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Abstract

The creation of electricity markets has raised the fundamental question as to whether markets provide the right incentives for the provision of the reserves needed to maintain system reliability, or whether some form of regulation is needed. In some states in the US, electricity retailers have been made responsible for providing such reserves by contracting capacity in excess of their forecasted peak demand. The so-called Installed Capacity Markets (ICAP) provide one means for contracting reserves, and are the subject of this paper. In particular, for given productive and transmission capacities, we identify firms' opportunity costs of committing resources in the capacity market, and hence, the costs of inducing full capacity commitment. Regulatory issues such as the optimal choice of the reserve margin and the capacity deficiency rate (which serves as a price-cap) are analyzed. From a welfare view-point, we also compare the desirability of providing reserves either through capacity markets or through the demand side (i.e. power curtailments).

Keywords: Electricity markets, capacity obligations, resource adequacy, PJM.

JEL No: C73, L13, E32.

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1 Introduction

Unlike virtually any other commodity, electricity is extremely costly -if not impossible- to store. Furthermore, electricity markets differ from virtually all other markets in that they require instantaneous and continuous balancing of its demand and supply resources. A failure to equate demand and supply endangers the stability of the network and may result in disruptions of consumption that not only affect the market participants that caused the imbalance, but the system as a whole. The challenge imposed by the need to maintain continuous electrical equilibrium is further exacerbated by the fact that almost all end-consumers do not have the metering technology to observe nor the economic incentives to respond to real-time prices. This implies that little or none of the supply/demand balancing can be done through the demand side.[1] The stability of the system at all times thus requires the adequacy of capacity resources to meet the peak of demand plus a reserve margin, capable of withstanding unanticipated loss of generation and transmission capacity.[2]

Under the traditional regulatory schemes, the electric utilities were responsible for providing adequate capacity of supply and for ensuring the security of the system through the efficient use of the available capacity resources. As these regulatory schemes have been replaced by market-based mechanisms, both functions have been unbundled. Whereas the System Operator has the responsibility of ensuring system security, the provision of adequate capacity resources is relied on market forces alone, under the expectation that prices would provide the right signals for the efficient investments.

Recent experience and the poor performance of some of these restructured electricity markets, have led several regulatory authorities to rely on alternative regulatory designs to bring forth the incentives to provide adequate capacity resources (see Hobbs and Kahal 2001, and Klein, 2001 for a detailed analysis of the different mechanisms that have been implemented in practice).

In broad terms, capacity payment systems can be classified as either price or quantity based. The basic principle of price-based systems is that capacity availability is rewarded either through lump-sum payments (as in Argentina and Spain) or via an uplift to energy

[1]See Borenstein and Holland (2003) for an analysis of Real Time Pricing and the potential effects it could have on the performance of electricity markets.

[2]The blackout that took place in the US East coast in August 2003 shows that the value of the losses caused by a system imbalance may be substantially large (See Joskow 2003b and The Economist 2003).

payments that depends on the probability of outages (as in the former UK pool). These solutions have been highly criticized, because they create poor incentives to alleviate the capacity problem and may even worsen it. For instance,[3] generators may try to increase capacity payments by making fewer capacity resources available thereby increasing, rather than decreasing, the probability of shortage.

Quantity-based systems are the focus of the policy debate in the US. To date, two quantity-based methods have been adopted: operating reserve markets, and installed or available capacity markets. The main purpose underlying the introduction of the latter has been to ensure that adequate capacity is committed on a daily or seasonal basis to meet system load and reserve requirements. The Load Serving Entities (LSEs), e.g. distributors that sell electricity to end-user consumers, must satisfy their capacity obligations, which equal their expected peak monthly loads plus a reserve margin. They can accomplish this, either by internal or bilateral transactions, or through the capacity market in which generators sell a recall right that empowers the System Operator to recall them in the event of shortages. The equilibrium price in the capacity market should be reflective of the overall capacity in the system in relation to LSEs' obligations.

Capacity markets of this kind have been introduced in several systems, such as New England or New York; the Californian Independent System Operator is currently considering the possibility of creating an available capacity market (CA-ISO, 2002). However, there is an ongoing-debate about the desirability of introducing capacity markets as a means to achieve adequate system reliability. On the one hand, the critics of ICAP markets argue that they are an unnecessary relict of regulation (Hobbs, Inon, Stoft, 2001), as markets provide the right incentives for agents to assure the desired reliability level. On the other hand, the advocates of ICAP markets affirm that they serve to mitigate the free-riding of some customers to benefit from system reliability paid by others (Jaffe and Felder, 1996).

This momentum has motivated our analysis. In particular, our paper provides the first analytical model that analyzes the performance and design of electricity capacity markets. Our work has two main objectives. The first one is to identify the link between the capacity and energy markets when generators also have the option (subject to a transmission constraint) to sell electricity in an adjacent, more profitable market. With this purpose, we characterize the generators' optimal strategies - which involve the three-fold decision

[3] See Newbery, 1992, Wolak and Patrick, 1997.

of how many resources to commit in the capacity market, and how much energy to offer in the national and foreign energy markets - and investigate how these decisions are affected by the degree of competition. Our second main objective is to analyze the design of capacity markets and determine, within our stylized set-up, the optimal capacity requirement and capacity deficiency rate that should be imposed in these markets. Related to this, we also asses whether it would be preferable to resort to power curtailment as a source of reserves, or to increase the energy price-cap in order to avoid the migration of capacity resources to more profitable markets. Throughout the paper, we will focus on short-term issues, i.e. reliability problems, and leave the question of whether capacity markets offer adequate incentives for investments in new generation capacity for further research.[4]

Our model has been inspired by the design of the Installed Capacity Market in Pennsylvania-New Jersey- Maryland (PJM),[5] whose main features are described in Section 2. The remaining part of the paper is organized as follows. Section 3 describes the model. Sections 4 and 5 characterize the firms' problem under the extreme cases of monopoly and perfect competition, and Section 6 provides the solution to the regulator's problem. Section 7 concludes, and most proofs are relegated to the Appendix, which also extends the analysis to the case of tradable transmission rights.

2 The Pennsylvania- New Jersey- Maryland System

Pennsylvania- New Jersey- Maryland was initially established in 1927 as a centrally dispatched control area pooling the generation and transmission facilities of several utilities. Today, PJM is the largest centrally dispatched electric power system in North America. PJM initiated a voluntary bid-based energy market (including day-ahead and hour ahead markets) on April 1, 1997, coincident with the implementation of its Open Access Transmission Tariff. PJM Interconnection became the first operational Independent System Operator (ISO) in the United States on January 1, 1998. Its objectives are to ensure the reliability of the transmission network and to facilitate a competitive wholesale market. The PJM System Operator has implemented a system of locational marginal prices, calculating prices for over 2.000 nodes every five minutes and providing real-time price of

[4]See Joskow and Tirole (2004) and Stoft (2000) for an analysis and discussion of this topic.

[5]Although the design of capacity markets differs from system to system, it should be noted that most of our analysis should be helpful in also clarifying the performance of the capacity markets implemented elsewhere.

transmission. PJM also operates the regulation market, providing ancillary services, and the fixed transmission right monthly auction market.

2.1 The Capacity Credit Market

From the inception of the pool, the PJM has relied upon capacity obligations to ensure reliability. Prior to the restructuring, Load Serving Entities (LSEs), e.g. distributors to final customers, had capacity obligations on an annual basis. Capacity resources consist in MW of generation capacity (net of planned outages) which are committed to serve specific PJM loads. Capacity obligations have played a critical role in maintaining reliability and contributing to realize a competitive energy market. In fact, following the Reliability Assurance Agreement (RAA), capacity obligation ensures that adequate capacity resources will be planned and made available to help solving emergencies. On April 1, 2002, the PJM-West Region joined PJM and on this occasion, a new reliability assurance agreement was developed (PJM, 2003).

After the liberalization of the energy sector, capacity obligations are met through market mechanisms. On October 1, 1998, PJM initiated monthly and multi-monthly capacity markets; daily capacity markets were introduced in 1999. Bilateral transactions on capacity are also allowed. Collectively, these arrangements are known as the Installed Capacity (ICAP) market.

