The Future Power Grid

Resilience and Systemic Risk

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Cascades in Infrastructure Networks

FLOODING IN THAILAND COULD CAUSE INDUSTRY-WIDE HARD DRIVE SHORTAGE

BY AMY FREELAND / 31 OCTOBER 2011 / 0 COMMENTS

Heavy monsoon rains that have left much of Thailand literally under water could impact the computer industry this holiday season and beyond. According to All Things D, the flooding already has affected the Thailand operations of two major hard drive manufacturers, Western Digital and Seagate Technology.

The New York Times

December 27, 2008

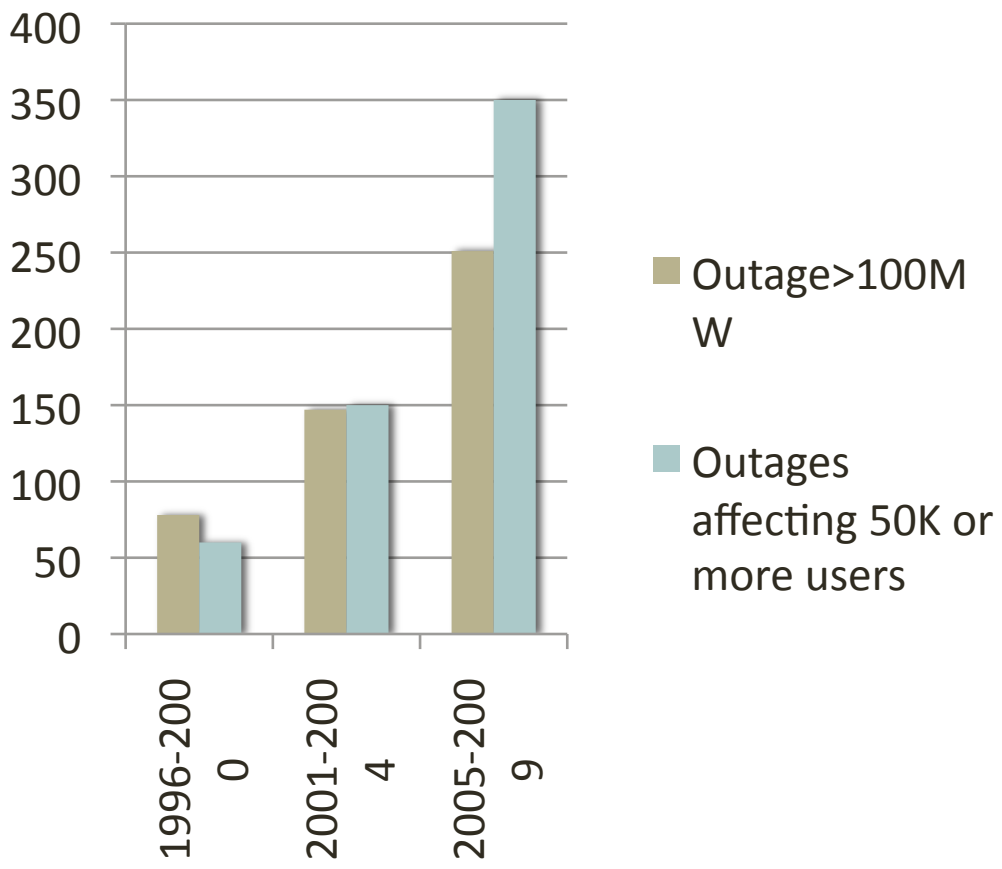
Flight Delays Radiate From Chicago and Atlanta

