Nodal peak load pricing

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Today's discussion

- Introduction
- The model
- Nodal pricing
- Peak load pricing
- Nodal peak load pricing
- Concluding remarks

Two separate strands of academic literature

- *Peak-load pricing*: optimal dispatch, prices, and investment, hence long-term marginal costs for a single market, i.e., ignoring congestion on the transmission grid (Boiteux (1949), Borenstein and Holland (2005), Joskow and Tirole (2006), and Léautier (2012))
- *Nodal pricing:* interconnected markets, i.e., explicitly models congestion on the transmission grid. *In its application* often considers only short term marginal costs (Schweppe et al. (1986), Hogan (1992)), or Léautier (2001))

In reality, power markets are interconnected *and* prices reflect long-term marginal costs (over the long-term, including possible capacity payment)

Research questions

- How are the main results of peak load pricing models, in particular the optimal generation mix, modified when one includes congestion on the transmission grid?
- What is the value of transmission reinforcement when long-term prices are taken into account?

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The model: demand

- State of the world $t \geq 0$; cumulative distribution $F(.)$; $f(.) = F^{'}(.)$
- Homogenous customers; individual demand $D(p, t)$; inverse demand $P(q, t)$

$$P_q = \frac{\partial P}{\partial q} < 0 \text{ and } P_t = \frac{\partial P}{\partial t} > 0$$

- Two markets, indexed by $n = 1, 2$. $p_n(t)$, $q_n^s(t)$, and $q_n^d(t)$ respectively the price, production, and demand in market n in state t.
- Total mass of customers normalized to 1, $\theta \in [0, 1]$ customers located in market 1. Thus

$$q_1^d(t) = \theta D(p_1(t), t) \Leftrightarrow p_1(t) = P\left(\frac{q_1^d(t)}{\theta}, t\right),$$

and

$$q_2^d(t) = (1 - \theta) D(p_2(t), t) \Leftrightarrow p_2(t) = P\left(\frac{q_2^d(t)}{1 - \theta}, t\right).$$

The model: supply and interconnection

- One production technology (c_n, r_n) located in market n. Technology 1 baseload: $c_1 < c_2$ and $r_1 > r_2$.
- Interconnection between both markets:
  - $\varphi(t)$ flow from market 1 to market 2 in state t
  - Φ transmission capacity on the interconnection, assumed identical for both directions
  - The transmission constraints are

$$|\varphi(t)| \leq \Phi.$$

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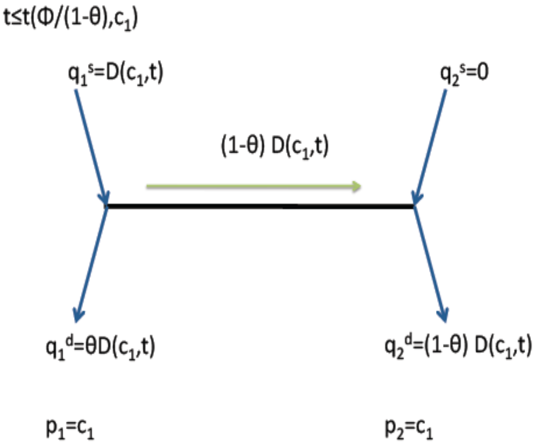
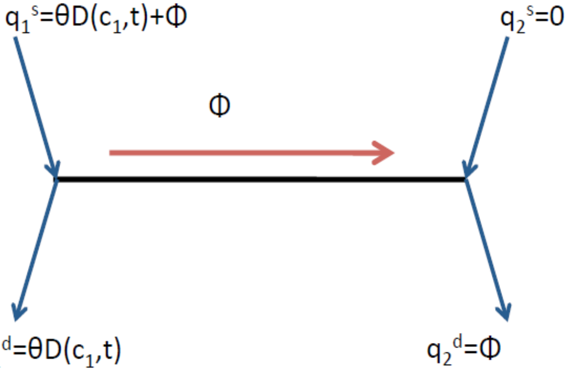
Interconnection not constrained



