The visible hand: ensuring optimal investment in electric power generation

Thomas-Olivier Léautier

Toulouse School of Economics (IDEI)

December 2013

Outline

- Related literature
- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets
- Policy implications

Outline

- Related literature

- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets
- Policy implications

Related literature

- *Generation investment in restructured power markets:* Borenstein and Holland (2005), Joskow and Tirole (2007), building on Boiteux (1949). Murphy and Smeers (2005), Boom (2009), Fabra et al. (2011). Two-stage Cournot game by Zöttl (2011). Garcia and Shen (2010)) multiperiod investment decisions
- *Possible "corrective" market designs:* Stoft (2002), Hogan (2005), Cramton and Stoft (2006 and 2008) and Cramton and Ockenfels (2011), Joskow and Tirole (2007), Chao and Wilson (2005), Zöttl (2011)

Outline

- Related literature
- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets
- Policy implications

Uncertainty, supply and demand

- State of the world $t \geq 0$; cumulative distribution $F(.)$; $f(.) = F^{'}(.)$

Uncertainty, supply and demand

- State of the world $t \geq 0$; cumulative distribution $F(.)$; $f(.) = F'(.)$
- A single generation technology, marginal cost c, investment cost r $(€/MWh)$. Sufficient to examine capacity adequacy

Uncertainty, supply and demand

- State of the world $t \geq 0$; cumulative distribution $F(.)$; $f(.) = F^{'}(.)$
- A single generation technology, marginal cost c, investment cost r $(€/MWh)$. Sufficient to examine capacity adequacy
- Homogenous customers; individual demand $D(p,t)$; inverse demand $P(q,t)$

$$P_q = \frac{\partial P}{\partial q} < 0, \; P_t = \frac{\partial P}{\partial t} > 0, \lim_{Q \to +\infty} P(Q,t) < c$$

and

$$P_q(Q,t) + qP_{qq}(Q,t) < 0, P_t(Q,t) + qP_{qt}(Q,t) > 0.$$

Uncertainty, supply and demand

- State of the world $t \geq 0$; cumulative distribution $F(.)$; $f(.) = F^{'}(.)$
- A single generation technology, marginal cost c, investment cost r $(€/MWh)$. Sufficient to examine capacity adequacy
- Homogenous customers; individual demand $D(p,t)$; inverse demand $P(q,t)$

$$P_q = \frac{\partial P}{\partial q} < 0, \; P_t = \frac{\partial P}{\partial t} > 0, \lim_{Q \to +\infty} P(Q,t) < c$$

and

$$P_q(Q,t) + qP_{qq}(Q,t) < 0, P_t(Q,t) + qP_{qt}(Q,t) > 0.$$

- Gross consumers surplus

$$S(p,t) = \int_0^{D(p,t)} P(q,t)\, dq.$$

Constant price customers and market failure to clear

Only $\alpha \in (0, 1]$ customers face and react to real time wholesale price ("price reactive" customers). Remaining $(1 - \alpha)$ customers face p^R constant in all states of the world ("constant price" customers). Thus, market may not clear, hence administrative intervention may be required

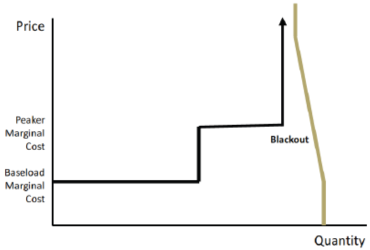


Figure 2.1. Absence of sufficient demand response

Administrative curtailment and Value of Lost Load

- *Serving ratio* $\gamma \in [0,1]$. $\mathcal{D}(p,\gamma,t)$ demand for serving ratio γ
- $\mathcal{D}_t > 0$, $\mathcal{D}_\gamma > 0$, $\mathcal{D}(p,0,t) = 0$, $\mathcal{D}(p,1,t) \equiv D(p,t)$
- $\mathcal{S}(p,\gamma,t)$ is gross surplus for serving ratio γ. $\mathcal{S}(p,1,t) \equiv S(p,t)$
- Value of Lost Load ($VoLL$)

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

Assumption

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

An example of VoLL

- Since customers are homogeneous, rationing is proportional: $\mathcal{D}(p, \gamma, t) = \gamma D(p, t)$

