production capacity to install. This is particularly the case when there are multiple retail providers serving the same geographic area. We analyze how firms adapt

to capacity obligations and financial compensation when they can trade energy and capacity credits between the two interconnected regions.

1.2 Security of supply

The capacity problem has been scrutinized in the economic literature from a number of quite different points of view.¹ The standard model is the same as in all industries: capacity is just one input among others to produce and sell energy. If some firms derive insufficient revenue from energy sales to cover all costs, in particular capacity costs, they will go out of business. Exit or reductions in capacity then drives up energy prices to rebalance demand and the remaining supply. Applied to the electricity industry, this is the ‘energy-only’ model (Hogan 2005, Joskow 2008): the number of active firms at equilibrium is the one that maximizes welfare. In this framework, if firms belonging to the set of firms active at first best cannot recoup their costs, it is due to regulatory distortions that create a ‘missing money’ problem. In practice, regulators impose price ceilings to limit occasional market price spikes and capacity requirements to guarantee security of supply. Price ceilings are motivated by the desire to prevent the abuse of a dominant position in the wholesale market and to limit consumer exposure to price volatility. Public authorities impose minimum capacity levels when producers do not fully internalize welfare losses from energy outages.

The ‘output-only’ model works quite well in industries where the product can be stored and there is demand response to scarcity signals. Price fluctuations provoke demand reactions, and shortage is not a particularly costly event. None of this is true however for electricity in large developed countries. As electricity is considered an essential commodity in all domestic, commercial and industrial activities, security of supply is a major concern for political authorities and industrial decision makers.

Guaranteeing long-term security of supply and short-term reliability without large fluctuations in energy prices requires complementary payment to producers for maintaining ready-to-produce capacity (Roques 2008). Finon and Pignon (2008) survey alternative capacity mechanisms that complement energy sales to reach capacity adequacy, in particular public procurement of reserve margins, capacity payments, capacity obligations with tradable rights. Bushnell et al. (2017) provide a detailed analysis of resource adequacy mechanisms in the USA.

We do not fully analyze these operations as we assume that producers and retailers are vertically integrated. Nor do we consider the integration of demand response in capacity mechanisms, like in Lambin (2016). Instead we focus on the advantages of energy and capacity credits exchange between two regions. For this reason, our paper is strongly related to the literature on international economics. Antweiler (2016) shows that as electricity demand is stochastic and correlated across jurisdictions, electric utilities can reduce their cost during peak periods by importing cheaper off-peak electricity from neighboring jurisdictions. We show how, as in standard trade model, cross-jurisdictional trade, e.g. of energy produced from capacity located abroad under

¹For an extensive analysis, see Léautier (2018), Chapter 9.

specific states of nature, can benefit both consumers and producers. However, going beyond Antweiler’s analysis, we consider the consequences of regulations on capacity decisions. Creti and Fabra (2007) examine the link between capacity and energy markets when generators have the option to sell electricity in an adjacent, more profitable market. They do not analyze how trade is determined by possible correlations between demand in the two inter-connected markets. Cepeda and Finon (2011) study a region where the lack of design harmonization between local markets may lead to undesirable side effects in the neighboring markets by distorting their normal functioning. Like most papers on the topic, the regulatory tool they consider is a price-cap, whereas our paper focusses on capacity obligations required by governments to fill the gap with investments by private firms that do not fully internalize the disutility from power cuts. A paper closely related to ours is Lambin and Leautier (2016) who consider two adjacent identical markets perfectly connected and managed by two independent system operators. They show that if a system operator wants to achieve a generation capacity target, it must have the right to reduce exports in order to avoid rationing in its own market. In a complementary way, we analyze the gains from cooperation between system operators to reach capacity targets in separate jurisdictions.

1.3 Outline

In section 2, we present the capacity problem faced by a social planner when demand is a random variable following a continuous probability distribution. We contrast the normative definition of adequate capacity with ad hoc definitions used in practice, namely maximal allowed outage duration and value of lost load.

Section 3 uses a model in which demand can take discrete values to assess sub-optimality when two adjacent markets or regions are managed independently. We show that an ex post energy market among electricity suppliers incentivizes producers to invest at first best levels, provided that firms fully internalize the surplus losses of consumers in case of electricity cuts, and that the energy market is competitive. We emphasize the role of demand correlation across regions.

Section 4 considers the case where producers and regulators differ in their evaluation of the losses incurred by consumers when they are rationed. We show that a system of capacity obligations compensated by capacity payment will reach first best investment levels when capacity credits are tradable, provided that payments are the same in the two regions.

Section 5 concludes with a brief discussion of existing capacity markets and auctions, and of how state aid favoring local markets can adversely affect capacity decisions.

2 Alternative definitions of the optimal capacity

We first present a model of social planning under demand uncertainty, to sustain the analysis of capacity needs. We then determine the welfare maximizing capacity and we compare it to capacities based on two indices commonly used in practice: *i*) a ceiling

on the probability of system failure, and *ii*) the social damage measured by the value of lost load.

2.1 Benefits and costs

Assume that the retail price is fixed. At this price, demand, q , is random and varies from hour to hour on the support (\underline{q}, \bar{q}) according to the distribution function $F(q)$ and density function $f(q)$. Thus, $F(q)$ is the probability that demand in any given hour will be less than q . If there is no rationing, the consumption of electricity q gives a net surplus $S(q)$, which is increasing and concave.² As demand is random and varies from hour to hour, so does surplus.

The social optimization problem is to install a capacity K , at cost $C(K)$ which is increasing and convex, so as to maximize the expected total surplus. A lack of capacity when $q > K$ results in a welfare loss $L(q - K)$, which is an increasing and weakly convex function.³ We do not discuss the design of the rationing rule implemented to allocate energy when necessary, although it can be a pivotal question since the loss function $L(\cdot)$ directly depends on the design of the mechanism used to allocate electricity shortage among consumers.⁴

In so far as we do not consider the question of system recovery after blackouts due to *force majeure*, our analysis concerns resource adequacy rather than system reliability. *Adequacy* is the ability of the electric system to supply the aggregate electrical demand, taking into account scheduled and reasonably expected unscheduled outages of system elements. *Reliability* is the ability of the bulk power system to withstand sudden disturbances, such as electricity short circuits or unanticipated loss of system elements, while avoiding uncontrolled cascading blackouts.⁵

In all what follows, we assume that energy suppliers have cost-based access to distribution and transmission services, so that we can focus on the production and supply stages. Also recall that we assume vertically-integrated energy-sellers, i.e. we do not examine how producers and retailers negotiate energy transactions or capacity obligations.

2.2 First Best

The first-best level of capacity is the solution to

$$\max_K -C(K) + \int_{\underline{q}}^K S(q)dF(q) + \int_K^{\bar{q}} [S(K) - L(q - K)] dF(q) \quad (1)$$

²See in Appendix 6.1 how this reduced-form model is derived from a more general setting.

³Convexity seems more realistic than the linear hypothesis often used in the literature (e.g. Llobet and Padilla, 2017).

⁴For a detailed analysis of reliability and optimal rationing when a fraction of consumers are price-reactive, see Joskow and Tirole (2007).

⁵From the ‘Glossary of Terms Used in NERC Reliability Standards’,

https://library.e.abb.com/public/f091b8ae9dec300f85257d6500660234/pa_Stand_Glossary-2.pdf

On the theoretical and empirical differences between adequacy, reliability and security of supply, see also European Commission (2016b).

Given the convexity properties of the surplus and cost functions, the first-order condition is sufficient to determine a unique solution. Assuming $L(0) = 0$ and after simplifying, the first-order condition can be written as

$$S'(K) [1 - F(K)] + \int_K^{\bar{q}} L'(q - K) dF(q) = C'(K) \quad (2)$$

Notice that the incremental value of capacity is zero for states of the world with low demand ($q < K$). An additional capacity investment has two benefits, which are realized when demand is high: first, higher capacity results in increased surplus from consumption since there are fewer hours of lost load, and each hour results in an incremental surplus of $S'(K)$.⁶ Second, larger capacity reduces the welfare loss from shortages ($L'(q - K) > 0$).

Let K^* be the solution to (2).

2.3 Operational targets

The above normative analysis provides a criterion for determining optimal capacity and the resulting probability of blackout. To be able to determine this optimal level of capacity, a social planner would require information about marginal net surplus $S'(\cdot)$, incremental value of loss load $L'(\cdot)$, and marginal capacity costs $C'(\cdot)$, as well as the upper part of the distribution of probability of demand $F(q)$. Regulatory authorities in charge of security of supply prefer, or are compelled, to use simpler rules based on criteria demanding less information. Hereafter, we consider two such criteria: the probability of failure, and the value of lost load.

2.3.1 Probability of failure

A simple practical way to choose the capacity level, based on engineering criteria, consists in fixing the probability (or the frequency) of sustained blackout $1 - \gamma$, given the distribution of demand $F(q)$. Under this rule, the capacity K should be set at a level such that the probability of failure (i.e. supply not meeting load requirement), $\Pr[q > K] = 1 - F(K)$ does not exceed the target rate. The constraint is then

$$F(K) \geq \gamma \quad (3)$$

For instance, if 10 hours a year of blackout is a maximum acceptable target, $\gamma = \frac{8750}{8760} = 99.9\%$.

The target γ is usually determined through a political or technological process. The result is that the level of capacity is likely to be set at an inefficient level. To be efficient, the level of no-blackout probability should be such that

$$\gamma = F(K^*) \quad (4)$$

⁶An alternative reading is that more capacity allows the supplier to ration fewer people if there is a black-out.

where K^* is the value determined by (2). Since $F(K)$ is a non-decreasing function, we can deduce from (4) that the optimal investment constraint (3) can be written as

$$K \geq K^*.$$

This criterion has the advantage of simplicity but will not result in an efficient choice of capacities unless (4) happens to be satisfied. In practice, the threshold γ is fixed with loose consideration of the gains and costs of additional capacity. Given the cost of maintaining capacity idle for most of the time, in developed countries γ is probably fixed much too high by public authorities who strongly dislike electricity outages because of the reactions of public opinion.