Major power outage hits New York, other large cities

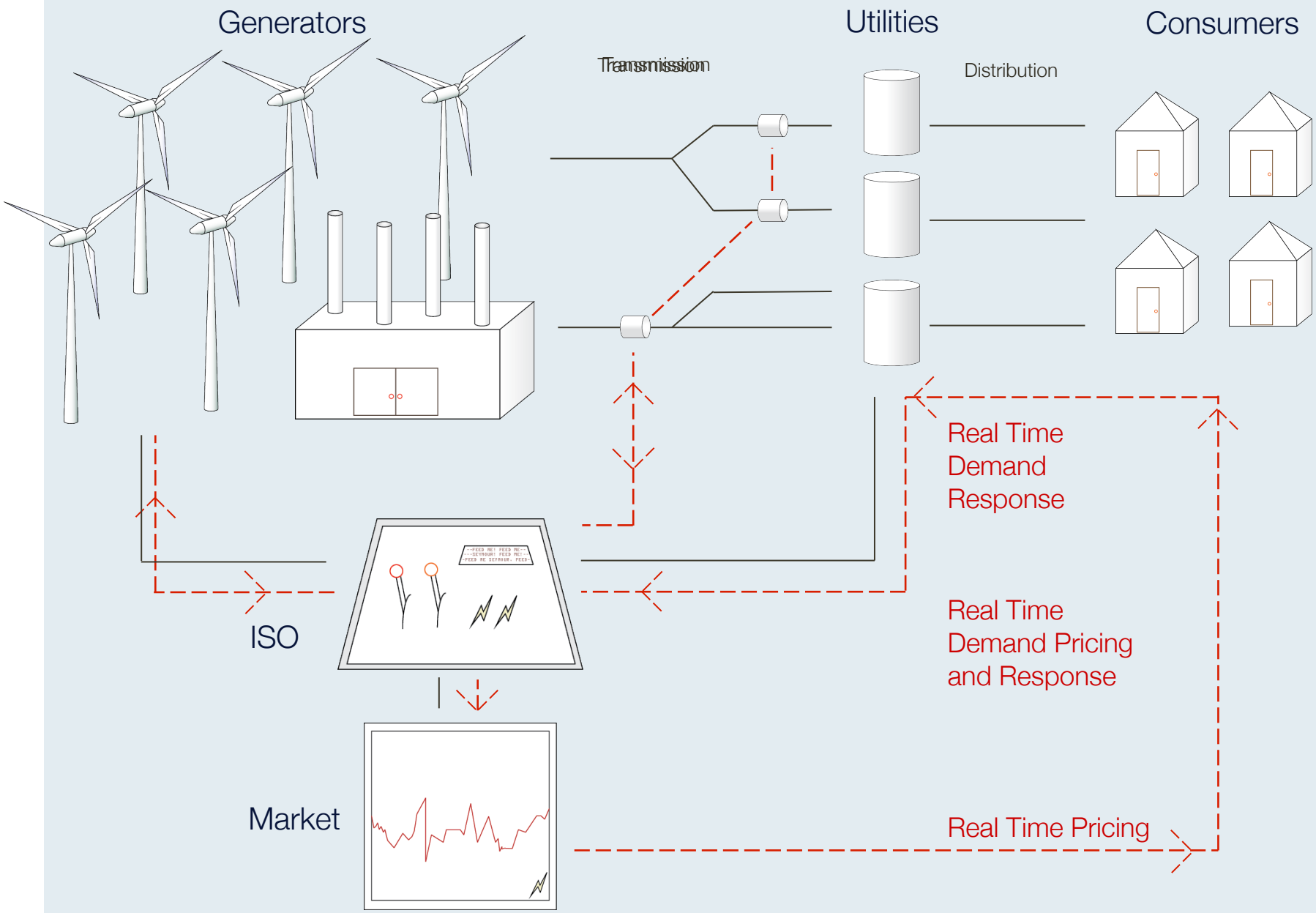
August 14, 2003

Economics

- Power outages cost US economy $80B -150B annually (0.01 % of GDP)



The Smart Grid



Efficiency and Reliability

- Efficiency and reliability at the component Level
- Efficiency and Reliability at the system level
  - Information and Decision Architecture
    - Modeling and simulation
    - Communication and Control Architectures
  - Market Architecture
- Incentives for Innovation
  - Regulation

Efficient Components

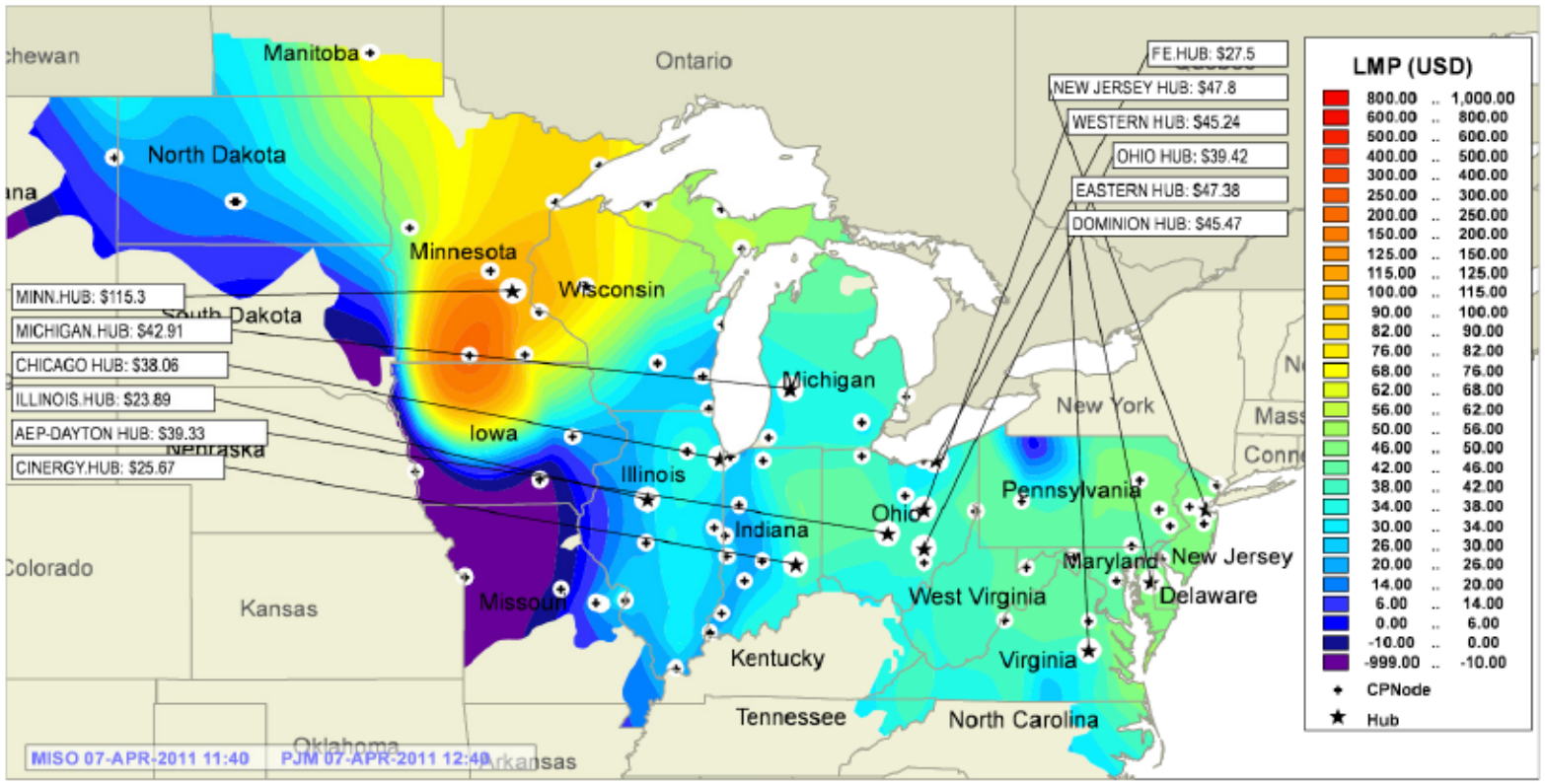
- Energy usage divided among sectors
  - Residential ~ 37%
  - Commercial ~34%
  - Industrial ~26%
  - Transportation ~ (currently) small
- Efficient power electronic Components
  - More effective lighting (e.g., LED lighting), air conditioning (e.g., high-efficiency inverter-driven AC), appliances (reduced standby power, higher efficiency), etc.
- Improved electronic controls, sensing and communication, and management offer substantial demand-side control