An example of VoLL

- Since customers are homogeneneous, rationing is proportional: $\mathcal{D}(p, \gamma, t) = \gamma D(p, t)$
- If rationing is anticipated, $\mathcal{S}(p, \gamma, t) = \gamma S(p, t)$

An example of VoLL

- Since customers are homogeneneous, rationing is proportional: $\mathcal{D}(p, \gamma, t) = \gamma D(p, t)$
- If rationing is anticipated, $\mathcal{S}(p, \gamma, t) = \gamma S(p, t)$
- Thus,

$$v(p, \gamma, t) = \frac{S(p, t)}{D(p, t)} > p$$

An example of VoLL

- Since customers are homogeneneous, rationing is proportional: $\mathcal{D}(p, \gamma, t) = \gamma D(p, t)$
- If rationing is anticipated, $\mathcal{S}(p, \gamma, t) = \gamma S(p, t)$
- Thus,

$$v(p, \gamma, t) = \frac{S(p, t)}{D(p, t)} > p$$

- For example, if $P(Q, t) = a(t) - bQ$, with $a(t) > 0$, $a'(t) > 0$, and $b > 0$, then

$$S(p, t) = \left(a(t) - \frac{b}{2} D(p, t)\right) D(p, t) \Rightarrow v(p, t) = \frac{a(t) + p}{2}$$

Administrative intervention

- If *SO* knew the *VoLL* for every rationing technology and state of the world (and in practice, for each customer class), the second best would be achieved. Analytical approach presented in this article

Administrative intervention

- If *SO* knew the *VoLL* for every rationing technology and state of the world (and in practice, for each customer class), the second best would be achieved. Analytical approach presented in this article
- In reality, *SO* does not know the *VoLL*, that depends on the customer class, state of the world, and duration and conditions of outages. Extremely wide range of estimates, from 2 000 $\$/MWh$ in the British Pool in the 1990*s* to 200 000 $\$/MWh$. She uses her best estimate of the average *VoLL*, and prioritizes curtailment by geographic zones (economic activity, political weight, etc.), thus implementing a third best

Administrative intervention

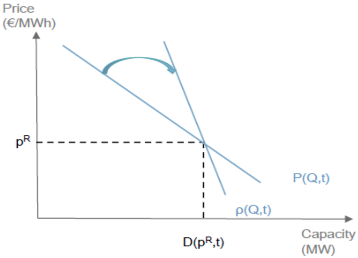
- If SO knew the $VoLL$ for every rationing technology and state of the world (and in practice, for each customer class), the second best would be achieved. Analytical approach presented in this article
- In reality, SO does not know the $VoLL$, that depends on the customer class, state of the world, and duration and conditions of outages. Extremely wide range of estimates, from 2 000 $\$/MWh$ in the British Pool in the 1990s to 200 000 $\$/MWh$. She uses her best estimate of the average $VoLL$, and prioritizes curtailment by geographic zones (economic activity, political weight, etc.), thus implementing a third best
- Both approaches produce downward sloping demand curves, and are analytically equivalent

Residual inverse demand curve

- Price reactive customers face the wholesale spot price, hence are never curtailed at the optimum
- $\rho(Q,t)$ the residual inverse demand curve with possible curtailment of constant price customers

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

where γ^* is the optimal serving ratio

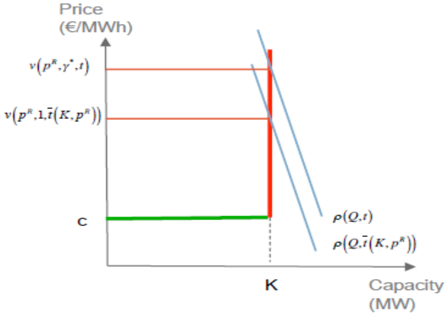


Possible curtailment

- If $\rho(K,t) \leq v\left(p^R, 1, t\right)$, $\gamma^*(K,t) = 1$. If $\rho(K,t) > v\left(p^R, 1, t\right)$, $\gamma^*(K,t) < 1$ defined by:

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

- If it exists, $\bar{t}\left(K, p^R\right)$ is the first state of the world when curtailment occurs. Assume curtailment occurs in all states $t \geq \bar{t}\left(K, p^R\right)$



Optimal capacity

- $\hat{t}_0(K,c)$ the first on-peak state of the world: $\rho(K,\hat{t}_0(K,c)) = c$, and $\Psi_0(K,c)$ the marginal social value of capacity

$$\Psi_0(K,c) = \int_{\hat{t}_0(K,c)}^{+\infty} (\rho(K,t) - c)\, f(t)\, dt$$

- Suppose $\rho(0,t) > c$ for all $t \geq 0$, and $\mathbb{E}[\rho(0,t)] > c + r$
- The optimal capacity K^* is uniquely defined by

$$\Psi_0(K^*,c) = \int_{\hat{t}_0(K,c)}^{+\infty} (\rho(K^*,t) - c)\, f(t)\, dt = r \tag{2}$$

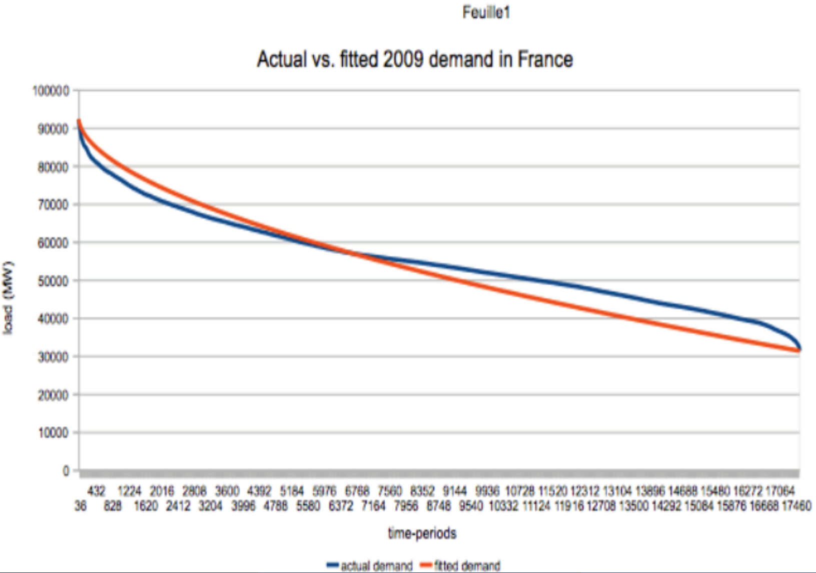
Numerical illustration

Specification: (i) linear inverse demand $P(q,t) = a(t) - bq$ where $a(t) = a_0 - a_1 e^{-\lambda_2 t}$, (ii) $f(t) = \lambda_1 e^{-\lambda_1 t}$, and (iii) anticipated (and proportional) rationing. a_0, a_1, λ, and $bQ^\infty = \frac{a_0 - p^R}{b}$ estimated by Maximum Likelihood using the load duration curve for France in 2010

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

- $c = 72$ €/MWh and $r = 6$ €/MWh, (CT, median case, *IEA* (2010)). $p^R = 50$ €/MWh.

Actual vs. estimated load duration curves



Perfect competition benchmark

- Perfectly competitive market ($N \to +\infty$)
- For $\eta = -0.1$

α (%)	2	5	10
K^* / Q^∞	.983	.975	.964

- For $\eta = -0.01$

α (%)	2	5	10
K^* / Q^∞	.987	.982	.976

- If $\eta = -0.01$, no rationing occurs for the optimal capacity for $\alpha \geq 3.9\%$ ($\alpha \geq 13.9\%$ if $\eta = -0.1$)
- If demand is more elastic (higher $|\eta|$), optimal capacity is lower, thus curtailment occurs for higher values of α

Outline

- Related literature
- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets
- Policy implications

Imperfect competition

- N producers play a two-stage game
  1. in stage 1, producer n installs capacity k^n
  2. in stage 2, he competes à la Cournot in each spot market t, facing inverse demand $\rho(Q,t)$, and produces $q^n(t) \leq k^n$
- Solved by backwards induction
- $Q(t) = \sum_{n=1}^{N} q^n(t)$ and $K = \sum_{n=1}^{N} k^n$ respectively aggregate production in state t and aggregate installed capacity
- K^C is symmetric the equilibrium capacity. $\hat{t}(K,c)$ is defined by:

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

Price cap

- To limit the exercise of market power, the *SO* may impose a cap $\bar{p}^W$ on the wholesale power price.

$$c + r < \bar{p}^W \leq \rho\,(0, 0) \tag{3}$$

- If it exists, $\hat{t}_0\left(Q, \bar{p}^W\right)$ is the first state of the world where the cap binding for production Q:

$$\rho\left(Q, \hat{t}_0\left(Q, \bar{p}^W\right)\right) = \bar{p}^W.$$

- The aggregate capacity constraint may be binding before or after the price cap constraint in the relevant range, i.e., $\hat{t}\,(K, c) < \hat{t}_0\left(K, \bar{p}^W\right)$ or $\hat{t}\,(K, c) \geq \hat{t}_0\left(K, \bar{p}^W\right)$, which occurs if α and $\bar{p}^W$ are very low
- Both cases yield the same economic insights, with slightly different equations. Only the case $\hat{t}\,(K, c) < \hat{t}_0\left(K, \bar{p}^W\right)$ is presented here

Marginal value of capacity wiht a price cap

- $\Pi^n\left(k^n, \mathbf{k}^{-n}, \bar{p}^W\right)$ is producer's n profit for the two-stage game
- For states $t \leq \hat{t}_0\left(K, \bar{p}^W\right)$, producers face inverse demand $\rho\left(K, t\right)$, while they face "horizontal" inverse demand $\bar{p}^W$ for $t \geq \hat{t}_0\left(K, \bar{p}^W\right)$
- The marginal (private) value of capacity at a symmetric equilibrium is

$$\begin{aligned} \Omega\left(K, p\right) &= \int_{\hat{t}(K,c)}^{\hat{t}_0(K,p)} \left(\rho\left(K, t\right) + \frac{K}{N}\rho_q\left(K, t\right) - c\right) f\left(t\right) dt \\ &+ \int_{\hat{t}_0(K,p)}^{+\infty} \left(p - c\right) f\left(t\right) dt. \end{aligned}$$

Equilibrium capacity and the non-intuitive impact of a price cap ...

- Imposition of the price cap $\bar{p}^W$ leads to curtailment

Equilibrium capacity and the non-intuitive impact of a price cap ...

- Imposition of the price cap $\bar{p}^W$ leads to curtailment
- Equilibrium capacity K^C uniquely defined by

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

Equilibrium capacity and the non-intuitive impact of a price cap ...

- Imposition of the price cap $\bar{p}^W$ leads to curtailment
- Equilibrium capacity K^C uniquely defined by

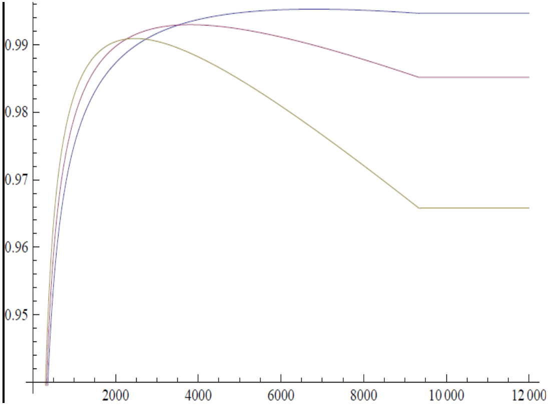
$$\Omega\left(K^C, \bar{p}^W\right) = r$$

- Thus

$$\frac{dK^C}{d\bar{p}^W}\left(-\frac{\partial\Omega}{\partial K}\right) = 1 - F\left(\hat{t}_0\right) + \frac{K^C}{N}\rho_q\left(K^C, \hat{t}_0\right) f\left(\hat{t}_0\right)\frac{\partial\hat{t}_0}{\partial p}$$