The *supply* in the capacity market is provided by generators in the PJM control area that meet specific technical and security criteria. A very interesting feature is that capacity resources can be de-listed, or exported, from the PJM control area and vice-versa, imported from neighboring systems. In fact generators sell a *recall right* to the energy produced by their units and sold to entities outside PJM. This right enables PJM to recall energy exports from capacity resources when needed. When capacity resources are recalled, the supplier is paid the prevailing PJM energy market price.

The *demand* in the capacity market is fixed, as indirectly determined by the System Operator through the choice of LSEs' capacity obligations, following complex rules set forth in the RAA.[6] The current rules require LSEs to own or purchase capacity resources greater than or equal to their expected peak-load plus a reserve margin, which is set on the basis of an annual reliability analysis performed by PJM and the standards established by

[6]The PJM forecasted capacity requirements (net of planned outages) were 56.623 MW in January 2002 and 57.328 MW in June 2002 (Klein, 2001).

the North American and the Mid-Atlantic Electric Reliability Councils. More precisely, the overall capacity obligation associated with load in the PJM-East region is defined for an annual period,[7] while the capacity obligation associated with load in the PJM-West region is defined daily.

An LSE can satisfy its obligation by reliance on self-supply, acquisition in bilateral markets, or acquisition of capacity credits from the daily, monthly and multi-monthly Capacity Credit Markets. All generation capacities contributing to the pool installed reserve are paid the market clearing price of capacity. Participation in any PJM capacity market is voluntary, the mandatory aspects being expired on May 31, 2001.

If an LSE is short of capacity and does not submit a buy bid in the capacity market, a mandatory bid covering its obligation will be submitted. This mandatory bid is equal to the Capacity Deficiency Rate (CDR), which is currently equal to $174.73 per MW-day (PJM, 2003).[8] This charge is intended to cover temporary imbalances and thus it is expected to apply to only a small fraction of total load, as "the intent of ICAP charge was to discourage participants from leaning on the capacity of the others" (FERC, 2001). Therefore, if an LSE is short of capacity, it pays a penalty that will equal the daily amount of capacity deficiency times the number of days in the season. More drastically, if an LSE does not comply its obligation when the system itself is short of capacity, the deficiency charge is the double of the CDR. It must be noted that, as FERC (2001) points out, "the level of the penalty charge effectively caps the capacity price, since customers will not pay more for capacity than the penalty charge". Conversely, if an LSE complies with its capacity obligation, it is also entitled to earn a revenue accrued from the deficiency charges (if any).[9]

[7]See FERC Docket EL01-63-003 amending the RAA -paragraph 7.4b, in response to a PJM filing. FERC affirms that committing capacity on a seasonal rather than a daily basis insulates capacity obligations from the volatility of energy spot prices and gives the LSEs the incentive to arrange for a long-term and assured supply of capacity.

[8]The Capacity Deficiency Rate is designed to reflect the annual fixed cost of a combustion turbine in PJM and the associated transmission investment, including a return on investment, depreciation and fixed operation and maintenance expenses. It is also adjusted for the forced outage rate and thus may change annually.

[9]See FERC, Docket No. ER01-1440-000, in force as from June 2001, amending the Schedule 11 D of the RAA. Previous to this amendment, only LSE and generators owners having excess capacity were entitled to share deficiency revenues in proportion to their excess capacity.

2.2 The Performance of the Capacity Credit Market

Transactions in the capacity credit market have mainly been concluded by entrants, and the volume of trade has been increasing steadily. The PJM Market Monitoring Unit (henceforth, MMU) reports that the functioning of these markets has been competitive in 1999 and 2002 (see PJM 2000 and 2003). Some price spikes have been observed in 2000 and,[10] for the first time since the introduction of the capacity markets in December 1998, the pool was deficient for some days in June, July and August 2000 - owners of capacity increased their exports for periods during which external prices exceeded the PJM price and therefore de-listed their resources from the PJM. In particular, on June 1, the total demand for daily capacity credits exceeded the sum of capacity net of planned outages and the pool was deficient by 334 MW. On June 2, the daily price was \$174/MW-day, and on June 3, it rose to \$177 (close to the binding CDR in 2000) and it remained at that level for the rest of the month. After investigation, the MMU reported that the opportunity costs of selling into the PJM market (defined as "the additional revenue foregone from not selling into an external energy and/or capacity market") appear to explain the level of supply available to the daily capacity credit markets, de-listing and imports by capacity owners and thus the shape of the supply function and the ultimate market price. The high levels of mandatory bids, that is the capacity deficiency charge, contributed to the observed level of market prices. After reviewing key measures of market structure and performance (net revenue, price-cost mark-up index, concentration and prices), the MMU concluded that the energy market in 2000 was "reasonably competitive", with no systematic exercise of market power, although "the evidence is not dispositive" (PJM, 2001a). In particular, the highest prices in the PJM real-time spot market occurred in December (\$802/MWh), while the next higher prices occurred during an early heat spell in May.

The only year that has raised serious concerns is 2001. Price spikes of about \$177 were observed on January 1 and 2, and for one day, January 3, the system was deficient and the daily capacity price rose to \$354. Prices then declined to \$177 where they remained until late March when prices began to decline further, reaching \$0 in early April (PJM, 2001b). It is worth noting that PJM locational marginal prices have shown price spikes

[10] The volume-weighted average price for the entire year was \$53.16/MW-day in the monthly and multi-monthly capacity credit markets, and \$69.39/MW-day in daily capacity credit markets; the volume weighted average of all the capacity credit markets for 2000 was \$7.69 higher than in 1999, reaching \$60.55/MW-day (PJM, 2001a).

during a single period of hot weather in the week of August 6.

In a report to the Public Utilities Commission, the MMU clearly affirms that the price spikes observed during 2001 have been caused by a seller exercising an effective monopoly position in the capacity market by taking advantage of the method used to allocate deficiency revenues. During 2001, these revenues were allocated to holders of uncommitted capacity resources (this rule has now been changed, see previous Section). According to the MMU, this methodology has encouraged one holder of unsold capacity to either withhold that capacity from the market or offer it for sale at a price equal to the CDR. This unilateral market power conduct, in turn, caused participants short of capacity either to be deficient (and pay the CDR, which then would be distributed to the withholder of the unsold capacity resources) or to purchase capacity at the CDR.

Delisted capacity in January reduced the net supply of capacity by a small amount (37MW). The MMU has calculated that for the period from January through the beginning of April, the price in the daily capacity market exceeded the additional value of selling energy to the Cinergy hub or N.Y. West Zone A for the next day rather than selling energy to the PJM West hub and capacity to the PJM capacity credit market. This shows that the alternative value of energy was lower in the neighboring system than in PJM capacity market, so that delisting became economically inefficient. This further supports the conclusion that market power during 2001 was due to the monopolistic behavior of one capacity holder.

To conclude, the MMU asserts that "market power remains a serious concern given the extreme inelasticity of demand and high levels of concentration in capacity credit markets. Market power is structurally endemic to PJM capacity markets and any redesign of capacity markets must address market power" (PJM, 2003).

3 The Model

Consider an electricity industry where total generation capacity is given by K. Marginal costs of production are normalized to zero for production levels below capacity, whereas production above capacity is impossible.

There are two energy markets: the national and the foreign market. Suppliers can either sell or buy energy in either of them. For simplicity, the foreign energy market is assumed to be perfectly competitive, and the prevailing foreign price is denoted f. In the national energy market, suppliers compete to sell their production. Demand D is determined each period as a random variable independent of the market price, i.e. it is perfectly price inelastic. In particular, $D \in [0,1]$ is distributed according to some known distribution function $G(D)$, with density $g(D)$. Prices in the national energy market are capped at P.

Exports and imports between the national and foreign energy markets are limited by the amount of total transmission capacity, β, which is assumed to be symmetrically divided among suppliers through non-tradable transmission rights. Transmission losses are equal to zero, so that transmission entails no costs.

