The visible hand: ensuring optimal investment in electric power generation

Thomas-Olivier Léautier

Toulouse School of Economics (IAE, IDEI, University of Toulouse)

21 allée de Brienne

F31 000 Toulouse

thomas.leautier@iae-toulouse.fr. and +33 6 33 34 60 68

March 11, 2013

Abstract

This article formally analyzes the various corrective mechanisms that have been proposed and implemented to alleviate underinvestment in electric power generation. It yields three main analytical findings. First, physical capacity certificates markets implemented in the United States restore optimal investment if and only if they are supplemented with a "no short sale" condition, i.e., producers can not sell more certificates than they have installed capacity. Then, they raise producers' profits beyond the imperfect competition level. Second, financial reliability options, proposed in many markets, are effective at curbing market power, although they fail to fully restore investment incentives. If "no short sale" conditions are added, both physical capacity certificates and financial reliability options are equivalent. Finally, a single market for energy and operating reserves subject to a price cap is isomorphic to a simple energy market. Standard peak-load pricing analysis applies: under-investment occurs, unless production is perfectly competitive and the cap is never binding.

This analysis highlight the limitations of the corrective mechanisms. This suggest that policy makers should first and foremost control and reduce the exercise of market power, then use these mechanisms as interim remedial measures.

Keywords: imperfect competition, market design, investment incentives

JEL Classification: L13, L94

1 Introduction

An essential objective of the restructuring of the electric power industry in the 1990s was to "push to the market" decisions and risks associated with investment in power generation, i.e., to have market forces, not bureaucrats, determine how much investment is required, and to have investors, not rate-payers, bear the risk of excess capacity, construction cost overruns and delays.

However, since the early 2000s, generation adequacy has become an issue of concern for policy makers, power System Operators (SOs), and economists. It would appear that, contrary to the initial belief, the "market" does not necessarily provide for the adequate level of generation capacity. Britain, that pioneered the restructuring of the electricity industry in 1990, constitutes the most recent and striking example: Ofgem, the energy regulator warns of possible power shortages around 2015 (Ofgem (2010)).

Operating and regulatory practices aimed at preventing the exercise of market power are often considered to be the primary cause of this "market failure". As shown in Marcel Boiteux (1949)'s seminal analysis, high prices in some states of the world are required to finance the optimal capacity. However, in most jurisdictions SOs impose *de jure* or *de facto* price caps, that deprive producers of these high prices. This revenue loss, called "missing money", is considered an important driver of underinvestment in generation (Joskow (2007)).

Therefore, SOs and policy makers worldwide have designed and implemented a variety of mechanisms to correct this apparent "market failure" (Finon and Pignon (2008)). For example, most US power markets have adopted highly structured and prescriptive physical certificates markets, and many European countries are considering, designing or implementing capacity mechanisms[1].

These mechanisms are extremely complex, hence expensive to set up and run. Furthermore, they constitute a partial reversion towards central planning, which restructuring precisely attempted to eliminate: using a centralized system reliability model, the SO sets a generation capacity target, and organizes its procurement. Risk of overcapacity is borne by consumers, while risk of cost overrun is borne by investors. A rigorous economic analysis of the performance of the various market designs implemented by SOs to restore investment incentives is therefore required. This is the objective of

[1] France formally instituted a capacity obligation mechanism in March 2012, to be effective in 2015. Britain, Germany, and Belgium are designing mechanisms to ensure adequate capacity.

this article. I am not aware of any previous systematic analytical comparison of these designs.

This work draws on a rich literature, that can be structured along two themes. A first group of articles examines generation investment in restructured power markets. While these works differ in important aspects, most model two stage games: in stage 1, producers decide on installed capacity; in stage 2 they produce and sell in the spot markets, subject to the installed capacity constraint. For example, Borenstein and Holland (2005) and Joskow and Tirole (2007), building on Boiteux (1949) and Crew and Kleindorfer (1976), have developed the "benchmark" model of optimal investment and production when (*i*) demand is uncertain at the time the investment decision is made, and (*ii*) a fraction of the demand does not react to price. The former article considers the perfect competition case, while the latter introduces some elements of imperfect competition. Murphy and Smeers (2005) have developed models of closed- and open-loop Cournot competition at the investment and spot market stages, and characterized the equilibria of these games. Boom (2009) has examined the impact of vertical integration on equilibrium investment, while Fabra et al. (2011) have examined the impact of the structure of the auction in the spot market on the equilibrium investment. A more recent literature (e.g., Garcia and Shen (2010)) examine multiperiod investment decisions. This article builds on the two-stage Cournot game formalized in Zöttl (2011).

A second group of works describes and analyzes the possible "corrective" mechanisms[2]. Stoft (2002) discusses average Value of Lost Load ($VoLL$) pricing, Hogan (2005) proposes an energy cum operating reserves markets, and Cramton and Stoft (2006 and 2008) and Cramton and Ockenfels (2011) propose a financial reliability options mechanism[3]. Joskow and Tirole (2007) show that a capacity market and a price cap do not restore the first best with more than two states of the world. Chao and Wilson (2005) examine the impact of options on spot market equilibrium, investment, and welfare. Zöttl (2011) determines the welfare maximizing price cap in the spot market. However, none of these works presents a rigorous comparison of these mechanisms in a general and common setting.

This article bridges these two strands of literature, that analyzes the proposals described in the second group of articles using a rigorous economic model developed in the first group: an extension of the two-stage Cournot model developed by Zöttl (2011) to include both "price reactive" customers and

[2] Since these mechanisms are described extensively in the article, they are not developped further here.

[3] Strictly speaking, these options ensure "resource adequacy", not "reliability". Nevertheless, I use the word "reliability options" as it was the term used in the original Cramton and Stoft articles.

"constant price customers", the latter being unable to react to spot energy prices and being rationed in some instances (Borenstein and Holland (2005), Joskow and Tirole (2007), Stoft (2002), and Hogan (2005)). Its contribution is to propose clear policy recommendations, building on the economic analysis of these mechanisms. While this work's primary focus is the electric power industry, the analysis presented here can serve as a basis to examine (under)investment issues in other industries where participants must select capacity in the presence of significant demand variability and uncertainty and limited storage possibilities, for example telecommunications and transport networks.

This article yields three main analytical findings. First, I examine the equilibrium of markets where energy and forward physical installed capacity certificates are separately exchanged. This is the case for example in the Northeast of the United States: 3 to 5 years ahead, the SO procures from producers physical capacity certificates (usually 15 to 20% higher than anticipated peak load to protect against supply and demand fluctuations). The cost of these purchases is then passed on to customers. Proposition 1 shows that the SO must impose a "no short sale" requirement, i.e., require producers to sell less certificates than have installed capacity (or to build as much capacity as they have sold certificates). If she does, a physical capacity certificates market restores investment incentives: the resulting capacity installed is optimal. For a given price cap, social welfare is thus maximized. However, producers profits are higher than the imperfect competition outcome without the capacity market. Numerical illustration suggests the additional rent from the capacity market is not negligible, that ranges ranges between 10 to 16% of the investment cost.

Second, I analyze the equilibrium of another form of forward markets, where producers are required to sell, through the SO, financial call options to customers, covering all the demand up to a certain level at a given strike price. Option sellers pay customers the difference between the actual spot energy price and the strike price (Oren (2005), Cramton and Stoft (2006 and 2008), Cramton and Ockenfels (2011)).

Proposition 2 proves that options sale reduces but does not eliminate market power. Installed capacity is higher with options sale than without, but still lower than socially optimal. To ensure optimal investment, the SO must again impose a "no short sale" requirement. If she does, Proposition 3 shows that financial reliability options and physical capacity certificates with the "no short sale" conditions are equivalent if the "technical" parameters are identical (e.g., if the option strike price equals the wholesale price cap). Reliability options thus also sur-remunerate strategic underinvestment. While Propositions 2 and 3 are consistent with Chao and Wilson (2005) and Allaz and Villa (1993)'s theoretical analysis of the interaction between forward and spot markets, they are new to the literature.

Finally, I consider the "energy cum operating reserves market" proposed by Hogan (2005). SOs procure operating reserves to protect against an unplanned generation outage. Hogan (2005) proposes the SO balances supply against demand for energy *and* operating reserves, using the average $VoLL$ as a price cap. Producers receive additional revenues since: (i) the resulting power price is higher than when the SO balances supply against demand for energy alone, and (ii) capacity providing operating reserves – but no energy – is remunerated. This additional revenue is expected to resolve the missing money problem, hence restores investment incentives. However, Proposition 4 shows this intuition is invalid: since these additional revenues are already accounted for in the determination of the installed capacity, the situation is isomorphic to standard peak-load pricing.

Each of these three mechanisms is examined individually in this article, while they may be implemented jointly in practice. For example, most US markets have a physical certificate mechanism and co-procurement of energy and operating reserves.

The analysis yields clear policy recommendations. If policy makers and the SO are confident a market is sufficiently competitive, as may be the case in Texas, there is no need to impose a price cap and set up a forward capacity market (physical or financial), which are complex and costly to administer. Average $VoLL$ pricing or an energy cum operating reserves market are simple to set up and, if the $VoLL$ used is close enough to the real $VoLL$, cause limited distortion compared to the optimum. Furthermore, an energy cum operating reserves market remunerates flexibility, an important issue which is not covered in this work.

On the other-hand, policy makers may determine that generation is insufficiently competitive in their jurisdiction. This may be the case in European markets, where in most markets less than 10 generation companies actually compete. This may also be the case where congestion on the transmission grid separates the market in smaller submarkets, and producers may be able to exert local market power. Then, policy makers should set up a (physical or financial) forward capacity market as an interim measure while removing barriers to competition.

The article is structured as follows. Section 2 presents the model structure and examines the causes of underinvestment. Section 3 examines markets for physical installed capacity certificates. Section 4 analyzes financial reliability options. Section 5 analyzes the "energy cum operating reserves market". Finally, Section 6 suggests future research directions. Technical proofs are included in the Appendix.

2 Underinvestment

The model used throughout this article is developed in Léautier (2013), building on the analysis presented by Zöttl (2011). This Section presents its main features and conclusions. The interested reader is referred to Léautier (2013) for a comprehensive presentation of the model.

2.1 Model structure

Uncertainty Uncertainty is an essential feature of power markets. In this work, demand uncertainty is explicitly modeled, while production uncertainty is taken into account implicitly through operating reserves (presented in Section 5). This representation is suitable for markets that rely mostly on controllable generation technologies, such as thermal and nuclear (see for example Chao and Wilson (1987)). Extension to markets where intermittent sources constitute an important portion of the generation portfolio is left for further work.

The number of possible states of the world is infinite, and these are indexed by $t \in [0, +\infty)$. The functions $f(t)$ and $F(t)$ are respectively the ex ante probability and cumulative density functions of state t. Since all market participants have the same information about future demand projections and construction plans, $f(t)$ and $F(t)$ are common to all stakeholders.

Supply This article considers a single generation technology, characterized by marginal cost $c > 0$ and investment cost[4] r. A single technology is sufficient to analyze total installed capacity, that depends solely on the characteristics of the marginal technology (see for example Boiteux (1949) for the perfect competition case and Zöttl (2011) for the imperfect competition case).

Underlying demand

[4]Both are expressed in €$/MWh$. r is the annual capital cost expressed in €$/MW/year$ divided by $8,760$ hours. It includes the cost of risk.

Assumption 1 *All customers have the same underlying demand $D(p;t)$ in state t, where p the electric power price, up to a scaling factor.*

Assumption 1 greatly simplifies the derivations, while preserving the main economics insights. Inverse demand is $P(q;t)$ defined by $D(P(q;t);t) = q$, and gross consumers surplus is $S(p;t) = \int_0^{D(p;t)} P(q;t)\,dq$. $P(q;t)$ is downward sloping: $P_q(q;t) < 0$. States of the world are ordered by increasing demand: $P_t(q;t) > 0$.

Constant price customers, curtailment, and Value of Lost Load Only a fraction $\alpha > 0$ of customers face and react to real time wholesale price ("price reactive" customers), while the remaining fraction $(1-\alpha)$ of customers face constant price p^R in all states of the world ("constant price" customers).

Since a fraction of customers does not react to real time price, there may be instances when the *SO* has no alternative but to curtail demand, i.e., to interrupt supply. As discussed for example in Joskow and Tirole (2007), there exists multiple rationing technologies. Curtailment is represented by a *serving ratio* $\gamma \in [0,1]$: $\gamma = 0$ represents no serving (i.e., all energy to all consumers is curtailed), while $\gamma = 1$ represents full serving (i.e., no customer is curtailed). $\mathcal{D}(p,\gamma;t)$ is the demand for price p and serving ratio γ in state t, $\mathcal{S}(p,\gamma;t) = \int_0^{\mathcal{D}(p,\gamma;t)} \mathcal{P}(q,\gamma;t)\,dq$ is the gross consumer surplus, and $\mathcal{P}(q,\gamma;t)$ is the inverse demand for a given serving ratio γ: $\mathcal{D}(\mathcal{P}(q,\gamma;t),\gamma;t) = q$.

Assumption 2 *The SO has the technical ability to curtail "constant price" consumers while not curtailing "price reactive" customers.*

Assumption 2 holds only partially today: most *SOs* can only organize curtailment by geographical zones, and cannot differentiate by type of customer. However, most price reactive customers are large enough that they are connected directly to individual transformers or to the high voltage grid, hence they need not be curtailed when the *SO* curtail constant price customers. Assumption 2 will hold fully in a few years, when "smart meters" are rolled out, as is mandated in most European countries and many US states. *SOs* will then be able to differentiate among adjacent customers, on the basis of the information provided by power suppliers.

