Dynamics of Power*

LCCC Lund University, Sweden

Based on tutorial & panel lectures at *Energy Systems Week*, Cambridge UK

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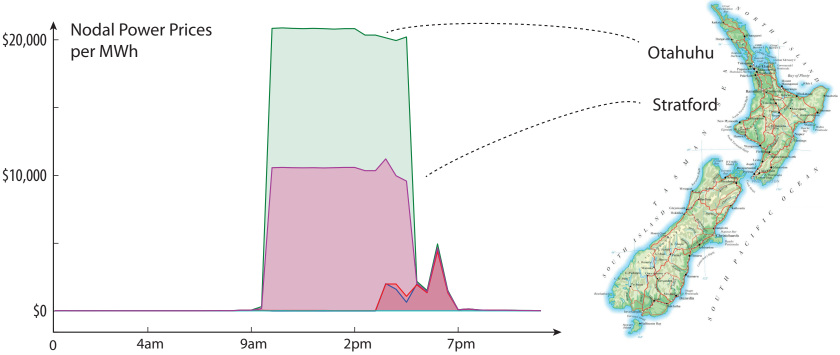
Thanks to NSF, AFOSR, and DOE / TCIPG

*Dynamik i Makten (i grossistledet elmarknaderna)

May 19, 2011

Outline



Spot the Competitive Equilibrium

Competitive Equilibrium

Standard economic setting

Perfect competition

Long-run setting with uncertainty:

$$K_{\mathrm{D}}(G_{\mathrm{D}}) = \mathsf{E}\Big[\int e^{-\gamma t}\mathcal{W}_{\mathrm{D}}(t)\,dt\Big]$$

$$K_{\mathrm{S}}(G_{\mathrm{S}}) = \mathsf{E}\Big[\int e^{-\gamma t}\mathcal{W}_{\mathrm{S}}(t),dt\Big]$$

Consumers and suppliers each wish to maximize their individual welfare.

Welfare functions defined with a price-process $\{P(t) : t \geq 0\}$

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Consumers and suppliers each wish to maximize their individual welfare.

Welfare functions defined with a price-process $\{P(t) : t \geq 0\}$

Price-taking assumption

Key assumption of equilibrium theory: The price of power $P(t)$ *does not depend on the decisions of the market agents*.

Competitive Equilibrium

Efficiency

Efficient Equilibrium

Social Planner's Problem:

$$\textbf{max} \quad K(G) = \mathsf{E}\Big[\int e^{-\gamma t}\big(\mathcal{W}_{\mathrm{S}}(t) + \mathcal{W}_{\mathrm{D}}(t)\big)\, dt\Big]$$

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- Suppose that there exists a price process $\{P^*(t)\}$ that forms an *equlibrium*: The consumers and suppliers agree, $G_{\mathrm{S}} = G_{\mathrm{D}} = G$.
- Suppose the agreed upon decisions G solve the SPP.

Then, the market is called *efficient*.

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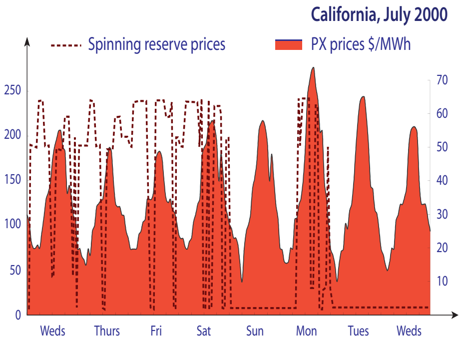
Let's look for examples of efficient equilibria!

Efficient Equilibrium?

California, 2000



Efficient Equilibrium?

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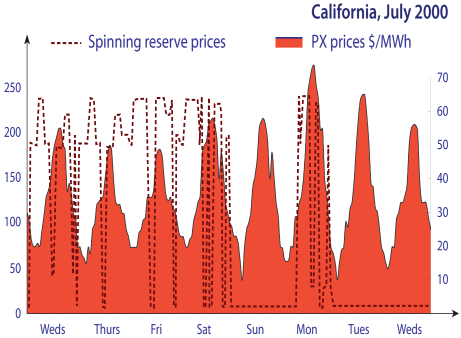

"Ripping off *those poor grandmothers*"

Efficient Equilibrium?