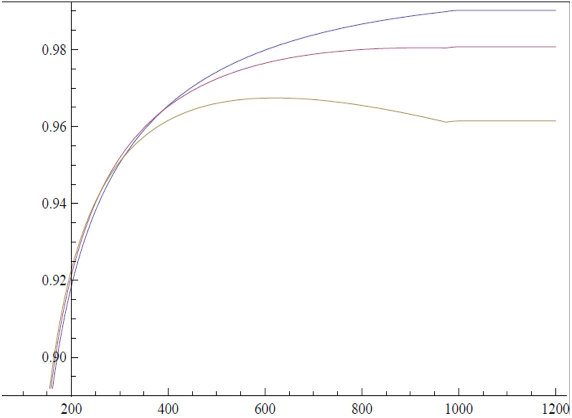
Imperfectly competitive investment for low elasticity

$\eta = -0.01$ and $N = 6$. $K^C\left(\bar{p}^W\right)/K^*(\alpha)$ for $\alpha = 2\%$ (top line), $\alpha = 5\%$ (center line), and $\alpha = 10\%$ (bottom line)



Imperfectly competitive investment for high elasticity

$\eta = -0.1$ and $N = 6$. $K^C\left(\bar{p}^W\right)/K^*(\alpha)$ for $\alpha = 2\%$ (top line), $\alpha = 5\%$ (center line), and $\alpha = 10\%$ (bottom line)



Outline

- Related literature
- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets
- Policy implications

Physical capacity certificates market description

1. The SO designs the rules of the energy and capacity markets. All parameters are set
2. Producers sell physical capacity certificates
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 capacity obligation (physical or financial)

Steps 2 and 3 can be inverted or simultaneous. Analysis is proven to be identical for all three timings.

Certificates demand curve

- *SO* imposes price cap $\bar{p}^W$ and procures at least K^* physical capacity certificates from producers
- ϕ^n and $\Phi = \sum_{m=1}^{N} \phi^m$ respectively the certificates sold by producer n and the aggregate volume of certificates sold. *SOs* offer a "smoothed" (inverse) demand curve:

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

where (i) r maximum price the *SO* is offering for capacity, (ii) $\Delta\bar{K} > 0$, and (iii) $h^{'}(\Phi) < 0$, $2h'(\Phi) + \phi h''(\Phi) < 0$ for all ϕ, and

$$\left| h^{'}(K^*) \right| \geq \frac{Nr}{K^*}. \tag{4}$$

Equilibrium with the physical capacity certificates market

Proposition

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.

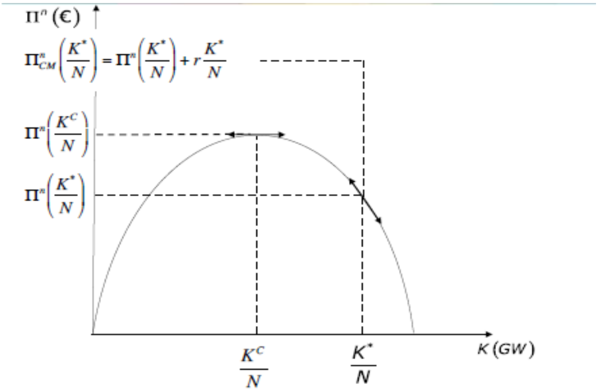
Proof.

$$\Pi^n_{CM} = \phi^n H(\Phi) + \Pi^n\left(k^n, \mathbf{k}_{-n}, \bar{p}^W\right),$$

thus a capacity market alone does not modify investment incentives. □

The *SO* must impose a performance mechanism in addition to the capacity market (Wolak (2006), *ISO* New England (2012))

Expected profits with a physical capacity certificates market



If strategic supply reduction is indeed the primary cause for under-investment, the possibility of a capacity market increases the *ex ante* incentives to under-invest (cf. Germany today)

Outline

- Related literature
- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets
- Policy implications

Market description

- *SO* purchases from producers, on behalf of customers, call options at strike price $\bar{p}^S$
  - If $p(t) \leq \bar{p}^S$, producers make no payment
  - If $p(t) > \bar{p}^S$, producer n pays $\left(p(t) - \bar{p}^S\right)$ times his share of the total options sold times the realized demand
- θ^n and $\Theta = \sum_{m=1}^{N} \theta^m$ respectively the options sold by producer n and the aggregate volume of options sold
- No cap on wholesale prices. *SO* (i) runs an auction for financial reliability options, using an inverse demand curve, and (ii) imposes $\theta^n \geq k^n$ (Cramton and Ockenfels (2011))
- When the spot price exceeds the strike price, price-reactive consumers pay $\bar{p}^S$ as the effective price. Demand does not depend on the spot price, which leads to rationing

