Dynamic Models and Dynamic Markets for Electric Power Networks

Based on tutorial & panel lectures at Energy Systems Week, Cambridge UK
http://www.newton.ac.uk/programmes/SCS/scsw07p.html

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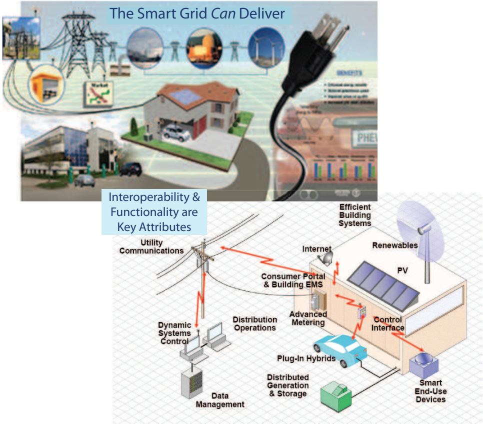
University of Illinois at Urbana-Champaign, USA

July 16, 2010

Outline

TCIPG



TCIPG

Trustworthy Cyber Infrastructure for Power Grid

tcipg.iti.illinois.edu

TCIPG

The Challenge:

Trustworthy Smart Grid Operation, even in Hostile Environments

TCIPG

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Trustworthy Smart Grid Operation, even in Hostile Environments

- Trustworthy
  A system which does what is supposed to do — *nothing else*.
  Availability, Security, Safety, ...
- Hostile Environment
  Accidental Failures, Design Flaws, Malicious Attacks
- Cyber Physical Must make the whole system trustworthy:
  The physical & cyber components, *and* their interaction.

Extending the Realm of Optimization

Complex Systems: *Uncertainty, Competition and Dynamics*

The Challenge:

Planning & operations for the next generation of engineering-economic systems

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Complex Systems: *Uncertainty, Competition and Dynamics*

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Planning & operations for the next generation of engineering-economic systems

- Stochastic Systems & Stochastic Games:
  Analysis, approximations, distributed algorithms
- Dynamic optimization and games: *Efficiency and reliability*
  What does a dynamic equilibrium look like?
  What is the impact of strategic behavior?
- Mean-field approximations: *Model reduction, decentralized outcomes, learning schemes*

Uncertainty & Dynamics ⊕ Risk-aversion

Firms bid in forward market, subject to equilibrium in spot-market

When competing firms have volatile generation assets, integrating uncertainty and risk-aversion is crucial

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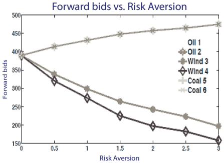
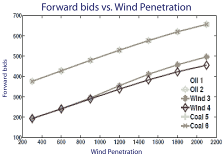
Contributions:

- Nash equilibria:
  Existence, uniqueness, computation
- Application: 53-node network with 6 generators (2 of whom have wind assets)
- With increased risk-aversion, wind-based generators participate less in forward markets



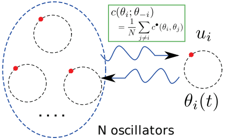


A. Kannan, U. Shanbhag, and H. Kim:
1. Risk-based Generalized Nash Games in Power Markets: Characterization and Computation of Equilibria, 2009
2. Strategic behavior in power markets under uncertainty, 2010

Synchronization of coupled oscillators is a game

Autonomous dynamical systems coupled by objectives

Oscillator model: $\mathrm{d}\theta_i = (\omega_i + u_i(t))\,\mathrm{d}t + \sigma\,\mathrm{d}\xi_i$



Each seeks to minimize the coupled cost,

$$\eta_i(u_i;u_{-i}) = \lim_{T\to\infty} \frac{1}{T}\int_0^T \mathrm{E}[\ \underbrace{c(\theta_i;\theta_{-i})}_{\text{cost of anarchy}} + \underbrace{\tfrac{1}{2}Ru_i^2}_{\text{cost of control}}\ ]\,\mathrm{d}s$$

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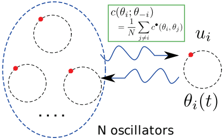