Interconnection constrained, peaking technology not producing

$t(\Phi/(1-\theta),c_1) \leq t \leq t(\Phi/(1-\theta),c_2)$

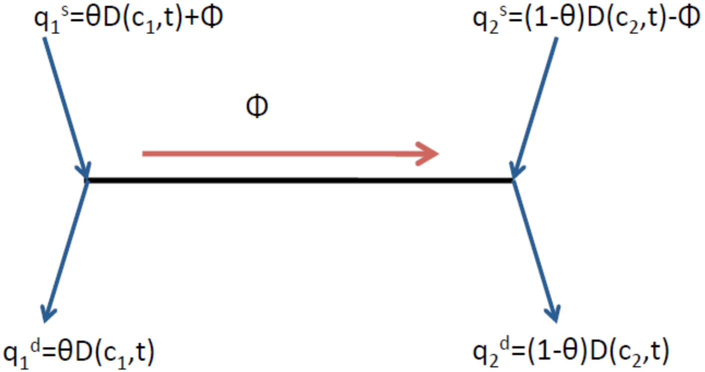


$p_1=c_1$

$p_2=P(\Phi/(1-\theta),t)$

Interconnection constrained, peaking technology producing

$t \geq t(\Phi/(1-\theta), c_2)$



$p_1 = c_1$

$p_2 = c_2$

Expected value of the prices difference

$$
\begin{aligned}
\mathbb{E}\left[p_2(t) - p_1(t)\right] &= \int_{\widehat{t}\left(\frac{\Phi}{1-\theta}, c_1\right)}^{\widehat{t}\left(\frac{\Phi}{1-\theta}, c_2\right)} \left(P\left(\frac{\Phi}{1-\theta}, t\right) - c_1\right) f(t)\, dt \\
&\quad + \int_{\widehat{t}\left(\frac{\Phi}{1-\theta}, c_2\right)}^{+\infty} (c_2 - c_1) f(t)\, dt \\
&= \beta\left(\frac{\Phi}{1-\theta}, c_1, c_2\right).
\end{aligned}
$$

Marginal value of transmission capacity, once prices are set to cover long term marginal costs?

- Heuristic 1: add r_2, the missing money in market 2

$$\gamma_1(\Phi) = \beta\left(\frac{\Phi}{1-\theta}, c_1, c_2\right) + r_2$$

- Heuristic 2: add r_1 and r_2 to c_1 and c_2 on peak

$$\gamma_2(\Phi) = \beta\left(\frac{\Phi}{1-\theta}, c_1, c_2\right) + (r_2 - r_1)\Pr(peak)$$

- Comparing both heuristics

$$\gamma_2(\Phi) < \beta\left(\frac{\Phi}{1-\theta}, c_1, c_2\right) < \gamma_1(\Phi)$$

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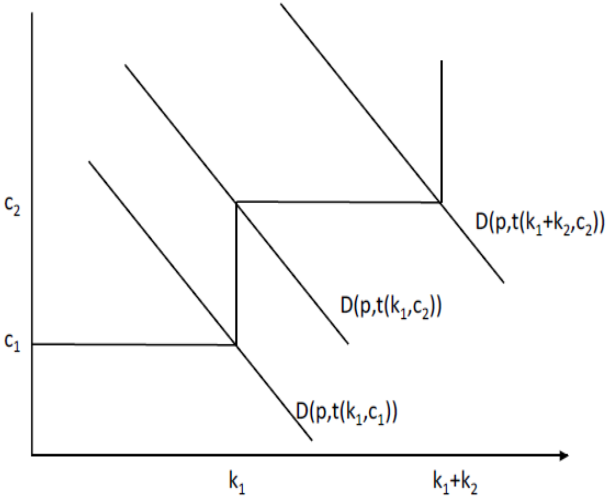
Peak load pricing: dispatch and prices



Optimal unconstrained capacities

- $\left(k_1^U + k_2^U\right)$ uniquely determined by:

$$\int_{\hat{t}\left(k_1^U+k_2^U,c_2\right)}^{+\infty} \left(P\left(k_1^U + k_2^U, t\right) - c_2\right) f\left(t\right) dt = \Psi\left(k_1^U + k_2^U, c_2\right) = r_2$$