For benchmarking purposes, operators and regulators use two main indexes (see Figure 1).⁷ The System Average Interruption Duration Index (SAIDI) represents the average *amount of time* (minutes per customer per year) that power supply is interrupted. The System Average Interruption Frequency Index (SAIFI) represents the average *number of interruptions* (per customer per year).⁸ There is a lack of consistency in how the inputs to these indices are measured, both domestically and internationally. In particular, there is discrepancy on whether storm-related outages are to be counted as outage events. Some jurisdictions consider storm-related outages as ‘extreme’ events, and therefore do not include them in power outage statistics. (Campbell, 2012).

On the consumer side it is difficult to distinguish between outages due to energy shortage and those due to transport failure. In France, the energy regulator uses a reference average duration of interruptions in year N, expressed in minutes, to compute premiums or penalties inserted into the tariff paid to transport and distribution operators. The reference was set to 68 minutes in 2014, 67 min in 2015, 66 min in 2016 and 65 min in 2017. (CRE, 2013, p.31). For French producers, the acceptable average duration of cuts due to imbalance between supply and demand is fixed at 3 hours a year.⁹

2.3.2 Value of Lost Load

The Value of Lost Load (VoLL) more closely matches the economic norm of section 2.2. It measures the consumers’ marginal surplus. It is an index of how to value security of electricity supply. In their approach to the optimal level of ‘Reliable Capacity’, Cramton *et al.* (2013) define “... the ‘Value of Lost Load’ as the amount that consumers would pay to avoid having supply of power interrupted during a blackout”. As shown in Figure 2, the willingness-to-pay (WTP) to avoid an outage is not the only possible definition

⁷For details, see http://www.l2eng.com/Reliability_Indices_for_Utilities.pdf

⁸Another index is CAIDI: Customer Average Interruption Duration Index. It gives the average duration of an interruption. With both SAIFI and SAIDI, a reduction in value indicates an improvement in the continuity of supply. This is not necessarily true with CAIDI since it is obtained as the ratio of SAIDI and SAIFI.

⁹Décret n° 2006-1170 du 20 septembre 2006 relatif aux bilans prévisionnels pluriannuels d’équilibre entre l’offre et la demande d’électricité (article 11). The 3h constraint has reportedly not been binding for the past two decades..

Country	SAIDI (minutes lost/year)	SAIFI (# interruptions/year)
Austria	52	0.8
Denmark	12	0.3
France	52	0.7
Germany	13	0.4
Italy	94	2.0
Netherlands	20	2.8
Spain	53	1.2
UK	92	0.7

source : 6TH CEER Benchmarking Report on the Quality of Electricity and Gas Supply 2016, Annex A

Figure 1: Unplanned interruptions per consumer in 2014 (including all events)

of VoLL. One alternative is the willingness-to-accept (WTA) payment for an outage. Figure 2 shows that they take significantly different values.¹⁰

Knowing that additional capacity allows providers to decrease blackout duration, for a given value of VoLL new capacity should be installed up to the point where the additional cost (the rental cost of reliable capacity, RCC) just matches the value lost by consumers during blackouts: $VoLL \times Duration = RCC$.¹¹

Starting from (2), in order to obtain

$$Duration = \frac{RCC}{VoLL} \quad (5)$$

we must assume that

- i) $RCC = C'(K)$, a constant in Cramton *et al.*
- ii) $S'(K)$ is negligible
- iii) $VoLL = L'(q - K)$, a constant in Cramton *et al.*

¹⁰See OFGEM and DECC (2013). The difference between WTA and WTP is probably related to the "endowment effect" analyzed by Thaler (1980): individuals value what they already own more than something they do not yet own.

¹¹"... suppose the average annual Duration of blackouts is five hours per year and that $VoLL = \$20,000/MWh$. Suppose further that the rental cost of reliable capacity (RCC) is $\$80,000/MW$ -year. If one MW of capacity is added, it will run five hours per year on average and reduce the cost of blackouts by $\$100,000$ /year. That is more than the cost of capacity so new capacity should be built up to the point where the duration of blackouts falls to 4 hours per year and the marginal cost of capacity equals the marginal reduction in the cost of lost load." (Cramton *et al.* (2013). Actually, additional capacity is likely to decrease the VoLL on top of the decrease in blackout duration.

Table 1: Comparison of WTA and WTP £/MWh estimates by time of outage – domestic customers, based on a time varying electricity demand profile

	Not Winter	Not Winter	Not Winter	Not Winter	Winter	Winter	Winter	Winter
	Not Peak	Not Peak	Peak	Peak	Not Peak	Not Peak	Peak	Peak
	Weekend	Weekday	Weekday	Weekend	Weekend	Weekday	Weekday	Weekend
WTA (£/MWh)	9,550	6,957	9,257	11,145	10,982	9,100	10,289	11,820
WTP (£/MWh)	2,766	(101)	(105)	1,805	2,240	315	208	1,651

Note: The figures are based on figures for a one hour electricity outage. Converted based on an assumed annual electricity consumption of 3.934 MWh per annum but the numbers have been adjusted for different electricity demands across outage scenarios. This is discussed in Annex 12. Estimates in bold indicate statistical significance at the 95% confidence interval.

Source: London Economics analysis

Figure 2: VoLL in the UK (source: OFGEM and DECC, 2013)

Under these conditions, (2) can be rewritten as

$$1 - F(K) = \frac{C'(\cdot)}{L'(\cdot)} \quad (6)$$

i.e. capacity must be increased up to the point where the failure rate is equal to the ratio of marginal capacity cost to the marginal value of power outages. The criterion is totally dependent on the $VoLL$, which is difficult to compute and strongly varies with time as shown in Table 2.

Assumption (ii) may be justified when considering investment criteria. This will be the case when production plants can be the split into two categories:

- plants K_c managed in order to supply consumers. These operators solve

$$\max_{K_c} \left\{ -C_c(K_c) + \int_{\underline{q}}^{K_c+K_r} S(q) dF(q) + \int_{K_c+K_r}^{\bar{q}} S(K_c+K_r) dF(q) \right\}$$

which gives the first order condition

$$S'(K_c+K_r) [1 - F(K_c+K_r)] = C'_c(K_c) \quad (7)$$

- and plants K_r devoted to capacity adequacy, controlled by the system operator. Their capacity is determined by

$$\max_{K_r} \left\{ -C_r(K_r) - \int_{K_c+K_r}^{\bar{q}} L(q - K_c - K_r) dF(q) \right\}$$

and the first order condition is

$$\int_{K_c+K_r}^{\bar{q}} L'(q - K_c - K_r) dF(q) = C'_r(K_r) \quad (8)$$

Because the two optimization problems are separate, the total capacity determined by (7) and (8) cannot be exactly the same¹² as the one determined by (2). Nevertheless, the marginal surplus $S'(\cdot)$ is indirectly represented in (8) as in (7), K_c depends on the shape of the surplus function. It remains true that the separate solution is suboptimal because of the lack of internalization of the private and public gains by each category of producer.

If the marginal loss $L'(\cdot)$ is a constant, then (8) can be written in the same form as (6), which is similar to the Cramton's formula (5).

2.4 The implementation of ad hoc criteria

The observed level of capacity will typically depart from the optimal one because criteria for resource adequacy are based on political/technical considerations. Policy makers' risk aversion results in overestimation of the *VoLL* and of reliability requirement γ . The resulting capacity is larger than the optimal one calculated using economic criteria, i.e. utility from consumption, disutility from curtailment, installation cost, and probability distribution of demand. To cover these capacity costs, producers need large financial resources. If energy-only markets do not work competitively because of poor design and/or price-caps, producers will demand financial compensation for the extra capacity required by regulations.

In section 2.3.2 we have seen that retail service providers might prefer a different level of capacity than a system operator when the latter is mainly concerned about outages and the former are mainly concerned about revenues from energy sales. This is an extreme case of lack of internalization. Inefficiency would also arise from the inability of sellers to fully internalize the utility losses suffered by consumers during outages. If sellers take into account only a fraction of welfare losses from power cuts, a financial penalty covering the remaining fraction could provide the incentives to install the first-best capacity. Unfortunately, this type of policy is not easy to implement when there are several producers, since the lack of capacity is a kind of 'public bad'. Allocating the penalty among the producers is an economic challenge. A alternative solution considered in section 4 is to pay producers a capacity reward or allow investors in capacity to accrue revenues from the sale of capacity credits.

Public authorities also justify their intervention in capacity requirements by an alleged lack of coordination in investment decisions among competing producers and the market's failure to provide the right incentives. Under pure market mechanisms, coordination should exclusively come from exogeneous price signals. However, we know

¹²For a given *VoLL*, whether $K_c + K_r > K^*$ or $< K^*$ depends on the shape of the cost function(s). If there is some form of economies of scale, splitting the activities increases the production cost. Consequently, the commercial producers and the system operator install less capacity than the optimal level. However, an overestimation of *VoLL* pushes up the needs for capacity.

that they can fail to transmit information about externalities such as the disutility of energy outages.

The discrepancy between public and private capacity choices can be even wider when there are several interconnected regions, each with its own regulation (see Tables 1 and 2). In the next section we analyze the capacity decisions taken by independent price-taking producers located in separate markets or regions, in both cases when they can and cannot trade energy after they have built capacity.

3 Energy-only trading

In this section we examine the type of sub-optimality that results from independent management.¹³ We show that coordinated production as well as ex post energy allocation is necessary for the regions to reach a global optimum when they differ in terms of net surplus, loss value, investment cost or probability of peak demand. We allow random demands to be independent or correlated.

3.1 Demand uncertainty

To isolate the effects of uncertainty, we adopt a simplified demand side model in which demand can just be high (H) with probability ρ , or low (L) with probability $1 - \rho$ rather than the atomless demand of the former section.

