The visible hand: ensuring optimal investment in electric power generation

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Outline

- Related literature
- Model structure
- Underinvestment: imperfect competition and price cap
- Physical capacity certificates
- Financial reliability options
- Operating reserves markets
- Policy implications
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State of the world $t \geq 0$; cumulative distribution $F(.)$; $f(.) = F'(.)$
Uncertainty, supply and demand

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- A single generation technology, marginal cost $c$, investment cost $r$ ($\€/\text{MWh}$). Sufficient to examine capacity adequacy
Uncertainty, supply and demand

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

\[
Q = \frac{\partial P}{\partial q} < 0, \quad P_t = \frac{\partial P}{\partial t} > 0, \quad \lim_{Q \to +\infty} P(Q, t) < c
\]

and

\[
P_q(Q, t) + qP_{qq}(Q, t) < 0, \quad P_t(Q, t) + qP_{qt}(Q, t) > 0.
\]
Uncertainty, supply and demand

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\]

- 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.

![Graph showing absence of sufficient demand response](image)

*Figure 2.1. Absence of sufficient demand response*
Administrative curtailment and Value of Lost Load

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

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

**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:
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An example of VoLL

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  \[ D(p, \gamma, t) = \gamma D(p, t) \]
- If rationing is anticipated, \( S(p, \gamma, t) = \gamma S(p, t) \)
- Thus,
  \[ \nu(p, \gamma, t) = \frac{S(p, t)}{D(p, t)} > p \]
An example of VoLL

- Since customers are homogeneous, rationing is proportional:
  \[ D(p, \gamma, t) = \gamma D(p, t) \]
- If rationing is anticipated, \[ S(p, \gamma, t) = \gamma S(p, t) \]
- 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
  \[ S(p, t) = \left( a(t) - \frac{b}{2} D(p, t) \right) D(p, t) \Rightarrow v(p, t) = \frac{a(t) + p}{2} \]
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...
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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.
Administrative intervention

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- 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

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

(1)

where $\gamma^*$ is the optimal serving ratio

\[\text{Graph showing price vs. capacity with curves for } \rho(Q, t) \text{ and } D(p^R, t) \text{ at different capacities.}\]
Possible curtailment

- If $\rho(K,t) \leq v(p^R,1,t)$, $\gamma^*(K,t) = 1$. If $\rho(K,t) > v(p^R,1,t)$, $\gamma^*(K,t) < 1$ defined by:
  \[ v(p^R,\gamma^*(K,t),t) = \rho(K,t) \]
- If it exists, $\bar{t}(K,p^R)$ is the first state of the world when curtailment occurs. Assume curtailment occurs in all states $t \geq \bar{t}(K,p^R)$.
\( \hat{t}_0 (K, c) \) 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 \( \mathbb{E} [\rho (0, t)] > c + r \)

\( \Psi_0 (K^*, c) \) is uniquely defined by

\[
\Psi_0 (K^*, c) = \int_{\hat{t}_0(K,c)}^{+\infty} (\rho (K^*, t) - c) f (t) \, dt = r
\] (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. $a_0$, $a_1$, $\lambda$, and $bQ^\infty = \frac{a_0 - p^R}{b}$ estimated by Maximum Likelihood using the load duration curve for France in 2010.

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

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

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Actual vs. estimated load duration curves

Feuille1

Actual vs. fitted 2009 demand in France

load (MW)

432 1224 2016 2808 3600 4392 5184 5976 6768 7560 8352 9144 9936 10728 11520 12312 13104 13896 14688 15480 16272 17064
36 828 1620 2412 3204 3996 4788 5580 6372 7164 7956 8748 9540 10332 11124 11916 12708 13500 14292 15084 15876 16668 17460

time-periods

actual demand fitted demand
Perfect competition benchmark

- Perfectly competitive market \((N \to +\infty)\)

- For \(\eta = -0.1\)

<table>
<thead>
<tr>
<th>(\alpha , (%))</th>
<th>2</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^*/Q^\infty)</td>
<td>.983</td>
<td>.975</td>
<td>.964</td>
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- For \(\eta = -0.01\)

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</tr>
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- 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 \(\alpha\)
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Imperfect competition

- $N$ producers play a two-stage game
  - in stage 1, producer $n$ installs capacity $k^n$
  - 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:

$$\rho(K, \hat{t}(K, c)) + \frac{K}{N} \rho_q(K, \hat{t}(K, c)) = c.$$
To limit the exercise of market power, the SO may impose a cap $\bar{p}^W$ on the wholesale power price.