When consumers are curtailed, the marginal Value of Lost Load ($VoLL$) represents the value they place on an extra unit of electricity (Joskow and Tirole (2007), Stoft (2002)), formally defined as

$$v(p,\gamma;t) = \frac{\frac{\partial \mathcal{S}}{\partial \gamma}}{\frac{\partial \mathcal{D}}{\partial \gamma}}(p,\gamma;t).$$

If the SO knew the $VoLL$ for every rationing technology and state of the world (and each customer class), the second best (as defined in the next Section) would be achieved. In reality, regulators, SOs and economists have little idea of the $VoLL$. Estimation is extremely difficult, because the $VoLL$ varies drastically across customer classes, states of the world, and duration and conditions of outages. Estimates vary in an extremely wide range from 2 000 $£/MWh$ in the British Pool in the 1990s to 200 000 $\$/MWh$ (see for example Cramton and Lien (2000) and Praktiknjo and Erdmann (2012)). In practice, the SO uses her best estimate of the average $VoLL$, and prioritizes curtailment by geographic zones (economic activity, political weight, network conditions, etc.), thus implementing a third best.

Both approaches produce downward sloping demand curves, hence are analytically equivalent. In this work, I assume the SO knows exactly the $VoLL$. While this assumption is highly unrealistic, it constitutes a useful analytical benchmark.

2.2 Socially optimal consumption and investment

Optimal consumption The residual inverse demand curve with possible curtailment of constant price customers is

$$\rho(Q;t) = P\left(\frac{Q-(1-\alpha)\mathcal{D}\left(p^R,\gamma^*;t\right)}{\alpha};t\right), \tag{1}$$

where γ^* is the optimal serving ratio in state t for production Q.

Price reactive customers face the wholesale spot price $\rho(Q;t)$, hence are never curtailed at the optimum. Off-peak, demand is low, and production $Q(t)$ is determined by $\rho(Q(t);t) = c$. On-peak, demand is set by installed capacity K, and the wholesale price is $\rho(K;t)$.

As long as $\rho(K;t) \leq v\left(p^R,1;t\right)$, constant price customers are not curtailed in state t. If $\rho(K;t) > v\left(p^R,1;t\right)$, then $\gamma^* < 1$ is set to equalize constant price customers' $VoLL$ and the wholesale price

$$v\left(p^R,\gamma^*;t\right) = \rho(K;t).$$

Define $\widehat{t}(K)$ the first state of the world when curtailment may occur[5]. If curtailment never occurs, $\widehat{t}(K) \to +\infty$. With a slight abuse of notation, define $\rho_q = \frac{1}{\alpha} P_q \left(\frac{Q-(1-\alpha)D\left(p^R;t\right)}{\alpha}; t \right)$ if no rationing occurs, and $\rho_q = \frac{\partial v}{\partial K} = \frac{\partial v}{\partial \gamma} \frac{\partial \gamma^*}{\partial K}$ if rationing occurs. Léautier (2013) derives sufficient conditions for $\rho(Q;t)$ to be well-behaved, even when curtailment occurs.

As an illustration, suppose (i) inverse demand is linear with constant slope: $P(q;t) = a(t) - bq$, and (ii) rationing anticipated and proportional: $\mathcal{S}(p,\gamma;t) = \gamma S(p;t)$ and $\mathcal{D}(p,\gamma;t) = \gamma D(p;t)$. If no rationing occurs,

$$\rho(Q;t) = \frac{a(t) - bQ - (1-\alpha)p^R}{\alpha}. \tag{2}$$

Since rationing is anticipated and proportional,

$$v\left(p^R,\gamma;t\right) = \frac{S\left(p^R;t\right)}{D\left(p^R;t\right)} = a(t) - b\frac{D\left(p^R;t\right)}{2} = \frac{a(t)+p^R}{2}.$$

Optimal investment The marginal social value capacity is

$$\Psi(K,c) = \int_{\bar{t}(K,c)}^{+\infty} (\rho(K;t) - c) f(t)\, dt,$$

where $\bar{t}(K,c)$ is the first state of the world such that price (weakly) exceeds the marginal cost for production K

$$\rho(K;\bar{t}(K,c)) \geq c.$$

$\Psi(K,c)$ is decreasing in both arguments. If $\rho(0,0) > c + r$, the optimal capacity K^* is the unique solution to

$$\Psi(K^*,c) = r. \tag{3}$$

Off-peak, as long as capacity is not constrained, price equals marginal cost, hence marginal capacity generates no economic profit. On-peak, when capacity is constrained, price exceeds marginal cost. The optimal capacity is set such that the marginal social value capacity is exactly equal to the marginal capacity cost r.

If α is small, rationing of constant price customers may occur at the optimal capacity, an issue

[5] $\widehat{t}$ is a function of all the parameters. The notation $\widehat{t}(K)$ is used since the dependency on installed capacity K is the most important in this analysis.

known as the Theoretical (capacity) Adequacy Problem (TAP). With the specification summarized in Appendix A, Léautier (2013) finds that rationing occurs at the optimal capacity until $\alpha = 3.9\%$ if the price elasticity of demand $\eta = -0.01$, and $\alpha = 13.9\%$ if $\eta = -0.1$. This result may seem counter-intuitive: a less elastic demand results in less curtailment! The intuition is that, for a given α, capacity is higher when demand is more inelastic, hence, curtailment is less frequent.

If the presence of constant price customers was the only imperfection in power markets, an energy only market design, sometimes referred to as average $VoLL$ pricing, would be efficient (Stoft (2002), Oren (2005)): when constant price customers are curtailed, the SO pays energy at the $VoLL$, which yields optimal investment (conditional on the $VoLL$). If the SO knew exactly the $VoLL$, this would achieve a second best. Otherwise, this would yield a third best.

However, power markets are subject to other imperfections. First, competition among producers is less than perfect. Second, producers may be risk averse, which reduces their investment. Finally, investment decisions are dynamic and long-lived, more complex than a simple static model suggests. This article focusses on the first imperfection, that examines the performance of corrective mechanisms in a static model where agents are risk neutral. Extensions to a dynamic model and risk-averse agents are left for further work.

2.3 Imperfect competition, price cap, and underinvestment

Consider now N producers, that play a two-stage game: in stage 1, producer n installs capacity k^n; in stage 2 he produces $q^n(t) \leq k^n$ in the spot market in state t. Producers are assumed to compete à la Cournot in the spot markets, facing inverse demand $\rho(Q,t)$ defined by equation (1). Stage 2 can be interpreted as a repetition of multiple states of the world over a given period (for example one year), drawn from the distribution $F(.)$.

The game is solved by backwards induction: producers first compute profits from a Nash equilibrium in the energy spot market for each state of the world t, given installed capacities $\left(k^1, ..., k^N\right)$; then they make their investment choice in stage 1 based on the expectation of these spot market profits.

Aggregate production in state t and aggregate installed capacity are respectively $Q(t) = \sum_{n=1}^{N} q^n(t)$

and $K=\sum_{n=1}^{N}k^n$. Producer's n profit for the two-stage game is $\Pi^n\left(k^n,\mathbf{k}^{-n}\right)$.

The results presented in this article hold for other forms of imperfect competition in the spot market, as long they yield an equilibrium price higher than the marginal cost c, and a profit function $\Pi^n\left(k^n,\mathbf{k}^{-n}\right)$ with the required concavity. Cournot competition is used as it provides simple analytical expressions that can be illustrated numerically.

To limit the exercise of market power, the SO imposes a cap $\bar{p}^W$ on the wholesale power price[6], assumed to satisfy

$$c+r\leq\bar{p}^W\leq\rho\left(0,0\right). \tag{4}$$

A price cap lower than the full marginal cost of the first unit of energy would block any investment. A cap higher than the value of the first unit of energy consumed would have limited effectiveness.

$t^N\left(K\right)$ is the first on-peak state of the world under imperfect competition, i.e., where the marginal revenue for production K equals marginal cost:

$$\rho\left(K;t^N\left(K\right)\right)+\frac{K}{N}\rho_q\left(K;t^N\left(K\right)\right)=c.$$

The aggregate capacity constraint may be binding before or after the price cap constraint in the relevant range, i.e., $t^N\left(K\right)\leq\bar{t}\left(K,\bar{p}^W\right)$ or $t^N\left(K\right)>\bar{t}\left(K,\bar{p}^W\right)$. Introducing constant price customers makes $t^N\left(K\right)>\bar{t}\left(K,\bar{p}^W\right)$ is a distinct possibility, in particular if the residual demand $\rho\left(Q,t\right)$ is very inelastic, i.e., if α or $|\eta|$ are very low.

Léautier (2013) proves that, if certain technical sufficient conditions are met, the equilibrium capacity $K^C\left(\bar{p}^W\right)$ is characterized by

$$\Omega\left(K^C,\bar{p}^W\right)=r,$$

where $\Omega\left(K,\bar{p}^W\right)$ is defined piecewise as follows:

[6] In practice, most SOs in the United States impose a cap on *bids* into the wholesale markets, not a cap on wholesale price. A wholesale price cap simplifies the analysis, while preserving the main economic insights.

1. If generation produces at capacity before the cap is reached,

$$\Omega\left(K,\bar{p}^{W}\right)=\Omega_{1}\left(K,\bar{p}^{W}\right)=\int_{t^{N}(K)}^{\bar{t}\left(K,\bar{p}^{W}\right)}\left(\rho\left(K;t\right)+\frac{K}{N}\rho_{q}\left(K;t\right)-c\right)f\left(t\right)dt+\int_{\bar{t}\left(K,\bar{p}^{W}\right)}^{+\infty}\left(\bar{p}^{W}-c\right)f\left(t\right)dt.$$

2. If the price cap is reached before generation produces at capacity,

$$\Omega\left(K,\bar{p}^{W}\right)=\Omega_{2}\left(K,\bar{p}^{W}\right)=\int_{\bar{t}\left(K,\bar{p}^{W}\right)}^{+\infty}\left(\bar{p}^{W}-c\right)f\left(t\right)dt.$$

This result illustrates the two distortions that reduce investment. First, if generation produces at capacity before the cap is reached, imperfect competition reduces the marginal value of capacity by two terms: the reduction in profit on the inframarginal units as in all Cournot competition models $\left(\frac{K}{N}\int_{t^{N}(K)}^{\bar{t}\left(K,\bar{p}^{W}\right)}\rho_{q}\left(K;t\right)f\left(t\right)dt\right)$, but also the lost margin $\left(\rho\left(K;t\right)-c\right)$ in the states of the world $t\in\left[\bar{t}\left(K,c\right),t^{N}\left(K\right)\right]$. Both effects are negative. Second, whether the cap or the generation capacity constraint is reached first, the price cap reduces the marginal value, since the *SO* values energy at $\rho\left(K;t\right)$, while producers receive only $\bar{p}^{W}<\rho\left(K;t\right)$. This is the "missing money" discussed for example by Joskow (2007), and Cramton and Stoft (2006).

Léautier (2013) then computes the resulting capacity, and proposes sufficient conditions for the existence of price cap that maximizes investment. The latter result extends Zöttl (2011) result to the presence of constant price customers ($\alpha\in(0,1)$). Taking these constant price customers into account yields investment maximizing price caps that are much higher than those observed in most markets. Thus existing price caps will lead to underinvestment, hence the need for corrective mechanisms.

3 Physical capacity certificates

The *SO* imposes price cap $\bar{p}^{W}$ on the energy markets and procures at least K^{*} physical capacity certificates from producers. To simplify the notation and analysis, operating reserves are ignored: as will be proven in Section 5, including them would not modify the economic insights. All units (old and new) receive the same compensation in the physical certificates markets.

The timing is as follows:

1. The *SO* designs the rules of the energy and capacity markets. All parameters are set

2. Producers sell physical capacity certificates to the SO, according to the rules set up previously

3. Producers build new capacity if needed

4. The spot markets are played. In each state, producers compete à la Cournot facing $\rho(Q;t)$, given their installed capacity and their physical capacity obligation. The SO pays the physical certificates to the producers, and passes the cost of purchase to customers. To simplify the analysis, this pass-through is assumed not to distort consumption decisions in the spot market, e.g., the pass-through is proportional to the size of the meter.

Steps 2 and 3 can be inverted or simultaneous: generators first build the plants, then sell physical capacity certificates, or build and sell simultaneously[7].

ϕ^n and $\Phi = \sum_{m=1}^{N} \phi^m$ are respectively the certificates sold by producer n and the aggregate volume of certificates sold. In practice, SOs offer a "smoothed" (inverse) demand curve:

$$H(\Phi) = \begin{cases} r & if \quad \Phi \leq K^* \\ h(\Phi) & if \quad K^* < \Phi < K^* + \Delta\bar{K} \\ 0 & if \quad \Phi \geq K^* + \Delta\bar{K} \end{cases}$$

where (i) r, the capital cost of capacity, is the maximum price the SO is offering for capacity, (ii) $\Delta\bar{K} > 0$ is an arbitrary capacity increment, and (iii) $h(.)$ is such that $H(.)$ is C^2, except maybe at K^* and $K^* + \Delta\bar{K}$, $h^{'}(\Phi) < 0$, $2h'(\Phi) + \phi h''(\Phi) < 0$ for all ϕ, and

$$\left| h^{'}(K^*) \right| \geq \frac{Nr}{K^*}. \tag{5}$$

As will be discussed below, condition (5) simplifies the exposition, but is not essential. It is met in practice. For example, Cramton and Ockenfels (2011) suggest a linear form for $h(.)$ with $\frac{\Delta\bar{K}}{K^*} = 4\%$. Condition (5) is then equivalent to $N\frac{\Delta\bar{K}}{K^*} \leq 1$, and holds as long as less than 25 producers compete.