System Level Reliability-Resilience

- Robust communication and control architecture
- Caveats:
  - Feedback (e.g., Real-time demand response)
  - Coordination vs Strategic (e.g., demand shift)
  - Network effect

Price Volatility

Locational Marginal Prices at PJM ISO 07-April-2011 **12:40** EST



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Price Volatility

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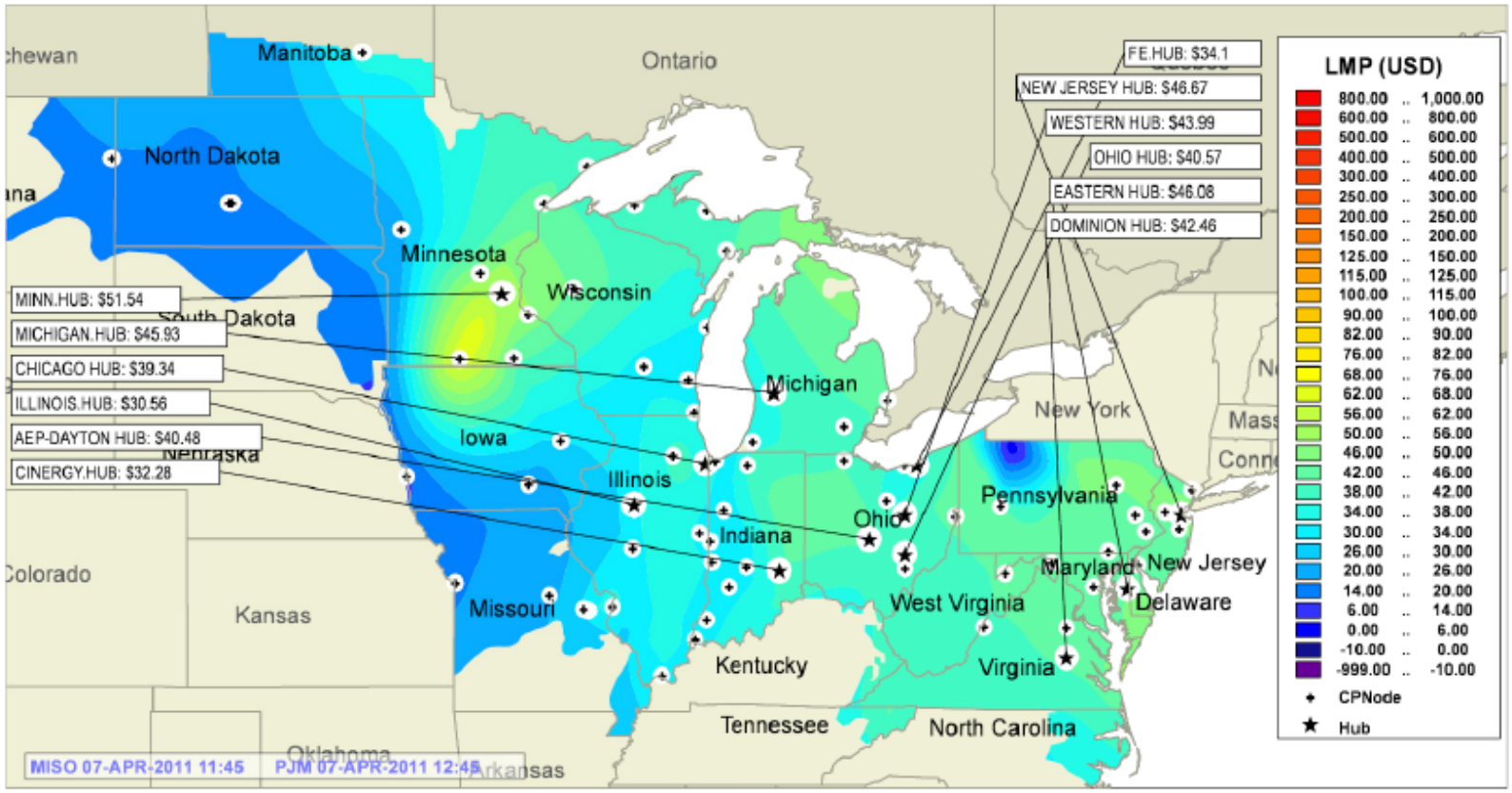