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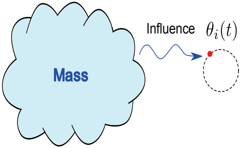
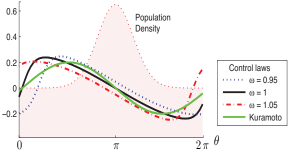
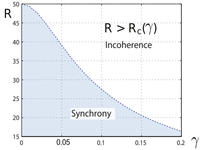






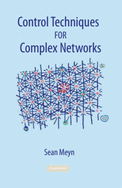
H. Yin, P. G. Mehta, S. P. Meyn and U. V. Shanbhag:

1. "Synchronization of coupled oscillators is a game," American Control Conference 2010, Baltimore, MD
2. "Learning in mean-field oscillators games," IEEE Conference on Decision and Control, 2010

Control Techniques for Complex Networks

Breaking the curse of dimensionality

- *Convex relaxations*
- *Workload relaxations*
- Algorithms for learning and simulation



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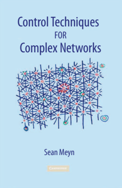
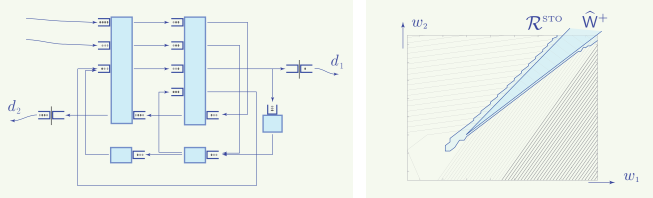
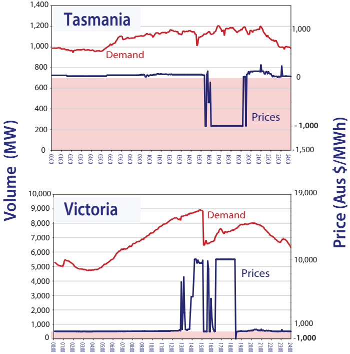




Demand driven network and its workload relaxation



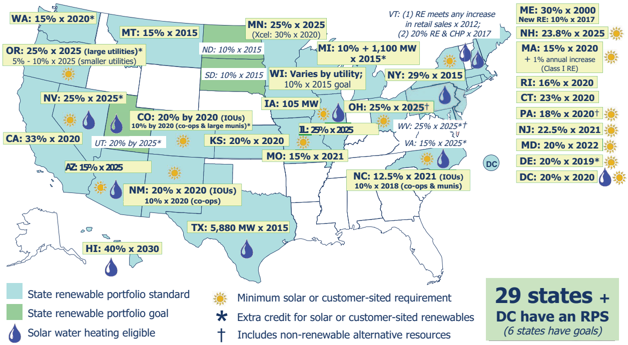
Australia - January 16, 2007

Issues and Approaches

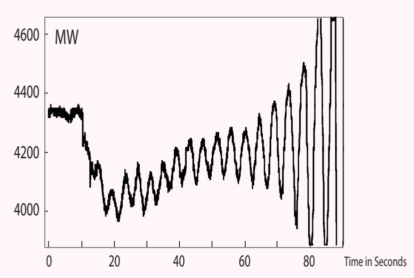
Issues: Political *Mandates come, and go...*

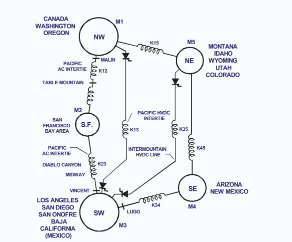
Renewable Portfolio Standards

www.dsireusa.org / February 2010



Issues: Dynamics *Coupled generators and consumers*

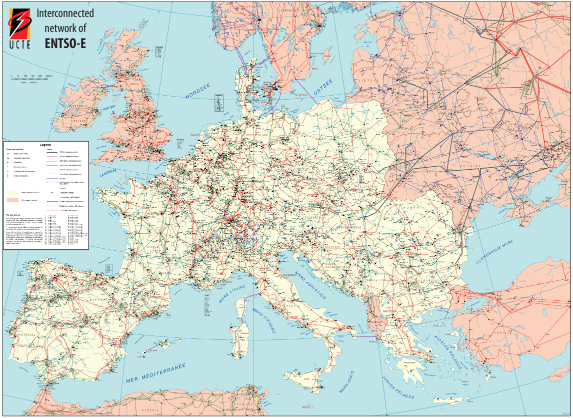




Mass-spring model

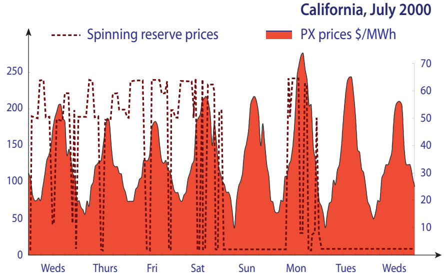
Instability in the North-West U.S.