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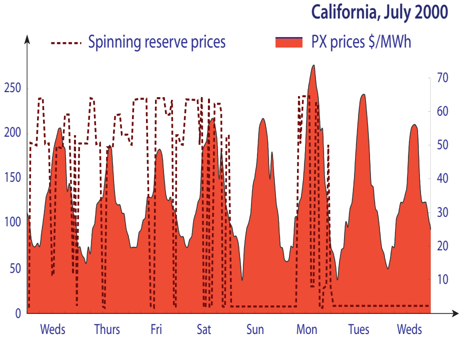


Enron traders openly discussed manipulating California's power market during profanity-laced telephone conversations in which they merrily gloated about ripping off "those poor grandmothers" during the state's energy crunch in 2000-01 ... [AP by Kristen Hays, 06/03/04]

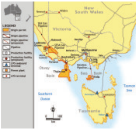
ENRON As Jeffrey Skilling, the first but sadly not the last guy to package up a big sample of nothing and sell it to a greedy public, Samuel West oozes self-belief; his boss, Ken Lay (Tim Piggott-Smith) and stooge, Andy Fastow (Tom Goodman-Hill) end up smeared with it. But Lucy Prebble's play is rather more than a simple tale ... -Time Out, London 2010

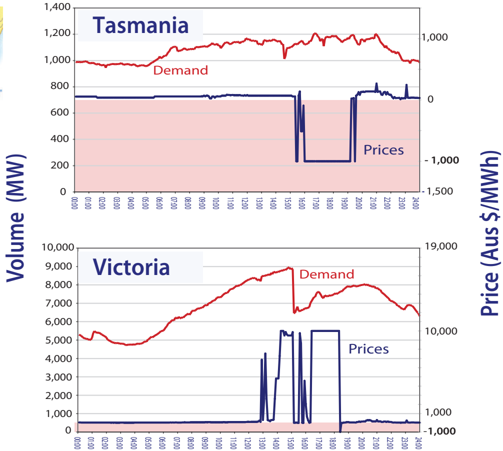
"Ripping off *those poor grandmothers*"

Not efficient?

Efficient Equilibrium?

Australia, January 16, 2007





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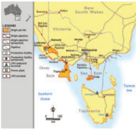
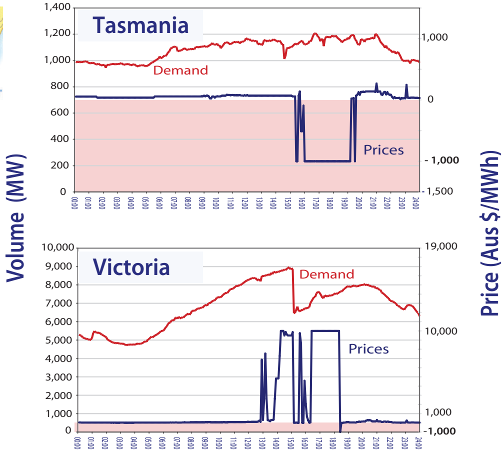
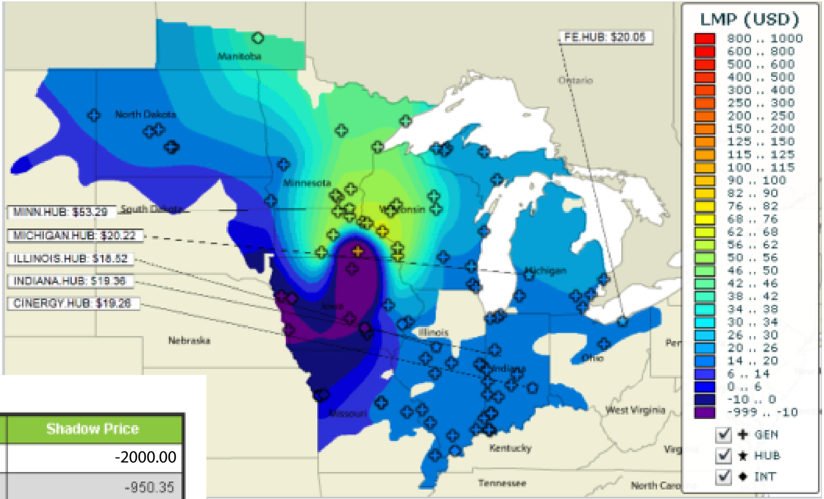




Fires cause chaos – *Is this efficient?*

Efficient Equilibrium?

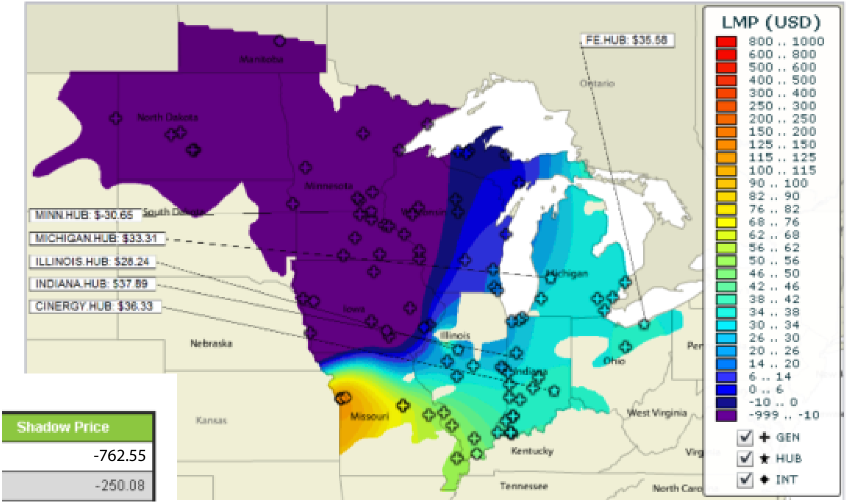
Midwest ISO today: Friday afternoon, March 4, 2011 3:30 p.m.