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Price Volatility

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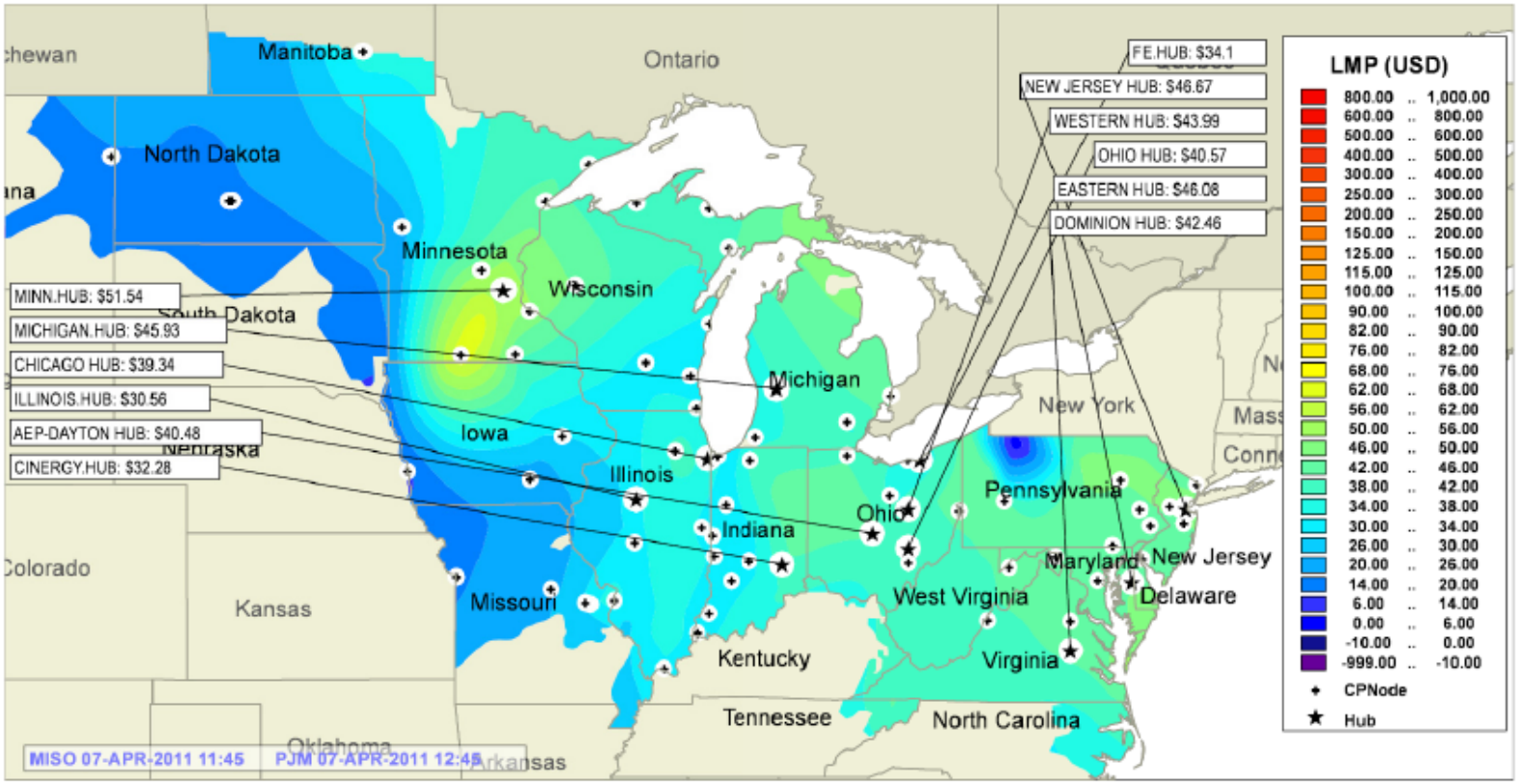