Furthermore, there exists a capacity market where suppliers have the option to make their capacity resources available if needed to cover the peaks of demand. When a supplier commits some of his capacity resources, he entitles the regulator to 'recall' them when there is excess demand in the energy market.[11] The supplier is not obliged to make the committed resources available otherwise. The demand side in the capacity market is composed of the Load Serving Entities, which are obliged to contract enough capacity resources so as to cover a fraction of their expected demand plus a regulated reserve margin. Hence, total demand in the capacity market- fixed and perfectly inelastic- is indirectly determined by the capacity requirement chosen by the regulator. For simplicity, we will just refer to it as total demand in the capacity market, and will denote it by Θ. The inelasticity of demand implies that prices need to be capped at some level, C, which is equivalent to the capacity deficiency rate imposed on those LSE who are capacity deficient.

Throughout the paper, we will make the following assumptions, in order to restrict the set of parameter values to reasonable ones.

$A1$: The portion of total capacity that cannot be exported (referred to as *'non-exportable capacity'*) is positive but not enough to satisfy peak demand in the national energy market, i.e. $0 < K - \beta < 1$.

$A2$: If the transmission line were fully utilized to import energy from the foreign market, this would be enough to satisfy peak demand in the national energy market, i.e. $K + \beta \geq 1$.

$A3$: The foreign energy price is higher than the national energy price-cap, i.e. $f > P$.

[11] If recalled, the generator also has the option to default on its commitment and pay a fine. We assume that such a fine is large enough so that it does not pay the generator to default.

$A4$: Every unit consumed reports a gross utility equal to $v > f > P$.

$A5$: Demand in the capacity market does not exceed peak demand, i.e. $\Theta \leq 1$.

The first two assumptions set upper and lower bounds for aggregate productive capacity K, in relation to transmission capacity β. First, if the transmission line were fully utilized to export energy abroad, the remaining productive capacity (referred to as non-exportable capacity) would not be enough to satisfy the peak of demand. Otherwise, there would be no need to have a capacity market.[12] And second, if the transmission line were fully used to import energy from abroad, there would be enough capacity to satisfy the peak of demand. Otherwise, the regulator could not be sure that all demand would be satisfied even if he offered to pay a very large capacity price for the committed resources.

The third assumption states that the foreign energy price is higher than the national energy price-cap. Given our previous assumptions, having a capacity market would unnecessary otherwise.[13] The fourth assumption states that the gross utility of every unit consumed, v,[14] exceeds the foreign price f- this is reasonable if one expects that consumers are more or less homogeneous across the borders.

Last, we have assumed that demand in the capacity market does not exceed peak demand, given that there is no need (and it is costly) to demand capacity resources that will never be recalled.[15]

The timing of the game proceeds as follows. Prior to the realization of demand in the energy market, suppliers compete in the capacity market and receive their payments for the amounts committed. Once demand in the energy market is realized and observed by all suppliers, suppliers compete in the national and foreign energy markets. If there is excess demand in the energy market, the regulator recalls the suppliers' committed

[12] See for instance FERC (2001, p.3), "The Commission should impose a reserve capacity requirement on electricity customers only if, without the requirement, the market would fail to elicit either sufficient reserve capacity, or an appropriate mix of sufficient reserve capacity and voluntary curtailment, to meet demand and avoid involuntary curtailments".

[13] We will also consider the case in which the regulator sets $P = f$ in order to induce full capacity commitment. This will imply that the capacity-market is not needed, but will also result in higher expected energy prices. See the Regulator's problem in Section 6 for more on this.

[14] Alternatively, we will also interpret v as consumers' reservation value, e.g. their costs of resorting to alternative energy sources, or equivalently, the minimum price that consumers will accept to be curtailed.

[15] This comes from the fact that there are no random outages in the productive capacity.

capacity resources, which are paid at the prevailing national energy market price. Last, suppliers receive their payments for the energy sold.

We now proceed to characterize the Subgame Perfect Equilibrium of the game by backward induction. First, we solve for the energy market competition game. Second, we move to the capacity market competition game to characterize firms' capacity commitments and the equilibrium price, for given Θ and C. Last, we analyze the regulator's problem, who has to choose how many resources to demand in the capacity-market, Θ, and has to set the capacity price-cap, C. Given these optimal choices, he has to decide whether to introduce a capacity market or to resort to power curtailment as a source of reserves.

4 Monopoly

Consider first the monopoly case. Since the monopolist faces no competition, he is able to extract all the rents by bidding at the price-cap in both the energy and capacity markets. He has nevertheless to decide how much energy to offer, and how many capacity resources to commit. Given that the foreign energy market is more profitable, i.e. $f > P$, the first decision is trivial: the monopolist will fully utilize the transmission link, and he will therefore only offer to produce his non-exportable capacity, $K - \beta$.

In the capacity market, the monopolist faces a trade-off when deciding how many capacity resources to commit: committing a large amount of capacity resources leads to large capacity market payments, but this comes at the cost of reducing the monopolist's energy market profits, given that in the event of recall, he will have to sell his energy at the national energy price-cap, P, rather than at the foreign market price, f.

The monopolist solves this trade-off by choosing the capacity commitment, θ, that maximizes his total profits $C\theta + \pi_m(\theta)$, i.e. the sum of capacity payments plus energy market profits. The latter are given by,

$$\begin{aligned}\pi_m(\theta) &= \int_0^{K-\beta} [PD + f\beta]\, dG(D) + \int_{K-\beta}^{\overline{\theta}} [PD + f[K-D]]\, dG(D) \\ &\quad + \int_{\overline{\theta}}^{1} \left[P\overline{\theta} + f\left[K - \overline{\theta}\right]\right] dG(D)\end{aligned} \tag{1}$$

where $\overline{\theta} = \max\{K-\beta, \theta\}$.

The first term in equation (1) represents the profit that the monopolist earns when demand does not exceed his non-exportable capacity: the monopolist satisfies all internal demand at a price P and fully exploits his transmission line to export energy at a price f. The second element in equation (1) gives the profits made by the monopolist when demand is larger than his non-exportable capacity but still lower than his capacity commitment. In this case, the monopolist will sell his non-exportable capacity at P, and the difference between his commitment and his production will be recalled and paid at the prevailing price. Therefore, the monopolist will only be able to export what he can produce with its remaining productive capacity, so that the transmission capacity will no longer be binding. As represented by the third element of the equation, when demand exceeds the monopolist's capacity commitment, the monopolist will sell up to his commitment in the national market, and will export his remaining capacity. Last, note if the monopolist cannot fulfill his commitment with his own productive capacity, i.e. $\theta > K$, he has to import the difference from abroad. The monopolist thus makes profits PK but looses the price differential $[f - P]$ times the excess of his commitment over his productive capacity.[16]

Let us now asses the effect on the monopolist's profits of a marginal increase in his capacity commitment. First, for values $\theta \in [0, K - \beta]$, increases in θ have a positive marginal effect on the monopolist's profits, given that increases in θ within this interval have no effect on his energy market profits (the regulator cannot recall more than what the monopolist is already producing) but lead to larger capacity market revenues. This implies that the monopolist finds it always profitable to commit at least his non-exportable capacity resources.

For values $\theta \in [K - \beta, \Theta]$, a marginal increase in θ increases the monopolist's capacity revenues by C but reduces his energy market profits by $[f - P][1 - G(\theta)]$, where $[f - P]$ gives the price differential that the monopolist gives up when he marginally increases θ, and $[1 - G(\theta)]$ gives the marginal increase in the probability of being recalled. Therefore, the monopolist's marginal opportunity cost from committing θ is given by $C - [f - P][1 - G(\theta)]$. Clearly, the marginal benefit C is independent of θ, whereas the marginal cost $[f - P][1 - G(\theta)]$ decreases with θ. All this implies that the opportunity cost of listing capacity increases with θ, or equivalently, that the monopolist's profit function $\pi_m(\theta) + C\theta$ is convex in θ for $\theta \in [K - \beta, \Theta]$. Accordingly, we have corner solutions, with the monopolist either committing $K - \beta$ or Θ capacity resources, depending on the

[16]Note that if there is excess transmission capacity and capacity deficit in the spot market, the system operator could export energy from abroad and pay it a price f; we exclude this possibility and relax it in the appendix.

value of C.