Producers profits

Lemma

The expected profit of producer n is:

$$\Pi^n_{RO} = \theta^n H_{RO}(\Theta) + \Pi^n\left(k^n; \mathbf{k}_{-n}, \bar{p}^S\right) + \left(k^n - \frac{\theta^n}{\Theta}K\right)\Psi_0\left(K, \bar{p}^S\right).$$

Proof.

Reliability options are equivalent to imposing price cap $\bar{p}^S$*, then removing the cap, and imposing a payment proportional to the share of certificates sold. Thus, producer n first receives* $\Pi^n\left(k^n; \mathbf{k}_{-n}, \bar{p}^S\right)$*. However, for* $t \geq \hat{t}_0\left(K, \bar{p}^S\right)$*, he receives* $\left(\rho\left(K, t\right) - \bar{p}^S\right)$ *on every unit he sells since no price cap is imposed, and pays* $\left(\rho\left(K, t\right) - \bar{p}^S\right)$ *on his fraction* $\frac{\theta^n}{\Theta}$ *of total demand. Since* $\hat{t}\left(K, c\right) \leq \hat{t}_0\left(K, \bar{p}^S\right)$*, this occurs on-peak, hence producer n produces* k^n *and aggregate demand is* K*.* □

Equilibrium capacity with financial reliability options

Proposition

Reliability options reduce but do not solve the underinvestment problem. K_{RO}^C, the unique symmetric equilibrium of the options and investment game, verifies:

$$K^C\left(\bar{p}^S\right) \leq K_{RO}^C < K^*$$

with equality occurring when $N = 1$.

Proof.

Suppose for example producers first invest, then sell certificates. Solving backwards, one shows that $\theta^n = \frac{K^*}{N}$ is the unique symmetric equilibrium in the certificates market. This then yields the necessary and sufficient first-order condition for a symmetric equilibrium:

$$\frac{\partial \Pi_{RO}^n}{\partial k^n} = \frac{\partial \Pi^n}{\partial k^n} + \frac{N-1}{N}\Psi_0\left(K, \bar{p}^S\right) = 0. \quad (5)$$

Performance of reliability options

- For $N > 1$, reliability options are more effective than physical certificates. However, not sufficient to restore optimal investment incentives: at the symmetric equilibrium, the penalty represents only $\frac{N-1}{N}\left(\rho\left(K;t\right)-\bar{p}^{S}\right)$
- Result mirrors/extends Allaz and Villa (1993) to options (and not forward sales), and multiple states of the world.

Equivalence between the two "dual markets" designs when "no short sale" condition is added

Proposition

If (i) the SO imposes and monitors that the installed capacity exceeds the options sold by each generator: $\theta^n \leq k^n$, (ii) the wholesale price cap in the capacity market is set equal to the strike price of the reliability option $(\bar{p}^S = \bar{p}^W)$, and (iii) the demand functions for reliability options and for capacity credits are identical and satisfy condition (4), then (i) producers sell as many options as they install capacity, and (ii) both market designs yield the same symmetric equilibrium.

Proof.

Set $\theta^n = k^n$ in

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

Outline

- Related literature
- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets
- Policy implications

Market description

- *SOs* must secure operating reserves to protect the system against catastrophic failure
- Hogan (2005) proposes that the *SO* runs a single market for energy and operating reserves:
    - Energy producers receive the wholesale price $w(t)$
    - Operating reserves providers receive $w(t) - c$
    - Producers therefore indifferent between producing energy or providing reserves
- Operating reserves requirements are expressed as a percentage of demand, denoted $h(t)$, and assumed to be nondecreasing
- The retail price $p(t)$ is:

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

$\Leftrightarrow$

$$p(t) - c = (1 + h(t))(w(t) - c) \tag{6}$$

Socially optimal capacity

- 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 $\rho\left(.;t\right)$
- The marginal social value of capacity in state t is

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

- The marginal social value of capacity is

$$\Psi_0^{OR}\left(K\right)=\int_{\hat{t}_0^{OR}(K,c)}^{+\infty}\frac{\rho\left(\frac{K}{1+h(t)};t\right)-c}{1+h\left(t\right)}f\left(t\right)dt$$

where $\hat{t}_0^{OR}\left(K,c\right)\left(K,c\right)$ is uniquely defined by $\rho\left(\frac{K}{1+h(t)};\hat{t}_0^{OR}\left(K,c\right)\right)=c$.