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Price Volatility

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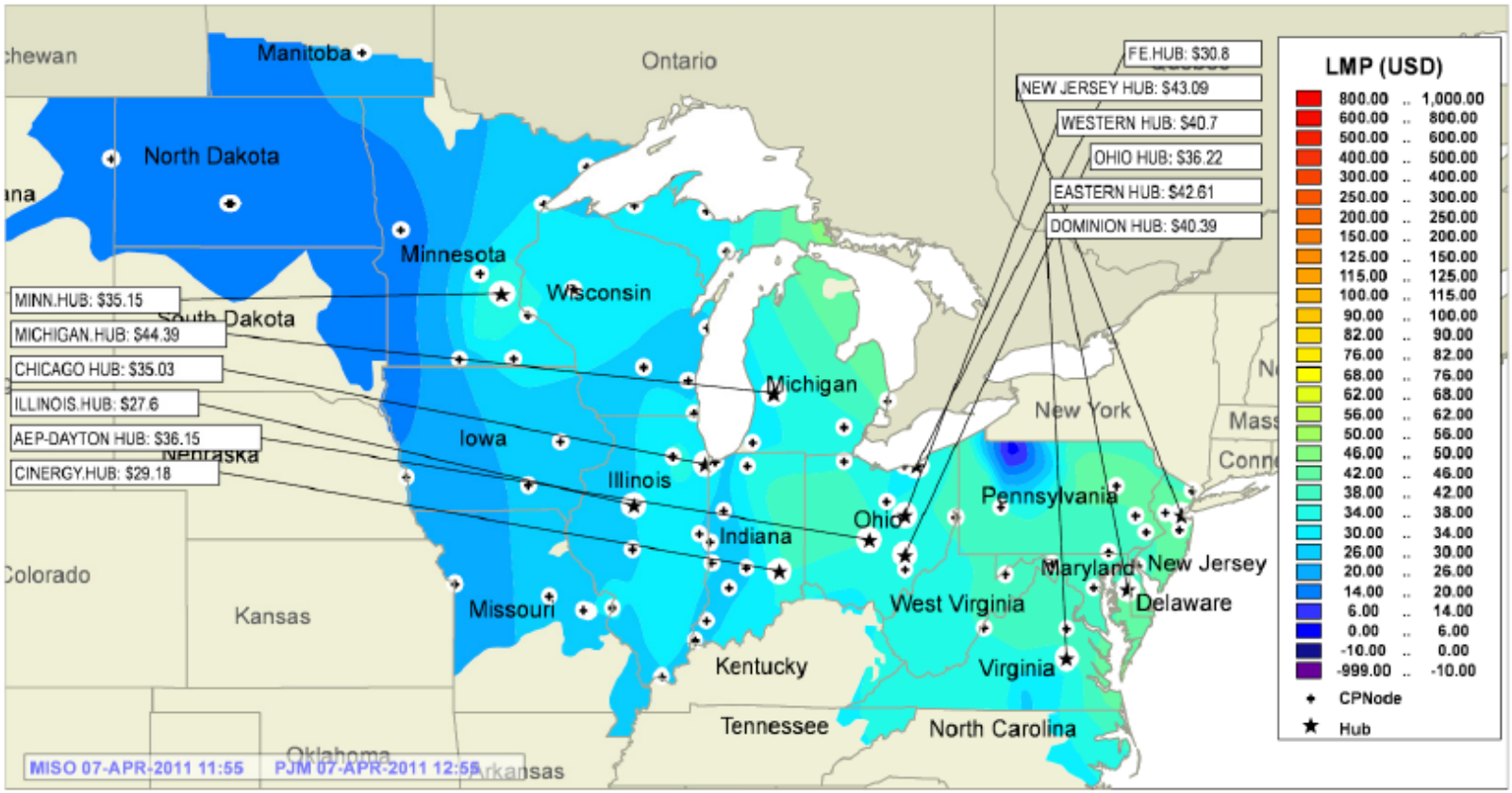

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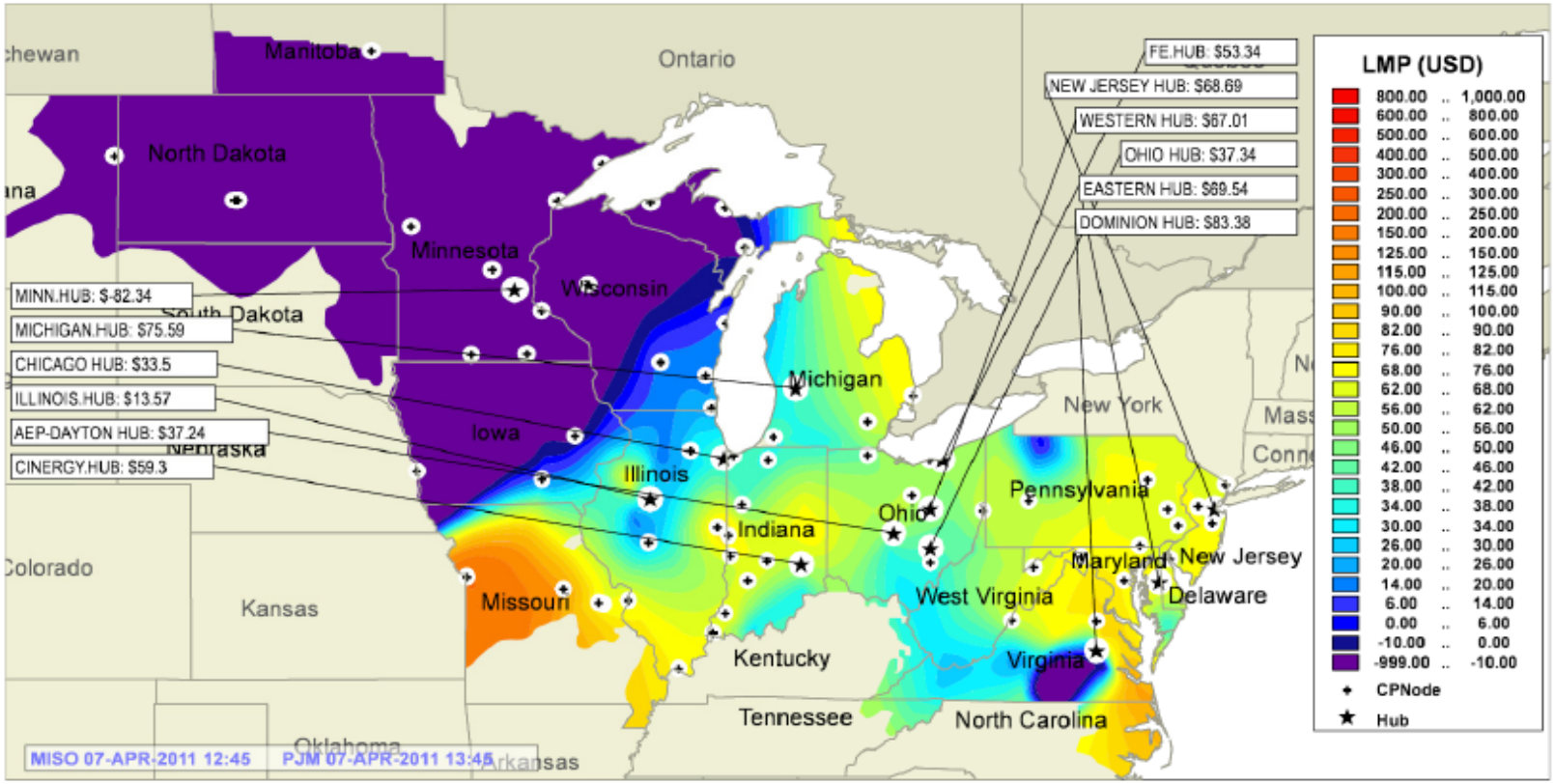
Price Volatility