	Shadow Price
	-2000.00
	-950.35

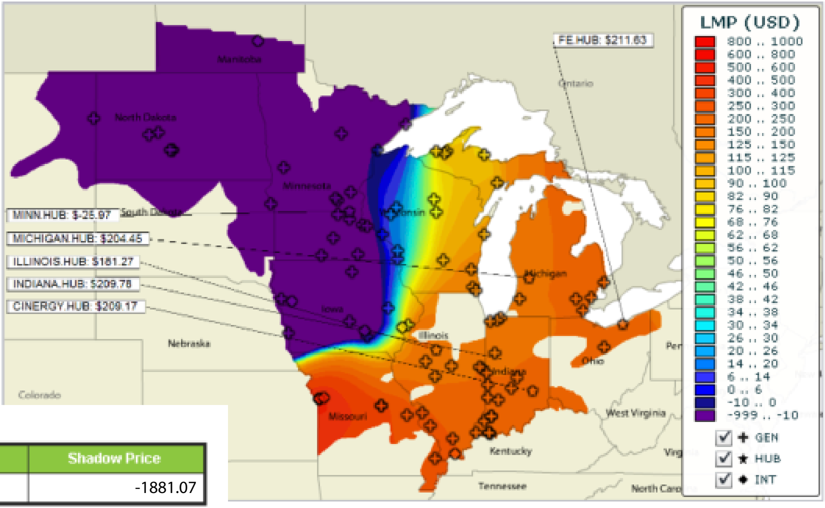
Efficient Equilibrium?

Midwest ISO today: Friday afternoon, March 4, 2011 3:50 p.m.



Efficient Equilibrium?

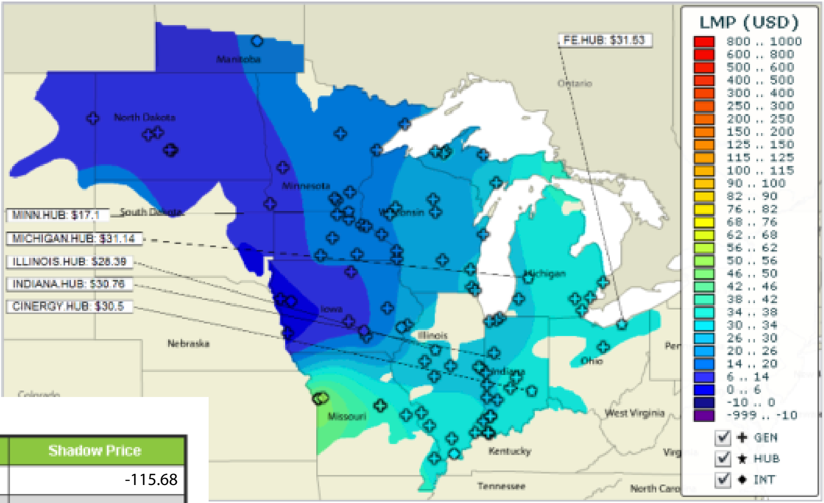
Midwest ISO today: Friday afternoon, March 4, 2011 4:15 p.m.



	Shadow Price
	-1881.07

Efficient Equilibrium?

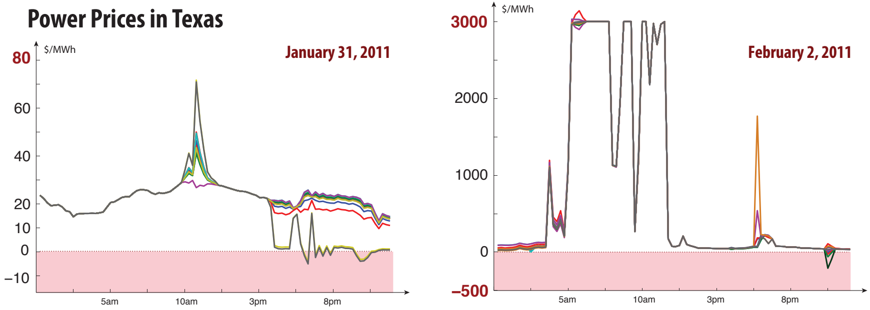
Midwest ISO today: Friday afternoon, March 4, 2011 4:30 p.m.



	Shadow Price
	-115.68
	-70.02

Efficient Equilibrium?