$\Leftrightarrow$

$$k_1^U + k_2^U = \xi\left(c_2, r_2\right) \quad (1)$$

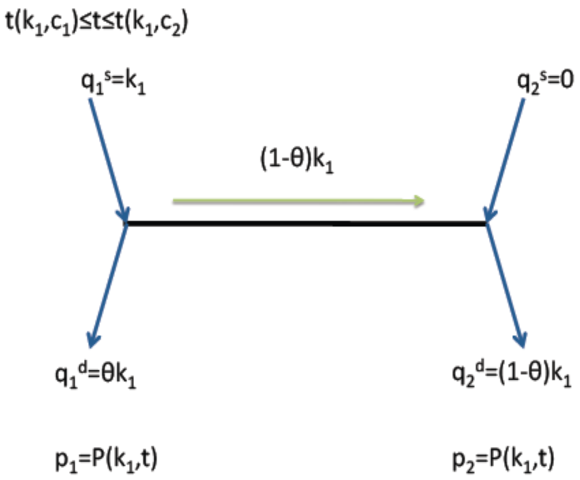
- k_1^U uniquely determined by:

$$\int_{\hat{t}\left(k_1^U,c_1\right)}^{+\infty} \left(p\left(t\right) - c_1\right) f\left(t\right) dt = r_1$$

$\Leftrightarrow$

$$\beta\left(k_1^U, c_1, c_2\right) = r_1 - r_2. \quad (2)$$

Maximum power flows



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Optimal generation mix

Transmission capacity is fixed at Φ.

Proposition

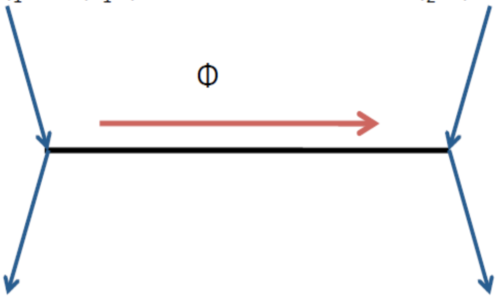
1. *If* $\Phi \geq (1-\theta)\, k_1^U$*, the transmission line is never congested.*
2. *If* $\Phi \in \left[\frac{\theta}{2} k_2^U, (1-\theta)\, k_1^U\right)$*, the transmission line is congested from market 1 to market 2. The total installed capacity is unchanged. As transmission capacity increases, baseload capacity is substituted one for one for peaking capacity.*
3. *If* $\Phi \in \left[0, \frac{\theta}{2} k_2^U\right)$*, the transmission line is congested in both directions. As transmission capacity increases, peaking capacity increases one for one. The impact on baseload capacity is undetermined.*