Issues: Complexity



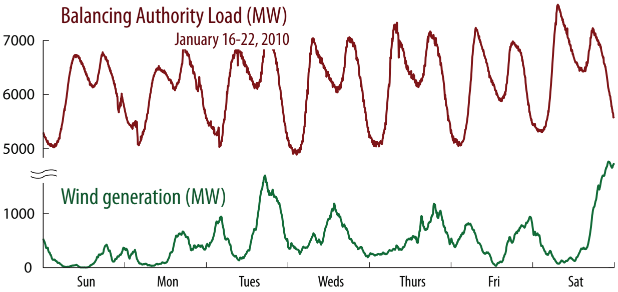
European Network of Transmission System Operators for Electricity

Issues: Market Power *Risk to consumers*



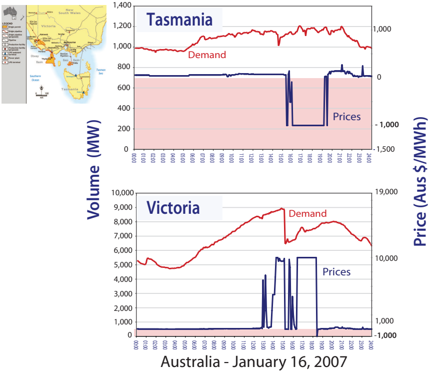
"Ripping off *those poor grandmothers*"

Issues: *Risks to suppliers*



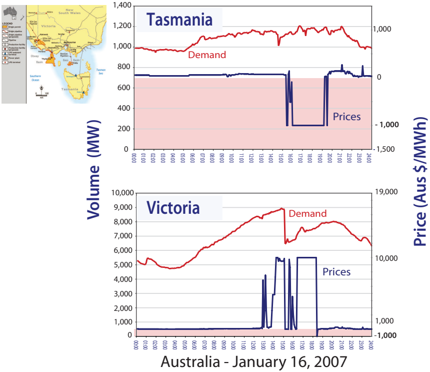
Who will buy my power if the wind is blowing?

Issues: Friction



Power flows according to Kirchoff's Laws, and subject to constraints ...

Issues: Friction



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... Mechanical and thermal constraints, ramp constraints, security constraints, ...

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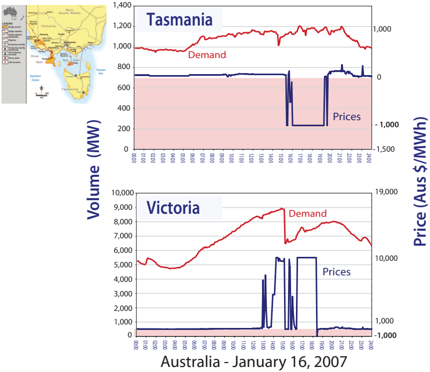

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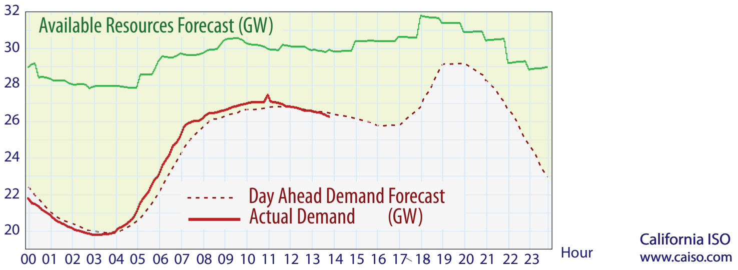
Market and physical system are tightly coupled

Issues: Uncertainty



ISO new england Mission:

- Operate the grid reliably and efficiently
- Provide fair and open transmission access
- Promote environmental stewardship
- Facilitate effective markets ...