Texas today: Winter of 2011



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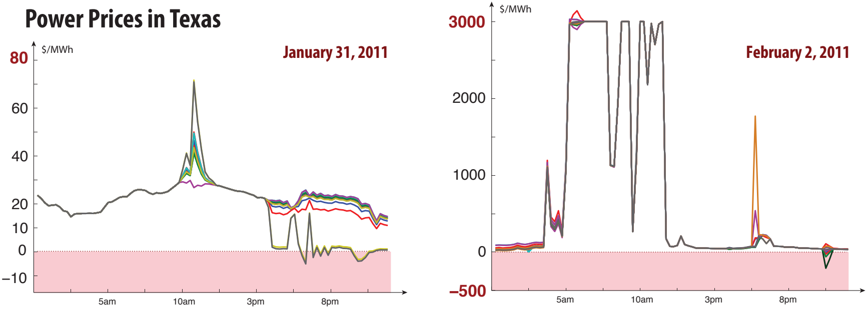


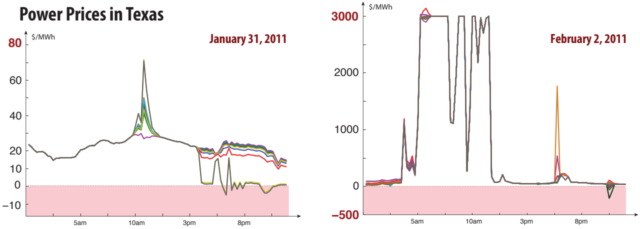
There will be multiple autopsies of the causes for the latest power breakdowns ... Who profited off this near-meltdown and what can be done to incentivize power producers to maintain adequate reserve capacity for emergencies rather than waiting for emergency windfalls? – HOUSTON CHRONICLE, Feb 12, 2011

> New report hits ERCOT, electricity deregulation: *A report released Monday concludes that electric deregulation has cost Texas residential consumers more than $11 billion in higher rates...* – Dallas Morning News, Feb 14, 2011

Efficient Equilibrium?

Texas today: Winter of 2011

What do the experts say?



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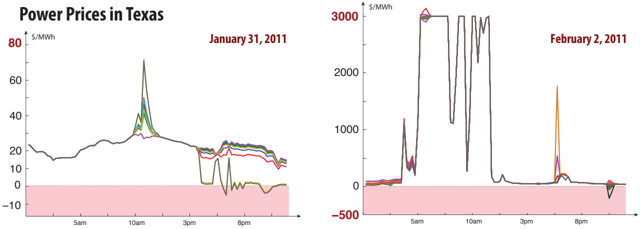

...long-term contracts could reduce market power... ...the larger the proportion of total demand auctioned in advance, the lower are both the contract and the average spot price of energy...

–M. Soledad Arellano and Pablo Serra, 2010

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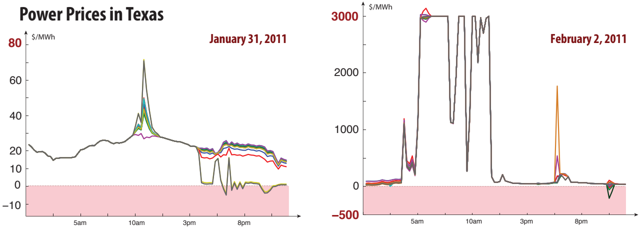

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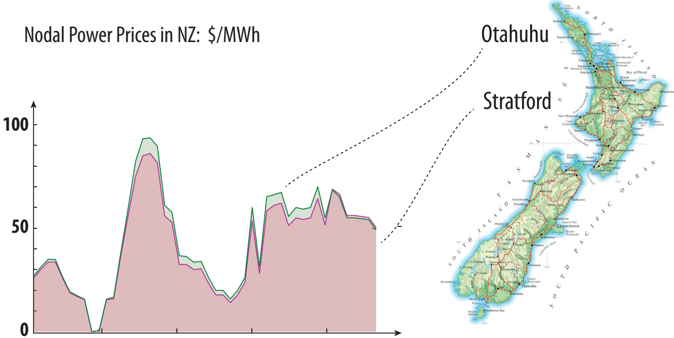
...forward markets do not mitigate market power... ...forward markets systematically enhance market power in some symmetric capacity-constrained markets..."

–Frederic Murphy and Yves Smeers, 2010

Efficient Equilibrium?

New Zealand today: March 25, 2011

A typical day in the New Zealand power market on the N. Island

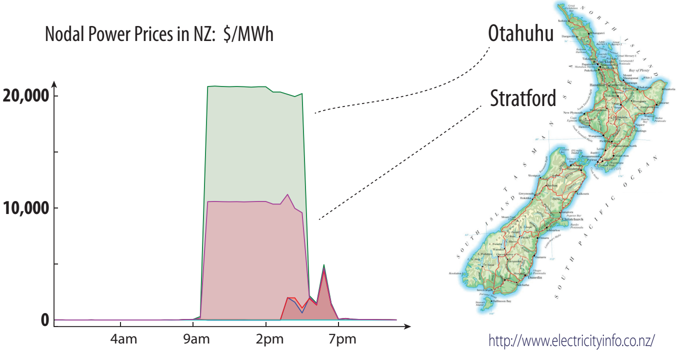


http://www.electricityinfo.co.nz/

Efficient Equilibrium?