One way congestion; both technologies producing

$t(\Phi/(1-\theta),c_2) \leq t \leq t((k_1-\Phi)/\theta,c_1)$

$q_1^s=\theta D(c_1,t)+\Phi$

$q_2^s=(1-\theta)D(c_2,t)-\Phi$



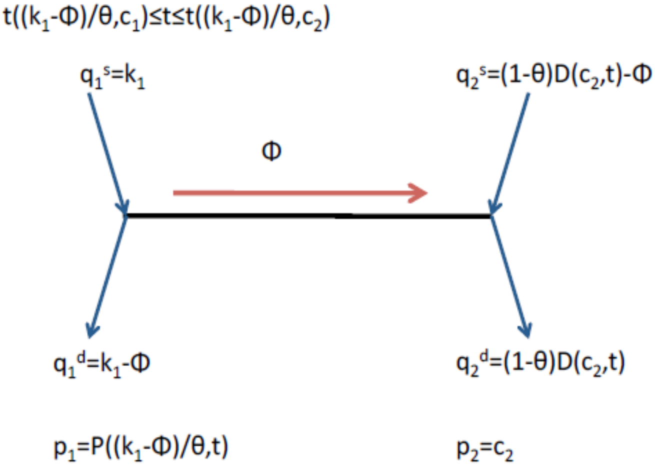
$q_1^d=\theta D(c_1,t)$

$q_2^d=(1-\theta)D(c_2,t)$

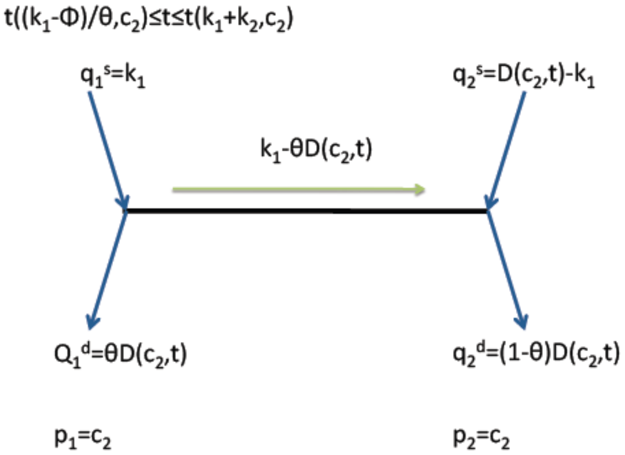
$p_1=c_1$

$p_2=c_2$

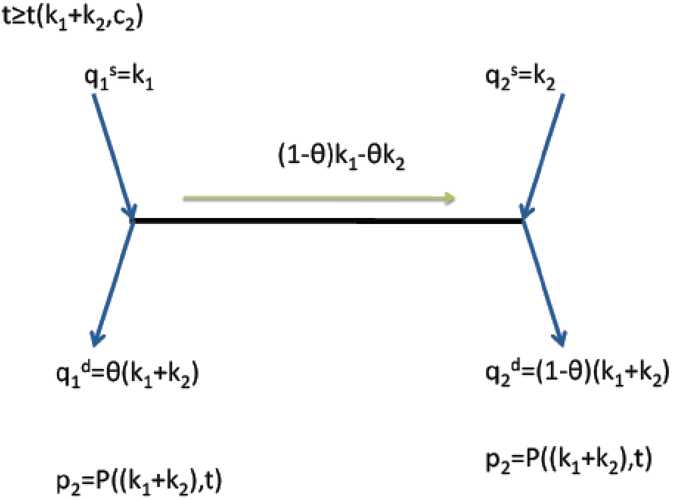
Baseload technology at capacity



Peaking technology marginal



Peaking technology at capacity



Total capacity

$$\int_{\widehat{t}(k_1+k_2,c_2)}^{+\infty} \left(P\left(k_1+k_2,t\right)-c_2\right) f\left(t\right) dt = \Psi\left(k_1+k_2,c_2\right) = r_2$$

$\Leftrightarrow$

$$k_1+k_2 = \xi\left(c_2,r_2\right) = k_1^U + k_2^U.$$

Baseload capacity

$$r_1 = \int_{\widehat{t}\left(\frac{k_1-\Phi}{\theta},c_1\right)}^{\widehat{t}\left(\frac{k_1-\Phi}{\theta},c_2\right)} \left(P\left(\frac{k_1-\Phi}{\theta},t\right)-c_1\right) f(t)\,dt$$
$$+\int_{\widehat{t}\left(\frac{k_1-\Phi}{\theta},c_2\right)}^{\widehat{t}(k_1+k_2,c_2)} (c_2-c_1)\, f(t)\,dt$$
$$+\int_{\widehat{t}(k_1+k_2,c_2)}^{+\infty} \left(P(k_1+k_2,t)-c_1\right) f(t)\,dt$$

$\Leftrightarrow$

$$\beta\left(\frac{k_1-\Phi}{\theta},c_1,c_2\right) = r_1 - r_2 = \beta\left(k_1^U,c_1,c_2\right)$$

$\Leftrightarrow$

$$k_1 = \theta k_1^U + \Phi = k_1^U - \left(\left(1-\theta\right)k_1^U - \Phi\right). \quad (3)$$