Net surplus is linear $S^t \equiv sq^t$ ($t = L, H$) where the net unit surplus s is the difference between the unit gross surplus c and the unit operating cost c . Thus, S^H and S^L measure consumer welfare in states H and L respectively if there is no shortage. Net surplus is $sK - L(q^t - q)$ if there is a shortage, i.e. if the quantity q delivered from capacity K is smaller than demand q^t .

The two markets (or regions) are indexed by 1 and 2. We first consider the case of separate management. We then analyze the case of a single jurisdiction covering the two regions. The social planner(s) has (have) a two-stage decision to take: *i*) how much capacity K_i to install in market i ($i = 1, 2$), and *ii*) knowing the installed capacity and the state(s) of nature, how much energy q_i to deliver to market i . In the case of a single jurisdiction, we assume that the two markets are perfectly interconnected and there are no thermal losses on the lines.

3.2 First best

3.2.1 Autarky case

In each region $i = 1, 2$, the social planner must determine first the capacity K_i , and then the energy supplied q_i . When capacity is $K_i < q_i^L$ rather than $q_i^L \leq K_i \leq q_i^H$, the savings on construction costs may not outweigh the loss in consumers' surplus. Moreover power rationing will be necessary in all states of nature instead of only state H , and the lost

¹³This and the next section apply both to two adjacent markets or two adjacent countries or regions as long as there is no transmission constraint.

surplus will be larger in state H . To limit the number of relevant cases, we assume that the net social savings from investing in low capacity never exceed the loss in welfare from outages. Thus, we examine only the case $q_i^L \leq K_i \leq q_i^H$.¹⁴ In state L the system operator will provide consumers with $q_{iL}^* = q_i^L$ so that $L_i(\cdot) = 0$. In state H , $q_{iH} = K_i$, so that $L_i(q_i^H - K_i) \geq 0$. Therefore, the optimal K_i is the solution to

$$\max_{K_i} \left\{ -C_i(K_i) + \rho_i (s_i K_i - L_i(q_i^H - K_i)) + (1 - \rho_i) s_i q_i^L \right\} \quad (9)$$

where ρ_i is the probability of state H in region i . The optimal capacity is determined by the first-order condition

$$\rho_i \left(s_i + L'_i(q_i^H - K_i^*) \right) = C'_i(K_i^*) \quad (10)$$

which is the transposition of condition (2) into our framework with two states of nature. Consumption in state H will be $q_{iH}^* = K_i^*$.

3.2.2 Joint optimisation

Assume now there is one single decision maker for the two regions. Without any transmission constraints, the ex post decision in each state of nature will be taken under the common constraint $q_1 + q_2 \leq K_1 + K_2$ with dual variable β . We maintain the assumption that it would be socially inefficient to cut power when demand is low, which means that $q_1^L + q_2^L \leq K_1 + K_2$ will always be satisfied at the optimum.

Energy The following describes the optimal volumes of energy supplied to consumers in 1 and 2 in each state of nature given K_1 and K_2 .

- In state HH (demand is high in both regions), energy supply is given by

$$\max_{q_1, q_2} s_1 q_1 - L_1(q_1^H - q_1) + s_2 q_2 - L_2(q_2^H - q_2) + \beta^{HH} (K_1 + K_2 - q_1 - q_2)$$

where β^{HH} denotes the dual variable of the capacity constraint in the current state. The first order conditions give

$$s_1 + L'_1(q_1^H - q_1) = \beta^{HH} = s_2 + L'_2(q_2^H - q_2) > 0 \quad (11)$$

Then, by complementary slackness conditions, the constraint is an equality:

$$q_1 + q_2 = K_1 + K_2 \quad (12)$$

Conditions (11) and (12) jointly determine the ex post solution in state HH as a function of $K_1 + K_2$. We denote it by $q_{i,HH}$, $i = 1, 2$.

¹⁴It also corresponds better to what we can observe in developed countries. In less developed ones, we unfortunately find that $K_i < q_i^L$.

- In state HL (high demand is in region 1 and low in region 2), since we have assumed it would be too costly not to serve low demand, the problem is

$$\max_{q_1} s_1 q_1 - L_1 (q_1^H - q_1) + s_2 q_2^L + \beta^{HL} (K_1 + K_2 - q_1 - q_2^L)$$

Given the first-order condition $s_1 + L_1' (q_1^H - q_1) = \beta^{HL} > 0$, we obtain

$$q_{1,HL} = K_1 + K_2 - q_2^L, q_{2,HL} = q_2^L \quad (13)$$

- Symetrically, in state LH ,

$$q_{1,LH} = q_1^L, q_{2,LH} = K_1 + K_2 - q_1^L \quad (14)$$

- Finally, in state LL , we already know that

$$q_{1,LL} = q_1^L, q_{2,LL} = q_2^L$$

Capacity Anticipating these ex post adjustments, the capacity problem is

$$\begin{aligned} \max_{K_1, K_2} EW &= \rho^{HH} [s_1 q_{1,HH} - L_1 (q_1^H - q_{1,HH}) + s_2 q_{2,HH} - L_2 (q_2^H - q_{2,HH})] \\ &+ \rho^{HL} [s_1 q_{1,HL} - L_1 (q_1^H - q_{1,HL}) + s_2 q_2^L] \\ &+ \rho^{LH} [s_1 q_1^L + s_2 q_{2,LH} - L_2 (q_2^H - q_{2,LH})] \\ &+ \rho^{LL} [s_1 q_1^L + s_2 q_2^L] - C_1 (K_1) - C_2 (K_2) \end{aligned} \quad (15)$$

The first-order condition with respect to K_i is

$$\begin{aligned} &\rho^{HH} \left[[s_1 + L_1' (q_1^H - q_{1,HH})] \frac{\partial q_{1,HH}}{\partial K_i} + [s_2 + L_2' (q_2^H - q_{2,HH})] \frac{\partial q_{2,HH}}{\partial K_i} \right] \\ &+ \rho^{HL} \left[[s_1 + L_1' (q_1^H - q_{1,HL})] \frac{\partial q_{1,HL}}{\partial K_i} \right] + \rho^{LH} \left[[s_2 + L_2' (q_2^H - q_{2,LH})] \frac{\partial q_{2,LH}}{\partial K_i} \right] \\ &= C_i' (K_i) \quad i = 1, 2 \end{aligned}$$

Given the ex post adjustment (11) and (12) for state HH , (13) for state HL and (14) for state LH , we can reduce the first-order condition in region i to

$$\rho^{HH} [s_i + L_i' (q_i^H - q_{i,HH})] + \rho^{HL} [s_1 + L_1' (q_1^H - q_{1,HL})] + \rho^{LH} [s_2 + L_2' (q_2^H - q_{2,LH})] = C_i' (K_i) \quad (16)$$

The gains from coordination Since condition (16) is to be met in both regions $i = 1, 2$, using (11) we have the following:

Proposition 1 *Under joint optimization, installed capacities must satisfy*

$$C'_1(K_1^{**}) = C'_2(K_2^{**}) \quad (17)$$

This is one advantage of joint optimization: the cost of installing $K_1 + K_2$ is minimized, whatever the total capacity.

A second important difference with the autarky case is that the installed capacity in each region depends not only on the surplus of local consumers but also on the surplus of consumers from the other region. For example, consider region 1. Capacity K_1 will be used to supply energy in region 1 but some imports will come from region 2 in state HL and some exports will feed region 2 in state LH . To emphasize these interrelations, note that since $\rho^{HH} + \rho^{HL} = \rho_1$, we can write condition (16) as

$$\begin{aligned} & \rho_1 \left[s_1 + L'_1 (q_1^H - q_{1,HH}) \right] \\ & + \rho^{HL} \left[L'_1 (q_1^H - q_{1,HL}) - L'_1 (q_1^H - q_{1,HH}) \right] + \rho^{LH} \left[s_2 + L'_2 (q_2^H - q_{2,LH}) \right] \\ & = C'_1(K_1) \end{aligned} \quad (18)$$

Since $q_{1,HL} > q_{1,HH}$, the second term on the left-hand side is negative, whereas the first and third ones are positive. The installed capacity will be higher or lower than in the framework of separate decisions given by (10), depending on the relative weights of the second and third terms. If ρ^{HL} is large and ρ^{LH} small, the left hand side of (18) is smaller than the LHS of (10). The installed capacity in region 1 is then smaller under the coordinated framework since the most likely event is that region 1 will import from a region with structural low demand when local demand is high. Conversely, if ρ^{HL} is small and ρ^{LH} large, excess capacity is to be installed in region 1 with the purpose of exporting to region 2 when state LH occurs.

3.2.3 Correlated and independent demands

We now consider the two extreme cases of negative and positive demand correlation, followed by the case of independent demands in order to emphasize some characteristics of the benefits of coordination.

Perfect negative correlation: $\rho^{HH} = \rho^{LL} = 0$. Since $\rho_1 = \rho^{HL}$, $\rho_2 = \rho^{LH}$, from (16) we obtain

$$\rho_1 \left[s_1 + L'_1 (q_1^H - q_{1,HL}) \right] + \rho_2 \left[s_2 + L'_2 (q_2^H - q_{2,LH}) \right] = C'_1(K_1) = C'_2(K_2) \quad (19)$$

This clearly shows the interdependence of the two regions, both in terms of capacity building and in terms of energy allocation. Indeed, since $q_1^H - q_{1,HL} = (q_1^H + q_2^L) -$

$(K_1 + K_2)$ and $q_2^H - q_{2,LH} = (q_1^L + q_2^H) - (K_1 + K_2)$, the marginal value of losses in each region depends on the overall capacity instead of just on local capacity. Under perfect negative correlation, each region insures the other one, since high demand in one is always accompanied with low demand in the other. Inter-connection is highly valuable in this situation as long as energy exchanges are feasible. Having a sum of marginal surpluses on the left-hand side of (19) lightens the public good characteristics of capacity since it can be used for non-mutually exclusive purposes.