The following Lemma identifies the critical value of C that determines the monopolist's optimal commitment:

Lemma 1 *There exists $C_m = C_m(\Theta, K-\beta, f-P)$ such that the monopolist's optimal decision is to offer to commit at least Θ capacity resources if and only if $C \geq C_m$ (market clearing equilibrium) and to only offer to commit its non-exportable capacity, $K-\beta$, otherwise (capacity-deficit equilibrium).*

The critical value C_m represents the opportunity cost of committing Θ rather than $(K-\beta)$ resources, i.e. the loss in the energy market revenues relative to the gain in capacity payments:

$$C_m = \frac{\pi_m(K-\beta) - \pi_m(\Theta)}{\Theta - (K-\beta)}$$

Using the profit expression (1) evaluated at $K-\beta$ and Θ, gives

$$C_m = [f-P]\left[\int_{K-\beta}^{\Theta} \frac{D-(K-\beta)}{\Theta-(K-\beta)} dG(D) + [1-G(\Theta)]\right] \tag{2}$$

The level of demand in the capacity market Θ will affect the value of these opportunity costs, through three effects. First, for a given demand realization below Θ, increases in Θ raise capacity market gains and leave energy market losses unaffected; hence, within this range, the ratio of the losses over the gains goes down. Second, for a given demand realization above Θ, increases in Θ raise capacity market gains and energy market losses in the same proportion, so that the ratio remains unaffected. And third, increases in Θ shift down (up) the probability given to demand realizations above (below) Θ. Since the ratio of the losses over the gains is higher when demand lies above Θ than when it lies below Θ the opportunity cost of committing Θ rather than $(K-\beta)$ goes down as Θ increases.

Changes in the value non-exportable capacity $(K-\beta)$ only influence the ratio of the gains over the losses for demand values below Θ. Over this range, increases in $(K-\beta)$ reduce more the gains in terms of capacity payments than the energy market losses. Hence C_m decreases with the value of non-exportable capacity.

Last, when a supplier chooses to commit capacity resources, it gives up the price differential between the foreign and national energy markets. Hence, the opportunity cost is increasing in $(f-P)$ and indeed, if there is no spread between the internal energy market price and the external one, or the system is isolate, so export are impossible, the opportunity costs of committing the full capacity requirement falls to zero.

5 Perfect Competition

Consider now the case of $n > 1$ price-taking firms. Since both the energy and capacity markets are perfectly competitive, the energy equilibrium price will be equal to (zero) marginal costs, and the capacity equilibrium price will be given by the opportunity cost of committing capacity resources.

Given that profits in the internal energy market will be zero, firms' revenues can only come from two sources: exports, which are paid at f, and capacity payments. The value of exports is constrained by the amount of committed resources that are recalled to satisfy internal demand. In the event of no recall, firms fully exploit the transmission line, thus making profits βf. If there is recall, which may occur whenever demand exceeds $K - \beta$, total exports are given by the value of total productive capacity net of those resources committed to satisfy the recall requirement.

Aggregate industry profits from selling energy are similar to those of the monopolist, except from the fact that the competitive firms make no profits in the internal energy market:

$$\pi_c(\theta) = \int_0^{K-\beta} \beta f dG(D) + \int_{K-\beta}^{\overline{\theta}} [K - D] f dG(D) + \int_{\overline{\theta}}^1 [K - \theta] f dG(D) \qquad (3)$$

where $\overline{\theta} = \max\{K - \beta, \theta\}$.

In the capacity market, firms bid at their opportunity costs. Committing any amount equal or less than $K - \beta$ has no opportunity cost, since those resources will in any case be offered internally. Committing more than that, and in particular, committing Θ, implies a loss in export revenues, and thus a strictly positive opportunity cost. The profit function in the capacity market is thus independent of θ for $\theta \in [0, K - \beta]$, while for higher values of the capacity commitment, $\theta \in [K - \beta, \Theta]$, firms earn (3) plus the capacity market revenues; over this latter range, capacity market profits are convex in θ.

Similarly to the monopoly case, if the price cap is larger than the opportunity cost of committing the total amount of resources demanded, the capacity market will clear at that cost. Otherwise, firms will optimally choose to only commit their non-exportable capacity.

The following Lemma identifies the critical value of the opportunity cost C_c that determines the competitive industry's optimal commitment:

Lemma 2 *There exists $C_c = C_c(\Theta, K-\beta, f)$ such that the competitive industry's optimal decision is to offer to commit at least Θ capacity resources if $C \geq C_c$ (market-clearing equilibrium) and to only offer to commit the non-exportable capacity, $K-\beta$, otherwise (capacity-deficit equilibrium).*

Again, the critical value C_c represents the opportunity cost of committing Θ rather than $(K-\beta)$ resources, i.e. the loss in market revenues relative to the gain in capacity payments. Using the profit expression (3) evaluated at $K-\beta$ and Θ, gives

$$C_c = f\left[\int_{K-\beta}^{\Theta} \frac{D-(K-\beta)}{\Theta-(K-\beta)} dG(D) + [1-G(\Theta)]\right] \tag{4}$$

A similar interpretation as the one given in the monopoly case can be applied here to show that increases in Θ and $(K-\beta)$ both have a negative impact on C_c, and that if the neighboring energy market is as profitable as the internal one (i.e. $f=0$), or trade is impossible, supplying capacity comes at no cost.

In a perfectly competitive environment, the capacity market clears at C_c that represents the opportunity cost of listing capacity.[17] Hence prices above this value signal market power. It is straightforward to see that:

$$C_c = \frac{f}{f-P} C_m > C_m \tag{5}$$

As long as the energy market abroad is more profitable that the national one (i.e. under the assumption $(f-P) > 0$), the costs of inducing market clearing in the capacity market are larger in the competitive case than in the monopoly case. Clearly, the opportunity costs are larger in the former: giving up the external price f to earn a price equal to marginal costs if recalled is more costly than giving it up in exchange of earning P in the event of recall. Said differently, capacity requirements transfer funds to generators via a

[17]Interestingly, the MMU (2001) affirms that "for a daily capacity market, a conservative approximation of the comparative price can be calculated by multiplying the differential between the external forward energy price and the internal forward energy price by the 16 on peak hours, as that is a conservative estimate of the value of the opportunity foregone by selling capacity in the PJM capacity markets". It is specified that the 16 on peak hours are used because the forward price contracts in the energy price comparison are price over 16 hours.

capacity markets, and so, when these markets exists, they reduce the size and profitability of price spikes (Stoft, 2002).

6 The Regulator's Problem

In this section we solve the regulator's problem, under the assumption that he has complete information concerning the value of firms' opportunity costs. The regulator's decision is two-fold. First, he has to decide whether to introduce a capacity market or not. And second, in the case in which the regulator has introduced a capacity market, he has to choose how many resources to demand in the capacity-market, Θ, and has to set the capacity price-cap, C. It is assumed that the regulator aims at maximizing total surplus, defined as the sum of consumer surplus (from $A4$, every unit consumed reports a gross utility equal to v, with $v > f > P$) plus a share of suppliers' profits, weighted by the parameter $\alpha \in [0, 1]$.

The following Lemmas identify the conditions under which introducing a capacity market is preferred over power curtailments as a source of reserves. These Lemmas also characterize the optimal reserve requirement and price-caps, both under monopoly as under perfect competition.

Lemma 3 *Under Monopoly,*

(i) There exists $\underline{v}_m = \underline{v}_m(\alpha, f, P, K - \beta)$ *such that the regulator finds it optimal to introduce a capacity market if and only if* $v > \underline{v}_m$.

(ii) If $v > \underline{v}_m$*, the regulator's optimal choice of the capacity requirement equals peak demand,* $\Theta^*_m = 1$*, and his optimal choice of capacity price-cap equals the minimum value at the which the capacity market clears,* $C^*_m = C_m(1, K - \beta, f - P)$.

The previous Lemma shows that v needs to be large enough in order to make it optimal to introduce a capacity market. Otherwise, the costs of inducing the monopolist to commit as many resources so as to cover the reserve margin would be too large with respect to the gains of avoiding shortages.