Efficiency of the physical certificates market is conditional on the quality of the SO's estimate of the optimal capacity K^*. Assuming the SOs knows perfectly K^*, equilibrium is characterized as follows:

[7] The formal proof can be found in a previous version of this article, available at http://idei.fr/doc/wp/2012/visible.pdf.

Proposition 1 *The SO must impose and monitor that the installed capacity exceeds the capacity certificates sold by each generator:* $k^n \geq \phi^n$*. Then (i) producers issue as many credits as they install capacity, and (ii)* K^* *is the unique symmetric equilibrium investment level. Compared to the no installed capacity market situation, producer's profit and overall welfare are increased.*

Proof. *The full proof is presented in Appendix B. Existence of a physical capacity certificates market alone does not alter investment incentives. The SO must impose* $k^n \geq \phi^n$*, otherwise* K^C *remains the installed capacity.*

If she does, producers sell exactly as many certificates as they have installed capacity since incremental capacity is unprofitable unless it collects capacity markets revenues. Then, since $k^n = \phi^n$ *at the equilibrium, producer* n *program is:*

$$\max_{k^n} \Pi^n_{CM}(k^n; \mathbf{k}_{-n},) = \Pi^n(k^n; \mathbf{k}_{-n}) + k^n H(K)$$

Given the shape of the inverse demand function $H(.)$*,* $k^n = \frac{K^*}{N}$ *for all* n *is the unique symmetric equilibrium, and producers' profit is:*

$$\Pi^n_{CM}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) = \Pi^n\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) + \frac{K^*}{N} r.$$

Then, since $\Pi^n(k, ..., k)$ *is concave and* $K^C \leq K^*$*,*

$$\Pi^n\left(\frac{K^C}{N}, ..., \frac{K^C}{N}\right) \leq \Pi^n\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) + \left(\frac{K^C - K^*}{N}\right)\frac{\partial \Pi^n}{\partial k}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right)$$

$\Leftrightarrow$

$$\Delta = \Pi^n_{CM}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) - \Pi^n\left(\frac{K^C}{N}, ..., \frac{K^C}{N}\right) \geq -\frac{K^C}{N}\frac{\partial \Pi^n}{\partial k}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) + \frac{K^*}{N}\left(\frac{\partial \Pi^n}{\partial k}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) + r\right) > 0$$

since $\frac{\partial \Pi^n}{\partial k}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) < 0$ *and* $\frac{\partial \Pi^n}{\partial k}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) + r = \Omega(K^*) > 0$.

Producers' profits increase compare to the no installed capacity market situation. Finally, since overall welfare $W(K)$ *increases up to to* $K = K^*$*,* $W(K^*) \geq W(K^C)$*.* ■

Capacity markets do not automatically restore investment incentives. In the model, producers exercise market power by reducing capacity *ex ante*, and not by withholding output on-peak. The *SO* must therefore ensure that producers cannot sell short, i.e., sell more certificates than their installed capacity.

This observation is not original to this work, for example it has been articulated by Wolak (2006). Yet it remains an important practical challenge for SOs, that monitor that existing generation assets providing certificates are still operational, and that planned capacity having received certificates has indeed be installed. SOs then impose a penalty on producers that, when requested, do not offer in the spot market energy up to the certificates they have sold forward. This process is still evolving. For example, ISO New England recently proposed new rules for its forward market to ensure producers have incentives to produce[8]. The ban on short-selling is not universal: demand-side resources can effectively sell-short in most US markets.

Physical capacity markets increase overall welfare, and also increase transfers from customers to producers. This result is very general. Denote K^E (not necessarily equal to K^*) the equilibrium capacity including the certificates markets. As long as $\Pi^n(K, ..., K)$ is concave, and $K^E > K^C$, the marginal value of capacity for the producers at K^E is negative: $\frac{\partial \Pi^n}{\partial k}\left(\frac{K^E}{N}, ..., \frac{K^E}{N}\right) < 0$. The equilibrium price in the capacity market (r in this case) must compensate for this negative marginal value, otherwise K^E would not be an equilibrium: $\frac{\partial \Pi^n}{\partial k}\left(\frac{K^E}{N}, ..., \frac{K^E}{N}\right) + r \geq 0$. This is sufficient for the proof.

Although I had never seen its formal proof, this result is intuitive: producers must receive a rent to induce them to invest beyond the oligopoly capacity. The illustrative model developed by Léautier (2013) provides an estimate of this additional rent Δ. It varies slightly with the price cap $\bar{p}^W$ and the proportion of price reactive customers α. To simplify, I provide the average value of Δ over all admissible values of $\bar{p}^W$ and for $\alpha = 5\%$, which appears appropriate for most markets. For $\eta = -0.01$ the average rent is around $5,100$ €$/MWh$, approximately 10% of investment cost; for $\eta = -0.1$ the average rent is around $8,400$ €$/MWh$, approximately 16% of investment cost. These estimates illustrate that the rent created by the capacity market is not trivial.

Is there an optimal structure to the physical certificates market? With the above design, the only parameter that can be modified in the price cap $\bar{p}^W$. I choose as an objective function the net surplus from consumption, therefore transfers from consumers to producers do not impact social

[8] http://www.iso-ne.com/committees/comm_wkgrps/mrkts_comm/mrkts/mtrls/2012/nov162012/fcm_performance_white_pape

welfare. Then, since the resulting capacity is K^* for all admissible $\bar{p}^W$, the latter has no impact on the resulting capacity. However, increasing $\bar{p}^W$ always increases welfare, as it reduces the probability of curtailment: when the cap is binding, no customer can respond to price, hence the SO must curtail. Thus, there exists no optimal binding price cap with a capacity market as modeled here.

Finally, if condition (5) is not met, the aggregate capacity at the unique symmetric equilibrium is $K^C_{CM} \in \left(K^*, K^* + \Delta\bar{K}\right]$. Welfare increases if and only if $\Delta\bar{K}$ is small enough that $W\left(K^* + \Delta\bar{K}\right) \geq W\left(K^C\right)$.

4 Financial reliability options

Financial contracts constitute another mechanism used in power markets. This Section examines financial reliability options, proposed by Oren (2005), Cramton and Stoft (2006 and 2008), and more recently Cramton and Ockenfels (2011). Options and not forward contracts are the financial instruments analyzed here, since Chao and Wilson (2005), that examine a slightly different option design, argue that options are in general preferable. These options constitute an insurance against spot energy prices higher than a pre-agreed strike price $\bar{p}^S$, sold by producers to customers. If the spot price $p(t)$ is lower than $\bar{p}^S$, producer n does not make any payment. If $p(t) > \bar{p}^S$, producer n pays $\left(p(t) - \bar{p}^S\right)$ times a fraction of the realized demand equal to his fraction of the total options sale.

The SO does not impose a cap on wholesale prices, and runs an auction for financial reliability options. θ^n and $\Theta = \sum_{m=1}^{N} \theta^m$ are respectively the options sold by producer n and the aggregate volume of options sold. The timing and notation are identical to the capacity market case, except that the subscript $_{RO}$ is added when appropriate. A very simple auction setup is assumed, similar to the one suggested by Cramton and Stoft (2008): the SO determines the volume she desires to purchase, assumed to be K^*, sets the capital cost of capacity r as the reserve price for the auction, and proposes a downward sloping inverse demand curve for options:

$$H_{RO}(\Theta) = \begin{cases} r & if \quad \Theta \leq K^* \\ h_{RO}(\Theta) & if \quad K^* < \Theta < K^* + \Delta\bar{K}_{RO} \\ 0 & if \quad \Theta \geq K^* + \Delta\bar{K}_{RO} \end{cases}$$

where (i) $\Delta\bar{K}_{RO} > 0$ is an arbitrary capacity increment, and (ii) $h_{RO}(.)$ is such that $H_{RO}(.)$ is C^2, except maybe at K^* and $K^* + \Delta\bar{K}$, $h'_{RO}(\phi) < 0$, $2h'_{RO}(\phi) + \phi h''_{RO}(\Phi) < 0$ for all ϕ, and $h_{RO}(.)$ verifies condition (5). To limit the potential exercise of market power, Cramton and Ockenfels (2011) propose the SO impose $\theta^n \geq k^n$: all capacity must be committed forward through option sales.

When the spot price exceeds the strike price, price-reactive consumers then pay $\bar{p}^S$ as the effective price, i.e., they know when making their consumption decision they receive rebate $\max\left(\rho(Q,t) - \bar{p}^S, 0\right)$ per unit of energy purchased. Then, actual demand does not depend on the spot price, which leads to rationing.

$\bar{t}\left(K, \bar{p}^S\right)$ is the first state of the world such that the spot price exceeds the strike price, and is defined by $\rho\left(K, \bar{t}\left(K, \bar{p}^S\right)\right) \geq \bar{p}^S$. We assume $\bar{p}^S$ satisfies

$$\Psi\left(K^C\left(\bar{p}^S\right), \bar{p}^S\right) \leq r. \tag{6}$$

Condition (6) simplifies the exposition, as it guarantees that $\Theta = K^*$ is the unique equilibrium of the options market, however it is not essential. As shown in Appendix C, $\Psi\left(K^C(p), p\right)$ is decreasing in p, and and $\Psi\left(K^C(p), p\right) \to 0$ as p stops binding. Thus, condition (6) is met for $\bar{p}^S$ sufficiently high.

Chao and Wilson (2005) examine a slightly different market structure: they consider physical options paired (or not) with a complementary price insurance, and compute the linear supply function equilibrium for options forward sales and power spot sales. Their findings are aligned with those presented below.

4.1 Expected profits with financial reliability options

The producers profit function is characterized below:

Lemma 1 *The expected profit of producer n is*

$$\Pi^n_{RO}\left(k^n, \theta^n; \mathbf{k}_{-n}, \boldsymbol{\theta}_{-n}\right) = \theta^n H_{RO}(\Theta) + \Pi^n\left(k^n; \mathbf{k}_{-n}\right) + \left(k^n - \frac{\theta^n}{\Theta}K\right)\Psi\left(K, \bar{p}^S\right), \tag{7}$$

with the convention that $\bar{p}^S$ acts as the price cap in Π^n.

Proof. *Producer n receives the revenues from options sale $\theta^n H_{RO}(\Theta)$, plus profits from the energy market. Suppose first $t^N(K) \leq \bar{t}\left(K, \bar{p}^S\right)$. First, the producer receives profit $\Pi^n\left(k^n; \mathbf{k}_{-n}\right)$ previously* *computed, assuming* $\bar{p}^S$ *as price cap. Second, since there is no price cap, he receives the difference between the spot price* $\rho(K,t)$ *and the cap* $\bar{p}^S$ *for every unit produced when the price exceeds* $\bar{p}^S$*. Since* $t^N(K) \leq \bar{t}(K,\bar{p}^S)$*, he produces his entire capacity* k^n*, hence he receives* $k^n \int_{\bar{t}(K,\bar{p}^S)}^{+\infty} (\rho(K,t) - \bar{p}^S) f(t)\,dt = k^n \Psi(K,\bar{p}^S)$*.*

Finally, when the spot price exceeds the strike price $\bar{p}^S$*, each generator must pay* $(\rho(K,t) - \bar{p}^S)$ *times his fraction* $\frac{\theta^n}{\Theta}$ *of the total demand. Since* $t^N(K) \leq \bar{t}(K,\bar{p}^S)$*, total demand is equal to total capacity* K *and the payment is proportional to* $\frac{\theta^n}{\Theta}K$*. Total expected payment from generator* n *is thus:* $\frac{\theta^n}{\Theta} K \int_{\bar{t}(K,\bar{p}^S)}^{+\infty} (\rho(K,t) - \bar{p}^S) f(t)\,dt = \frac{\theta^n}{\Theta}\Psi(K,\bar{p}^S)$*. Summing these terms yields equation (7).*

Appendix C proves that Equation (7) also obtains if $\bar{t}(K,\bar{p}^S) < t^N(K)$*.* ■

The profit realized in states higher than $\bar{t}(K,\bar{p}^S)$ is $\pi^n_{RO}(K;t) = k^n \left(\left(1 - \frac{\theta^n}{\Theta}\frac{K}{k^n}\right) \rho(K;t) + \frac{\theta^n}{\Theta}\frac{K}{k^n}\bar{p}^S - c \right)$. Producers face a weighted average of the spot price and the option price, hence are less sensitive to an increase in spot price. Consistent with Allaz and Villa (1993) and Chao and Wilson (2005), a producer holding forward contracts faces lower incentives to exert market power in the spot market.