One Hour Later...

Price Volatility

Locational Marginal Prices at PJM ISO 07-April-2011 **13:45** EST



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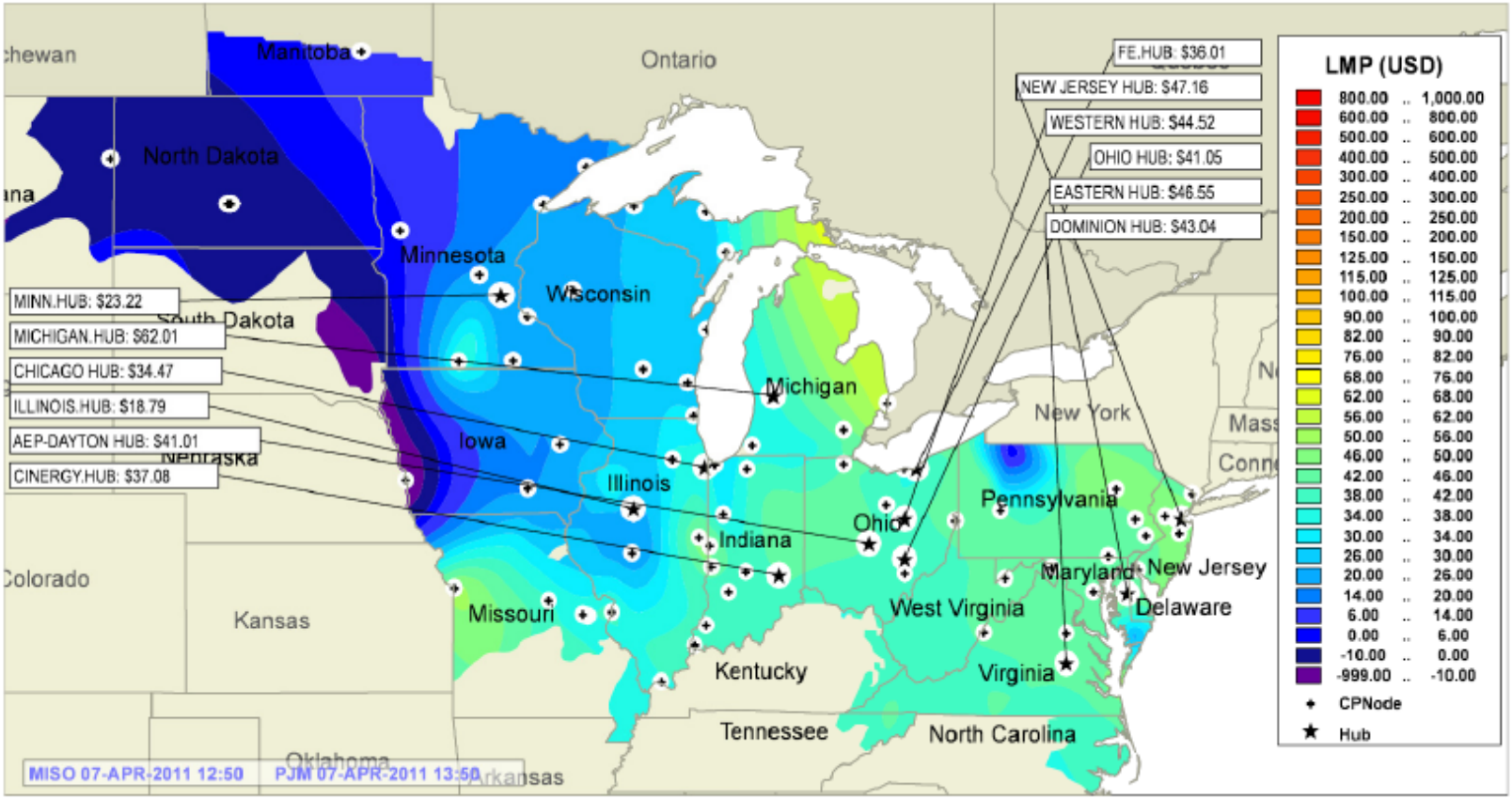
Price Volatility