Control solution: *Model based*

Simplest model that offers insight & leads to useful policy

Listed in order of complexity:

1. Generation is modeled via overall ramp-rate:

$$\frac{G(t_1)-G(t_0)}{t_1-t_0} \leq \zeta^+, \qquad 0 \leq t_0 < t_1 < \infty$$

We may also impose lower bounds.

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2. Distinguish primary and ancillary service:

$$\frac{G^p(t_1)-G^p(t_0)}{t_1-t_0} \le \zeta^{p+}, \quad \frac{G^a(t_1)-G^a(t_0)}{t_1-t_0} \le \zeta^{a+}$$

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3. Introduce transmission constraints:
   Power flow on transmission lines = linear function of nodal power values

   $F(t) = \Delta Z(t)$, Δ = *distribution factor matrix*

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   Power flow on transmission lines = linear function of nodal power values

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   $F(t) \in \mathsf{F} := \{x \in \mathbb{R}^{\ell_t} : -f^+ \le x \le f^+\}$

Market Analysis: *Perfect competition*

A beautiful world...

In this lecture, Dynamic market equilibria
under the most ideal circumstances:

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No "ENRON games" – no "market power"

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- Externalities are disregarded

  No government mandates

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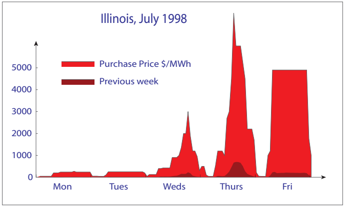
- Price manipulation is excluded

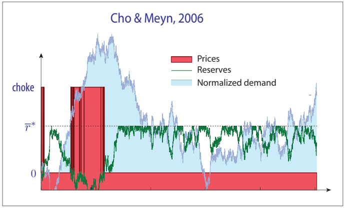
  No "ENRON games" – no "market power"

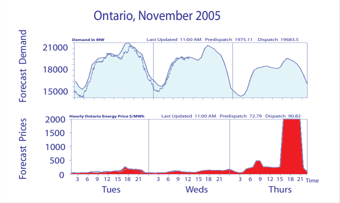
- Externalities are disregarded

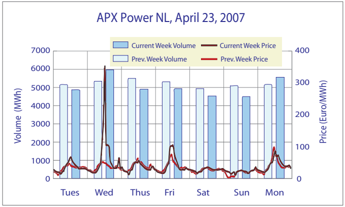
  No government mandates

- Consumers own available wind generation resources









Dynamic Markets and their Equilibria

Market Structure

Day-ahead market

The day-ahead market (DAM) is cleared one day prior to the actual production and delivery of energy.

Economic world...

Forward markets for electricity which improve market efficiency and serve as a hedging mechanism

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Day-ahead market

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Economic world...

Forward markets for electricity which improve market efficiency and serve as a hedging mechanism

...Physical world

Facilitate the scheduling of generating units

Market Structure

Real-time market

At close of the DAM: The ISO generates a schedule of generators to supply specific levels of power for each hour over the next 24 hour period.

RTM = Balancing Market

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

Market Structure

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RTM = Balancing Market

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

Market Analysis

First Welfare Theorem

Efficient Equilibrium

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

$$\textbf{subject to} \quad G_{\mathrm{S}}(t) = G_{\mathrm{D}}(t) \quad \text{for all } t$$

Market Analysis

First Welfare Theorem

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Welfare functions defined with a nominal price function $P(t)$

Market Analysis

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Key component of equilibrium theory:

Perfect competition

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).

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"price-taking assumption"

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Special case: *Welfare functions are piecewise linear,*

$$\mathcal{W}_{\rm S}(t) := P(t)G_{\rm S}(t) - cG(t)$$

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

Market Analysis
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Price function $P(t)$ *is irrelevant when* $G_{\rm S}(t) = G_{\rm D}(t)$

Market Analysis
First Welfare Theorem

First Welfare Theorem $\Longleftrightarrow$ Lagrangian Decomposition

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

Market Analysis

First Welfare Theorem

First Welfare Theorem $\iff$ Lagrangian Decomposition

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Assume: Social planner's problem has a solution, and there is no duality gap.