4.2 Equilibrium capacity with financial reliability options

Proposition 2 *Reliability options reduce but do not eliminate the underinvestment problem.* K^C_{RO}*, the unique symmetric equilibrium of the options and investment game, verifies*

$$K^C(\bar{p}^S) \leq K^C_{RO} < K^*,$$

with equality occurring when $N = 1$*.*

Proof. *Appendix C proves that, if producers invest first then sell options, there exists a unique symmetric equilibrium that satisfies:*

$$\frac{\partial \Pi^n_{RO}}{\partial k^n}\left(\frac{K^C_{RO}}{N}, ..., \frac{K^C_{RO}}{N}\right) = \Omega(K^C_{RO}, \bar{p}^S) - r + \frac{N-1}{N}\Psi(K^C_{RO}, \bar{p}^S) = 0 \quad (8)$$

Then,

$$\Omega(K^C_{RO}, \bar{p}^S) = r - \frac{N-1}{N}\Psi(K^C_{RO}, \bar{p}^S) \leq r.$$

Hence $K_{RO}^{C} \geq K^{C}\left(\bar{p}^{S}\right)$. *Then,*

$$\begin{aligned}
\frac{\partial \Pi_{RO}^{n}}{\partial k^{n}}\left(\frac{K^{*}}{N}, ..., \frac{K^{*}}{N}\right) &= -\int_{\bar{t}(K,c)}^{t^{N}(K)}\left(\rho\left(K^{*};t\right)-c\right) f(t)\, dt+\frac{K^{*}}{N} \int_{t^{N}(K)}^{\bar{t}\left(K,\bar{p}^{S}\right)} \rho_{q}\left(K^{*};t\right) f(t)\, dt \\
&\quad -\frac{1}{N} \Psi\left(K^{*}, \bar{p}^{S}\right) \\
&< 0.
\end{aligned}$$

Then $K^{*} > K_{RO}^{C}$ *since we prove in Appendix C that* $\Pi_{RO}^{n}\left(\frac{K}{N}, ..., \frac{K}{N}\right)$ *is concave.*

A previous version of this work, available at http://idei.fr/doc/wp/2012/visible.pdf, shows that the result also holds if producers sell certificates, then invest, or sell certificates and invest simultaneously.

■

For $N > 1$, reliability options curb the exercise of market power: the resulting installed capacity is higher than the Cournot capacity. Thus, they are more effective than physical certificates alone, that have no impact on installed capacity without the "no short sale" obligation.

However, reliability options are not sufficient to completely eliminate market power and restore optimal investment incentives. This result may appear surprising, since reliability options impose a penalty of $\left(\rho(K;t)-\bar{p}^{S}\right)$ on each unit a producer is "short" energy. However, a closer examination of the mechanism reveals that, at the symmetric equilibrium, this penalty represents only $\frac{N-1}{N}\left(\rho(K;t)-\bar{p}^{S}\right)$, which is not sufficient to fully compensate for the "missing money" $\left(\rho(K;t)-\bar{p}^{S}\right)$.

Proposition 2 mirrors Allaz and Villa (1993) analysis of the interaction between spot and forward markets: assuming Cournot competition in both, they show that introducing forward markets reduces but does not eliminate market power, and has not impact on a monopoly ($N = 1$).

4.3 Equivalence between physical certificates and financial reliability options when "no short sale" conditions are added

If the SO cannot impose a "no short sale" condition, Proposition 2 above proves that financial reliability options yield higher investment. Which one should the SO choose if she can impose a "no short sale" condition? Proposition 3 below shows that both mechanisms are equivalent, if the technical parameters are equivalent:

Proposition 3 *Suppose* (i) *the SO imposes and monitors that the installed capacity exceeds the options sold by each generator:* $k^n \geq \theta^n$, (ii) *the wholesale price cap in the capacity market is set equal to the strike price of the reliability option* $\left(\bar{p}^S = \bar{p}^W\right)$ *and satisfies condition* (6), *and* (iii) *the demand functions for reliability options and for capacity credits are identical and satisfy condition* (5). *Then, financial reliability options yield the same equilibrium as a capacity market with a no short-sale condition.*

Proof. *Since the SO imposes* $\theta^n \geq k^n$ *(all capacity must be committed) and* $\theta^n \leq k^n$, *producers chose* $\theta^n = k^n$ *Equation* (7) *then yields*

$$\Pi^n_{RO}\left(k^n; \mathbf{k}_{-n}\right) = \Pi^n\left(k^n; \mathbf{k}_{-n}\right) + k^n H_{RO}\left(K\right).$$

If $\bar{p}^S = \bar{p}^W$ *and* $H_{RO}(.) = H(.)$, *then, with the no short sale conditions,* $\Pi^n_{RO} = \Pi^n_{CM}$. *Thus the equilibria are identical.* ■

As mentioned earlier, since producers sell exactly as many options as their installed capacity (or install as much capacity as they sold options), the profit net of the payment on the option is equivalent to a cap on prices. Therefore, if the "technical parameters" are identical, both approaches are equivalent.

5 Energy cum operating reserves market

SOs must secure operating reserves to protect the system against catastrophic failure. Hogan (2005) suggests that remuneration of these operating reserves can solve the missing money problem.

The representation of operating reserves is that of Borenstein and Holland (2005). For simplicity, only one type of reserves is considered, the non-spinning one (i.e., plants that are not running, but can start up and produce energy within a short pre-agreed time frame). Since the plant is not running, the marginal cost of providing reserves is normalized to zero. In reality, *SOs* run multiple markets for operating reserves, for example, spinning, 10-minutes, 30-minutes. The economic insights are not modified, as long as the no-arbitrage condition presented below holds.

Hogan (2005) proposes that the *SO* runs a single market for energy and operating reserves. Generating units called to produce receive the wholesale price $w(t)$, generating units that provide operating reserves receive the wholesale price $w(t)$ less the marginal cost of generation c, assumed to be perfectly known by the SO. Generators are therefore indifferent between producing energy or providing reserves, an essential condition (Borenstein and Holland (2005)). When an unscheduled generation outage occurs, operating reserves produce energy and receive the full price $w(t)$.

Operating reserves requirements are expressed as a percentage of demand, denoted $h(t)$, and taken as given here[9]. Defining the optimal $h(t)$ requires advanced network analysis, hence is beyond the scope of this work. Joskow and Tirole (2007) show the optimal reserve ratio increases with the state of the world; hence $h(t)$ is assumed to be nondecreasing.

The retail price $p(t)$ must be higher than wholesale price $w(t)$ to cover generators' revenues from the operating reserves market. A natural choice is to directly include the cost of reserves in the retail price faced by "price reactive" customers[10]:

$$p(t) = w(t) + h(t)(w(t) - c)$$

$\Leftrightarrow$

$$p(t) - c = (1 + h(t))(w(t) - c) \tag{9}$$

Throughout this section, the retail and wholesale prices are assumed to be related by equation (9). The notation and model structure are identical to the previous Sections, except that the subscript $_{OR}$ is added when appropriate.

Only the fraction $\frac{1}{1+h(t)}$ of installed capacity is used to meet demand in state t, hence $\frac{K}{1+h(t)}$ and not K is the output appearing in the function $\rho(.;t)$ (a formal proof is presented in Appendix D). Thus, the marginal social value of capacity in state t is

$$w(K,t) - c = \frac{p(t) - c}{1 + h(t)} = \frac{\rho\left(\frac{K}{1+h(t)}; t\right) - c}{1 + h(t)}.$$

[9] In practice, various metrics for operating reserves are used, including absolute values expressed in MW. Expressing reserves as a percentage of peak demand simplifies the analysis while preserving the main economic intuition.

[10] Borenstein and Holland (2005) show it to be the perfect competition outcome.

The marginal social value of capacity is

$$\Psi_{OR}(K) = \int_{\bar{t}_{OR}(K,c)}^{+\infty} \frac{\rho\left(\frac{K}{1+h(t)};t\right) - c}{1+h(t)} f(t)\, dt,$$

where $\bar{t}_{OR}(K,c)$ is uniquely defined[11] by $\rho\left(\frac{K}{1+h(t)};\bar{t}_{OR}(K,c)\right) = c$.

The socially optimal capacity is thus uniquely defined by

$$\Psi_{OR}(K^*_{OR}) = r. \tag{10}$$

Consider now the producers' problem. By construction, producers are indifferent between producing energy or providing reserves. In state t, they offer $s^n(t)$ into the energy cum operating reserves market. $S(t) = \sum_{n=1}^{N} s^n(t)$ is the total offer. Energy available to meet demand is $Q(t) = \frac{S(t)}{1+h(t)}$. The *SO* then (*i*) verifies that $s^n(t) \leq k^n$, and (*ii*) allocates each $s^n(t)$ between energy $q^n(t)$ and reserves $b^n(t)$. Producer n profit is then

$$\begin{aligned} \pi^n(t) &= (q^n(t) + b^n(t))(w(t) - c) \\ &= \frac{s^n(t)}{1+h(t)}\left(\rho\left(\frac{S(t)}{1+h(t)}\right) - c\right), \end{aligned}$$

since (*i*) energy and operating reserves receive same net revenue by construction, and (*ii*) wholesale $(w(t))$ and retail $\left(\rho\left(\frac{S(t)}{1+h(t)}\right)\right)$ prices are linked by equation (9). The problem is then isomorphic to standard peak load pricing, except that $\frac{s^n(t)}{1+h(t)}$ replaces production $q^n(t)$.

$t^N_{OR}(K)$, the first on-peak state of the world under imperfect competition, is uniquely defined[12] by $\rho\left(\frac{K}{1+h(t)};t\right) + \frac{1}{N}\frac{K}{1+h(t)}\rho_q\left(\frac{K}{1+h(t)};t\right) = c$.

The *SO* imposes a wholesale price cap $\overline{v}$ equal to her best estimate of $VoLL$. $\bar{t}_{OR}(K,\overline{v})$, the first state of the world where the cap may be binding, is uniquely defined by $\rho\left(\frac{K}{1+h(t)};\bar{t}_{OR}(K,\overline{v})\right) = \overline{v}$. For simplicity, $\overline{v}$ is assumed to be binding after the capacity constraint under imperfect competition:

[11] Since $h(t)$ is nondecreasing, $m_1(K;t) = \rho\left(\frac{K}{1+h(t)};t\right)$ is increasing in t: $\frac{\partial m_1}{\partial t} = -\rho_q \frac{Kh'(t)}{(1+h(t))^2} + \rho_t > 0$.

[12] Similarly, $m_2(t) = \rho\left(\frac{K}{1+h(t)};t\right) + \frac{1}{N}\frac{K}{1+h(t)}\rho\left(\frac{K}{1+h(t)};t\right)$ is increasing in t since $m_2'(t) = -\left(\frac{N+1}{N}\rho_q + \frac{1}{N}\frac{K}{1+h(t)}\rho_{qq}\right)\frac{Kh'(t)}{(1+h(t))^2} + \rho_t > 0$.

$t_{OR}^{N}(K) \leq \bar{t}_{OR}(K,\overline{v})$. The inverse demand function for producers is then: $\rho\left(\frac{K}{1+h(t)};t\right)$ as long as price cap is not reached, and a horizontal inverse demand at $\overline{v}$ afterwards.

Following the steps of the "standard" peak load analysis, the marginal value of capacity for a producer at the symmetric equilibrium is

$$\Omega_{OR}(K) = \int_{t_{OR}^{N}(K)}^{\bar{t}_{OR}(K,\overline{v})} \left(\rho\left(\frac{K}{1+h(t)};t\right) + \frac{1}{N}\frac{K}{1+h(t)}\rho_q\left(\frac{K}{1+h(t)};t\right) - c\right) f(t)\,dt + \int_{\bar{t}_{OR}(K,\overline{v})}^{+\infty} \frac{\overline{v}-c}{1+h(t)} f(t)\,dt,$$

and there exists a unique symmetric equilibrium for which each generator invests $\frac{K_{OR}^{C}}{N}$ defined by:

$$\Omega_{OR}\left(K_{OR}^{C}\right) = r. \tag{11}$$

Proposition 4 *Suppose the SO runs an energy cum operating reserves market and imposes a price cap $\overline{v}$. The problem is isomorphic to standard peak load pricing. $K_{OR}^{C} < K_{OR}^{*}$ unless (i) generation is perfectly competitive $(N \to +\infty)$,* and *(ii) the price cap is never binding $(\bar{t}_{OR}(K,\overline{v}) \to +\infty)$.*

Proof. *The result follows immediately from equations* (11) *and* (10). ■

Including an operating reserve market leads to the same investment incentives as average $VoLL$ pricing. This result is surprising: one would have expected the operating reserves market to alleviate the missing money problem, since (i) all producing units receive a higher price, and (ii) units providing capacity but not energy are remunerated.

However, the discussion above shows these two effects are already included in the determination of the socially and privately optimal capacities K_{OR}^{*} and K_{OR}^{C}. Then, units providing reserve capacity receive the same profit $(w(t) - c)$ as units producing electricity, to avoid arbitrage between markets. No additional profit is generated. The operating reserves market remunerates reserves, which are needed, not capacity investment.

6 Conclusion

This article formally analyzes the various corrective mechanisms that have been proposed and implemented to alleviate underinvestment in electric power generation. It yields three main analytical findings. First, physical capacity certificates markets implemented in the United States restore optimal investment if and only if they are supplemented with a "no short sale" condition, i.e., producers can not sell more certificates than they have installed capacity. Then, they raise producers' profits beyond the imperfect competition level. Second, financial reliability options, proposed in many markets, are effective at curbing market power, although they fail to fully restore investment incentives. If "no short sale" conditions are added, both physical capacity certificates and financial reliability options are equivalent. Finally, a single market for energy and operating reserves subject to a price cap is isomorphic to a simple energy market. Standard peak-load pricing analysis applies: under-investment occurs, unless production is perfectly competitive and the cap is never binding.

This analysis highlight the limitations of the corrective mechanisms. This suggest that policy makers should first and foremost control and reduce the exercise of market power, then use these mechanisms as interim remedial measures.