As an illustration, assume that the two regions are exactly the same. Let $K(\gamma)$ denote the capacity needed to achieve the same level of reliability required by the authorities in each region. If they can coordinate their capacity planning and trade energy, in each region firms invest K and buy (resp sell) $K - q^L$ when local demand is high (resp. low). To meet the constraint, capacity must be such that $K + (K - q^L) = K(\gamma)$ when demand is high. The solution to this obligation is $K^*(\gamma) = \frac{K(\gamma) + q^L}{2}$. Consequently, the capacity savings from coordination and trade is $K(\gamma) - K^*(\gamma) = \frac{K(\gamma) - q^L}{2}$. That is, each region would need to invest only half the surplus capacity of the low demand state in order to achieve the targeted level of reliability. The rest is provided by the neighboring region.

Perfect positive correlation: $\rho^{HL} = \rho^{LH} = 0$. Since $\rho^{HH} = \rho_i$, from (16) we have

$$\rho_i \left[s_i + L'_i (q_i^H - q_{i,HH}) \right] = C'_i (K_i), i = 1, 2 \quad (20)$$

First, note that the left-hand side of this condition (in contrast to (19)) has only one term. This is because there are no complementarities: the two regions always face peak capacity needs at the same times. Second, this condition is apparently similar to (10). However the argument of the marginal loss function is not exactly the same. Because of the possibility of energy trade across the two regions, here there is no reason here for it to be the case that $q_{i,HH} = K_i$, contrary to the autarky case. The efficiency condition (17) requires that the allocation of total capacity $K_1 + K_2 = q_{1,HH} + q_{2,HH}$ across the two regions is done in a way that depends on marginal cost functions (recall that we assume no transmission constraints). Except for very specific values of the parameters, even though states of nature are perfectly positively correlated, we will then have $q_{i,HH}^{**} \neq K_i^{**}$.

This is shown in Figure 3 where the optimal joint allocation is represented by points C and D determined by the simultaneous equality of expected marginal surpluses and capacity marginal costs in both regions when there is perfect positive correlation between demands. If the two regions are not interconnected, the best choice is given by two separate equalities (10); see points A and B, with region 2 represented from right to left. In this configuration, the necessity of having only locally installed capacity would result in a difference in valuations: points A and B have different heights. By contrast, under the possibility that one market's capacity can provide energy to the other market, energy and capacity values are made equal (points C and D have equal heights), resulting in an increase of social surplus represented by area ADBC. In the graph, the marginal

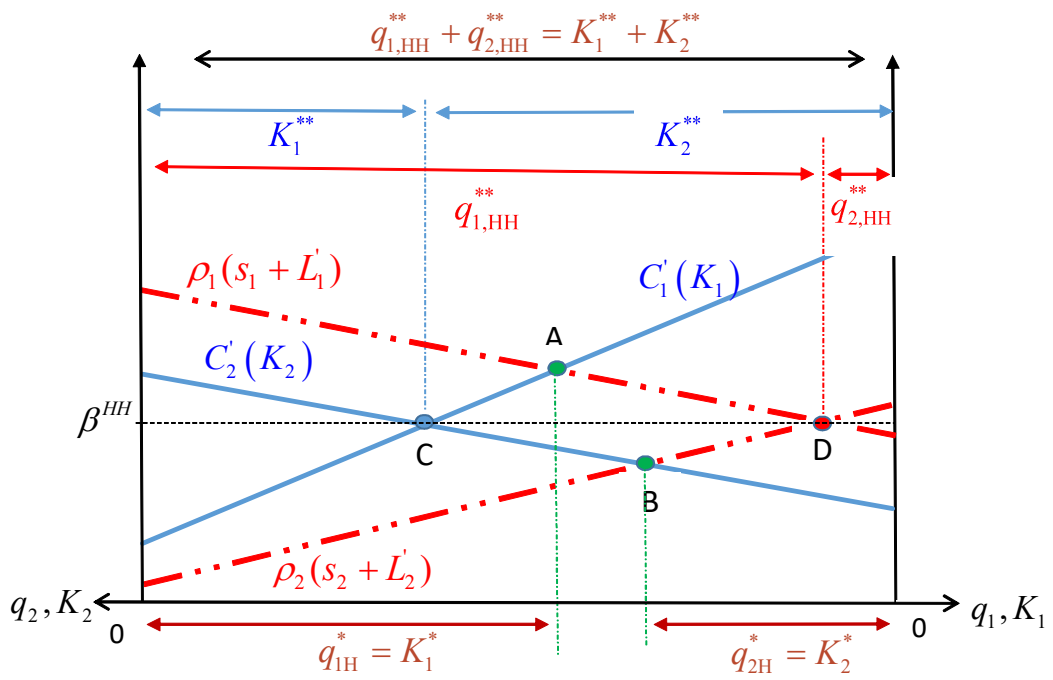


Figure 3: Building and using capacity

cost function of firms 1 is larger than that of firms 2. Thus, it is efficient to build less capacity ($K_1^{**} < K_1^*$) in 1 and more in 2 ($K_2^{**} > K_2^*$). In phase 2, at times of peak demand (in both regions), with a willingness to pay higher in 1 than in 2, a large proportion $q_{1,HH}^{**} - K_1^{**}$ of the supply $q_{1,HH}^{**}$ in market 1 comes from the capacity installed in market 2. We also see from Figure 3 that $K_1^{**} + K_2^{**} > K_1^* + K_2^*$. This is due to increasing marginal costs. Indeed, $K_1^* + K_2^*$ can be installed at a lower cost by reallocating the plants between the two regions up to the point where their marginal costs are equal. This means that $C_1(K_1^*) + C_2(K_2^*) > C_1(K_1^* - \Delta) + C_2(K_2^* + \Delta)$ for Δ not too large. For the same total cost, more capacity can then be installed when decisions are coordinated.

If the two regions are the same from all points of view, there is no opportunity for benefitting from trade, and therefore no gain from coordination. This can be seen from a revised version of Figure 3: if the two regions are exactly the same, the curves of costs and expected gains are identical in both, so that points A, B, C and D are all located at the same place. Capacities are then the same in autarky and under coordination.

Independent demands: $\rho^{HH} = \rho_1\rho_2, \rho^{HL} = \rho_1(1 - \rho_2), \rho^{LH} = (1 - \rho_1)\rho_2$. The first-order condition (18) of firm 1 is now

$$\begin{aligned} & \rho_1\rho_2 \left[s_i + L'_i (q_i^H - q_{i,HH}) \right] + \rho_1(1 - \rho_2) \left[s_1 + L'_1 (q_1^H - q_{1,HL}) \right] \\ & + (1 - \rho_1)\rho_2 \left[s_2 + L'_2 (q_2^H - q_{2,LH}) \right] \\ & = C'_i(K_i) \end{aligned}$$

Let $E\pi'_{1-}$ denote the left-hand side of (19) and $E\pi'_{1+}$ the left-hand side of (20). The above condition can then be written

$$\rho_2 E\pi'_{1+} + (1 - \rho_2) E\pi'_{1-} + \rho_2(\rho_2 - \rho_1) \left[s_2 + L'_2 (q_2^H - q_{2,LH}) \right] = C'_1(K_1) \quad (21)$$

We see that the expected marginal revenue consists of three terms. If $\rho_1 = \rho_2$, the third term vanishes and the marginal revenue of firms 1 is just an average value of the cases of perfect negative and positive correlations weighted by the probabilities of demand in region 2. Consequently, the capacity installed by firm 1 is generically between the values corresponding to these extreme cases. It is not a simple average though. The higher (lower) ρ_2 , the closer capacity in 1 is to the perfect positive (negative) correlation level. This shows that in spite of the independence of demands, investment still depends on the possibility to trade energy among regions. The third term is an adjustment that increases or decreases the expected marginal gains depending on firms in region 1 having more opportunities to export to region 2 ($\rho_2 > \rho_1$) or to import from region 2 ($\rho_2 < \rho_1$) when demand is high.

For identical regions, given (21) and the two above results, the installed capacity is smaller than in autarky.

To sum up the above results:

Proposition 2 *Whatever the statistical relationship between demands in neighboring jurisdictions, cooperation between Regional System Operators increase overall welfare. If the two regions are identical, total capacity is smaller than under autarky.*

Note that in the above we have considered situations in which demand is either high or low in each region. The results concerning the gains of social surplus arising from coordination extend to the case of continuous probability distributions, whatever their shape, for coordination and trade enlarge the feasible set of social planners, and social performance cannot therefore decrease in relation to autarky.

3.3 Energy markets

Assume there is a large set of competitive energy producers in each region. In region i , consumers are billed the non-contingent retail price p_i^r for each unit of energy consumed. If producers fully internalize the social value of the lost load, which could be the case if regulators impose a large penalty in case of outage, or if suppliers are obliged to fix the damages due to energy cuts, then producers will install the optimal capacity K_1^{**}, K_2^{**} and trade energy at contingent wholesale prices. This is a direct result of the optimality properties of perfect competition when there is no externality, and technology and preferences are convex. A formal proof is provided in the Appendix 6.2.

The exchange of energy across borders increases efficiency since it allows saving on capacity costs arising from the technical advantages of the firms located in adjacent jurisdictions serving each others' energy consumers. Energy can flow in either direction depending on the state of nature. This corresponds to what Antweiler (2016) names 'reciprocal load smoothing'.

Proposition 3 *Free trade of energy among jurisdictions allows the same capacity outcome to be reached as under coordinated planning, provided that i) private operators have no market power and ii) they fully internalize the disutility from lost load.*

However implementation of open electricity markets faces political obstacles, as we briefly discuss in the following subsection,.

3.4 Political constraints

It is clear that when capacity is chosen in a coordinated way among two inter-connected heterogeneous regions, the optimal capacity levels are generically different from their autarky values. Joint optimization is more efficient than separate optimization in each region. However, coordinated allocation of capacity and energy is not always politically feasible for a number of reasons. One is the possibility that overall welfare increase comes at the expense of one of the two regions. For example, assume that $K_2^* > q_{2,HH}^{**}$, i.e. when demand is high in the two regions, consumers in region 2 consume less under the joint decision mechanism than under autarky (this is the case represented in Figure 3).