New Zealand today: March 26, 2011

$25 **million dollars** extracted by the generators in just six hours



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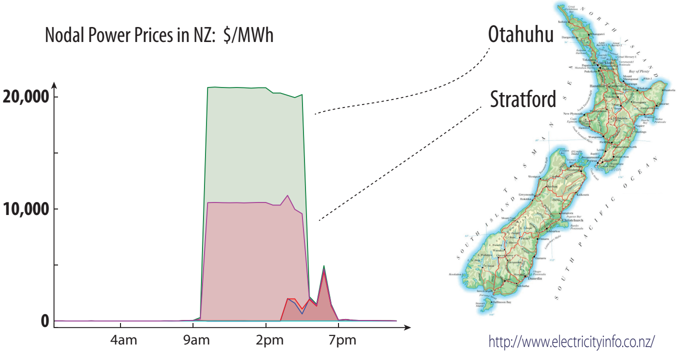

Efficient? Energy consultant Bryan Leyland said the high wholesale prices showed *how dysfunctional the electricity market is.*

Jacking the prices up sends no worthwhile signal to anyone — it is nothing to do with a shortage of generating capacity, he said. *It just exposes the nonsense of it all.*

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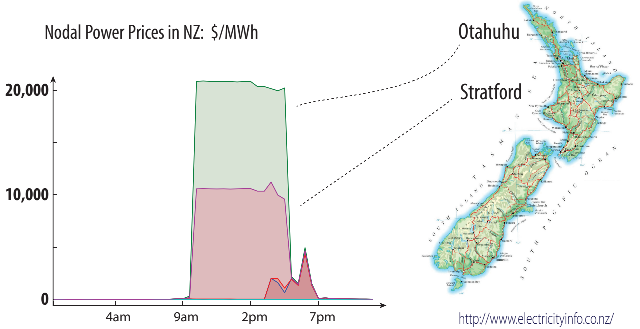

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Efficient! Preliminary view of NZ Electrical Authority: *Genesis was not guilty of "manipulative", ... or "deceptive" conduct.*

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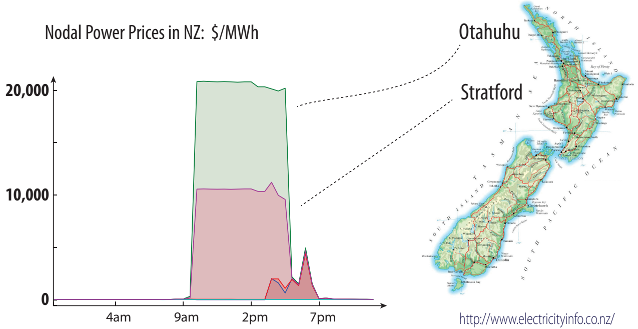

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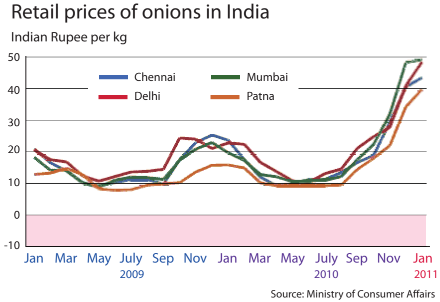
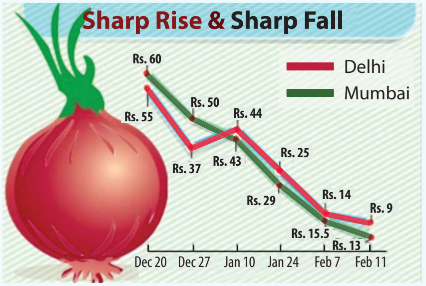
Efficient! Preliminary view of NZ Electrical Authority: *Genesis was not guilty of "manipulative", ... or "deceptive" conduct*. However, high prices threatened to *undermine confidence in, and ... damage the integrity and reputation of the wholesale electricity market*

3:59 PM Friday May 6, 2011 www.nzherald.co.nz

Efficient Equilibrium?

It's not just about power!

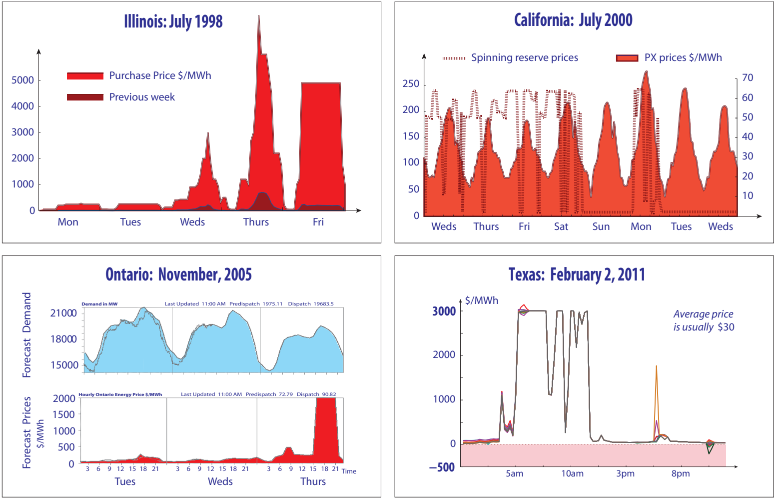




India's ban on onion exports to Nepal ... caused wholesale price to jump 50% in a week.
NepaliEconomy.com, Jan 3, 2011