These results provide a sound basis for policy makers decision making. Different avenues for further work would increase their applicability. First, expand the economic models to other types of technologies: (i) intermittent and uncontrollable production technologies such as photovoltaic and on- and off-shore wind mills, which will provide an increasingly important share of power supply; (ii) reservoir hydro production, which has almost zero marginal cost, but limited overall production capacity, and (iii) voluntary curtailment, i.e., consumers reducing their consumption upon the SO's request.

Second, expand the model to multiple investment periods. Observation suggests the power industry, like many capital-intensive industries, displays cycle of over- and under-investment ("boom bust" cycles). Understanding how various market designs perform in a dynamic setting is therefore extremely important.

7 Acknowledgments

I am grateful to Claude Crampes, Bill Hogan, Patrick Mouttapa, Marie-Anne Plagnet, David Salant, Jean Tirole, three anonymous reviewers, and participants to the 2010 $IDEI$ conference on the Economics of Energy Markets for insightful discussions and comments on previous drafts, and for a grant from Electricité de France that supported this research. All errors and omissions are my responsibility.

References

[1] B. Allaz and J.-L. Vila. Cournot competition, futures markets and efficiency. *Journal of Economic Theory*, 59:1–16, 1993.

[2] M. Boiteux. La tarification des demandes en pointe: Application de la théorie de la vente au cout marginal. *Revue Générale d'Electricité*, 58:321–40, 1949.

[3] A. Boom. Vertically integrated firm's investments in electricity generating capacities. *International Journal of Industrial Economics*, 27:544–551, October 2009.

[4] S. Borenstein. The long-run efficiency of real time pricing. *The Energy Journal*, 26(3):93–116, April 2005.

[5] S. Borenstein and S. Holland. On the efficiency of competitive electricity markets with time-invariant retail prices. *RAND Journal of Economics*, 36:469–493, 2005.

[6] H. Chao and R. Wilson. Priority service: Pricing, investment, and market organization. *American Economic Review*, 77:899–916, 1987.

[7] H. Chao and R. Wilson. Resource adequacy and market power mitigation via option contracts. Technical Report 1010712, Electric Power Research Institute, 2005. http://stoft.com/metaPage/lib/Chao-Wilson-2003-04-resource-adequacy-options.pdf.

[8] P. Cramton and J. Lien. Value of lost load, 2000. Mimeo, University of Maryland.

[9] P. Cramton and A. Ockenfels. Economics and design of capacity markets for the power sector. Mimeo, University of Maryland, May 2011. http://www.cramton.umd.edu/papers2010-2014/cramton-ockenfels-economics-and-design-of-capacity-markets.pdf.

[10] P. Cramton and S. Stoft. The convergence of market designs for adequate generation capacity. White Paper for the California Electricity Oversight Board, April 2006.

[11] P. Cramton and S. Stoft. Forward reliability markets: Less risk, less market power, more efficiency. *Utilities Policy*, 16(3):194–201, September 2008.

[12] M. Crew and P. Kleindorfer. Peak load pricing with a diverse technology. *The Bell Journal of Economics*, 7(1):207–231, Spring 1976.

[13] N. Fabra, N.-H. V. der Fehr, and M.-A. de Frutos. Market design and investment incentives. *The Economic Journal*, 121:1340–1360, December 2011.

[14] D. Finon and V. Pignon. Capacity mechanisms in imperfect electricity markets. *Utilities Policy*, 16(3), September 2008.

[15] A. Garcia and Z. Shen. Equilibrium capacity expansion under stochastic demand growth. *Operations Research*, 58(1):30–42, January-February 2010.

[16] W. Hogan. On an "energy only" electricity market design for resource adequacy. Mimeo, Center for Business and Government, John F. Kennedy School of Government, Harvard University, September 2005.

[17] IEA. *Projected Cost of Generating Electricity*. OECD/IEA, 2010.

[18] P. Joskow and J. Tirole. Reliability and competitive electricity markets. *RAND Journal of Economics*, 38(1):60–84, Spring 2007.

[19] P. L. Joskow. Competitive electricity markets and investment in new generating capacity. in: Helm, D. (Ed.), The New Energy Paradigm, Oxford University Press, 2007.

[20] T.-O. Léautier. Constant price customers, scarcity pricing, and imperfect competition. Mimeo, Toulouse School of Economics, February 2013.

[21] M. Lijesen. The real-time price elasticity of electricity. *Energy Economics*, 29:249–258, 2007.

[22] F. Murphy and Y. Smeers. Generation capacity expansion in imperfectly competitive restructured electricity markets. *Operations Research*, 53(4):646–661, July-August 2005.

[23] Ofgem. Project discovery – updated energy markets scenarios. htttp://www.ofgem.ogv.uk/, February 2010. Ref 16a/10.

[24] S. Oren. Ensuring generation adequacy in competitive electricity markets. In J. Griffin and S. Puller, editors, *Electricity Deregulation: Choices and Challenges*, pages 388–415. University of Chicago Press, 2005.

[25] A. J. Praktiknjo and G. Erdmann. Costs of blackouts and supply security in the context of climate protection and nuclear energies in germany. Mimeo, TU Berlin, Department of Energy Systems, 2012.

[26] S. Stoft. *Power System Economics*. Wiley-Interscience, 2002.

[27] F. Wolak. What's wrong with capacity markets? http://stoft.com/metaPage/lib/WolaK-2004-06-contract-adequacy.pdf, June 2004. Mimeo, Department of Economics, Stanford University.

[28] G. Zoettl. On optimal scarcity prices. *International Journal of Industrial Organization*, 29(5):589–605, September 2011.

A Numerical illustration

Inverse demand is $P(q;t) = a_0 - a_1 e^{-\lambda_2 t} - bq$, states of the world are distributed according to $f(t) = \lambda_1 e^{-\lambda_1 t}$, and rationing is anticipated and proportional. a_0, a_1, $\lambda = \frac{\lambda_1}{\lambda_2}$, and bQ^∞ where $Q^\infty = \frac{a_0 - p_0}{b}$ is the maximum demand for price p_0, are the parameters to be estimated. λ is estimated by Maximum Likelihood using the load duration curve for France in 2010. The same load duration curve provides an expression of a_0 and a_1 as a function of bQ^∞. The average demand elasticity η is then used to estimate bQ^∞. Two estimates of demand elasticity at price $p_0 = 100$ €$/MWh$ are tested: $\eta = -0.01$ and $\eta = -0.1$, respectively the lower and upper bound proposed by Lijesen (2007). The resulting estimates are

$$
\begin{array}{c} for\ \eta = -0.1 \\ \left\{ \begin{array}{c} bQ^\infty = 1\ 873 \text{ €}/MWh \\ a_0 = 1\ 973 \text{ €}/MWh \\ a_1 = 1\ 236 \text{ €}/MWh \\ \lambda = 1.78 \end{array} \right. \end{array}, \ and \ \begin{array}{c} for\ \eta = -0.01 \\ \left\{ \begin{array}{c} bQ^\infty = 18\ 727 \text{ €}/MWh \\ a_0 = 18\ 827 \text{ €}/MWh \\ a_1 = 12\ 360 \text{ €}/MWh \\ \lambda = 1.78 \end{array} \right. \end{array} .
$$

Generation costs are those of a gas turbine, $c = 72$ €$/MWh$ and $r = 6$ €$/MWh$ as provided by the International Energy Agency, IEA (2010). The regulated energy price is $p^R = 50$ €$/MWh$, from Eurostat[13].

B Physical capacity certificates

B.1 No short sale condition

Suppose first the SO imposes no condition on certificates sales. Producer n's expected profit, including revenues from the capacity market is: $\Pi^n_{CM}\left(k^n, \phi^n; \mathbf{k}_{-n}, \boldsymbol{\phi}_{-n}\right) = \Pi^n\left(k^n; \mathbf{k}_{-n}\right) + \phi^n H(\Phi)$. Since ϕ^n does not enter $\Pi^n\left(k^n; \mathbf{k}_{-n}\right)$,

$$\frac{\partial \Pi^n_{CM}}{\partial k^n}\left(\frac{K}{N}, ..., \frac{K}{N}\right) = \frac{\partial \Pi^n}{\partial k^n}\left(\frac{K}{N}, ..., \frac{K}{N}\right) :$$

[13] Table 2 Figure 2 from http://epp.eurostat.ec.europa.eu/statistics_explained/images/a/a1/Energy_prices_2011s2.xls

the certificate market has no impact on equilibrium investment.

Suppose now the SO imposes $k^n \geq \phi^n$. Consider the case where producers first sell credits, then install capacity. When selecting capacity, each producer maximizes $\bar{\Pi}^n_{CM}(k_n; \mathbf{k}_{-n})$ subject to $k^n \geq \phi^n$. The first-order condition is then

$$\frac{\partial \mathcal{L}^n}{\partial k^n} = \frac{\partial \bar{\Pi}^n}{\partial k^n} + \mu_1^n,$$

where μ_1^n is the shadow cost of the constraint $k^n \geq \phi^n$. Suppose first $\hat{\phi}^n < \hat{k}^n$ $\forall n$, then $\mu_1^n = 0$ $\forall n$ and $\hat{k}^n = \frac{K^C}{N}$ at the symmetric equilibrium. When selecting the amount of credits sold, the producers then maximize $\phi^n H(\Phi)$. Given the shape of $H(.)$, the symmetric equilibrium is $\hat{\phi}^n \geq \frac{K^*}{N}$. But then, $K^C > \Phi \geq K^*$, which is a contradiction, hence $\hat{\phi}^n = \hat{k}^n$.

Since $k^n = \phi^n$ at the equilibrium, producer n program is

$$\max_{k^n} \Pi^n_{CM}(k^n; \mathbf{k}_{-n},) = \Pi^n(k^n; \mathbf{k}_{-n}) + k^n H(K)$$

We prove below that $\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right)$ is the unique symmetric equilibrium.

B.2 Equilibrium investment if generation produces at capacity before the cap is reached

Suppose $t^N(K) \leq \bar{t}\left(K, \bar{p}^W\right)$. As observed by Zöttl (2011), the profit function $\Pi^n\left(k^1, ..., k^n, ..., k^N\right)$ is not concave in k^n, so one must separately consider a positive and negative deviation from a symmetric equilibrium candidate to prove existence of the equilibrium. Consider first a negative deviation, i.e., $k^1 < \frac{K^*}{N}$ while $k^n = \frac{K^*}{N}$ for all $n > 1$. Since $K = k^1 + \frac{N-1}{N}K^* < K^*$,

$$\frac{\partial \Pi^1_{CM}}{\partial k^1}\left(k^1, \frac{K^*}{N}, ..., \frac{K^*}{N}\right) = \frac{\partial \Pi^1}{\partial k^1}\left(k^1, \frac{K^*}{N}, ..., \frac{K^*}{N}\right) + r.$$

Analysis of the two-stage Cournot game (Zöttl (2011) for $\alpha = 1$, Léautier (2013) for $\alpha \in (0,1)$) yields:

$$\begin{aligned}\frac{\partial \Pi^1}{\partial k^1}\left(k^1, \frac{K^*}{N}, ..., \frac{K^*}{N}\right) &= \int_{t^1}^{t^N(K)} \left(\rho\left(\hat{Q}\left(k^1;t\right)\right) + k^1 \rho_q\left(\hat{Q}\left(k^1;t\right)\right)\frac{\partial \hat{Q}}{\partial k^1} - c\right) f(t)\, dt \\ &+ \int_{t^N(K)}^{\bar{t}\left(K,\bar{p}^W\right)} \left(\rho(K) + k^1 \rho_q(K) - c\right) f(t)\, dt \\ &+ \int_{\bar{t}\left(K,\bar{p}^W\right)}^{+\infty} \left(\bar{p}^W - c\right) f(t)\, dt - r,\end{aligned} \tag{12}$$

where t^1 is the first state of the world where producer 1 is constrained, $\hat{Q}\left(k^1;t\right) = k^1 + (N-1)\,\phi^N\left(k^1;t\right)$ is the aggregate production, and $\phi^N\left(k^1;t\right)$ is the equilibrium production from the remaining $(N-1)$ identical producers, that solves

$$\rho\left(k^1 + (N-1)\,\phi^N\left(k^1;t\right)\right) + \phi^N\left(k^1;t\right)\rho_q\left(k^1 + (N-1)\,\phi^N\left(k^1;t\right)\right) = c.$$

$\phi^N\left(k^1;t\right) \geq k^1$ for $t \in \left[t^1, t^N(K)\right]$: lower-capacity producer 1 is constrained, while the $(N-1)$ higher capacity producers are not. Since quantities are strategic substitutes, $\frac{\partial \phi^N}{\partial k^1} < 0$ and

$$0 < \frac{\partial \hat{Q}}{\partial k^1} = 1 + (N-1)\frac{\partial \phi^N}{\partial k^1} < 1.$$

$\rho\left(\hat{Q}\right) + k^1 \rho_q\left(\hat{Q}\right) - c = \left(k^1 - \phi^N\right)\rho_q\left(\hat{Q}\right)\frac{\partial \hat{Q}}{\partial k^1} \geq 0$ for $t \in \left[t^1, t^N(K)\right]$. $\rho\left(K; t^N(K)\right) + k^1 \rho_q\left(K; t^N(K)\right) = c$, and $\rho_t(K) + k^1 \rho_{qt}(K) \geq 0$, hence $\rho(K) + k^1 \rho_q(K) - c \geq 0$ for $t \geq t^N(K)$. Therefore

$$\frac{\partial \Pi^1}{\partial k^1}\left(k^1, \frac{K^*}{N}, ..., \frac{K^*}{N}\right) + r > 0$$

for $k^1 < \frac{K^*}{N}$: no negative deviation is profitable.