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Market Analysis

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Market analysis assumptions

Disutility from power loss

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of the form $cG(t)$ for some constant $c > 0$.

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Value of power

Consumer obtains v units of utility per unit of power consumed:
Utility to the consumer $= v \min(D(t), G(t))$.

What does an efficient equilibrium look like?

Answer: Marginal value

Equilibrium price

The *equilibrium price functional* is a piecewise constant function of the equilibrium reserve process,

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

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Answer: Marginal value

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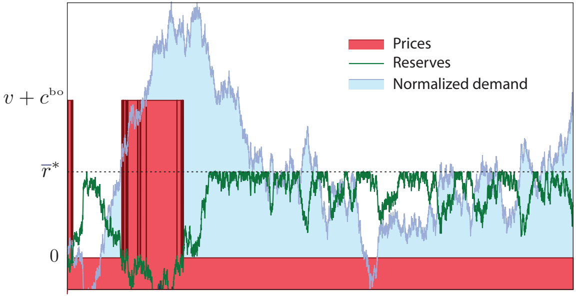
$P^*(t) = p^e(R^e(t))$: *marginal value* of power to the consumer

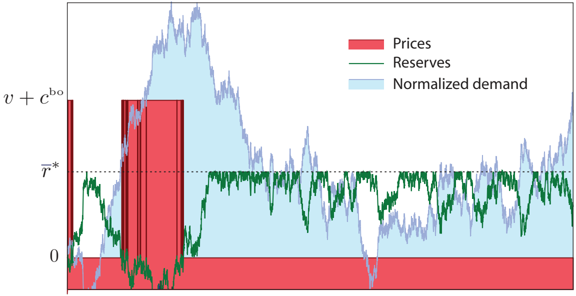
Market Equilibrium

Price Dynamics



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

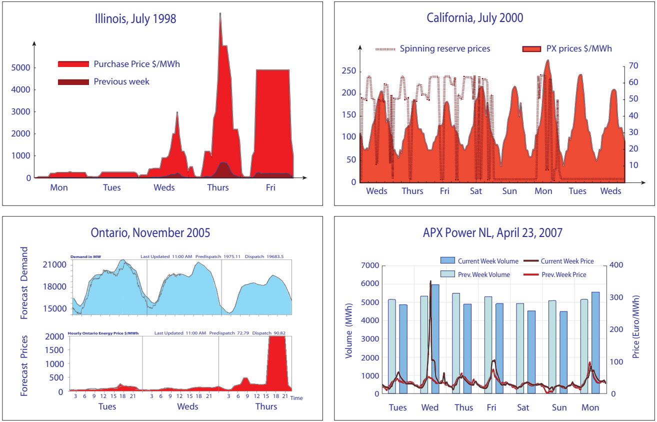
Market Equilibrium
Price Dynamics



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

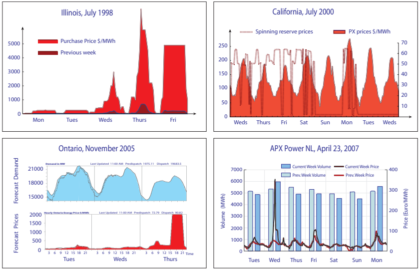
Smoother prices obtained when cost/utility are strictly convex

Familiar, right?



Sustainable business?

Marginal value of electricity may be $v + c^{\mathrm{bo}} =$ \$200,000/MWh!



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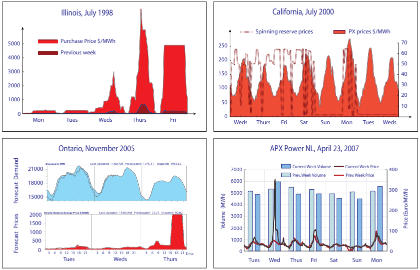

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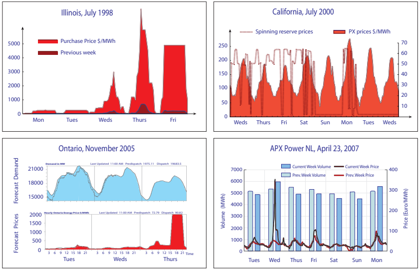

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Is this a sustainable business?

Who Commands the Wind?