Producers' problem

- In state t, producers 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 price $w(t)$ and retail price $\rho\left(\frac{S(t)}{1+h(t)}\right)$ are linked by equation (6)
- The problem is then isomorphic to the previous Sections, except that $\frac{s^n(t)}{1+h(t)}$ replaces production $q^n(t)$

Underinvestment

Proposition

If the SO runs an energy cum operating reserves market and imposes a price cap $\bar{p}^W$, *underinvestment occurs unless* (i) *generation is perfectly competitive, and* (ii) *the price cap is never expected to be binding.*

- Surprising result:
  - one would have expected the operating reserves market to alleviate the missing money problem, since (i) all capacity producing energy receives a higher price, and (ii) capacity providing reserve is also remunerated
  - However, these two effects are already included in the determination of the socially and privately optimal capacities K^*_{OR} and K^C_{OR}
  - Since capacity providing reserve capacity receive the same profit $(w(t) - c)$ as capacity producing energy, no additional profit is generated

Outline

- Related literature
- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets

- Policy implications

Policy implications from the analysis

1. As long as only a small share of electricity demand is responsive to price (less than 10%?), administrative intervention will be required to manage scarcity, either through a generation adequacy standard, or, equivalently a $VoLL$ estimate

Policy implications from the analysis

1. As long as only a small share of electricity demand is responsive to price (less than 10%?), administrative intervention will be required to manage scarcity, either through a generation adequacy standard, or, equivalently a *VoLL* estimate
2. If policy makers are confident markets are sufficiently competitive, this intervention is sufficient

Policy implications from the analysis

1. As long as only a small share of electricity demand is responsive to price (less than 10%?), administrative intervention will be required to manage scarcity, either through a generation adequacy standard, or, equivalently a $VoLL$ estimate
2. If policy makers are confident markets are sufficiently competitive, this intervention is sufficient
3. An energy cum operating reserves markets can be implemented to remunerate flexibility

Policy implications from the analysis

1. As long as only a small share of electricity demand is responsive to price (less than 10%?), administrative intervention will be required to manage scarcity, either through a generation adequacy standard, or, equivalently a *VoLL* estimate
2. If policy makers are confident markets are sufficiently competitive, this intervention is sufficient
3. An energy cum operating reserves markets can be implemented to remunerate flexibility
4. If policy makers are concerned about potential exercise of market power, policy intervention should aim to alleviate market power

Policy implications from the analysis

1. As long as only a small share of electricity demand is responsive to price (less than 10%?), administrative intervention will be required to manage scarcity, either through a generation adequacy standard, or, equivalently a *VoLL* estimate
2. If policy makers are confident markets are sufficiently competitive, this intervention is sufficient
3. An energy cum operating reserves markets can be implemented to remunerate flexibility
4. If policy makers are concerned about potential exercise of market power, policy intervention should aim to alleviate market power
5. Meanwhile, a physical capacity certificates market or a financial reliability option market may be set up, that includes a performance requirement mechanism

Policy implications from the analysis

1. As long as only a small share of electricity demand is responsive to price (less than 10%?), administrative intervention will be required to manage scarcity, either through a generation adequacy standard, or, equivalently a *VoLL* estimate
2. If policy makers are confident markets are sufficiently competitive, this intervention is sufficient
3. An energy cum operating reserves markets can be implemented to remunerate flexibility
4. If policy makers are concerned about potential exercise of market power, policy intervention should aim to alleviate market power
5. Meanwhile, a physical capacity certificates market or a financial reliability option market may be set up, that includes a performance requirement mechanism
6. However, a capacity mechanism reduces incentives for demand response.