Consider now a positive deviation, i.e., $k^N > \frac{K^*}{N}$ while $k^n = \frac{K^*}{N}$ for all $n < N$. Since $K = k^N + \frac{N-1}{N}K^* > K^*$:

$$\frac{\partial \Pi^N_{CM}}{\partial k^N}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}, k^N\right) = \frac{\partial \Pi^N}{\partial k^N}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}, k^N\right) + k^N H'(K) + H(K),$$

and

$$\frac{\partial^2\Pi^N_{CM}}{(\partial k^N)^2}\left(\frac{K^*}{N},...,\frac{K^*}{N},k^N\right)=\frac{\partial^2\Pi^N}{(\partial k^N)^2}\left(\frac{K^*}{N},...,\frac{K^*}{N},k^N\right)+k^N H^{''}(K)+2H^{'}(K).$$

Zöttl (2011) shows that, for $k^N > \frac{K}{N}$,

$$\begin{aligned}\frac{\partial^2\Pi^N}{\partial\left(k^N\right)^2}\left(\frac{K^C}{N},...,\frac{K^C}{N},k^N\right) &= \int_{t^N}^{\bar{t}\left(K,\bar{p}^W\right)}\left[2\rho_q\left(\hat{K};t\right)+k^N\rho_{qq}\left(\hat{K};t\right)\right]f(t)\,dt \\ &\quad +k^N\rho_q\left(\hat{K};\bar{t}\left(K,\bar{p}^W\right)\right)f\left(\bar{t}\left(K,\bar{p}^W\right)\right)\frac{\partial\bar{t}\left(K,\bar{p}^W\right)}{\partial k^N} \\ &< 0.\end{aligned}\tag{13}$$

Thus,

$$\frac{\partial\Pi^N_{CM}}{\partial k^N}\left(\frac{K^*}{N},...,\frac{K^*}{N},k^N\right)<\frac{\partial\Pi^N}{\partial k^N}\left(\frac{K^*}{N},...,\frac{K^*}{N}\right)+\frac{K^*}{N}H^{'}(K^*)+r<0$$

since condition (5) implies $\frac{K^*}{N}H^{'}(K^*)+r<0$.

Hence, $\left(\frac{K^*}{N},...,\frac{K^*}{N}\right)$ is a symmetric equilibrium. Finally, no other symmetric equilibrium exists since $\Pi^n\left(\frac{K}{N},...,\frac{K}{N}\right)+\frac{K}{N}H(K)$ is concave.

B.3 Equilibrium investment if the cap is reached before generation produces at capacity

Suppose $\bar{t}\left(K,\bar{p}^W\right)<t^N(K)$. To simplify the exposition, generators are ordered by increasing capacity $k^1\leq...\leq k^N$, and suppose that the price cap is reached before the first generator produces at capacity. Léautier (2013) proves that the expected equilibrium profit is

$$\Pi^n\left(k^n;\mathbf{k}_{-n}\right)=\int_0^{\tilde{t}^0}\frac{\hat{Q}(t)}{N}\left(\rho\left(\hat{Q}\right)-c\right)f(t)\,dt+\left(\bar{p}^W-c\right)\left(\sum_{i=0}^{n-1}\int_{\tilde{t}^i}^{\tilde{t}^{i+1}}\tilde{q}^{i+1}(t)\,f(t)\,dt+k^n\left(1-F\left(\tilde{t}^n\right)\right)\right)-rk^n,\tag{14}$$

where $\hat{Q}(t)$ is the unconstrained Cournot output in state t, $\tilde{t}^0$ is the first state of the world such that the price cap is reached, defined by $\rho\left(\hat{Q}\left(\tilde{t}^0\right);\tilde{t}^0\right)=\bar{p}^W$, $\tilde{t}^{i+1}$ for $i=0,...,(N-1)$ is the first state of the world such that producer $(i+1)$ is constrained, defined by $\rho\left(\sum_{j=1}^{i}k^j+(N-j)\,k^{i+1};t\right)=\bar{p}^W$, and $\tilde{q}^{i+1}(t)$ is defined on $\left[\tilde{t}^{i}, \tilde{t}^{i+1}\right]$ by

$$\rho\left(\sum_{j=1}^{i} k^{j}+(N-j)\, \tilde{q}^{i+1}(t)\,; t\right)=\bar{p}^{W}.$$

For $t \leq \tilde{t}^{0}$, unconstrained Cournot competition takes place. For $t \geq \tilde{t}^{0}$, the Cournot price would exceed the cap, hence wholesale price is capped at $\bar{p}^{W}$. All generators play a symmetric equilibrium characterized by $\rho\left(N\tilde{q}^{1}(t)\,; t\right)=\bar{p}^{W}$. When t reaches $\tilde{t}^{1}$ generator 1 produces its capacity. For $t \geq \tilde{t}^{1}$, the remaining $(N-1)$ generators play a symmetric equilibrium characterized by $\rho\left(k^{1}+(N-1)\,\tilde{q}^{2}(t)\,; t\right)=\bar{p}^{W}$. This process continues until all generators produce at capacity. $\tilde{t}^{N}$ is such that $\rho\left(\sum_{j=1}^{N} k^{j}; \tilde{t}^{N}\right)=\bar{p}^{W}$, hence $\tilde{t}^{N}=\bar{t}\left(K, \bar{p}^{W}\right)$ previously defined. For $t>\tilde{t}^{N}$, since wholesale price is fixed at $\bar{p}^{W}$ and generation is at capacity, the SO must curtail constant price consumers.

Differentiation of equation (14) yields

$$\frac{\partial \Pi^{n}}{\partial k^{n}}\left(k^{1}, \ldots, k^{N}\right)=\int_{\tilde{t}^{n}}^{+\infty}\left(\bar{p}^{W}-c\right) f(t)\, dt-r, \tag{15}$$

and

$$\frac{\partial^{2} \Pi^{n}}{\left(\partial k^{n}\right)^{2}}\left(k^{1}, \ldots, k^{N}\right)=-\left(\bar{p}^{W}-c\right) f\left(\tilde{t}^{n}\right) \frac{\partial \tilde{t}^{n}}{\partial k^{n}}<0.$$

$\Pi^{n}\left(k^{1}, \ldots, k^{N}\right)$ is concave in k^{n}. The previous analysis then shows that $\left(\frac{K^{*}}{N}, \ldots, \frac{K^{*}}{N}\right)$ is the unique symmetric equilibrium.

B.4 Producers extra profits from the capacity markets

Léautier (2013) shows that, for common values of the parameters, $\bar{t}\left(K, \bar{p}^{W}\right)<t^{N}(K)$. This is the case considered to evaluate Δ. At a symmetric equilibrium, equation (14) yields

$$\Pi^{n}\left(\frac{K}{N}, \ldots, \frac{K}{N}\right)=\frac{1}{N}\left(\begin{array}{c}\int_{0}^{\tilde{t}^{0}} \hat{Q}(t)\left(\rho\left(\hat{Q}(t), t\right)-c\right) f(t)\, dt+\left(\bar{p}^{W}-c\right) \int_{\tilde{t}^{0}}^{\bar{t}\left(K, \bar{p}^{W}\right)} \tilde{Q}(t) f(t)\, dt \\ +K\left(\left(\bar{p}^{W}-c\right)(1-F(\bar{t}))-r\right)\end{array}\right),$$

$\Delta=\Pi^{n}\left(\frac{K^{*}}{N}, \ldots, \frac{K^{*}}{N}\right)+r \frac{K^{*}}{N}-\Pi^{n}\left(\frac{K^{C}}{N}, \ldots, \frac{K^{C}}{N}\right)$ is then estimated numerically.

C Financial reliability options

The equilibrium is solved by backwards induction. In the second stage, producers solve the equilibrium of the option market, taking $(k^n, \mathbf{k}^{-n})$ as given.

We assume that including the option market does not decrease investment, i.e., $K \geq K^C\left(\bar{p}^S\right)$. As suggested by Cramton and Ockenfels, the SO imposes the restriction that all capacity is sold forward: $\theta^n \geq k^n$. This restriction is made operational by conditioning profits from the option market to $\theta^n \geq k^n$. Since these profits are positive, $\theta^n \geq k^n$ is a dominant strategy, hence holds.

C.1 Derivation of the profit function if the strike price is reached before generation produces at capacity

If reliability options are in effect, the price cap is eliminated. For simplicity, assume that the strike price is reached before the first generator produces at capacity, and denote $\tilde{t}^0$ this state of the world. For $t \geq \tilde{t}^0$, consumers consume as if the price was $\bar{p}^S$, since they internalize the impact of the reliability option. As long as total generation is not at capacity, the wholesale price is indeed $\bar{p}^S$, and the equilibrium is identical to the previous one. When total generation reaches capacity, since consumers consume using constant price $\bar{p}^S$, the SO must curtail constant price consumers. The wholesale price reaches the $VoLL$. Generators must then rebate the difference between the wholesale price and the strike price, in proportion to the volume of options sold.

The resulting equilibrium profit is

$$
\begin{aligned}
\Pi^n_{RO}\left(k^n;\mathbf{k}_{-n}\right) &= \int_0^{\tilde{t}^0} \frac{\hat{Q}(t)}{N}\left(\rho\left(\hat{Q}\right)-c\right) f(t)\,dt \\
&\quad + \left(\bar{p}^S - c\right)\left(\sum_{i=0}^{n-1}\int_{\tilde{t}^i}^{\tilde{t}^{i+1}} \tilde{q}^{i+1}(t) f(t)\,dt + k^n \int_{\tilde{t}^n}^{\bar{t}\left(K,\bar{p}^S\right)} f(t)\,dt\right) \\
&\quad + \int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left(k^n\left(\rho(K,t)-c\right) - \frac{\theta^n}{\Theta}K\left(\rho(K,t)-\bar{p}^S\right)\right) f(t)\,dt - rk^n \\
&= \Pi^n\left(k^n;\mathbf{k}_{-n}\right) + \int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left(k^n\left(\rho(K,t)-c\right) - \frac{\theta^n}{\Theta}K\left(\rho(K,t)-\bar{p}^S\right) - k^n\left(\bar{p}^S - c\right)\right) f(t)\,dt \\
&= \Pi^n\left(k^n;\mathbf{k}_{-n}\right) + \left(k^n - \frac{\theta^n}{\Theta}K\right)\int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left(\rho(K,t)-\bar{p}^S\right) f(t)\,dt \\
&= \Pi^n\left(k^n;\mathbf{k}_{-n}\right) + \left(k^n - \frac{\theta^n}{\Theta}K\right)\Psi\left(K,\bar{p}^S\right).
\end{aligned}
$$

C.2 Equilibrium in the options market

We first establish that $\frac{d\Psi}{dp}\left(K^{C}\left(p\right),p\right) < 0$ and $lim_{p\rightarrow\breve{p}}\Psi\left(K^{C}\left(p\right),p\right) = 0$, where $\breve{p}$ is the maximum price cap reached in equilibrium. Differentiation with respect to p yields

$$\frac{d\Psi}{dp}\left(K^{C}\left(p\right),p\right) = \int_{\bar{t}(K^{C}(p),p)}^{+\infty}\left(\rho_{q}\frac{dK^{C}}{dp} - 1\right) f\left(t\right) dt.$$

Suppose $t^{N}\left(K\right) > \bar{t}\left(K,\bar{p}^{W}\right)$. Then, $K^{C}\left(p\right)$ is defined by

$$\int_{\bar{t}(K^{C}(p),p)}^{+\infty}\left(p-c\right) f\left(t\right) dt = \left(p-c\right)\left(1-F\left(\bar{t}\left(K^{C}\left(p\right),p\right)\right)\right) = r.$$

Full differentiation with respect to p yields

$$\left(1-F\left(\bar{t}\right)\right) - \left(p-c\right) f\left(\bar{t}\right)\left(\frac{\partial\bar{t}}{\partial p} + \frac{\partial\bar{t}}{\partial K}\frac{dK^{C}}{dp}\right) = 0$$

$\Leftrightarrow$

$$\frac{\partial\bar{t}}{\partial p} + \frac{\partial\bar{t}}{\partial K}\frac{dK^{C}}{dp} = \frac{1-F\left(\bar{t}\right)}{\left(p-c\right) f\left(\bar{t}\right)}.$$

Differentiation of $\rho\left(K,\bar{t}\left(K,p\right)\right) = p$ yields $\frac{\partial\bar{t}}{\partial K} = -\frac{\rho_{q}}{\rho_{t}}$ and $\frac{\partial\bar{t}}{\partial p} = \frac{1}{\rho_{t}}$. Thus,

$$1-\rho_{q}\frac{dK^{C}}{dp} = \frac{\rho_{t}}{p-c}\frac{1-F\left(\bar{t}\right)}{f\left(\bar{t}\right)} > 0,$$

therefore $\frac{d\Psi}{dp}\left(K^{c}\left(p\right),p\right) < 0$.