This redistribution among regions 1 and 2 presents political impediments for achieving a jointly optimal outcome. Taking distributive aspects into account, the optimal solution requires a lump sum tax in region 1 to compensate losers in region 2. This is an impractical approach as *i*) raising taxes introduces additional distortions and *ii*) it can be difficult to transfer funds across regions. Moreover, paying the compensation ex post may not be credible. These difficulties will tend to induce region 2 to insist on retaining control of its own territory.

For these reasons, the participation condition $q_{2,HH} \geq K_2^*$ should be introduced into the joint optimization process as a political acceptability constraint. This is not purely hypothetical. In practice, system operators do not span multiple regions, which limits international coordination on resource adequacy, particularly within the European Union where the European Commission tries to build electrical regions different from those designed by system operators.¹⁵ More specifically, Member States are reluctant to cede control of their own electric system to a regional entity covering several countries. Their fear is that, in case of scarcity, the overall supervisor could opt for blackouts, based on rules contrary to national interests.

4 Capacity credits

This section examines the impact of trade in capacity credits on investment.

4.1 Why capacity requirements?

Many, if not most, Regional System Operators (RSO) impose some sort of capacity requirement on energy service providers to ensure resource adequacy. In this section we consider the effects of one such approach, that of capacity credits on investment levels.

A system of capacity credits requires energy suppliers to obtain certificates from owners of generation facilities in proportion to their load. The cost of the credits for the suppliers is an additional source of revenue for generation owners, which is one purpose of the credits. The System Operator (or the regulator) seeks to impose requirements that suppliers obtain sufficient credits to ensure system adequacy. At the same time, the SO will issue credits up to the amount of capacity deemed to be sufficient to ensure resource adequacy. In most cases, the SO will offer subsidies in proportion to the credits assigned to each generation facility. These subsidies are typically determined by means of tenders or auctions.¹⁶

The standard justification to these mechanisms is the so-called missing money problem resulting from price-caps. Consumers, who also are voters, dislike peaking prices,

¹⁵See Crampes et al (2017).

¹⁶See European Commission (2016a).

See https://ec.europa.eu/energy/sites/ener/files/documents/swd_2016_385_f1_other_staff_working_paper_en_v3_p1_870001 for details of the mechanisms implemented in Belgium, Croatia, Denmark, France, Germany, Ireland, Italy, Poland, Portugal, Spain and Sweden. For a recent analysis of capacity markets, see Cramton (2017).

which can result in political pressure to impose price ceilings. Competition policy concerns are an additional reason for regulators not to allow spot energy prices to spike during peak demand periods. Such price ceilings reduce producers' revenues and the returns on investment. In particular, these caps hit peak producers who are not able to recoup their fixed costs.¹⁷ A capacity payment on top of energy revenues would then fill the gap.

There is an alternative reason to justify the use of capacity mechanisms: contrary to our assumption in section 3.3, but in line with our discussion in section 2, firms do not internalize the value of lost load as much as public authorities do. Consequently, they do not invest as much as they should from the regulators' point of view. This is the case we consider in what follows.

We first discuss the need for additional financial incentives when firms are obliged to invest more than they would like to (4.2). We then consider the possibility of firms trading capacity rights across the two regions (4.3).

4.2 Obligation and compensation

Consider the former autarky problem (9) modified as follows:

$$\max_{K_i} -C_i(K_i) + \rho_i(m_i K_i - \alpha_i L_i(q_i^H - K_i)) + (1 - \rho_i)m_i q_i^L$$

where $\alpha_i \in [0, 1]$ is a coefficient measuring the weight of the loss function in the objective function of firms in i and m_i is the unit margin from energy sales. The solution is K_i^α given by

$$\rho_i(m_i + \alpha_i L_i'(q_i^H - K_i^\alpha)) = C_i'(K_i^\alpha)$$

Differentiating with respect to α_i we obtain

$$\frac{dK_i^\alpha}{d\alpha_i} = \frac{\rho_i L_i'(\cdot)}{C_i''(K_i^\alpha) + \alpha_i \rho_i L_i''(\cdot)} > 0 \quad (22)$$

Then, even if $m_i = s_i$, with a 'private α_i ' smaller than the 'social α_i ', firms will install capacity below the socially optimal level.¹⁸ In the following, we just assume that 'social α_i ' = 1 > 'private α_i ' so that $K_i^{\alpha=1} = K_i^* > K_i^\alpha$.¹⁹ Suppose that the regional system

¹⁷In this paper, we have not differentiated between base load and peaking capacity. Typically firms with peaking capacity must recoup their cost over a very limited number of hours. However they cannot do so when prices are capped.

¹⁸Investment below the first-best level can also result from market power. In our framework, it could be represented by the profit margin m_i decreasing in K_i . We would then have the usual result of a marginal revenue $m_i + m_i' K_i$ below the average margin $m_i = s_i$. With this lower financial incentive, firms would invest less than the optimal level. Here we consider that the competition authority can block this adverse effect to competition. On the consequences of Cournot competition for capacity levels, see Léautier (2017), chapter 9.

¹⁹We have seen in section 2 that governments try to impose capacity levels higher than the optimal one, K_i^* , which corresponds to $\alpha_i > 1$. For our discussion, it is sufficient to have a public α_i larger than the one used by private firms.

operator imposes capacity to cover at least a portion β_i of high demand, that is

$$K_i \geq \beta_i q_i^H > K_i^\alpha$$

Firms will obviously choose $K_i = \beta_i q_i^H$. Then to implement first best, the authority must fix $\beta_i^* = \frac{K_i^*}{q_i^H}$ and the expected profit of firms in region i is

$$-C_i(K_i^*) + \rho_i(m_i K_i^* - \alpha_i L_i(q_i^H - K_i^*)) + (1 - \rho_i)m_i q_i^L$$

Since K_i^* is a constrained choice, at $m_i = s_i$ the resulting profit is smaller than when capacity is K_i^a , freely chosen. Whether the β_i^* mechanism is implementable depends on the associated carrot and stick system. Severe penalties in case of default solve the capacity problem,²⁰ as was the case in section 3. However, this does not guarantee that the resulting profit is non-negative, i.e. we have an alternative source of missing money, different from price caps. As noted by Joskow (2007), price caps cannot be the only cause for the missing money problem because in most wholesale markets, they are rarely binding constraints despite being far below estimates of the VoLL.

To solve the missing money problem, one could increase the energy retail price, then the margin m_i . This would help vertically integrated firms, not pure producers. Moreover, it would apply to all demand, including the low demand regime. We rather consider the possibility for firms to be rewarded for the peak demand they serve or to be rewarded for the capacity they install.

4.2.1 Payment for peak-demand

Electricity retailers have the obligation to buy certificates from energy producers to prove they can serve (a given fraction of) their affiliated peak demand. In our model of vertical integration, the cost of these certificates or of additional capacities is simply a transfer from consumers to energy producers. When the payment is based on the exogenous value q_i^H , the investment and production problem of producers in i remains unchanged at the margin if consumers have an inelastic demand, which is true in the short run. However, the additional revenue makes a difference if it allows some firms to remain active whereas they would prefer to go out of business without public aid. If so, the payment for peak demand in region i can also benefit the consumers located in the interconnected regions.

4.2.2 Payment for capacity

If the complementary payment is based on installed capacity at unit price p_{K_i} , the profit maximizing capacity is the solution to

$$\begin{aligned} \max_{K_i} & -C_i(K_i) + \rho_i(m_i K_i - \alpha_i L_i(q_i^H - K_i)) + (1 - \rho_i)m_i q_i^L + p_{K_i} K_i \\ \text{s.t.} & K_i \geq \beta_i^* q_i^H \quad (\xi_i) \end{aligned}$$

²⁰Penalties are steep in US regional system operators' jurisdictions.

The first-order condition is then

$$\rho_i \left(s_i + \alpha_i L'_i (q_i^H - K_i) \right) + p_{K_i} - C'_i (K_i) + \xi_i = 0$$

and the complementary slackness conditions read

$$K_i \geq \beta_i^* q_i^H, \xi_i \geq 0, (K_i - \beta_i^* q_i^H) \times \xi_i = 0$$

If the capacity price p_{K_i} is very large, firms can have the incentive to invest beyond the target: $K_i > \beta_i^* q_i^H$. If so, $\xi_i = 0$ and the capacity installed is the solution to $\rho_i \left(m_i + \alpha_i L'_i (q_i^H - K_i) \right) + p_{K_i} - C'_i (K_i) = 0$. Otherwise, that is if $\xi_i = -\rho_i \left(m_i + \alpha_i L'_i (q_i^H - K_i^*) \right) - p_{K_i} + C'_i (K_i^*) > 0$, the capacity constraint is binding, then firms invest $K_i^* = \beta_i^* q_i^H$.

In our framework where consumers and producers have equal weights in the total surplus function, the regulator in region i is indifferent to the value of p_{K_i} . The capacity payment is a neutral financial transfer from consumers to producers. In real life, intensive lobbying by industry players can result in excessive payments that trigger unnecessary investment. To limit the burden on consumers, we assume that p_{K_i} is fixed at the lowest possible value, so that firms i) just invest at the level required by the RSO and ii) obtain the same profit as without the regulation. From the equality between the constrained and non-constrained expected profits, we can determine the required capacity payment $p_{K_i} K_i^*$:

$$p_{K_i} K_i^* = C_i (K_i^*) - C_i (K_i^\alpha) - \rho_i \left(m_i (K_i^* - K_i^\alpha) - \alpha_i [L_i (q_i^H - K_i^\alpha) - L_i (q_i^H - K_i^*)] \right) \quad (23)$$

We see that the driver for large capacity payment is the compensation required to cover the additional investment $C_i (K_i^*) - C_i (K_i^\alpha) > 0$. However, the two other terms on the right-hand side of (23) are negative, and they mitigate the required compensation to investors: i) with more capacity firms can sell more energy and gain the unit margin m_i on additional sales in state H ; ii) with more capacity there will be fewer outage hours. This second effect is strongly dependent on the value of α_i . If α_i is small, by (22) the difference $K_i^* - K_i^\alpha$ is large and p_{K_i} must be high. Conversely, when firms are already strongly concerned about power cuts (high α_i), p_{K_i} is low. For $\alpha_i = 1$, we have $K_i^\alpha = K_i^*$ and then $p_{K_i} = 0$. In other words, this compensation mechanism can be viewed as unfair since it rewards egoistic behavior.