– Soaring onion prices pushed food inflation again to a double-digit mark...
– Indian Express, Feb 12, 2011

In India, onion prices are as politically sensitive as mortgage rates are in Australia. ... rising cost of the staple has helped change governments in India.
– Fidelity International, Jan 2011



Competitive Equilibria in Dynamic Markets

Electricity Markets Today

Two coupled markets

Day-ahead market (DAM):

Cleared one day prior to the production and delivery of energy: The ISO generates a schedule of generators to supply specific levels of power for each hour over the next 24 hour period.

Facilitates the scheduling of generating units, and allows for hedging against uncertainty

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Real-time market (RTM):

As supply and demand are not perfectly predictable, the RTM plays the role of fine-tuning this resource allocation process

RTM is the focus here

RTM Model

Dynamic model for reserves

Cho & Meyn model: Math model explains volatile prices in power markets. *SIAM News*, Robinson. 2005.

- $R(t) =$ Available power $-$ Demand $= G(t) - D(t)$
- $D(t) =$ Actual demand $-$ Forecast

  For computation: Deviation in demand $\boldsymbol{D}$ is modeled as Brownian motion
- $G(t)$: Deviation in on-line capacity from day-ahead market

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Economic *Friction*

Generation cannot increase instantaneously:

$$\text{For all } t \geq 0 \text{ and } t' > t, \quad \frac{G(t') - G(t)}{t' - t} \leq \zeta$$

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In recent work we also impose lower bounds on generation, as well as network constraints.

Market Analysis: *A beautiful world...*

Perfect competition

Dynamic market equilibria under the most ideal circumstances:

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- Price manipulation is excluded

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What does an efficient equilibrium look like?

Market Analysis

Second Welfare Theorem

Efficient Equilibrium

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Special case: *Welfare functions are piecewise linear,*

$$\mathcal{W}_{\rm S}(t) := P(t)G_{\rm S}(t) - cG_{\rm S}(t)$$
$$\mathcal{W}_{\rm D}(t) := v\min(D(t), G_{\rm D}(t)) - c^{\rm bo}\max(0, -R_{\rm D}(t)) - P(t)G_{\rm D}(t)$$

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Key component of equilibrium theory: *Perfect competition*

Price-taking assumption:

The price of power $P(t)$ in the RTM is assumed to be exogenous (it does not depend on the decisions of the market agents).

Market Analysis

Second Welfare Theorem

Second Welfare Theorem $\iff$ Lagrangian Decomposition

$$\textbf{max} \quad K(G) = \max_{G_{\mathrm{S}}} \mathsf{E}\Big[\int e^{-\gamma t}\big(\mathcal{W}_{\mathrm{S}}(t) + \lambda(t) G_{\mathrm{S}}(t)\big)\, dt\Big] + \max_{G_{\mathrm{D}}} \mathsf{E}\Big[\int e^{-\gamma t}\big(\mathcal{W}_{\mathrm{D}}(t) - \lambda(t) G_{\mathrm{D}}(t)\big)\, dt\Big]$$

Market Analysis

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Market Analysis

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Answer: Marginal value

Equilibrium price

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$$P^*(t) = p^*(R^e(t))$$

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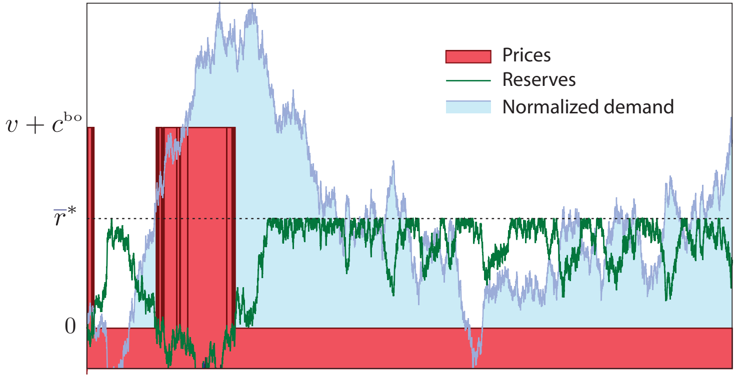
For linear cost/utility, marginal value is piecewise constant,