Suppose now $t^{N}\left(K\right) \leq \bar{t}\left(K,\bar{p}^{W}\right)$. $K^{C}\left(p\right)$ is defined by

$$\int_{t^{N}(K^{C}(p))}^{\bar{t}\left(K^{C}(p),p\right)}\left(\rho\left(K^{C}\left(p\right),t\right) + \frac{K^{C}\left(p\right)}{N}\rho_{q}\left(K^{C}\left(p\right),t\right) - c\right) f\left(t\right) dt + \int_{\bar{t}(K^{C}(p),p)}^{+\infty}\left(p-c\right) f\left(t\right) dt = r.$$

Full differentiation with respect to p yields

$$I\frac{dK^{C}}{dp} + \frac{K^{C}}{N}\rho_{q}\left(\frac{\partial\bar{t}}{\partial p} + \frac{\partial\bar{t}}{\partial K}\frac{dK^{C}}{dp}\right) + \left(1-F\left(\bar{t}\right)\right) = 0,$$

where $I = \int_{t^N}^{\bar{t}} \left(\frac{N+1}{N} \rho_q + \frac{K^C}{N} \rho_{qq} \right) f(t)\, dt < 0$. Substituting in $\frac{\partial \bar{t}}{\partial K}$ and $\frac{\partial \bar{t}}{\partial p}$ yields:

$$-I \rho_t \frac{dK^C}{dp} - \frac{K^C}{N} \rho_q \left(1 - \rho_q \frac{dK^C}{dp} \right) = \rho_t \left(1 - F(\bar{t}) \right)$$

$\Leftrightarrow$

$$1 - \rho_q \frac{dK^C}{dp} = \frac{\rho_t \left(\rho_q \left(1 - F(\bar{t}) \right) + I \right)}{I \rho_t - \frac{K^C}{N} \rho_q^2} > 0,$$

therefore $\frac{d\Psi}{dp} \left(K^c(p), p \right) < 0$.

Finally, $K^C(p)$ converges when $p \to \breve{p}$, thus $\left(P\left(K^c(p), t \right) - c \right)$ is bounded, thus $lim_{p \to \breve{p}} \Psi \left(K^c(p), p \right) = 0$ since $lim_{p \to \breve{p}} \bar{t} \left(K^c(p), p \right) = 0$.

We now prove that $\theta^n = \frac{K^*}{N} \geq k^n$ for all n is a symmetric equilibrium if condition (6) holds. Differentiation of equation (7) yields:

$$\frac{\partial \Pi_{RO}^n}{\partial \theta^n} \left(\theta^n; \boldsymbol{\theta}_{-n} \right) = H_{RO}(\Theta) + \theta^n H_{RO}^{'}(\Theta) - \frac{\Theta - \theta^n}{\Theta^2} K \Psi \left(K, \bar{p}^S \right),$$

and

$$\frac{\partial^2 \Pi_{RO}^n}{\left(\partial \theta^n \right)^2} \left(\theta^n; \boldsymbol{\theta}_{-n} \right) = 2 H_{RO}^{'}(\Theta) + \theta^n H_{RO}^{''}(\Theta) + 2 \frac{\Theta - \theta^n}{\Theta^3} K \Psi \left(K, \bar{p}^S \right).$$

For $\Theta \leq K^*$,

$$\frac{\partial^2 \Pi_{RO}^n}{\left(\partial \theta^n \right)^2} \left(\theta^n; \boldsymbol{\theta}_{-n} \right) = 2 \frac{\Theta - \theta^n}{\Theta^3} K \Psi \left(K, \bar{p}^S \right) > 0.$$

$\frac{\partial \Pi_{RO}^n}{\partial \theta^n}$ is increasing, thus the only equilibrium candidates are $\theta^n = \frac{K^*}{N}$ and $\theta^n = k^n$. Furthermore,

$$\frac{\partial^2 \Pi_{RO}^n}{\partial \theta^n \partial \theta^m} \left(\theta^n; \boldsymbol{\theta}_{-n} \right) = \left(2 \frac{\Theta - \theta^n}{\Theta^3} + \frac{\theta^n}{\Theta^2} \right) K \Psi \left(K, \bar{p}^S \right) > 0,$$

thus

$$\frac{\partial \Pi_{RO}^n}{\partial \theta^n} \left(\theta^n; \boldsymbol{\theta}_{-n} \right) \geq \frac{\partial \Pi_{RO}^n}{\partial \theta^n} \left(k^1, ..., k^N \right).$$

Then,

$$\frac{\partial \Pi_{RO}^n}{\partial \theta^n} \left(k^1, ..., k^N \right) = r - \frac{K - k^n}{K^2} K \Psi \left(K, \bar{p}^S \right) > r - \Psi \left(K, \bar{p}^S \right) \geq r - \Psi \left(K^C \left(\bar{p}^S \right), \bar{p}^S \right) > 0$$

since $K \geq K^C\left(\bar{p}^S\right)$ by assumption. Thus, if condition (6) holds, $\frac{\partial \Pi_{RO}^n}{\partial \theta^n}\left(\theta^n; \boldsymbol{\theta}_{-n}\right) > 0$ for all θ^n such that $\theta^n \geq k^n$ and $\Theta \leq K^*$. In particular, if $\theta^n = \frac{K^*}{N}$ for all $n > 1$, no negative deviation $\theta^1 < \frac{K^*}{N}$ is profitable.

Consider now a positive deviation, i.e., $\theta^N > \frac{K^*}{N} \geq k^N$ while $\theta^n = \frac{K^*}{N}$ for all $n < N$. We have:

$$\frac{\partial \Pi_{RO}^N}{\partial \theta^N}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}, \theta^N\right) = h\left(\Theta\right) + \theta^N h^{'}\left(\Theta\right) - \frac{\Theta - \theta^N}{\Theta^2} K \Psi\left(K, \bar{p}^S\right).$$

By construction, $\Theta = \theta^N + \frac{N-1}{N}K^* > K^*$ and $\theta^N - \frac{\Theta}{N} = \frac{N-1}{N}\left(\theta^N - \frac{K^*}{N}\right) > 0$, therefore

$$H_{RO}\left(\Theta\right) + \theta^N H_{RO}^{'}\left(\Theta\right) < H_{RO}\left(\Theta\right) + \frac{\Theta}{N} H_{RO}^{'}\left(\Theta\right) < H_{RO}\left(K^*\right) + \frac{K^*}{N} H_{RO}^{'}\left(K^*\right) < 0$$

by condition (5), hence $\frac{\partial \Pi_{RO}^N}{\partial \theta^N}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}, \theta^N\right) < 0$ for all $\theta^N > \frac{K^*}{N}$. No positive deviation is profitable. $\theta^n = \frac{K^*}{N}$ for all n is therefore an equilibrium.

We now prove $\theta^n = \frac{K^*}{N} \geq k^n$ for all n is the unique symmetric equilibrium. Since $\frac{\partial \Pi_{RO}^n}{\partial \theta^n}\left(\theta^n; \boldsymbol{\theta}_{-n}\right) > 0$, no equilibrium exists for θ^n such that $\theta^n \geq k^n$ and $\Theta \leq K^*$.

Finally, consider the case $\theta^n = \frac{\Theta}{N} > \frac{K^*}{N}$ for all n:

$$\frac{\partial \Pi_{RO}^n}{\partial \theta^n}\left(\frac{\Theta}{N}, ..., \frac{\Theta}{N}\right) = h\left(\Theta\right) + \frac{\Theta}{N} h^{'}\left(\Theta\right) - \frac{N-1}{N}\frac{K}{\Theta} K \Psi\left(K, \bar{p}^S\right) < 0.$$

There exists no symmetric equilibrium with $\frac{\Theta}{N} > \frac{K^*}{N}$.

C.3 Equilibrium investment

In the first stage, producers decide on capacity, taking into account the equilibrium of the options market. Denote $V^n\left(k^n; \mathbf{k}_{-n}\right)$ producer n profit function:

$$V^n\left(k^n; \mathbf{k}_{-n}\right) = \Pi_{RO}^n\left(k^n, \frac{K^*}{N}; \mathbf{k}_{-n}, \frac{\mathbf{K}^*}{\mathbf{N}}\right) = \Pi^n\left(k^n; \mathbf{k}_{-n},\right) + \frac{K^*}{N} r + \left(k^n - \frac{K}{N}\right) \Psi\left(K, \bar{p}^S\right).$$

Differentiation with respect to k^n yields

$$\frac{\partial V^n}{\partial k^n} = \frac{\partial \Pi^n}{\partial k^n} + \frac{N-1}{N} \Psi\left(K, \bar{p}^S\right) + \left(k^n - \frac{K}{N}\right) \frac{\partial \Psi}{\partial K}. \tag{16}$$

A necessary condition for a symmetric equilibrium $k^n = \frac{K}{N}$ is:

$$\frac{\partial V^n}{\partial k^n}\left(\frac{K}{N},...,\frac{K}{N}\right) = \frac{\partial \Pi^n}{\partial k^n}\left(\frac{K}{N},...,\frac{K}{N}\right) + \frac{N-1}{N}\Psi\left(K,\bar{p}^S\right)$$

$\frac{\partial V^n}{\partial k^n}\left(\frac{K}{N},...,\frac{K}{N}\right)$ is decreasing since $\frac{\partial \Pi^n}{\partial k^n}\left(\frac{K}{N},...,\frac{K}{N}\right)$ is decreasing and $\frac{\partial \Psi}{\partial K} < 0$. $\frac{\partial V^n}{\partial k^n}(0,...,0) = \frac{\partial \Pi^n}{\partial k^n}(0,...,0) + \frac{N-1}{N}\Psi\left(0,\bar{p}^S\right) > 0$ since (i) $\frac{\partial \Pi^n}{\partial k^n}(0,...,0) > 0$ and (ii) $\Psi\left(0,\bar{p}^S\right) > 0$ by construction. $\lim_{K\to+\infty}\frac{\partial V^n}{\partial k^n}(K) = -r < 0$. Hence, there exists a unique $K^C_{RO} > 0$ such that $\frac{\partial \Pi^n_{RO}}{\partial k^n}\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N}\right) = 0$. This is equation (8). We prove in the main text that $K^C\left(\bar{p}^S\right) \leq K^C_{RO} < K^*$.

We prove below that $k^n = \frac{K^C_{RO}}{N}$ for all n is an equilibrium, distinguishing the two cases $t^N(K) \leq \bar{t}\left(K,\bar{p}^S\right)$ and $t^N(K) > \bar{t}\left(K,\bar{p}^S\right)$.

C.3.1 Generation produces at capacity before the strike price is reached

Consider first a negative deviation: $k^1 < \frac{K^C_{RO}}{N}$ while $k^n = \frac{K^C_{RO}}{N}$ for all $n > 1$. Total installed capacity is $K = k^1 + \frac{N-1}{N}K^C_{RO} < K^C_{RO}$. Substituting expression (12) for $\frac{\partial \Pi^n}{\partial k^n}\left(k^1,\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N}\right)$ into equation (16)

$$\begin{aligned}\frac{\partial V^1}{\partial k^1}\left(k^1,\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N}\right) &= \int_{t^1}^{t^N(K)}\left(\rho\left(\hat{Q}\left(k^1;t\right)\right) + k^1\rho_q\left(\hat{Q}\left(k^1;t\right)\right)\frac{\partial \hat{Q}}{\partial k^1} - c\right)f(t)\,dt \\ &+ \int_{t^N(K)}^{\bar{t}\left(K,\bar{p}^S\right)}\left(\rho(K) + k^1\rho_q(K) - c\right)f(t)\,dt \\ &+ \int_{\bar{t}\left(K,\bar{p}^S\right)}^{+\infty}\left(\left(\bar{p}^S - c\right) + \frac{N-1}{N}\left(\rho(K,t) - \bar{p}^S\right) + \left(k^1 - \frac{K}{N}\right)\rho_q(K,t)\right)f(t)\,dt - r.\end{aligned}$$

Substituting in equation (8), observing that $t^N(K) < t^N\left(K_{RO}^C\right)$ and $\bar{t}\left(K, \bar{p}^S\right) < \bar{t}\left(K_{RO}^C, \bar{p}^S\right)$ since $K < K_{RO}^C$, and rearranging yields

$$\begin{aligned}
\frac{\partial V^1}{\partial k^1}\left(k^1, \frac{K_{RO}^C}{N}, ..., \frac{K_{RO}^C}{N}\right) = & \int_{t^1}^{t^N(K)} \left(\rho\left(\hat{Q}\right) + k_q^1 \rho\left(\hat{Q}\right) \frac{\partial \hat{Q}}{\partial k^1} - c\right) f(t)\, dt \\
& + \int_{t^N(K)}^{t^N\left(K_{RO}^C\right)} \left(\rho(K) + k_q^1 \rho(K) - c\right) f(t)\, dt \\
& + \int_{t^N\left(K_{RO}^C\right)}^{\bar{t}\left(K, \bar{p}^S\right)} \left(\rho(K) + k_q^1 \rho(K) - \left(\rho\left(K_{RO}^C\right) + \frac{K_{RO}^C}{N} \rho_q\left(K_{RO}^C\right)\right)\right) f(t)\, dt \\
& + \int_{\bar{t}\left(K, \bar{p}^S\right)}^{\bar{t}\left(K_{RO}^C, \bar{p}^S\right)} \begin{pmatrix} \bar{p}^S - \rho\left(K_{RO}^C; t\right) - \frac{K_{RO}^C}{N} \rho_q\left(K_{RO}^C\right) \\ + \frac{N-1}{N}\left(\rho(K;t) - \bar{p}^S + \rho_q(K;t)\left(k^1 - \frac{K_{RO}^C}{N}\right)\right) \end{pmatrix} f(t)\, dt \\
& + \frac{N-1}{N} \int_{\bar{t}\left(K_{RO}^C, \bar{p}^S\right)}^{+\infty} \left(\rho(K;t) - \rho\left(K_{RO}^C; t\right) + \rho_q(K;t)\left(k^1 - \frac{K_{RO}^C}{N}\right)\right) f(t)\, dt.
\end{aligned}$$

Each term is positive:

1. $\rho\left(\hat{Q}\right) + k_q^1 \rho\left(\hat{Q}\right) \frac{\partial \hat{Q}}{\partial k^1} - c = \left(k^1 - \phi^N\right) \rho_q\left(\hat{Q}\right) \frac{\partial \hat{Q}}{\partial k^1} \geq 0$ for $t \in \left[t^1, t^N(K)\right]$

2. $\rho\left(K; t^N(K)\right) + k_q^1 \rho\left(K; t^N(K)\right) = c$, and $\rho_t(K) + k^1 \rho_{qt}(K) \geq 0$, hence $\rho(K) + k_q^1 \rho(K) - c \geq 0$ for $t \in \left[t^N(K), t^N\left(K_{RO}^C\right)\right]$

3. $\rho_q(Q) + q\rho_{qq}(Q) < 0$, hence $\rho(K) + k^1 \rho_q(K) \geq \rho(K) + \frac{K_{RO}^C}{N} \rho_q(K) \geq \rho\left(K_{RO}^C\right) + \frac{K_{RO}^C}{N} \rho_q\left(K_{RO}^C\right)$ for $t \in \left[t^N\left(K_{RO}^C\right), \bar{t}\left(K, \bar{p}^S\right)\right]$

4. $\rho\left(K_{RO}^C; t\right) \leq \bar{p}^S$ for $t \leq \bar{t}\left(K_{RO}^C, \bar{p}^S\right)$ and $\rho(K;t) \geq \bar{p}^S$ for $t \geq \bar{t}\left(K, \bar{p}^S\right)$, hence

$$\left(\bar{p}^S - \rho\left(K_{RO}^C; t\right) - \frac{K_{RO}^C}{N} \rho_q\left(K_{RO}^C\right) + \frac{N-1}{N}\left(\rho(K;t) \geq \bar{p}^S\right)\right) \geq 0$$

   for $t \in \left[t^{\bar{p}^S}(K), t^{\bar{p}^S}\left(K_{RO}^C\right)\right]$

5. $K \leq K_{RO}^C$, yields $\rho(K;t) \geq \rho\left(K_{RO}^C; t\right)$ for all t

Thus, $\frac{\partial \Pi_{RO}^1}{\partial k^1}\left(k^1, \frac{K_{RO}^C}{N}, ..., \frac{K_{RO}^C}{N}\right) > 0$: a negative deviation is not profitable.

Consider now a positive deviation, $k^N > \frac{K_{RO}^C}{N}$ while $k^n = \frac{K_{RO}^C}{N}$ for all $n < N$. $K = k^N + \frac{N-1}{N} K_{RO}^C > K_{RO}^C$.

$$\begin{aligned}\frac{\partial^2 V^N}{(\partial k^N)^2}\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N},k^N\right) &= \frac{\partial^2\Pi^N}{(\partial k^N)^2}+2\frac{N-1}{N}\frac{\partial\Psi}{\partial K}+\left(k^N-\frac{K}{N}\right)\frac{\partial^2\Psi}{(\partial K)^2}\\ &= \frac{\partial^2\Pi^N}{(\partial k^N)^2}+\frac{N-1}{N}\int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left[2\rho_q(K;t)+\left(k^N-\frac{K^C_{RO}}{N}\right)\rho_{qq}(K;t)\right]f(t)\,dt\\ &\quad -\left(k^N-\frac{K}{N}\right)\rho_q\left(K;\bar{t}\left(K,\bar{p}^S\right)\right)f\left(\bar{t}\left(K,\bar{p}^S\right)\right)\frac{\partial\bar{t}\left(K,\bar{p}^S\right)}{\partial K}.\end{aligned}$$

Substituting in $\frac{\partial^2\Pi^N}{(\partial k^N)^2}$ from equation (13),

$$\begin{aligned}\frac{\partial^2 V^N}{(\partial k^N)^2}\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N},k^N\right) &= \int_{t^N}^{\bar{t}(K,\bar{p}^S)}\left[2\rho_q\left(\hat{K};t\right)+k^N\rho_{qq}\left(\hat{K};t\right)\right]f(t)\,dt\\ &\quad +\frac{N-1}{N}\int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left[2\rho_q(K;t)+\left(k^N-\frac{K^C_{RO}}{N}\right)\rho_{qq}(K;t)\right]f(t)\,dt\\ &\quad +\frac{K}{N}\rho_q\left(K;\bar{t}\left(K,\bar{p}^S\right)\right)f\left(\bar{t}\left(K,\bar{p}^S\right)\right)\frac{\partial\bar{t}\left(K,\bar{p}^S\right)}{\partial K}\\ &< 0.\end{aligned}$$

A positive deviation is not profitable. Therefore $\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N}\right)$ constitutes an equilibrium. Furthermore,

$$\begin{aligned}\frac{\partial^2 V^n}{\partial(k^n)^2}\left(\frac{K}{N},...,\frac{K}{N}\right) &= \int_{t^N}^{t^{\bar{p}^S}}\left[2\rho_q(K;t)+\frac{K}{N}\rho_{qq}(K;t)\right]f(t)\,dt+2\frac{N-1}{N}\int_{t^{\bar{p}^S}}^{+\infty}\rho_q(K;t)f(t)\,dt\\ &\quad +\frac{K}{N}\rho_q\left(K;\bar{t}\left(K,\bar{p}^S\right)\right)f\left(\bar{t}\left(K,\bar{p}^S\right)\right)\frac{\partial\bar{t}\left(K,\bar{p}^S\right)}{\partial K}\\ &< 0\end{aligned}$$

hence $\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N}\right)$ is the unique symmetric equilibrium.

C.3.2 The strike price is reached before generation produces at capacity

Substituting expression (15) for $\frac{\partial\Pi^n}{\partial k^n}\left(k^1,...,k^N\right)$ into equation (16) yields

$$\frac{\partial V^n}{\partial k^n}=\int_{\tilde{t}^n}^{+\infty}\left(\bar{p}^S-c\right)f(t)\,dt+\frac{N-1}{N}\int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left(\rho(K;t)-\bar{p}^S\right)+\left(k^n-\frac{K}{N}\right)\frac{\partial\Psi}{\partial K}\left(K,\bar{p}^S\right)-r.$$

Suppose $k^1 = ... = k^{N-1} = \frac{K_{RO}^C}{N}$. Then,

$$\begin{aligned}\frac{\partial^2 V^N}{\partial (k^N)^2} &= -\left(\bar{p}^S - c\right) f\left(\tilde{t}^N\right)\frac{\partial \tilde{t}^N}{\partial K} + \frac{N-1}{N}\int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left[2\rho_q(K;t) + \left(k^N - \frac{K_{RO}^C}{N}\right)\rho_{qq}(K;t)\right] f(t)\, dt \\ &\quad -\frac{N-1}{N}\left(k^N - \frac{K_{RO}^C}{N}\right)\rho_q\left(K;\bar{t}\left(K,\bar{p}^S\right)\right) f\left(\bar{t}\left(K,\bar{p}^S\right)\right)\frac{\partial \bar{t}\left(K,\bar{p}^S\right)}{\partial K}.\end{aligned}$$

Thus, if $k^N < \frac{K_{RO}^C}{N}$, $\frac{\partial^2 V^N}{\partial (k^N)^2} < 0$: a negative deviation is not profitable.

Consider now a positive deviation, $k^N > \frac{K_{RO}^C}{N}$. Since producer N is the last producer to be constrained, $\tilde{t}^N = \bar{t}\left(K,\bar{p}^S\right)$. Substituting equation (15) into equation (16) yields

$$\begin{aligned}\frac{\partial V^n}{\partial k^n}\left(\frac{K_{RO}^C}{N},...,\frac{K_{RO}^C}{N},k^N\right) &= \int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left[\left(\bar{p}^S - c\right) + \frac{N-1}{N}\left(\left(\rho(K;t) - \bar{p}^S\right) + \left(k^N - \frac{K_{RO}^C}{N}\right)\rho_q(K;t)\right)\right] f(t)\, dt \\ &\quad -\int_{\bar{t}\left(K_{RO}^C,\bar{p}^S\right)}^{+\infty}\left[\left(\bar{p}^S - c\right) + \frac{N-1}{N}\left(\rho\left(K_{RO}^C;t\right) - \bar{p}^S\right)\right] f(t)\, dt \\ &= -\int_{\bar{t}\left(K_{RO}^C,\bar{p}^S\right)}^{\bar{t}\left(K,\bar{p}^S\right)}\left(\bar{p}^S - c\right) f(t)\, dt \\ &\quad +\frac{N-1}{N}\left[\begin{array}{c}\int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\left(\rho(K;t) - \rho\left(K_{RO}^C;t\right)\right) f(t)\, dt \\ -\int_{\bar{t}\left(K_{RO}^C,\bar{p}^S\right)}^{\bar{t}\left(K,\bar{p}^S\right)}\left(\rho\left(K_{RO}^C;t\right) - \bar{p}^S\right) f(t)\, dt \\ +\left(k^N - \frac{K_{RO}^C}{N}\right)\int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\rho_q(K;t) f(t)\, dt\end{array}\right].\end{aligned}$$

Since $K > K_{RO}^C$, then $\bar{t}\left(K,\bar{p}^S\right) > \bar{t}\left(K_{RO}^C,\bar{p}^S\right)$ and $\rho(K;t) < \rho\left(K_{RO}^C;t\right)$, hence the first three terms are negative. The last term is negative since $k^N > \frac{K_{RO}^C}{N}$ and $\rho_q < 0$. Thus, $\frac{\partial V^n}{\partial k^n}\left(\frac{K_{RO}^C}{N},...,\frac{K_{RO}^C}{N},k^N\right) < 0$: a positive deviation is not profitable. $\left(\frac{K_{RO}^C}{N},...,\frac{K_{RO}^C}{N}\right)$ is therefore an equilibrium. Furthermore,

$$\frac{\partial^2 V^n}{\partial (k^n)^2}\left(\frac{K}{N},...,\frac{K}{N}\right) = -\left(\bar{p}^S - c\right) f\left(\bar{t}\right)\frac{\partial \bar{t}}{\partial K} + 2\frac{N-1}{N}\int_{\bar{t}(K,\bar{p}^S)}^{+\infty}\rho_q(K;t) f(t)\, dt < 0$$

hence $\left(\frac{K_{RO}^C}{N},...,\frac{K_{RO}^C}{N}\right)$ is the unique symmetric equilibrium.

D Energy cum operating reserves market

Define the total surplus

$$\mathring{\mathcal{S}}(p,\gamma;t) = \alpha S(p(t);t) + (1-\alpha)\mathcal{S}(p,\gamma;t)$$

and total demand

$$\mathring{\mathcal{D}}(p,\gamma;t) = \alpha S(p(t);t) + (1-\alpha)\mathcal{D}(p,\gamma;t).$$

The social planner's program is:

$$\begin{array}{ll} \max\limits_{\{p(t),\gamma(t)\},K} & \mathbb{E}\left\{\mathring{\mathcal{S}}(p(t),\gamma(t);t) - c\mathring{\mathcal{D}}(p(t),\gamma(t);t)\right\} - rK \\ st: & (1+h(t))\mathring{\mathcal{D}}(p(t),\gamma(t);t) \leq K \qquad (\lambda(t)) \end{array}$$

The associated Lagrangian is:

$$\mathcal{L} = \mathbb{E}\left\{\mathring{\mathcal{S}}(p(t),\gamma(t);t) - c\mathring{\mathcal{D}}(p(t),\gamma(t);t) + \lambda(t)\left[K - (1+h(t))\mathring{\mathcal{D}}(p(t),\gamma(t);t)\right]\right\} - rK$$

and:

$$\begin{cases} \frac{\partial \mathcal{L}}{\partial p(t)} = \{p(t) - [c + (1+h(t))\lambda(t)]\} \frac{\partial \mathring{\mathcal{D}}}{\partial p(t)} \\ \frac{\partial \mathcal{L}}{\partial \gamma(t)} = \left\{v_t\left[\mathring{\mathcal{D}}(p(t),\gamma(t)),\gamma(t)\right] - [c + (1+h(t))\lambda(t)]\right\} \frac{\partial \mathring{\mathcal{D}}}{\partial \gamma(t)} \\ \frac{\partial \mathcal{L}}{\partial K} = \mathbb{E}[\lambda(t)] - r \end{cases}$$

First, off-peak $\lambda(t) = 0$ and $\gamma(t) = 1$. Then $p(t) = c = w(t)$. This holds as long as $\rho\left(\frac{Q}{1+h(t)}, t\right) = c$ $for\ Q \leq K \Leftrightarrow t \leq \bar{t}_{OR}(K,c)$.

Second, on-peak, if constant price customers are not curtailed, $(1+h(t))\mathring{\mathcal{D}}(p(t);1,t) = K$ hence $\lambda(t) > 0$ and $\gamma(t) = 1$. Then $p(t) = c + \lambda(t)(1+h(t)) = \rho\left(\frac{K}{1+h(t)};t\right)$ and $\lambda(t) = w(t) - c = \frac{p(t)-c}{1+h(t)} > 0$.

Finally, constant price customers may have to be curtailed, $(1+h(t))\mathring{\mathcal{D}}(p(t),\gamma^*(t);t) = K$ for $\gamma^*(t) < 1$ such that $(1+h(t))\mathring{\mathcal{D}}(\bar{v},\gamma^*(t);t) = K$. Then $(1+h(t))\lambda(t) = \rho\left(\frac{K}{1+h(t)};t\right) - c$ as before.

The optimal capacity K^*_{OR} is then defined by $\mathbb{E}[\lambda(t)] = r$ which yields equation (10).