Two-way congestion

Transmission constraint from market 2 to market 1

$$(1-\theta)\,k_1 - \theta k_2 \geq -\Phi$$

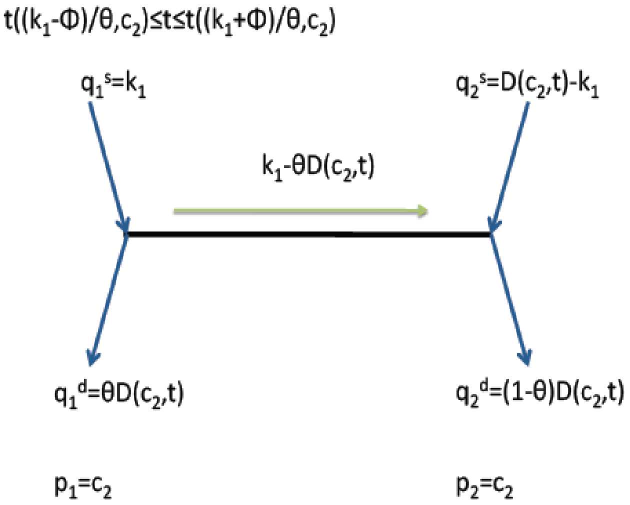
$\Leftrightarrow$

$$k_1 - \theta\,(k_1 + k_2) = \theta k_1^U + \Phi - \theta\left(k_1^U + k_2^U\right) = \Phi - \theta k_2^U \geq -\Phi$$

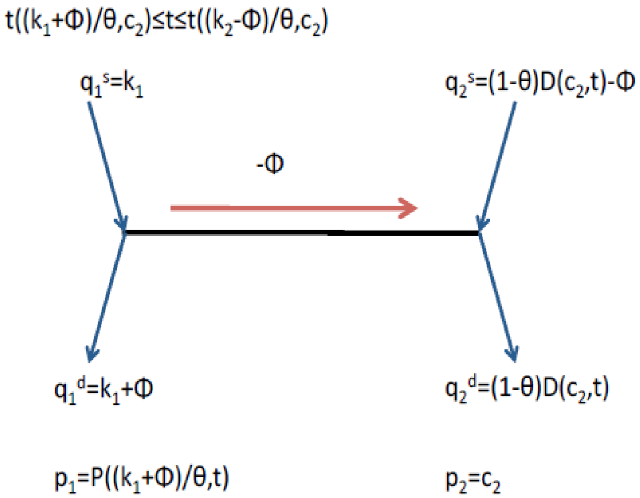
$\Leftrightarrow$

$$\Phi \geq \frac{\theta}{2} k_2^U$$

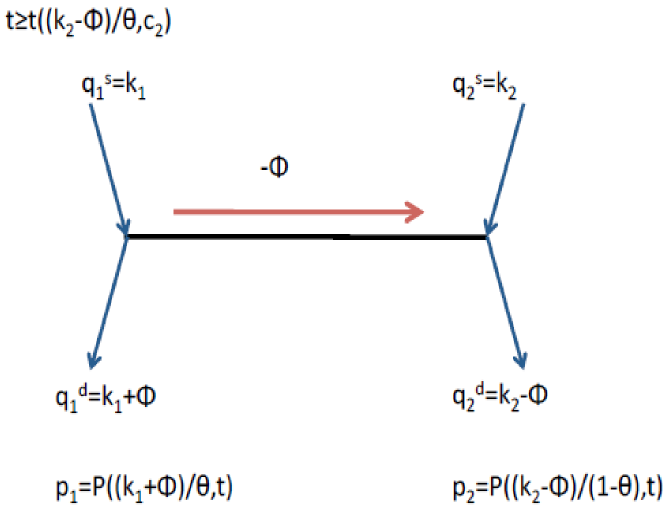
Peaking technology marginal, interconnection unconstrained



Interconnection constrained



Peaking technology at capacity



Optimal technology mix

$$k_2\left(\Phi\right) = \Phi + \left(1-\theta\right)\left(k_1^U + k_2^U\right). \tag{4}$$