$$p^*(r^e) = (v + c^{\mathrm{bo}})\mathbb{I}\{r^e < 0\}$$

Market Equilibrium

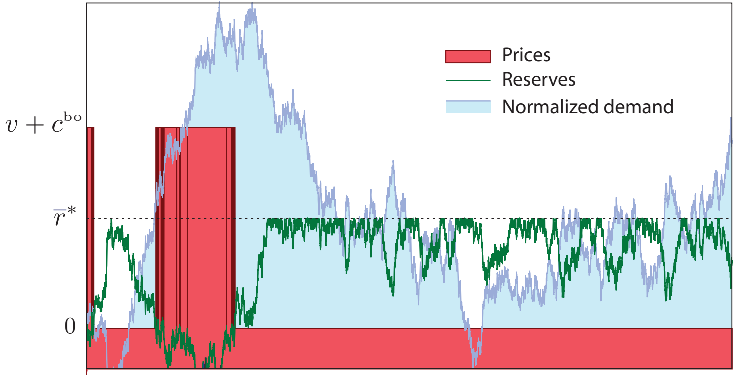
Price dynamics



$P^*(t) = p^*(R^e(t))$: The marginal value of power to the consumer

Market Equilibrium

Price dynamics

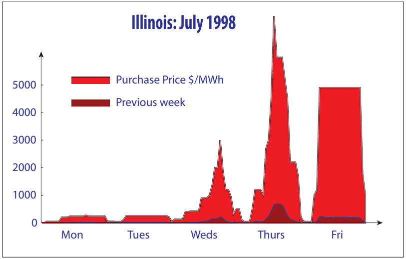


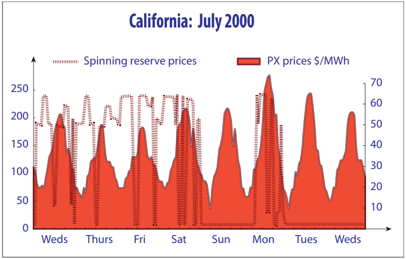
$P^*(t) = p^*(R^e(t))$: The marginal value of power to the consumer

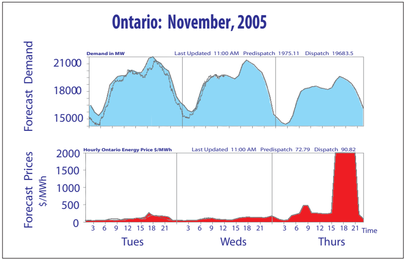
Smoother prices obtained when cost/utility are strictly convex

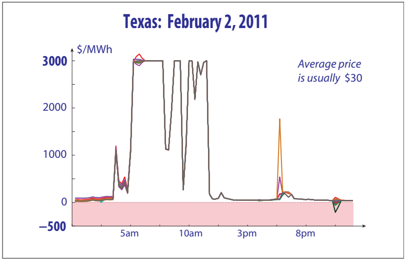
Familiar, right?

Real-world price dynamics





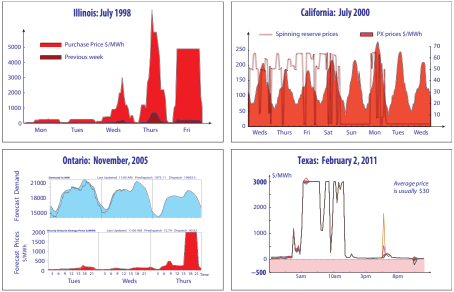




Sustainable business?

Marginal value of electricity may be

$$v + c^{\mathrm{bo}} = \text{\$100,000/MWh!}$$



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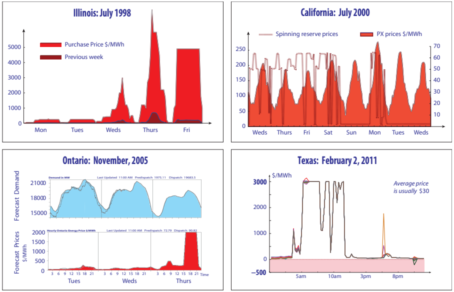

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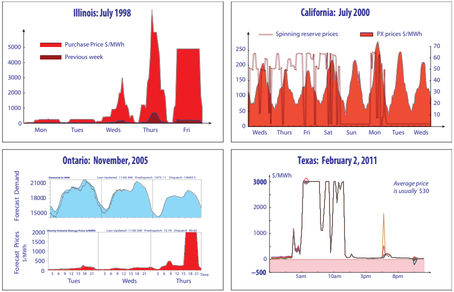

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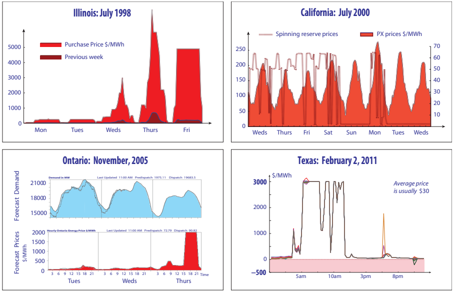

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Is this a sustainable business?