Extending the dynamic model

Goal

Extend the DA/RT market model to differentiate power generated by wind and by conventional generation units

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All the wind power available is injected into the system

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All the wind power available is injected into the system

Key issue

Conventional generators serve residual demand.

Volatility of the residual demand will result in higher reserves in the dynamic market equilibrium

Emerging issues

Not only mean energy

The details depend on both volatility of wind and its proportion of the overall generation

What about now?

If the penetration of wind resources is low, then the increase in load volatility will be negligible, and hence there will be negligible impact on the market outcomes

Emerging issues

Not only mean energy

The details depend on both volatility of wind and its proportion of the overall generation

What about now?

If the penetration of wind resources is low, then the increase in load volatility will be negligible, and hence there will be negligible impact on the market outcomes

What about in 2020?

Potential negative market outcomes are possible with a combination of high wind generation penetration and high volatility of wind

Who Commands the Wind?

Main findings

Volatility can have tremendous impact on the market outcome

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Asymmetric and surprising result

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Why?

1. Higher variance in forecasting $\Longrightarrow$ higher reserves in DAM from traditional sources such as coal.

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Asymmetric and surprising result

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Why?

1. Higher variance in forecasting $\Longrightarrow$ higher reserves in DAM from traditional sources such as coal.
2. Higher real-time volatility $\Longrightarrow$ greater reliance on 'peaking units' such as gas-turbine generators.

Consumers command the wind

Wind generating units are commanded by the demand side:

Consumers' and suppliers' welfare expressions

$$\begin{aligned}\mathcal{W}^{\mathrm{ttl}}_{\mathrm{D,W}}(t) = v\min(D^{\mathrm{ttl}}(t), G^{\mathrm{ttl}}(t) + G^{\mathrm{ttl}}_{\mathrm{W}}(t)) \\ - c^{\mathrm{bo}}\max(0, -R(t)) \\ - P(t)G(t) - p(t)g^{\mathrm{da}}(t)\end{aligned}$$

$$\mathcal{W}^{\mathrm{ttl}}_{\mathrm{S,W}}(t) = \big(P(t) - c^{\mathrm{rt}}\big)G(t) + \big(p(t) - c^{\mathrm{da}}\big)g^{\mathrm{da}}(t)$$

Consumers command the wind

Welfare expressions: DAM/RTM decomposition

$$\begin{aligned}\mathcal{W}^{\mathrm{ttl}}_{\mathrm{D,W}}(t) = \mathcal{W}^{\mathrm{rt}}_{\mathrm{D,W}}(t) \\ &+ \left\{ v d^{\mathrm{da}}(t) - p(t)(d^{\mathrm{da}}(t) - g^{\mathrm{da}}_{\mathrm{W}}(t)) \right\} \\ &+ \left\{ (P(t) - p(t)) r^{\mathrm{da}}_0 + v G_{\mathrm{W}}(t) \right\}\end{aligned}$$

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$\mathcal{W}^{\mathrm{rt}}_{\mathrm{D,W}}(t)$, $\mathcal{W}^{\mathrm{rt}}_{\mathrm{S,W}}(t)$: Welfare obtained in the RTM with residual demand $D^{\mathrm{net}}(t)$.

Numerical Results: Parameters

Penetration and volatility

Coefficient of variation to capture the relative volatility of wind:

$$c_v = \frac{\sigma_w}{\mathsf{E}[G_{\mathrm{W}}^{\mathrm{ttl}}(t)]}$$

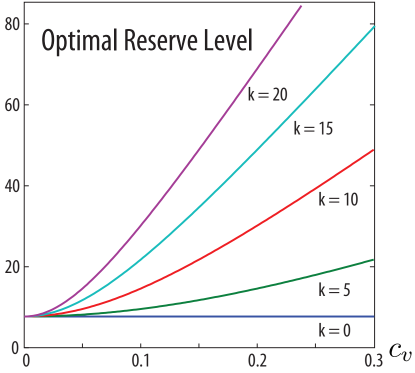
Percentage of wind penetration:

$$\mathrm{k} = 100 * \mathsf{E}[G_{\mathrm{W}}^{\mathrm{ttl}}(t)]/\bar{D}^{\mathrm{ttl}}$$

Remaining model/statistical details in 2010 preprint,
The value of volatile resources in electricity markets.