Thus,

$$k_2\left(0\right) = \left(1-\theta\right)\xi\left(c_2, r_2\right).$$

$$\beta\left(\frac{k_1\left(\Phi\right)-\Phi}{\theta}, c_1, c_2\right) + \Psi\left(\frac{k_1\left(\Phi\right)+\Phi}{\theta}, c_2\right) = r_1 \tag{5}$$

and

$$k_1\left(0\right) = \theta\xi\left(c_1, r_1\right)$$

Marginal value of transmission capacity

Proposition

1. *If* $\Phi \geq (1-\theta)\, k_1^U$,$\mathbb{E}\left[\eta\left(t\right)\right] = 0$.
2. *If* $\Phi \in \left[\frac{\theta}{2} k_2^U, (1-\theta)\, k_1^U\right)$,

$$\mathbb{E}\left[\eta\left(t\right)\right] = \beta\left(\frac{\Phi}{1-\theta}, c_1, c_2\right) + r_2 - r_1.$$

3. *If* $\Phi \in \left[0, \frac{\theta}{2} k_2^U\right)$,

$$\mathbb{E}\left[\eta\left(t\right)\right] \geq \beta\left(\frac{\Phi}{1-\theta}, c_1, c_2\right) + r_2 - r_1$$

and

$$\begin{aligned}\mathbb{E}\left[\eta\left(t\right)\right] \quad \leq \quad & \beta\left(\frac{\Phi}{1-\theta}, c_1, c_2\right) + r_2 - r_1 \\ & +2\left(\Psi\left(\xi\left(c_1, r_1\right), c_2\right) - \Psi\left(\xi\left(c_2, r_2\right), c_2\right)\right)\end{aligned}$$

Marginal value of transmission capacity: one way congestion

$$
\begin{aligned}
\mathbb{E}\left[\eta\left(t\right)\right] &= \int_{\widehat{t}\left(\frac{\Phi}{1-\theta},c_1\right)}^{\widehat{t}\left(\frac{\Phi}{1-\theta},c_2\right)} \left(P\left(\frac{\Phi}{1-\theta},t\right)-c_1\right) f\left(t\right)dt \\
&+ \int_{\widehat{t}\left(\frac{\Phi}{1-\theta},c_2\right)}^{\widehat{t}\left(\frac{k_1-\Phi}{\theta},c_1\right)} \left(c_2-c_1\right) f\left(t\right)dt \\
&+ \int_{\widehat{t}\left(\frac{k_1-\Phi}{\theta},c_1\right)}^{\widehat{t}\left(\frac{k_1-\Phi}{\theta},c_2\right)} \left(c_2-P\left(\frac{k_1-\Phi}{\theta},t\right)\right) f\left(t\right)dt \\
&= \beta\left(\frac{\Phi}{1-\theta},c_1,c_2\right)-\beta\left(\frac{k_1-\Phi}{\theta},c_1,c_2\right) \\
&= \beta\left(\frac{\Phi}{1-\theta},c_1,c_2\right)+r_2-r_1
\end{aligned}
$$

A practical implication

Technology 1 is nuclear, and technology 2 is Combined Cycle Gas Turbine. Cost estimates (IEA (2010)):

	1	2
c_n	11	49
r_n	34	8

- $c_2 - c_1 = 38$ €/ *MWh*. If the line is congested 50% of the time, this corresponds $\beta\left(\frac{\Phi}{1-\theta}\right) \approx 19$ € *per MW per hour* on average, 166, 440 € *per MW per year*, or € 1.7 million *per MW* discounted in perpetuity at 10%.
- However

$$\mathbb{E}\left[\eta\left(t\right)\right] = -7 \text{ € } per\ MW\ per\ hour$$

which suggests no expansion should be undertaken.

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Further work

- Check robustness of the results: additional technologies, additional markets
- Estimate magnitude of the impact on numerical example
- Extensions: market power, asymmetric regulation (capacity mechanism in one market, not in the other)