The parameter v can also be interpreted as the price that consumers would be willing to receive to be subject to power curtailment: this creates reserves coming out from the amount of load that consumers have agreed to reduce when called upon by the system. Given that a unit of electricity not requested by a customer has the same effect as an additional unit of electricity being generated (FERC, 2001), only for large values of v it is optimal to create a capacity market rather than to resort to voluntary curtailment as a source of reserves.

Interestingly enough, the larger the price-cap, the lower will be the critical value of v above which having a capacity market is optimal. The reason is that a higher P leads to lower opportunity costs of committing capacity resources, and hence to lower capacity payments. In other words, having a capacity market in a 'price-spike world' is cheap, and it may even turn out to be unnecessary when the price cap P is so large that it exceeds the foreign price f (see Lemma 5 below). Similarly, the smaller the transmission capacity and the lower the prevailing foreign energy price, the lower are the monopolist's opportunity costs, and hence, the lower is the critical v needed to make the capacity market optimal.

If the regulator has decided to introduce a capacity market, his optimal decision would be to set the capacity requirement at a level that guarantees no shortages, i.e. to set it equal to peak demand.[18] This does not only avoid the losses from power curtailment, but it also reduces total capacity payments to the monopolist.

Similar results can be derived for the competitive scenario.

Lemma 4 *Under Perfect Competition,*

(i) There exists $\underline{v}_c = \underline{v}_c(\alpha, f, K - \beta)$ *such that the regulator finds it optimal to introduce a capacity market if and only if* $v > \underline{v}_c$.

(ii) For all $v > \underline{v}_c$*, the regulator's optimal choice of the capacity requirement equals peak demand,* $\Theta_c^* = 1$*, and his optimal choice of capacity price-cap equals the minimum value at the which the capacity market clears,* $C_c^* = C_c(1, K - \beta, f)$.

The comparison of $\underline{v}_m$ and $\underline{v}_c$ shows that having a capacity market may be optimal under monopoly and suboptimal under perfect competition, i.e. $\underline{v}_c \geq \underline{v}_m$. This is so since the capacity payments needed to induce market clearing under perfect competition exceed those under monopoly, since by equation (5), $C_c^* > C_m^*$. If firms' profits are fully taken into account by the regulator ($\alpha = 1$), the difference between the two threshold values $\underline{v}_m$ and $\underline{v}_c$ vanishes.[19]

[18] Recall that we are assuming away the probability of capacity or transmission outages. Introducing it would be straightforward, and would imply that the optimal reserve margin is equal to peak demand plus the expected outage rate.

[19] See Corollary 1 and its proof in the appendix.

Nevertheless, even if capacity payments are larger under perfect competition, the social cost of monopoly resulting from larger energy prices is not offset. This implies that it is preferable to have a stringent pricing policy and an active competition policy in the energy market (i.e. low P and a larger number of firms) even it implies increasing capacity payments up to the point at which having a capacity market may no longer be optimal.[20]

To conclude this section, we have analyzed the optimality of resorting to an alternative source of reserves. Namely, 'importing the foreign price spike', i.e. raising the national energy market price cap P up to f, in order to avoid exports, induce imports and thereby eliminate the need to introduce a capacity market - the opportunity costs of committing more than the non-exportable capacity would equal zero.[21]

Lemma 5 *In the monopoly case, independently of* v, *it is not optimal to import the foreign price spike, i.e. to set* $P = f$, *in order to avoid the need of a capacity market.*

The reason for the above result is that the foreign market price affects the capacity payment only partially, whereas importing it by setting $P = f$ implies that it will be paid at all times. Thus, creating reserves through a capacity market is preferable to avoiding exports through increased market prices.

7 Conclusions

We have developed a simple model aimed at capturing some of the main features of electricity capacity markets. We have used it to characterize firms' optimal behavior and equilibrium outcomes, as well as to address some of the regulatory issues involved in the design of these markets.

First, we have identified the factors that determine the opportunity costs of committing capacity resources. When a generator commits a fraction of its capacity resources, he faces a trade-off: committing more capacity resources implies larger revenues through the capacity market, but it also implies that, in the event of recall, such a generator will have to give up the revenue from alternative sales, i.e. the price differential between the foreign and national energy prices. Therefore, the more profitable the foreign energy market relative

[20] See Corollary 2 and its proof in the appendix.

[21] This alternative is inconsequential under perfect competition, given that the price-cap is never binding.

to the national one, the higher the opportunity costs of committing capacity resources, and the larger the capacity payments required to induce full commitment. This observation is consistent with the evidence that, during the summer of 2000, the PJM capacity markets experienced price spikes at the same time as energy prices were fairly low. Furthermore, our model shows that the opportunity costs of committing capacity are also a function of the probability of recall, the amount of the resources required to ensure system reliability, the transmission capacity, and the intensity of price competition in the energy market. In this respect, decreasing spot market prices through more intense competition (or lower price caps) may come at the cost of increasing capacity payments. Our model also suggests that capacity markets may clear at zero prices (as in PJM during April 2001) if there is no spread between national and foreign energy prices, if non-exportable resources are enough to satisfy all capacity obligations, or if the system has excess capacity so that the probability of recall falls to zero.

We have also analyzed firms' optimal behavior in the capacity market, and thus equilibrium outcomes. Depending on the value of the capacity price-cap and the reserve requirement set by the regulator, two types of equilibria may arise. First, the *capacity-deficit equilibrium*, in which generators only commit the fraction of their capacities that has no opportunity costs. And second, the *market-clearing equilibrium*, in which generators jointly offer to commit enough capacity resources so as to cover the capacity requirement (and in fact eliminate the probability of shortages). Whether the first or the second type of equilibria arise mainly depends on the capacity price-cap: if it is too low, generators' opportunity costs would not be covered, and a capacity deficit would arise, as it has been the case, for instance, in PJM during the summer of 2000. Thus, even in the presence of capacity markets, the system would be short of resources, leaving the reliability problem unsolved.

Last, we have assessed the desirability of introducing capacity markets, and characterized the optimal reserve requirement and price-cap in these markets. We have found that a capacity market does not necessarily maximize social welfare. The costs of ensuring full reliability may exceed the gains from avoiding power curtailments, precisely when the generators' opportunity costs from committing capacity resources are extremely large. Conditionally on having a capacity market, the model shows that it is always optimal to fully avoid the risk of shortage by setting the capacity requirement equal to peak demand (plus expected outages) and to set the capacity price cap equal to firms' opportunity costs of providing full capacity commitment. Any departure from this level, either undermines the functioning of these markets, or leaves scope for the exercise of market power (as in the PJM capacity market during the first quarter of 2001).

Noteworthy, we have shown that the optimality of introducing capacity markets is unaffected by the existence of tradable transmission rights. This is true even though the additional rents achieved by trading these rights contribute to reduce firms' opportunity costs of committing capacity resources, and thus capacity payments. Nevertheless, as the optimal capacity price-cap is affected by the existence of transmission rights, the optimal design of capacity markets depends on the amount of tradable transmission rights as well as on the functioning of the transmission market and its microstructure (see Joskow and Tirole 2000 and 2003).

Last, we would like to stress that an important role of capacity markets is to provide incentives for the construction of new generation. Whereas it is sometimes argued that energy markets provide those incentives, the advocates of capacity markets argue that, if capacity decisions are let to the market alone, the capacity needed for reserve purposes will be built only after periods of intense price volatility, price spikes and shortages. An analysis of this issue is out of the scope of the paper.