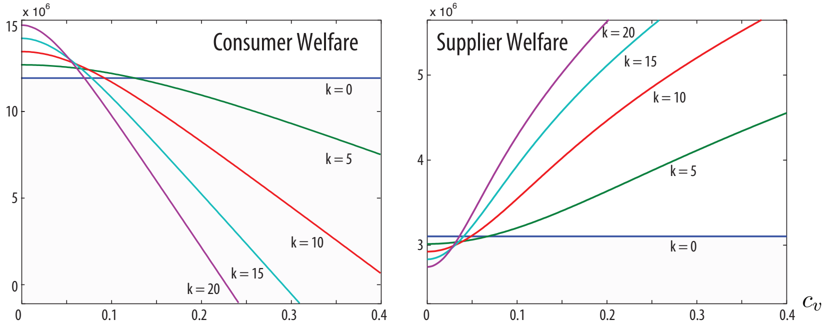
Numerical Results: Volatility Impacts

Optimal reserves rise with volatility



Numerical Results: Consumers command the wind

Consumer welfare falls and supplier welfare rises with volatility



Research Frontiers

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Strategic behavior

Q1

Building bridges

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Building bridges between researchers in economics, systems/statistical sciences, and power engineers.

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Approach: Follow the example of highway engineering:

Analysis of strategic behavior will be possible if agent behavior is suitably constrained

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Stalinist? The economic security of the region is at stake! Expectations to market participants must be made clear, and must be enforced!!

Research Frontiers
Statistics

Q2

Learning

Research Frontiers

Statistics

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Learning (a) Once a market framework is in place, agents will learn over time to optimize their reward

Research Frontiers
Statistics

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Research Frontiers

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(b) Forecasting energy demand and supply with uncertain wind, tides, sun, and a 'smart grid'.

Research Frontiers

Statistics

Q2

Learning (a) Once a market framework is in place, agents will learn over time to optimize their reward *Q-learning and TD-learning are potential approaches*

(b) Forecasting energy demand and supply with uncertain wind, tides, sun, and a 'smart grid'.

(c) Predicting blackout or cascading failures

(d), (e), ...

Research Frontiers

Controlling supply, storage, and demand

Q3

The impact of demand management and storage on the market

Research Frontiers

Controlling supply, storage, and demand

Q3

The impact of demand management and storage on the market

Q4

The impact of *supply* management and storage on the market.
e.g., modern wind turbines allow pitch angle control.

Research Frontiers

Controlling supply, storage, and demand

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The impact of demand management and storage on the market

Q4

The impact of *supply* management and storage on the market.
e.g., modern wind turbines allow pitch angle control.

Beyond arithmetic:

> *What are the dynamical properties of the power grid in LA county with dynamic pricing, hybrid cars, and automated water pumping?*

Research Frontiers

Facing volatility

Q5

Not just "missing money" —

Research Frontiers

Facing volatility

Q5

Not just "missing money" — Mechanisms to reduce consumers *and* suppliers exposure to volatility.

Research Frontiers

Facing volatility

Q5

Not just "missing money" — Mechanisms to reduce consumers *and* suppliers exposure to volatility.

Especially supply-side volatility with introduction of renewable energy, such as wind

Research Frontiers

Long-term incentives

Q6

How to create policies to protect participants on both sides of the market, while creating incentives for R&D on renewable energy?

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Research Frontiers

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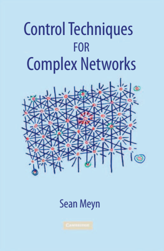
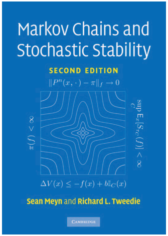
We hope that the ideas described here will form a building block for constructing and analyzing far more intricate models, taking into account a broader range of issues.

Thanks!

Celebrating with Dutch Babies after finishing *The value of volatile resources...*


Control Techniques
FOR
Complex Networks
Sean Meyn


Markov Chains and
Stochastic Stability
SECOND EDITION
$\|P^n(x,\cdot) - \pi\|_f \to 0$
$\Delta V(x) \le -f(x) + b\mathbb{I}_C(x)$
Sean Meyn and Richard L. Tweedie
CAMBRIDGE

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