4.3 Capacity credits trade

Whereas capacity mechanisms are mainly designed within national borders, private or public regional initiatives can arise to take advantage of the heterogeneity of neighbouring markets. The capacity requirement can be measured in different ways:

- the local authority imposes the autarky first best, i.e. capacity K_i^* defined by (10) in each region i , but firms remain free to trade capacity credits with firms in the other region;

- the target is K_i^{**} determined by joint optimization in (16);
- the target is not binding, i.e. it is below the freely determined value K_i^α , but capacity credits can be traded between the two regions.

Whatever the target, let us denote it by \widehat{K}_i .

In contrast to what we had in the case of energy trade (see section 3) capacity credits are not state contingent since they are exchanged ex ante. What is their precise nature? There are two main possibilities:

a) Credits entitle the right-holders to withdraw energy from the capacity of the emitters;

b) Capacity credits are pure financial instruments designed to complement the financial resources of producers without any additional right or obligation.

Let us denote by k_i the purchase (if positive) or sale (if negative) of capacity credits by producers in region i . In case a) the capacity that constrains energy consumption is $K_i + k_i$. In case b) it is K_i . We will successively consider the two cases.

In order to simplify the presentation, we assume that there is no organized ex post market for energy.

4.3.1 Withdrawal rights

When credits entitle the right-holders to withdraw energy from the installed capacity of the emitters, the framework is similar to one in which generation entitlements and Virtual Power Plants are traded.²¹ As shown in Appendix 6.3, firms now face a form of contingent contract for energy, essentially equivalent to that discussed in Section 3.3. However, the resulting contingent outcome is distorted by the domestic capacity payment, if there is one. Firms from the region with the lower willingness to pay for credits (region 2 in Figure 5 of Appendix 6.3) will be net sellers of credits at equilibrium. This can be due to lower investment costs $C'_2(\cdot) < C'_1(\cdot)$, which is efficient. It can also be due to higher capacity payments $p_{K2} > p_{K1}$, which is a regulatory distortion. The local investment given the obligation and the certificates traded is $K_i^* = \widehat{K}_i - k_i^*$ determined by

$$C'_1(\widehat{K}_1 - k_1^*) - p_{K1} = p_k^* = C'_2(\widehat{K}_2 - k_2^*) - p_{K2} \quad (24)$$

By comparing (24) with (17), we see that when capacity payments differ among the regions, they create a bias in the investment decisions.

4.3.2 Financial rights

If capacity credits are purely financial, firms in region i can only rely on their own investment to supply energy. Then they solve

²¹On VPP, see Willems (2005)

$$\begin{aligned}
& \max_{K_i, k_i} -C_i(K_i) + \rho_i (s_i K_i - \alpha_i L_i (q_i^H - K_i)) + (1 - \rho_i) s_i q_i^L - p_k k_i + p_{K_i} K_i \\
& \text{s.t. } K_i + k_i \geq \widehat{K}_i \qquad (\lambda_i)
\end{aligned}$$

When the constraint is binding, the solution is $K_i + k_i = \widehat{K}_i$, with

$$p_k = C'_i(\widehat{K}_i - k_i) - \rho_i \left(s_i + \alpha_i L'_i \left(q_i^H - \widehat{K}_i + k_i \right) \right) - p_{K_i}$$

As compared to demands leading to equilibrium (24), the willingness to pay for purely financial capacity credits is lower. In fact, here capacity credits do not have the additional value of opening access to the energy produced in the other region and sold in the local market. Then, as compared with composite rights, firms in region i ‘lose’ $\rho_i \left(s_i + \alpha_i L'_i \left(q_i^H - \widehat{K}_i + k_i \right) \right)$ for each additional certificate they buy. Additionally, we observe the same distortion effect provoked by asymmetric capacity payments p_{K_i} .

We can then state the following:

Proposition 4 *When firms can trade capacity credits among regions, if capacity payments differ from one region to the other, the installed capacities do not maximize overall welfare. Composite capacity certificates are more efficient than pure financial rights.*

Any capacity payment increase in region i , not compensated by an equal increase in region j , incentivizes producers to install more capacity in region i and to sell credits to region j where producers invest less. This foreign subsidization (Blonigen and Wilson, 2010) that drives the price of credits downwards is beneficial to consumers in j (there is less capacity to subsidize) but it may push some producers out of the j market and, in any case, it is inefficient since the cost to install $\widehat{K}_1 + \widehat{K}_2$ is not minimized. This result has similarities with those in Cepeda and Finon (2011) who show that when two interconnected markets are asymmetric in terms of market design (for example one has a price-cap system), markets obtain the highest benefits from integration if they have a common approach of capacity adequacy.

5 Conclusion

Capacity planning, also called resource adequacy, is critical for ensuring reliability of an electrical system. The shift from central planning to market approaches for investment and production decisions has the potential to leave gaps in reliability. This paper identifies the conditions under which market forces can be relied upon to ensure adequate supplies and the reasons for which, in practice, these conditions may not be met. The limitations of market mechanisms can be the result of: political forces that impose price ceilings on real-time electricity prices; a lack of markets or trade restrictions that reduce potential revenues and returns on investment; a lack of coordination across regions; and network externalities in which individual suppliers do not bear the full cost of outages.

We explain how policy intervention, such as setting minimum capacity requirements and introduction of capacity markets can improve reliability. However, without information about underlying supplier costs and the loss function from outages, a grid operator or regulator will still be unable to achieve an optimal outcome.

Capacity mechanisms also raise concerns regarding competition policy, which we have not addressed in the paper.²² Like other forms of State intervention, public support to capacity providers may distort competition in electricity markets, both locally and globally. Within each region, there is a risk of maintaining active old plants that should go out of business because they are no longer profitable and they emit pollutants. This is not new: all governments are constantly trading off between industrial, employment, environmental and competition-related policies. The problem is more difficult across jurisdictions. There is currently a strong momentum towards more inter-connected electric systems and we have shown that capacity payments distort competition when they are set at different levels in neighbouring regions. Regional regulators could therefore be inclined to limit competition effects from interconnecting lines by subsidizing their local producers through capacity payments. This is a matter of concern for the European Commission which has investigated how Member States implement such mechanisms (see European Commission 2016). By and large, the EC concludes its report saying that a better market design "should over time reduce the need for capacity mechanisms to guarantee security of supply". Member states are yet to be convinced.

6 Appendix

6.1 Derivation of the basic model

6.1.1 Consumers

Total and marginal surplus The gross surplus obtained by electricity buyers from consumption q is $\widetilde{GS}(q, \varepsilon)$, where ε denotes a date or an event (e.g. temperature). We assume that $\widetilde{GS}(q, \varepsilon)$ is increasing in both ε and q . Also, we assume it is a concave function and $\frac{\partial^2 \widetilde{GS}}{\partial q \partial \varepsilon} > 0$, so that both total surplus and marginal surplus are increasing in the randomness parameter ε .

Because consumers lack flexibility in the short run, and also for political and social reasons, the energy retail price p^r is fixed ex ante. It is not state contingent. Then, when in state ε , consumers choose to buy the quantity that solves

$$\max_q \widetilde{GS}(q, \varepsilon) - p^r q$$

Let $\tilde{q}(p^r, \varepsilon)$ denote the solution to the first order condition

$$\frac{\partial \widetilde{GS}(q, \varepsilon)}{\partial q} = p^r. \quad (25)$$

Given a retail price fixed exogenously and constant, we can simplify the notation:

²²For an analysis in terms of Cournot competition, see Léautier (2018), chapter 9.

$$q(\varepsilon) \stackrel{def}{=} \tilde{q}(p^r, \varepsilon)$$

and the inverse function will be denoted $\varepsilon(q)$.

By concavity, we have that

$$\begin{aligned} & \frac{\partial^2 \widetilde{GS}}{\partial q^2} < 0 \\ & \left| \begin{array}{cc} \frac{\partial^2 \widetilde{GS}}{\partial q^2} & \frac{\partial^2 \widetilde{GS}}{\partial q \partial \varepsilon} \\ \frac{\partial^2 \widetilde{GS}}{\partial \varepsilon \partial q} & \frac{\partial^2 \widetilde{GS}}{\partial \varepsilon^2} \end{array} \right| > 0 \end{aligned} \quad (26)$$

Consequently,

$$\varepsilon'(q) \stackrel{def}{=} \frac{d\varepsilon}{dq} = -\frac{\frac{\partial^2 \widetilde{GS}}{\partial q^2}}{\frac{\partial^2 \widetilde{GS}}{\partial q \partial \varepsilon}} > 0 \quad (27)$$

Now, let

$$\widehat{S}(q) \stackrel{def}{=} \widetilde{GS}(q, \varepsilon(q)) - p^r q$$

stand for the net consumer's surplus expressed in terms of the random consumption.

Differentiation gives

$$\widehat{S}'(q) = \left(\frac{\partial \widetilde{GS}}{\partial q} - p^r \right) + \frac{\partial \widetilde{GS}}{\partial \varepsilon} \varepsilon'(q) > 0$$

It is positive because the term into brackets is zero by (25), and the second term is positive. Differentiating a second time and using (27), we obtain

$$\widehat{S}''(q) = \varepsilon'(q) \left[\frac{\partial^2 \widetilde{GS}}{\partial q \partial \varepsilon} - \frac{\partial^2 \widetilde{GS}}{\partial \varepsilon^2} \frac{\partial^2 \widetilde{GS}}{\partial q^2} \right] + \frac{\partial \widetilde{GS}}{\partial \varepsilon} \varepsilon''(q)$$

The bracket on the right-hand side is negative by (26). Therefore, $\varepsilon''(q) \leq 0$ is sufficient, but not necessary, for $\widehat{S}''(q) < 0$ to hold.