Locational Marginal Prices at PJM ISO 07-April-2011 **13:50** EST



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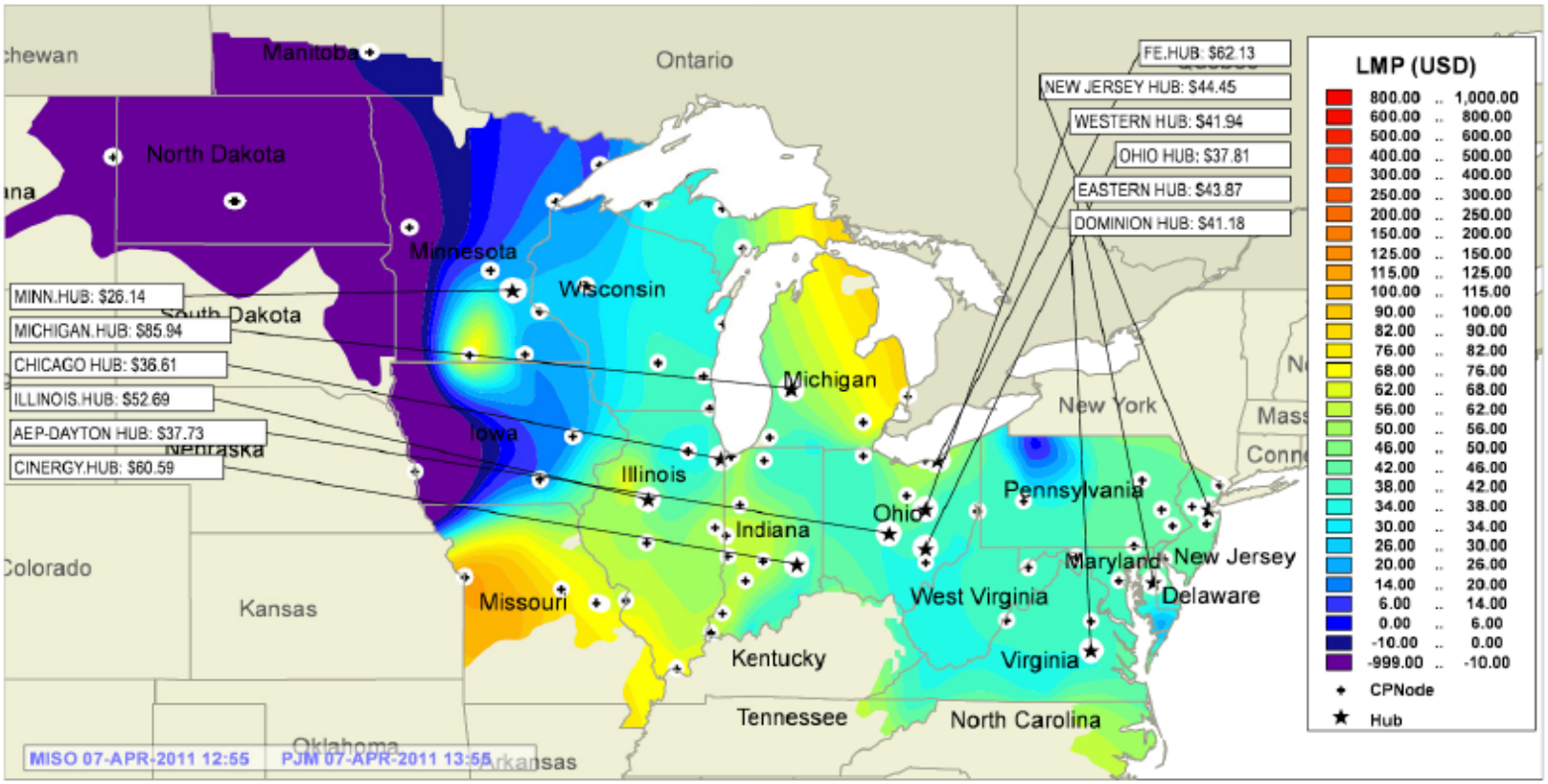
Price Volatility

Locational Marginal Prices at PJM ISO 07-April-2011 **13:55** EST



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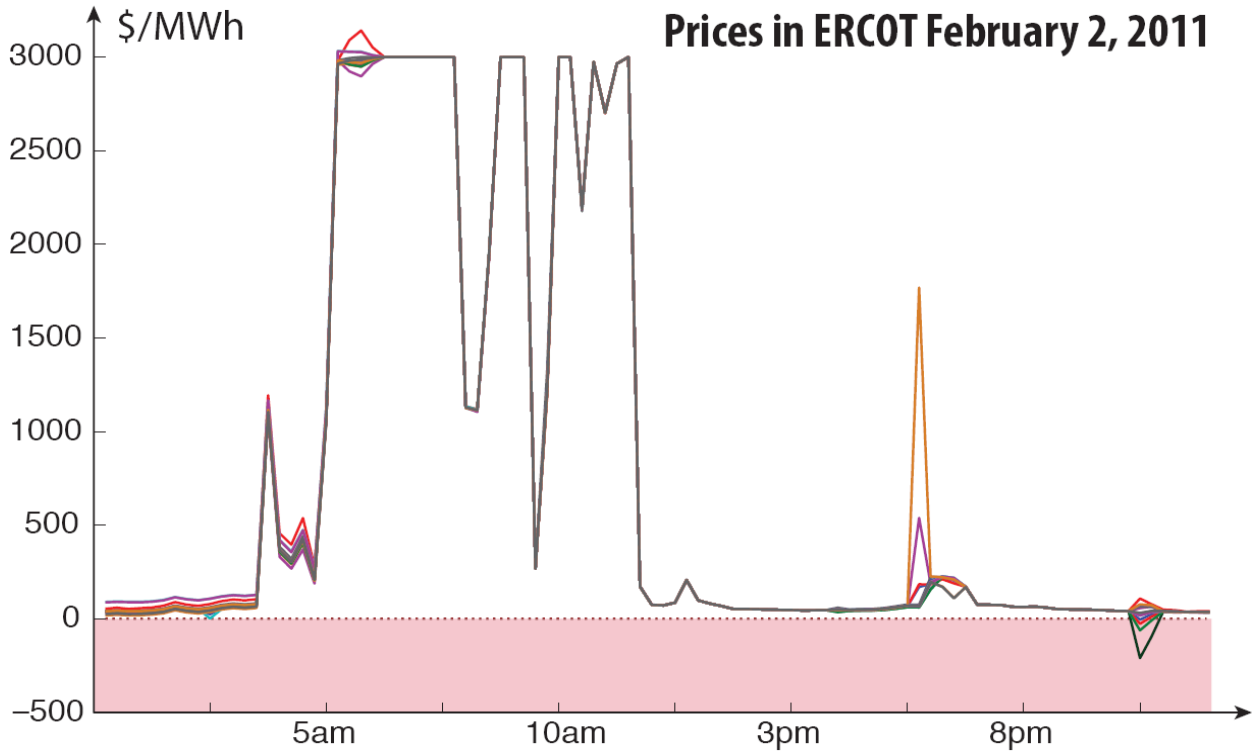
Price Volatility