Appendix A: Proofs

Monopoly

Proof of Lemma 1:

For a given capacity commitment θ, the monopolist's total profits are equal to $C\theta + \pi_m(\theta)$, where $\pi_m(\theta)$ is given in (1). Taking the first and second derivatives of the monopolist's total profit with respect to θ,

$$\frac{\partial\left[\pi_m(\theta)+C\theta\right]}{\partial\theta} = \begin{cases} C & \text{if } \quad \theta \leq K-\beta \\ C-[f-P]\left[1-G(\theta)\right] & \text{if } \quad \theta > K-\beta \end{cases}$$

$$\frac{\partial^2\left[\pi_m(\theta)+C\theta\right]}{\partial\theta^2} = \begin{cases} 0 & \text{if } \quad \theta \leq K-\beta \\ [f-P]\,g(\theta) & \text{if } \quad \theta > K-\beta \end{cases}$$

Given that $\frac{\partial[\pi_m(\theta)+C\theta]}{\partial\theta} > 0$ for $\theta \leq K-\beta$, then offering to commit any amount lower than $K-\beta$ is dominated by offering to commit $K-\beta$. Given $\frac{\partial^2[\pi_m(\theta)+C\theta]}{\partial\theta^2} > 0$ for $\theta > K-\beta$, the monopolist will optimally offer to commit either $K-\beta$ or at least Θ capacity resources. He will choose to commit Θ if and only if:

$$C\Theta + \pi_m(\Theta) \geq C\left[K-\beta\right] + \pi_m(K-\beta)$$

Rearranging terms,

$$C \geq C_m = \frac{\pi\left(K-\beta\right)-\pi\left(\Theta\right)}{\Theta-\left[K-\beta\right]}$$

And using (1), simple algebra leads to,

$$C_m = [f-P]\left[\int_{K-\beta}^{\Theta}\left[\frac{D-[K-\beta]}{\Theta-[K-\beta]}\right]dG(D) + [1-G(\Theta)]\right]$$

Last, some comparative statics:

$$\begin{aligned}
\frac{\partial C_m}{\partial\Theta} &= -\frac{f-P}{\left[\Theta-[K-\beta]\right]^2}\int_{K-\beta}^{\Theta}\left[D-[K-\beta]\right]dG(D) < 0 \\
\frac{\partial C_m}{\partial\left(K-\beta\right)} &= -\frac{f-P}{\left[\Theta-[K-\beta]\right]^2}\int_{K-\beta}^{\Theta}\left[\Theta-D\right]dG(D) < 0 \\
\frac{\partial C_m}{\partial\left(f-P\right)} &= \int_{K-\beta}^{\Theta}\left[\frac{D-[K-\beta]}{\Theta-[K-\beta]}\right]dG(D) + [1-G(\Theta)] > 0
\end{aligned}$$

Perfect Competition

Proof of Lemma 2:

The first part of the proof is similar to that of the monopolist (the single difference is that all the terms multiplied by P in the monopolist's profit expressions, disappear under perfect competition). Hence, we move directly to the characterization of the opportunity costs of committing Θ rather than $K-\beta$. The competitive industry will choose to commit Θ if and only if

$$c\Theta + \pi_c(\Theta) \geq c[K-\beta] + \pi_c(K-\beta)$$

where c is the equilibrium price in the capacity market. Rearranging terms,

$$c \geq C_c = \frac{\pi_c(K-\beta) - \pi_c(\Theta)}{\Theta - [K-\beta]}$$

Given perfect competition, the equilibrium price will equal C_c as long as this price is below the price-cap C. Using the profit expression (3) and solving for C_c,

$$C_c = f\left[\int_{K-\beta}^{\Theta}\left[\frac{D-[K-\beta]}{\Theta-[K-\beta]}\right]dG(D) + [1-G(\Theta)]\right]$$

Last, given that $C_c = \frac{f}{f-P}C_m$ the comparative statics of C_c with respect to Θ and $K-\beta$, and f are the same as in the monopoly case.

The Regulator's Problem

Proofs of Lemmas 3 and 4:

The regulator has to decide whether to create or not a capacity market; in the case in which he has decided to create a capacity market, he has to set a capacity requirement and a capacity market-price cap. We will analyze these two decisions by backward induction first for the monopoly case, and second for the case of perfect competition. Throughout, its is assumed that the regulator aims at maximizing the sum of consumer surplus (every unit consumed reports an utility equal to $v > f > P$) plus an $\alpha \in [0,1]$ share of producers' surplus.

Monopoly:

Assume that the regulator has created a capacity market. Clearly, we can ignore two cases: first, $\Theta \leq K-\beta$ - paying for capacity resources that the monopolist would in any case offer in the energy market would increase costs without decreasing shortages;

and second $C < C_m$ - by Lemma 1, the monopolist would just offer its non-exportable capacity, that he would use to produce internally even without a capacity market. Hence, we focus on parameter values $\Theta \in (K-\beta, 1]$ and $C \geq C_m$. Total welfare is given by

$$\begin{aligned} W_m^C(\Theta, C) &= [v-P]\left[\int_0^{\Theta} DdG(D) + \Theta[1-G(\Theta)]\right] - C\Theta \\ &+\alpha\left[\int_0^{K-\beta}[DP+\beta f]\,dG(D) + \int_{K-\beta}^{\Theta}[DP+[K-D]f]\,dG(D)\right] \\ &+\alpha\left[\int_{\Theta}^{1}[P\Theta+[K-\Theta]f]\,dG(D) + C\Theta\right] \end{aligned}$$

which can be re-written as,

$$\begin{aligned} W_m^C(\Theta, C) &= [v-[1-\alpha]P]\left[\int_0^{\Theta} DdG(D) + \Theta[1-G(\Theta)]\right] \\ &+\alpha f\left[\beta G(K-\beta) + \int_{K-\beta}^{\Theta}[K-D]\,dG(D) + [K-\Theta][1-G(\Theta)]\right] \\ &-[1-\alpha]\,C\Theta \end{aligned}$$

Clearly, $W_m^C(\Theta, C)$ is decreasing in C. Hence, the regulator will set C equal to the minimum level that induces the monopolist to commit the desired Θ, i.e. $C = C_m$.

The first derivative of $W_m^C(\Theta, C_m)$ with respect to Θ is given by:

$$\begin{aligned} \frac{\partial W_m^C(\Theta, C_m)}{\partial \Theta} &= [v-f][1-G(\Theta)] \\ &+[1-\alpha][f-P]\frac{[K-\beta]}{\Theta-[K-\beta]}\int_{K-\beta}^{\Theta}\left[\frac{D-[K-\beta]}{\Theta-[K-\beta]}\right]dG(D) > 0 \end{aligned}$$

It is therefore optimal to set the reserve requirement equal to peak-demand, $\Theta_m^* = 1$. The resulting level of welfare is given by

$$\begin{aligned} W_m^C(1, C_m) &= [v-[1-\alpha]P]\left[\int_0^1 DdG(D)\right] \\ &+\alpha f\left[\beta G(K-\beta) + \int_{K-\beta}^{1}[K-D]\,dG(D)\right] \\ &-[1-\alpha][f-P]\int_{K-\beta}^{1}\frac{D-[K-\beta]}{1-[K-\beta]}dG(D) \end{aligned} \tag{6}$$

Let us now analyze the regulator's decision of whether or not to introduce a capacity market. In the absence of a capacity market, only the non-exportable capacity $K-\beta$ is offered. Total welfare is given by

$$\begin{aligned} W_m^{NC} &= [v-P]\left[\int_0^{K-\beta} DdG(D) + [K-\beta][1-G(K-\beta)]\right] \\ &+\alpha\left[\int_0^{K-\beta}[DP+\beta f]\,dG(D) + [P[K-\beta]+\beta f][1-G(K-\beta)]\right] \end{aligned}$$

which can also be rewritten as

$$W_m^{NC} = [v - [1-\alpha] P] \left[\int_0^{K-\beta} DdG(D) + [K-\beta][1 - G(K-\beta)] \right] + \alpha\beta f \qquad (7)$$

Thus, for the regulator to optimally choose to implement a capacity market, we require that (6) exceeds (7). Taking the difference between the two gives

$$W_m^C(1, C_m) - W_m^{NC} = \left[[v-P] - [f-P] \frac{1-\alpha[K-\beta]}{1-[K-\beta]} \right] \int_{K-\beta}^{1} [D - [K-\beta]] \, dG(D)$$

which depends on the sign of the first element on the RHS Straightforward calculations show that this element is positive if and only if

$$v > \underline{v}_m(\alpha, f, P, K-\beta) = [f-P] \frac{1-\alpha[K-\beta]}{1-[K-\beta]} + P$$

The sign of the derivatives of $\underline{v}_m$ with respect to α and f is straightforward. Moreover:

$$\begin{aligned} \frac{\partial \underline{v}_m}{\partial P} &= -\frac{[1-\alpha][K-\beta]}{1-[K-\beta]} < 0 \\ \frac{\partial \underline{v}_m}{\partial [K-\beta]} &= \frac{[f-P][1-\alpha]}{[1-(K-\beta)]^2} > 0 \end{aligned}$$

Perfect Competition:

We use a similar reasoning as above; recall that the price in the energy market is now equal to (zero) marginal production costs.