Unconstrained and constrained consumption Except if both p^r and K are very high, it may occur that $\tilde{q}(p^r, \varepsilon) > K$ where K is the capacity installed by producers. Let $\varepsilon(p^r, K) \stackrel{def}{=} \arg[\tilde{q}(p^r, \varepsilon) = K]$. Then actual consumption will be

$$q^r(p^r, \varepsilon) = \begin{cases} \tilde{q}(p^r, \varepsilon) & \text{if } \varepsilon \leq \varepsilon(p^r, K) \\ K & \text{otherwise} \end{cases}$$

Let $\widetilde{F}(\varepsilon)$ be the distribution function of the random variable ε . Using $\widehat{S}(q)$ and $F(q) = \widetilde{F}(\varepsilon(q))$ we can analyze the effects of variations in ε as if they were exogenous variations in q .

As long as $q \leq K$, consumers have the net surplus $\widehat{S}(q)$. For $q > K$ it is $\widehat{S}(K)$. Moreover, consumers face a disutility due to the lack of electricity supplied K compared

to the quantity they expected to receive q . Let $L(q-K)$ be the loss incurred when $q > K$. It is an increasing and convex function. If there exists a system of (partial) compensation paid by producers for this loss, then the net surplus of consumers is

$$\widehat{S}(q) \text{ if } q \leq K \\ \widehat{S}(K) - (1 - \alpha) L(q - K) \text{ otherwise}$$

where $(1 - \alpha)$ is the part of the loss not compensated to consumers.

6.1.2 Producers, retailers and social planner

Retailers buy from producers and sell to consumers. Omitting the commercialization cost, their profit is $(p^r - p)q$ if $q \leq K$ and $(p^r - p)K$ otherwise where p is the wholesale price. Retailers are pure price-takers.

Producers invest capacity K at cost $C(K)$, produce at unit cost c (assumed constant) and sell at price p . Their ex post profit is then $(p - c)q$ if $q \leq K$ and $(p - c)K - \alpha L(q - K)$ otherwise, where α is the loss fraction compensated to consumers.

When vertically integrated, the ex post profit of the supply side is then $(p^r - c)q$ if $q \leq K$ and $(p^r - c)K - \alpha L(q - K)$ otherwise.

Finally, the ex post objective function of the social planner is

$$S(q) \stackrel{def}{=} \widetilde{GS}(q, \tilde{\varepsilon}(c, q)) - cq \text{ if } q \leq K \\ S(K) - L(q - K) \text{ otherwise}$$

6.2 Competitive energy markets

Each region is made of competitive energy producers. Let $m_i = p_i^r - c_i$ stand for the unit retail margin in region i . As for the welfare losses from energy shortage, producers internalize a part α of the missing expected social value.

6.2.1 Autarky

Without any possibility to exchange capacity or energy, producers in region i would solve a problem isomorphic to the problem of the regulator in the autarky framework if *i*) $m_i = s_i$, that is if each kWh is billed at the consumer's willingness-to-pay: $p_i^r = u_i$ and *ii*) $\alpha = 1$. In other words, regulators impose a large penalty, or suppliers are obliged to repair all the damages due to energy cuts so that producers fully internalize welfare losses. Then the market solution is the same as (10).

6.2.2 Interconnected regions

We now turn to the case where energy can be traded among electricity suppliers of the two regions. To keep things comparable with the former section, we assume that producers in each region must be able to satisfy at least low demand with the mix of their own capacity and energy imports or exports. As usual, the problem is solved backwards.

Energy market Ex post, capacity is fixed in both regions. Given K_i , the producers in i must decide how much to provide to their customers. Let e_i denote the quantity they intend to import from (if positive) or sell to (if negative) producers in region $-i$.

- When demand is high in i , producers solve

$$\max_{e_i} m_i(K_i + e_i) - \alpha_i L_i(q_i^H - K_i - e_i) - p e_i \quad \text{s.t.} \quad -e_i \leq K_i$$

where p is the unit price on the energy market.

Let $\mu_{iH} \geq 0$ denote the multiplier associated to the capacity constraint. The first order condition for $i = 1, 2$ is

$$m_i + \alpha_i L_i'(q_i^H - K_i - e_i) - p + \mu_{iH} = 0 \quad (28)$$

and the complementary slackness condition is

$$K_i + e_i \geq 0, \mu_{iH} \geq 0, (K_i + e_i) \mu_{iH} = 0 \quad (29)$$

First observe that from (28) $p \geq m_i$: the energy price cannot be smaller than the margin from retail. If it were smaller, firms in region i would like to be pure suppliers, buying energy from the other region to sell in their home market and earn the unit trade margin $m_i - p$. Competition would then push the energy price up to at least the value m_i .

Now, consider how firms in region i decide on being energy importers or exporters:

- – if $p > m_i + \alpha_i L_i'(q_i^H)$, then $\mu_{iH} > 0$ and by (29) we obtain $-e_i = K_i$. In words, the energy market is so profitable and the local benefit (margin + consumers' losses) so low that firms in i prefer to sell all the energy they produce to the other region.
- if $p < m_i + \alpha_i L_i'(q_i^H)$, then $K_i + e_i > 0$ and by (29) we obtain $\mu_{iH} = 0$. The energy to be bought or sold is given by

$$m_i + \alpha_i L_i'(q_i^H - K_i - e_i) - p = 0 \quad (30)$$

Differentiating this condition, we obtain e_i as a decreasing function of p : $\frac{de_i}{dp} = -\frac{1}{\alpha_i L_i''} < 0$.

Taking all this together, we can draw the energy demand of type 1 firms in Figure 4. For $p > m_1 + \alpha_1 L_1'(q_1^H - K_1)$ firms in region 1 want to sell energy ($e_1 < 0$) and they want to be buyers if p is smaller than this threshold ($e_1 > 0$). We also see that a smaller K_1 corresponds to a shift rightwards of the whole curve. Indeed with a low capacity, firms in 1 are more inclined at being buyers of energy. Conversely, equipped with $K_1 \geq q_1^H$ they only want to be sellers.

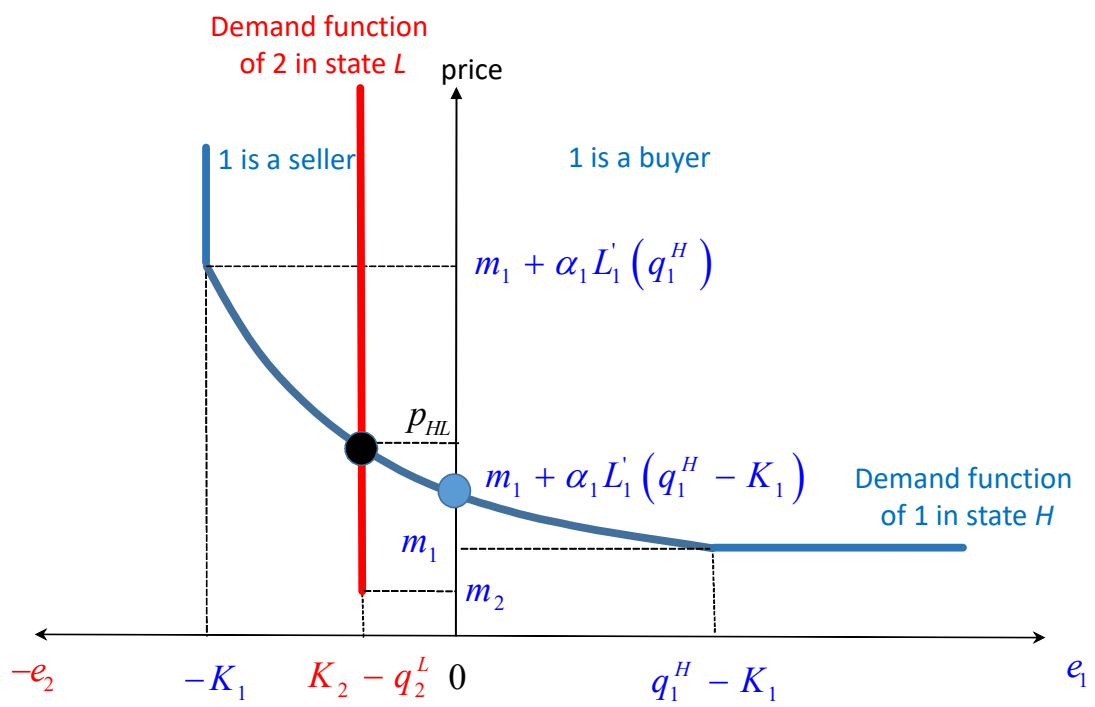


Figure 4: Demands for energy and equilibrium in state HL

- When demand is low in region i , producers solve

$$\max_{e_i} m_i (K_i + e_i) - \alpha_i L_i (q_i^L - K_i - e_i) - p e_i \quad \text{s.t. } q_i^L \leq K_i + e_i$$

Note that the constraint is different from the one in the high demand case. The first order condition is

$$m_i + \alpha_i L_i' (q_i^L - K_i - e_i) - p + \mu_{iL} = 0$$

and the complementary slackness condition is

$$K_i + e_i - q_i^L \geq 0, \mu_{iL} \geq 0, (K_i + e_i - q_i^L) \mu_{iL} = 0$$

Again, we see that there is no solution for $p < m_i$. Moreover

- ▶ if $p > m_i + \alpha_i L_i'(0) = m_i$, then $\mu_{iL} > 0$ and we obtain $-e_i = K_i - q_i^L$. In words, firms in i want to import or export the exact quantity that will satisfy demand q_i^L given the capacity: to export if $K_i > q_i^L$ and to import if $K_i < q_i^L$.²³
- ▶ if $p = m_i$, the only solution to $\alpha_i L_i' (q_i^L - K_i - e_i) + \mu_{iL} = 0$ is $\mu_{iH} = 0$ and $q_i^L - K_i - e_i = 0$.