Coping with Uncertainty and Constraints

Network Constraints

Entropic prices

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It is not always obvious. With the introduction of network constraints,

- Prices can go well *beyond marginal value*
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See [Wang et. al., 2011]

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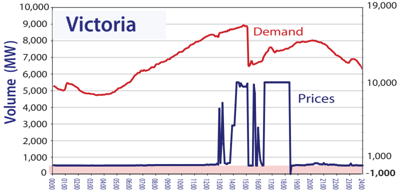
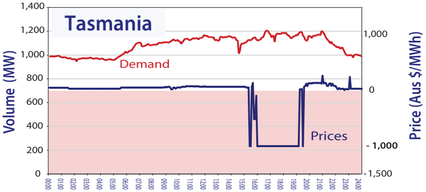
Without price-caps, Australia might look like an efficient equilibrium:





The Value of Volatile Resources

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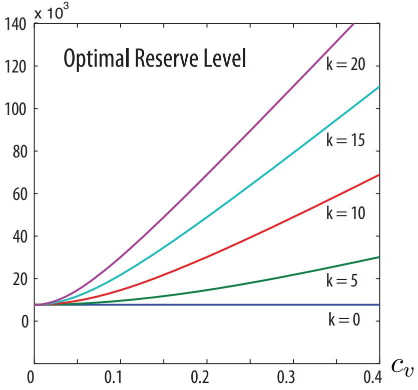

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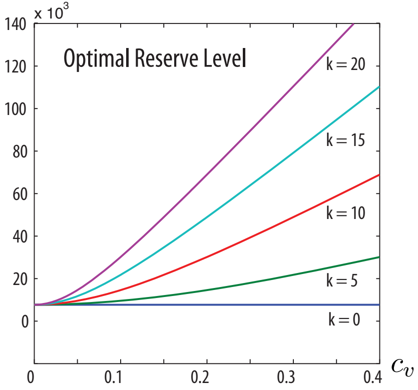

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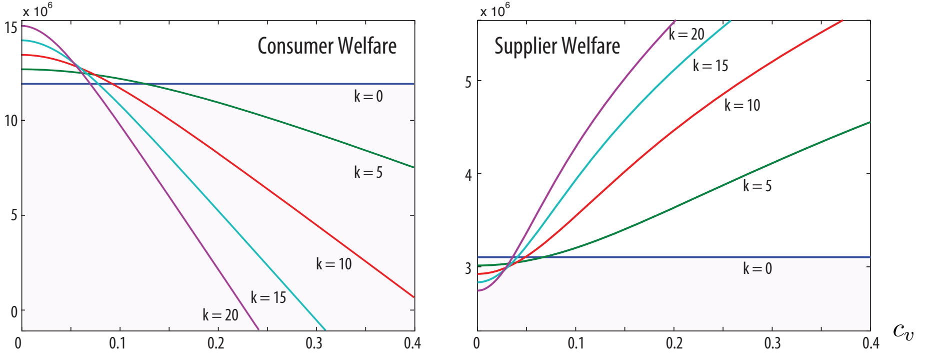
$\Rightarrow$ Social welfare falls with wind.

[Value of Volatile Resources, CDC, 2010]

The Value of Volatile Resources

Distribution of welfare *(consumers command wind resources)*

With increased volatility: Consumer welfare falls, supplier welfare rises:



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Conclusions

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A gentle debate. *Please*, no shouting!

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What we need is *Intelligent Design*

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Analysis of strategic behavior will be possible,

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The economic security of the region is at stake:

We need well-designed lanes and speed limits in the energy highway!

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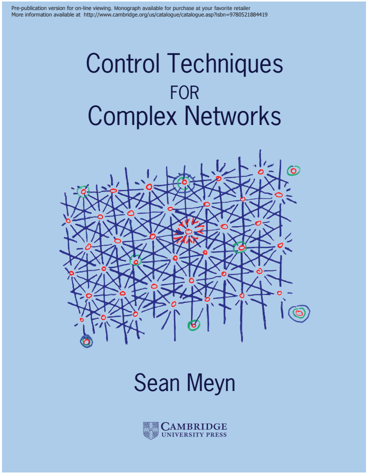
The best architecture for tomorrow's energy highway?
This is *the* central open question.

Its solution opens many exciting research challenges!

Thanks!

Celebrating with Dutch Babies after finishing part of this work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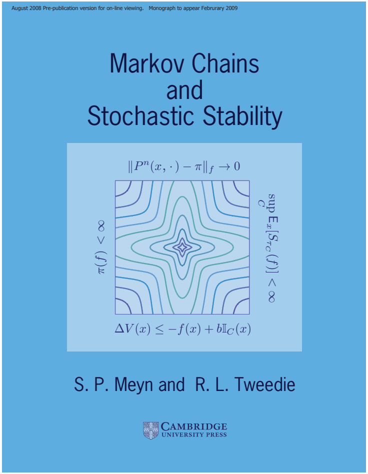
August 2008 Pre-publication version for on-line viewing. Monograph to appear Februrary 2009
Markov Chains
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Stochastic Stability
$\|P^n(x,\cdot) - \pi\|_f \to 0$
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$\sup_C E_x[S_{\tau_C}(f)] < \infty$
$\Delta V(x) \leq -f(x) + b\mathbb{I}_C(x)$
S. P. Meyn and R. L. Tweedie
CAMBRIDGE
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