Assume that the regulator has created a capacity market and focus on parameter values $\Theta \in (K-\beta, 1]$ and $C \geq C_c$. Total welfare is given by

$$\begin{aligned} W_c^C(\Theta, C) &= v \left[\int_0^{\Theta} DdG(D) + \Theta[1 - G(\Theta)] \right] \\ &\quad + \alpha f \left[\beta G(K-\beta) + \int_{K-\beta}^{\Theta} [K-D] \, dG(D) + [K-\Theta][1-G(\Theta)] \right] \\ &\quad - [1-\alpha] C\Theta \end{aligned}$$

Clearly, $W_c^C(\Theta, C)$ is decreasing in C. Hence, the regulator will set C equal to the minimum level that induces the monopolist to commit the desired Θ, i.e. $C = C_c$.

The first derivative of $W_c^C(\Theta, C_c)$ with respect to Θ is given by:

$$\frac{\partial W_c^C(\Theta, C_c)}{\partial \Theta} = [v - f][1 - G(\Theta)] > 0$$

It is therefore optimal to set the reserve requirement equal to peak-demand, $\Theta_c^* = 1$. The resulting level of welfare is given by

$$\begin{aligned} W_c^C(1, C_c) &= v\int_0^1 DdG(D) \\ &+\alpha f\left[\beta G(K-\beta)+\int_{K-\beta}^1 [K-D]\,dG(D)\right] \\ &-[1-\alpha]\,f\int_{K-\beta}^1 \frac{D-[K-\beta]}{1-[K-\beta]}dG(D) \end{aligned} \tag{8}$$

Total welfare in the absence of a capacity market is given by

$$W_c^{NC} = v\left[\int_0^{K-\beta} DdG(D)+[K-\beta]\,[1-G(K-\beta)]\right]+\alpha\beta f \tag{9}$$

Thus, for the regulator to optimally choose to introduce a capacity market, we require that (8) exceeds (9). Taking the difference between the two gives

$$W_c^C(1, C_c) - W_c^{NC} = \left[v - f\frac{1-\alpha\,[K-\beta]}{1-[K-\beta]}\right]\left[\int_{K-\beta}^1 [D-[K-\beta]]\,dG(D)\right]$$

which depends on the sign of the first element on the RHS Straightforward calculations show that this element is positive if and only if

$$v > \underline{v}_c(\alpha, f, K-\beta) = f\frac{1-\alpha\,[K-\beta]}{1-[K-\beta]}$$

The sign of the derivatives of $\underline{v}_c$ with respect to α, f and $(K-\beta)$ is straightforward and does not contradict comparative statics results found for the monopoly case.

Corollary 1 $\underline{v}_c \geq \underline{v}_m$.

Proof of Corollary 1:

The comparison with the critical v value in the monopoly case yields,

$$\underline{v}_c - \underline{v}_m = P\,[1-\alpha]\,\frac{K-\beta}{1-[K-\beta]} \geq 0$$

Corollary 2 *Given the regulator's optimal decisions, the total level of welfare is always larger under perfect competition as compared to monopoly, regardless of the level of optimal capacity payments, and regardless of whether having a capacity market is optimal or not.*

Proof of Corollary 2:

When having a capacity market is optimal in both the monopoly and the perfect competition cases, i.e. $v \geq \underline{v}_c$:

$$W_m^C - W_c^C = -[1-\alpha] P \left[\int_0^{K-\beta} DdG(D) + \frac{[K-\beta]}{1-[K-\beta]} \int_{K-\beta}^1 [1-D] dG(D) \right] < 0$$

which is clearly negative.

When having a capacity market is optimal under monopoly but not under perfect competition, i.e. $\underline{v}_m \leq v < \underline{v}_c$, we have $W_m^C - W_c^{NC} \leq W_m^C - W_c^C < 0$ given that $W_c^{NC} > W_c^C$.

When having a capacity market is not optimal neither under monopoly nor under perfect competition, i.e. $v < \underline{v}_m$, we have $W_c^{NC} > W_m^{NC}$ since consumer surplus is trivially larger under perfect competition.

Proof of Lemma 5:

If the regulator sets $P = f$ he would guarantee that the monopolist does not export his energy, since he is indifferent between selling it in the foreign or in the national market. There thus would not need for a capacity market. The resulting level of welfare surplus is equal to

$$W_m^{NC}\big|_{P=f} = [v-f] \int_0^1 DdG(D) + \alpha K f \tag{10}$$

Assume $v > \underline{v}_m$. For the regulator to optimally choose to implement a capacity market rather than to import the foreign price spike, we require that (6) exceeds (10). Taking the difference,

$$\begin{aligned} W_m^C\big|_{P<f} - W_m^{NC}\big|_{P=f} &= [1-\alpha][f-P] \left[\int_0^{K-\beta} DdG(D) + \int_{K-\beta}^1 (1-D) \frac{K-\beta}{1-[K-\beta]} dG(D) \right] \\ &\quad + \alpha f \int_0^{K-\beta} [D - [K-\beta]] dG(D) \end{aligned}$$

Which is always positive and independent of v. That is, it is preferable to have a capacity market, rather than to import the price spike, no matter how small f is.

Assume $v \leq \underline{v}_m$. Thus, for the regulator to optimally choose not to implement a capacity market and set $P < f$ rather than to import the foreign price spike, we require that (7) exceeds (10). Since $W_m^C(1, C_m(1))\big|_{P<f} > W_m^{NC}\big|_{P=f}$ for every value of v, and $W_m^C(1, C_m(1)) < W_m^{NC}\big|_{P<f}$ for $v \leq \underline{v}_m$, it follows that ,

$$W_m^{NC}\big|_{P<f} > W_m^{NC}\big|_{P=f}$$

That is, it is preferable not to have a capacity market, rather than importing the price spike, no matter how small f is.

Appendix B: Tradable Transmission Rights

In this appendix, we relax the assumption that transmission rights are non-tradable.

Monopoly

Assume that the monopolist owns the transmission rights and that he has the choice of renting the line to the regulator (or the System Operator). The monopolist will set an access charge equal to the regulator's maximum willingness to pay, $v - f$. We have to assume $P < v - f < f$, since otherwise the regulator would prefer to import energy rather than to buy it from the monopolist, and the monopolist would prefer to rent the transmission line rather than to produce energy himself.

The monopolist chooses his capacity commitment $\theta \in [0, \Theta]$ to maximize expected profits $\pi_m^t(\theta) + C\theta$, where

$$\pi_m^t(\theta) = \begin{cases} \pi_m(\theta) & \text{if} \quad \theta \leq K - \beta \\ \pi_m(\theta) + [v - f] \int_\theta^1 [D - \theta] \, dG(D) & \text{if} \quad \theta > K - \beta \end{cases}$$

Taking the first and second derivatives of the monopolist's total profit with respect to θ,

$$\frac{\partial \left[\pi_m^t(\theta) + C\theta\right]}{\partial \theta} = \begin{cases} C & \text{if} \quad \theta \leq K - \beta \\ C - [f - P][1 - G(\theta)] - [v - f][1 - G(\theta)] & \text{if} \quad \theta > K - \beta \end{cases}$$

$$\frac{\partial^2 \left[\pi_m^t(\theta) + C\theta\right]}{\partial \theta^2} = \begin{cases} 0 & \text{if} \quad \theta \leq K - \beta \\ [v - f] \, g(\theta) & \text{if} \quad \theta > K - \beta \end{cases}$$

With tradable transmission rights, the monopolist's opportunity costs decrease with respect to the base case (by the amount $[v - f][1 - G(\theta)]$, that is the access rate times the probability of recall). Hence, capacity payments guaranteeing the market clearing equilibrium will also decrease, given the rental revenues, as the following Lemma shows.