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

If it exists, $\hat{t}_0 (Q, \bar{p}^W)$ 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., $\hat{t} (K, c) < \hat{t}_0 (K, \bar{p}^W)$ or $\hat{t} (K, c) \geq \hat{t}_0 (K, \bar{p}^W)$, which occurs if $\alpha$ and $\bar{p}^W$ are very low.

Both cases yield the same economic insights, with slightly different equations. Only the case $\hat{t} (K, c) < \hat{t}_0 (K, \bar{p}^W)$ is presented here.
Marginal value of capacity with a price cap

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

$$
\Omega (K, p) = \int_{\hat{t}_0 (K, p)}^{\hat{t}_0 (K, c)} \left( \rho (K, t) + \frac{K}{N} \rho_q (K, t) - c \right) f (t) \, dt \\
+ \int_{\hat{t}_0 (K, p)}^{+\infty} (p - c) f (t) \, dt.
$$
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
  \[
  \frac{dK^C}{d\bar{p}^W} \left( - \frac{\partial \Omega}{\partial K} \right) = 1 - F(\hat{t}_0) + \frac{K^C}{N} \rho_q \left( K^C, \hat{t}_0 \right) f(\hat{t}_0) \frac{\partial \hat{t}_0}{\partial \rho}
  \]
Imperfectly competitive investment for low elasticity

\[ \eta = -0.01 \text{ and } N = 6. \ K^C(\bar{p}^W) / K^*(\alpha) \text{ for } \alpha = 2\% \text{ (top line)}, \ \alpha = 5\% \text{ (center line)}, \text{ and } \alpha = 10\% \text{ (bottom line)}. \]
Imperfectly competitive investment for high elasticity

\[ \eta = -0.1 \text{ and } N = 6. \]

\[ K^C \left( \bar{p}^W \right) / K^* (\alpha) \text{ for } \alpha = 2\% \text{ (top line)}, \alpha = 5\% \text{ (center line)}, \text{ and } \alpha = 10\% \text{ (bottom line)}. \]
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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.

- $\phi^n$ 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:

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

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 $\phi$, and

$$\left|h'(K^*)\right| \geq \frac{Nr}{K^*}.$$  \hspace{1cm} (4)
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.

$$\Pi_{CM}^n = \phi^n H(\Phi) + \Pi^n (k^n, k_{-n}, \bar{p}^W),$$

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 \textit{ex ante} incentives to under-invest (cf. Germany today)
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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

- $\theta^n$ 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:

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

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 $\Pi^n \left( k^n; k_{-n}, \bar{p}^S \right)$. 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 $K$. $\square$
Proposition

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

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

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:

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

\[
\Pi^n_{RO} = \theta^n H_{RO} (\Theta) + \Pi^n \left( k^n; k_{-n}, \bar{p}^S \right) + \left( k^n - \frac{\theta^n}{\Theta} K \right) \Psi \left( K, \bar{p}^S \right)
\]
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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:

\[
p(t) = w(t) + h(t)(w(t) - c)
\]

\[
\Leftrightarrow
p(t) - c = (1 + h(t))(w(t) - c)
\]  

(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 \( \rho(\cdot; t) \)

- The marginal social value of capacity in state \( t \) is

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

- The marginal social value of capacity is

\[
\Psi_{0}^{OR}(K) = \int_{\hat{t}_{0}^{OR}(K, c)}^{+\infty} \frac{\rho \left( \frac{K}{1 + h(t)}; t \right) - c}{1 + h(t)} f(t) \, dt
\]

where \( \hat{t}_{0}^{OR}(K, c) \) is uniquely defined by

\[
\rho \left( \frac{K}{1 + h(t)}; \hat{t}_{0}^{OR}(K, c) \right) = c.
\]
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:
  \[
  \pi^n(t) = (q^n(t) + b^n(t))(w(t) - c) \\
  = \frac{s^n(t)}{1+h(t)} \left( \rho \left( \frac{S(t)}{1+h(t)} \right) - c \right)
  \]
  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
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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 \textit{VoLL} estimate.
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2. If policy makers are confident markets are sufficiently competitive, this intervention is sufficient.
Policy implications from the analysis

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3. An energy cum operating reserves markets can be implemented to remunerate flexibility.
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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.
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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

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6. However, a capacity mechanism reduces incentives for demand response.