Consequently, when demand is low, the demand function of firms in region i is a vertical line above m_i with value $e_i = q_i^L - K_i$ on the x -axis. This is portrayed in Figure 4 for firms in region 2, reading from right to left, i.e. $-e_2 = K_2 - q_2^L$. In the graph, firms in region 2 intend to import since $K_2 < q_2^L$.

- The market equilibrium condition is

$$e_1 + e_2 = 0 \tag{31}$$

The curves e_i and $-e_j$ can intersect in different ways depending on the parameters and on the capacity chosen at the initial stage. To simplify our analysis, we assume that the equilibrium solution is interior when at least one demand is high.

We have four different possibilities, depending on the states of the world:

- ▶ in state HH , using (30),

$$p_{HH} = m_1 + \alpha_1 L_1' (q_1^H - K_1 - e_1) = m_2 + \alpha_2 L_2' (q_2^H - K_2 + e_1) \tag{32}$$

in the case where $e_2 = -e_1 \neq 0$.

These equations determine the equilibrium demand and supply of energy e_{iHH} , $i = 1, 2$, and the price p_{HH} as functions of the capacity installed by the two groups of producers. It is easy to check that $\frac{\partial e_{iHH}}{\partial K_i} = -\frac{L_i''}{L_i'' + L_j''} < 0$ and $\frac{\partial e_{iHH}}{\partial K_j} = \frac{L_j''}{L_i'' + L_j''} > 0$ since if firms i have invested more in capacity, they will demand (alt. sell) less (alt. more) energy, and the opposite stands for the firms in region j .

²³Recall that this is the consequence of the constraint we set from the very beginning. Without it, firms would like to sell more abroad and incur the cost of lost load even when demand is low.

- in state HL , since $e_{2HL} = q_2^L - K_2 = -e_{1HL}$,

$$p_{HL} = m_1 + \alpha_1 L_1' (q_1^H + q_2^L - K_1 - K_2)$$

This is the case represented in Figure 4.

- symmetrically in state LH , $e_{1LH} = q_1^L - K_1 = -e_{2LH}$

$$p_{LH} = m_2 + \alpha_2 L_2' (q_1^L + q_2^H - K_1 - K_2)$$

- finally in state LL , there is no trade since $e_1 + e_2 = q_1^L + q_2^L - K_1 - K_2 < 0$.

Capacity stage Anticipating the energy equilibrium, at the ex ante stage firms i solve

$$\begin{aligned} \max_{K_i} \quad & \rho^{HH} (m_i (K_i + e_{iHH}) - \alpha_i L_i (q_i^H - K_i - e_{iHH}) - p_{HH} e_{iHH}) \\ & + \rho^{HL} (m_i (K_i + e_{iHL}) - \alpha_i L_i (q_i^H - K_i - e_{iHL}) - p_{HL} e_{iHL}) \\ & + \rho^{LH} (m_i (K_i + e_{iLH}) - \alpha_i L_i (q_i^L - K_i - e_{iLH}) - p_{LH} e_{iLH}) \\ & + \rho^{LL} m_i q_i^L - C_i (K_i) \end{aligned} \quad (33)$$

In the perfect competition framework, producers do not internalize any effect of their decisions on the future energy equilibrium. In particular, we have that $\frac{\partial p}{\partial K_i} \equiv 0$ in all states of nature. Given the equilibrium defined in (32) and the similar conditions in the other states of nature, the first-order condition writes

$$\begin{aligned} & \rho^{HH} (m_i + \alpha_i L_i' (q_i^H - K_i - e_{iHH})) + \rho^{HL} (m_i + \alpha_i L_i' (q_i^H - K_i - e_{iHL})) \\ & + \rho^{LH} (m_i + \alpha_i L_i' (q_i^L - K_i - e_{iLH})) = C_i' (K_i) \quad i = 1, 2 \end{aligned}$$

Since $K_i + e_i$ is the energy supplied by firm i to its consumers, and since energy values are equal in the two markets given (32) and the equivalent conditions in the other states of nature, this pair of equalities is the same as (16) and (17) as long as i) firms have no market power, i.e. $m_i = s_i$, and ii) they fully internalize welfare losses, i.e. $\alpha_i = 1$.

6.3 The trading of composite capacity rights

When firms in region i can rely on energy from the capacity credits bought, they solve

$$\begin{aligned} \max_{K_i, k_i} \quad & -C_i (K_i) + \rho_i (s_i (K_i + k_i) - \alpha_i L_i (q_i^H - K_i - k_i)) + (1 - \rho_i) s_i q_i^L - p_k k_i + p_{K_i} K_i \\ \text{s.t.} \quad & K_i + k_i \geq \widehat{K}_i \quad (\lambda_i) \end{aligned}$$

where k_i stands for the purchases (if positive) or sales (if negative) of withdrawal rights and p_k for the credits unit price. As for the capacity payment, it is p_{K_i} indexed by i

since in each region regulators can have different objectives and constraints. The value of p_{K_i} also depends on the target \widehat{K}_i . In particular, $p_{K_i} = 0$ whenever $\widehat{K}_i \leq K_i^\alpha$.

The first order conditions (assuming $K_i > 0$) are

$$\begin{aligned} K_i &: -C'_i(K_i) + \rho_i \left(s_i + \alpha_i L'_i(q_i^H - K_i - k_i) \right) + p_{K_i} + \lambda_i = 0 \\ k_i &: \rho_i \left(s_i + \alpha_i L'_i(q_i^H - K_i - k_i) \right) - p_k + \lambda_i = 0 \end{aligned}$$

For large values of p_{K_i} and/or small values of the target \widehat{K}_i , firms invest and trade beyond the requirement ($K_i + k_i > \widehat{K}_i$), so that $\lambda_i = 0$. The solution K_i, k_i would be given by²⁴

$$C'_i(K_i) - p_{K_i} = p_k = \rho_i \left(s_i + \alpha_i L'_i(q_i^H - K_i - k_i) \right)$$

Like in section 4.2, we rather assume that p_{K_i} is low enough for having $\lambda_i > 0$. Then, by complementary slackness conditions, the solution is $K_i + k_i = \widehat{K}_i$, with

$$C'_i \left(\widehat{K}_i - k_i \right) - p_{K_i} = p_k \quad (34)$$

This is the inverse demand for certificates. It is a decreasing relationship between quantities k_i and price p_k

$$\frac{dk_i}{dp_k} = -\frac{1}{C''_i \left(\widehat{K}_i - k_i \right)} < 0$$

This demand function is shifted downwards when the capacity payment increases. Given the demand in each region, at equilibrium, $k_1^* + k_2^* = 0$, or

$$C'_1 \left(\widehat{K}_1 - k_1^* \right) - p_{K1} = p_k^* = C'_2 \left(\widehat{K}_2 - k_2^* \right) - p_{K2}$$

This is shown in Figure 5 where demand from region 1 (resp. 2) reads from left to right (resp. from right to left). In the left part of the graph, firms in region 1 intend to sell and firms in region 2 intend to buy. In the right part, it is the opposite. In the case considered here, firms in region 2 (resp. 1) invest more (resp. less) than required by the authority: $K_1^* = \widehat{K}_1 - k_1^* < \widehat{K}_1$ and $K_2^* = \widehat{K}_2 - k_2^* > \widehat{K}_2$.

²⁴This is obviously the case when $\widehat{K}_i \leq K_i^\alpha$.

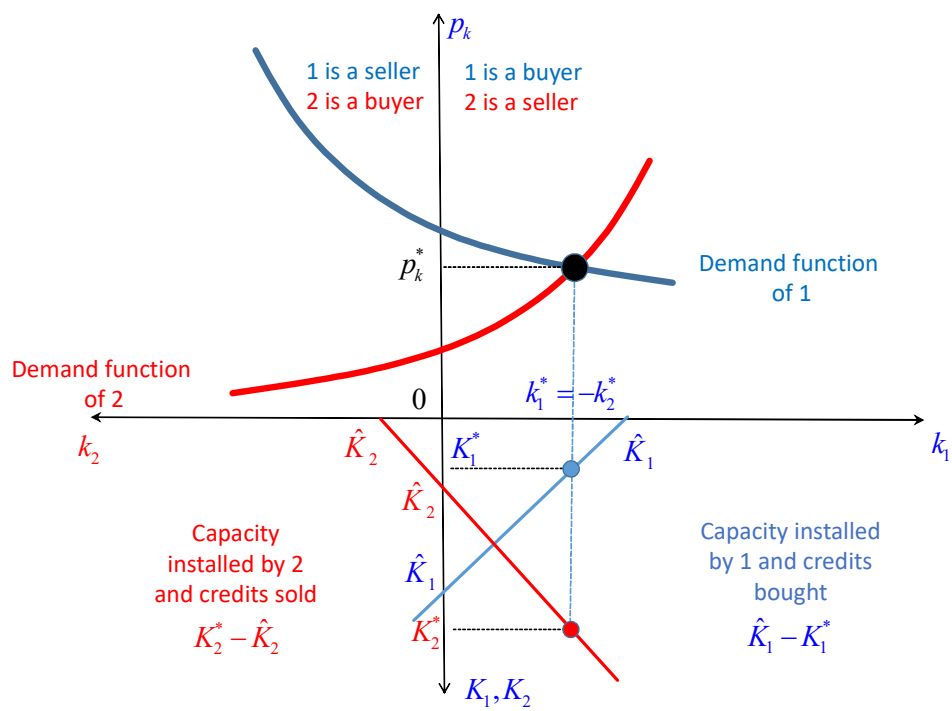


Figure 5: Equilibrium in the market for capacity credits

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