Lemma 6 *There exists $C_m^t = C^t(\Theta, v - f, K - \beta) \leq C_m$ such that the monopolist's optimal commitment decision when he can rent the transmission line is to commit all his resources if $C \geq C_m^t$ and to only commit his non-exportable capacity otherwise*, where

$$C_m^t = C_m - \frac{v - f}{\Theta - [K - \beta]} \int_\Theta^1 [D - \Theta] \, dG(D)$$

Proof of Lemma 6:

The monopolist's optimal commitment decision is given by Θ if the following condition is satisfied, and $K-\beta$ otherwise.

$$C\Theta+\pi_m^t\left(\Theta\right)\geq C\left[K-\beta\right]+\pi_m^t\left(K-\beta\right)$$

Rearranging terms,

$$\begin{aligned}
C &\geq \frac{\pi_m^t\left(K-\beta\right)-\pi_m^t\left(\Theta\right)}{\Theta-\left[K-\beta\right]}\\
&= \frac{\pi_m\left(K-\beta\right)-\pi_m\left(\Theta\right)}{\Theta-\left[K-\beta\right]}-\frac{v-f}{\Theta-\left[K-\beta\right]}\int_\Theta^1\left[D-\Theta\right]dG\left(D\right)\\
&= C_m-\frac{v-f}{\Theta-\left[K-\beta\right]}\int_\Theta^1\left[D-\Theta\right]dG\left(D\right)=C_m^t\leq C_m
\end{aligned}$$

as $D-\Theta\geq 0$ for $D\in\left[\Theta,1\right]$.

All the comparative statics are ambiguous, as to the effects that we know on C_m, some counterbalancing forces due to the term $-\frac{v-f}{\Theta-[K-\beta]}\int_\Theta^1\left[D-\Theta\right]dG\left(D\right)$ appear.

We now analyze the regulator's problem. With respect to the monopoly case, the welfare function is augmented by the term $\alpha\left[v-f\right]\int_\Theta^1\left[D-\Theta\right]dG\left(D\right)$ which decreases with Θ. Hence, when one increases the capacity requirement, the monopolist makes lower rents since the regulator will rent the line less often. Nevertheless, this negative effect of the capacity requirement is weighted by α and therefore counterbalanced by the positive effect of Θ on the other terms of the welfare function. We conclude that:

Lemma 7 *The regulator's optimal decisions are unaffected by the possibility of renting the line.*

Proof of Lemma: 7:

When the monopolist has committed θ capacity resources and the regulator has set a price cap equal to C and accepted the monopolist's take-it-of-leave it offer to rent his excess transmission capacity at a unit price $v-f$, the welfare function is

$$\begin{aligned}
W_m^{C^t}\left(\Theta,C\right) &= \left[v-P\right]\left[\int_0^\Theta DdG\left(D\right)+\Theta\left[1-G(\Theta)\right]\right]-C\Theta\\
&\quad+\alpha\left[\int_0^{K-\beta}\left[DP+\beta f\right]dG\left(D\right)+\int_{K-\beta}^\Theta\left[DP+\left(K-D\right)f\right]dG\left(D\right)\right]\\
&\quad+\alpha\left[\int_\Theta^1\left[P\Theta+\left[K-\Theta\right]f\right]dG\left(D\right)+C\Theta\right]+\alpha\left[v-f\right]\int_\Theta^1\left[D-\Theta\right]dG\left(D\right)
\end{aligned}$$

Given that $W_m^{Ct}(\Theta, C)$ is decreasing in C, the regulator will set C equal to the minimum level that induces the monopolist to commit the desired Θ. Taking the first derivative of $W_m^{Ct}(\Theta, C)$ with respect to Θ gives

$$\frac{\partial W_m^{Ct}(\Theta, C)}{\partial \Theta} = [1-\alpha]\left[[v-f][1-G(\Theta)] + [f-P]\frac{K-\beta}{\Theta-[K-\beta]}\int_{K-\beta}^{\Theta}\frac{D-[K-\beta]}{\Theta-[K-\beta]}g(D)dD\right] > 0$$

Therefore, conditional on deciding to implement a capacity market, it is still optimal to set $\Theta = 1$. Given that $C_m^t(1) = C_m(1)$, the regulator is indifferent between renting the line or not (i.e. the level of welfare and capacity payments are the same as in the case in which renting the line was not possible).

Last, since total welfare is equal when $\Theta^* = 1$, then it must be that $v \geq \underline{v}_m$.

Perfect Competition

If both the energy and the transmission rights market are competitive, the value of one unit of transmission rights is equal to the nodal price, i.e. the difference between foreign price and national prices: $\eta = f - 0$. Given that we have assumed $v > f$, this implies that all the rights will be sold at f.

Competitive firms choose their capacity commitment $\theta \in [0, \Theta]$ to maximize expected profits $\pi_c^t(\theta) + c\theta$, where

$$\pi_c^t(\theta) = \begin{cases} \pi_c(\theta) & \text{if} \quad \theta \leq K-\beta \\ \pi_c(\theta) + f\int_\theta^1 [D-\theta]\, dG(D) & \text{if} \quad \theta > K-\beta \end{cases}$$

and c is the capacity market price. Taking the first and second derivatives of the competitive firms' total profit with respect to θ,

$$\frac{\partial\left[\pi_c^t(\theta) + c\theta\right]}{\partial\theta} = \begin{cases} c & \text{if} \quad \theta \leq K-\beta \\ c - 2f[1-G(\theta)] & \text{if} \quad \theta > K-\beta \end{cases}$$

$$\frac{\partial^2\left[\pi_c^t(\theta) + C\theta\right]}{\partial\theta^2} = \begin{cases} 0 & \text{if} \quad \theta \leq K-\beta \\ 2fg(\theta) & \text{if} \quad \theta > K-\beta \end{cases}$$

Similarly to the monopoly case, with tradable transmission rights, firms' opportunity costs and the capacity payments guaranteeing the market clearing equilibrium decrease with respect to the no-right case, whereas regulatory decisions remain unchanged:

Lemma 8 *There exists* $C_c^t = C^t(\Theta, v - f, K - \beta) < C_c$ *such that the competitive firms will rent their spare transmission capacity at* f*, and will commit all available capacity resources if* $C \geq C_c^t$*, and only the non-exportable capacity otherwise, where*

$$C_c^t = C_c - \frac{f}{\Theta - [K - \beta]} \int_\Theta^1 [D - \Theta] \, dG(D)$$

The regulator's decisions are unaffected by the possibility of renting the line.

Proof of Lemma 8:

The competitive firms' optimal commitment decision is given by Θ if the following condition is satisfied, and $K - \beta$ otherwise.

$$c\Theta + \pi_c^t(\Theta) \geq c[K - \beta] + \pi_c^t(K - \beta)$$

Rearranging terms,

$$\begin{aligned} c \geq C_c^t &= \frac{\pi_c^t(K - \beta) - \pi_c^t(\Theta)}{\Theta - [K - \beta]} \\ &= \frac{\pi_c(K - \beta) - \pi_c(\Theta)}{\Theta - [K - \beta]} - \frac{f}{\Theta - (K - \beta)} \int_\Theta^1 [D - \Theta] \, dG(D) \\ &= C_c - \frac{f}{\Theta - [K - \beta]} \int_\Theta^1 [D - \Theta] \, dG(D) \leq C_c \end{aligned}$$

Comparative statics are ambiguous.

Since the transmission rights imply a pure rent transfer from consumers to firms with respect to the basic model, the welfare function can be rewritten as:

$$W_c^{C^t}(\Theta, C) = W_c^C(\Theta, C) - f(1 - \alpha) \int_\Theta^1 [D - \Theta] \, dG(D)$$

Hence:

$$\frac{\partial W_c^{C^t}(\Theta, C)}{\partial \Theta} = (v - f)[1 - G(\Theta)] + f(1 - \alpha)[1 - G(\Theta)] > 0$$

which implies $\Theta^* = 1$ and $C_c^t(1) = C_c(1)$.

Last, since when setting $\Theta^* = 1$ welfare is equal to the no-right case, then having a capacity market is optimal under the same condition as before, i.e. $v \geq \underline{v}_c$.

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