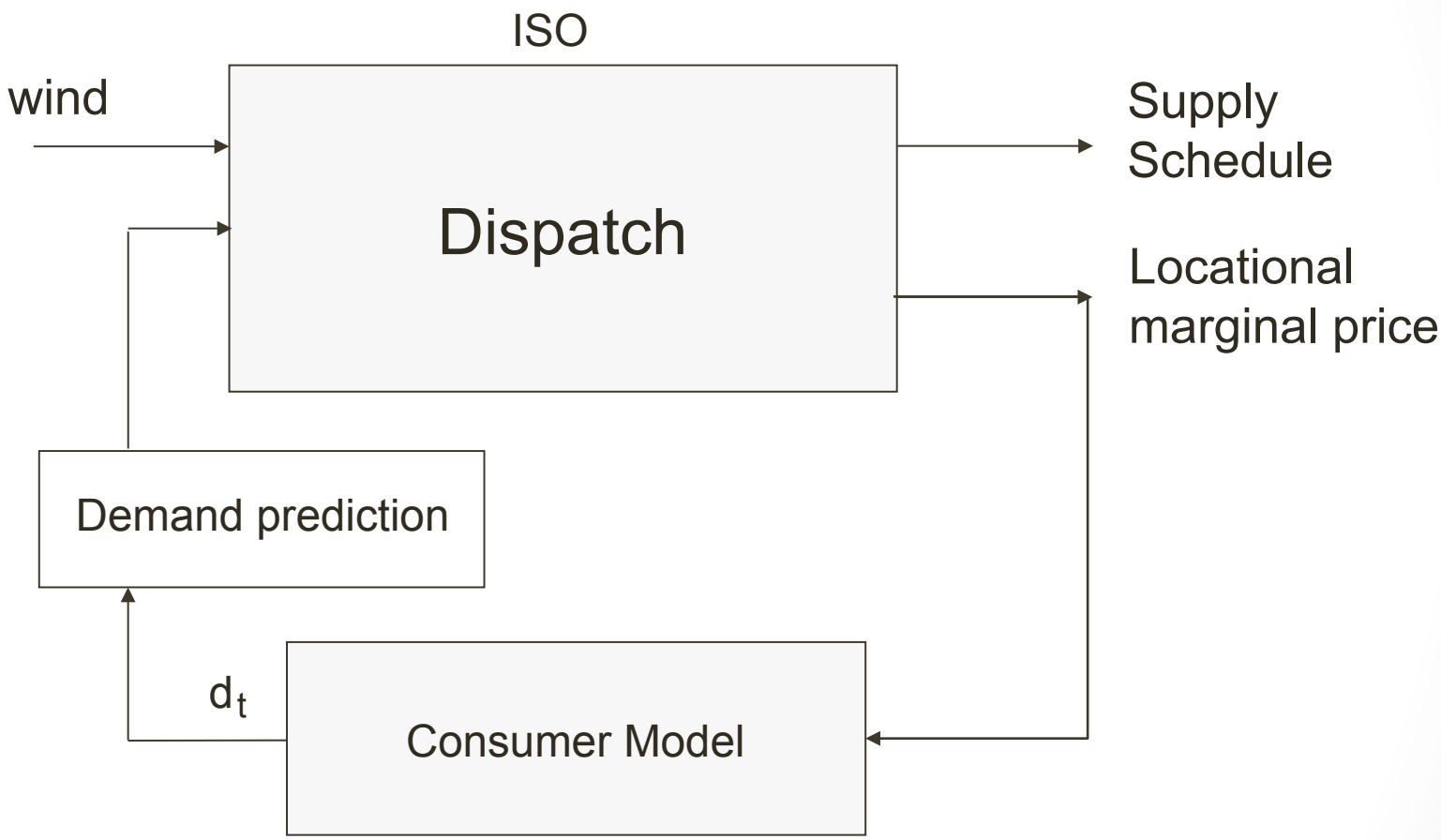
It does get even more dramatic...



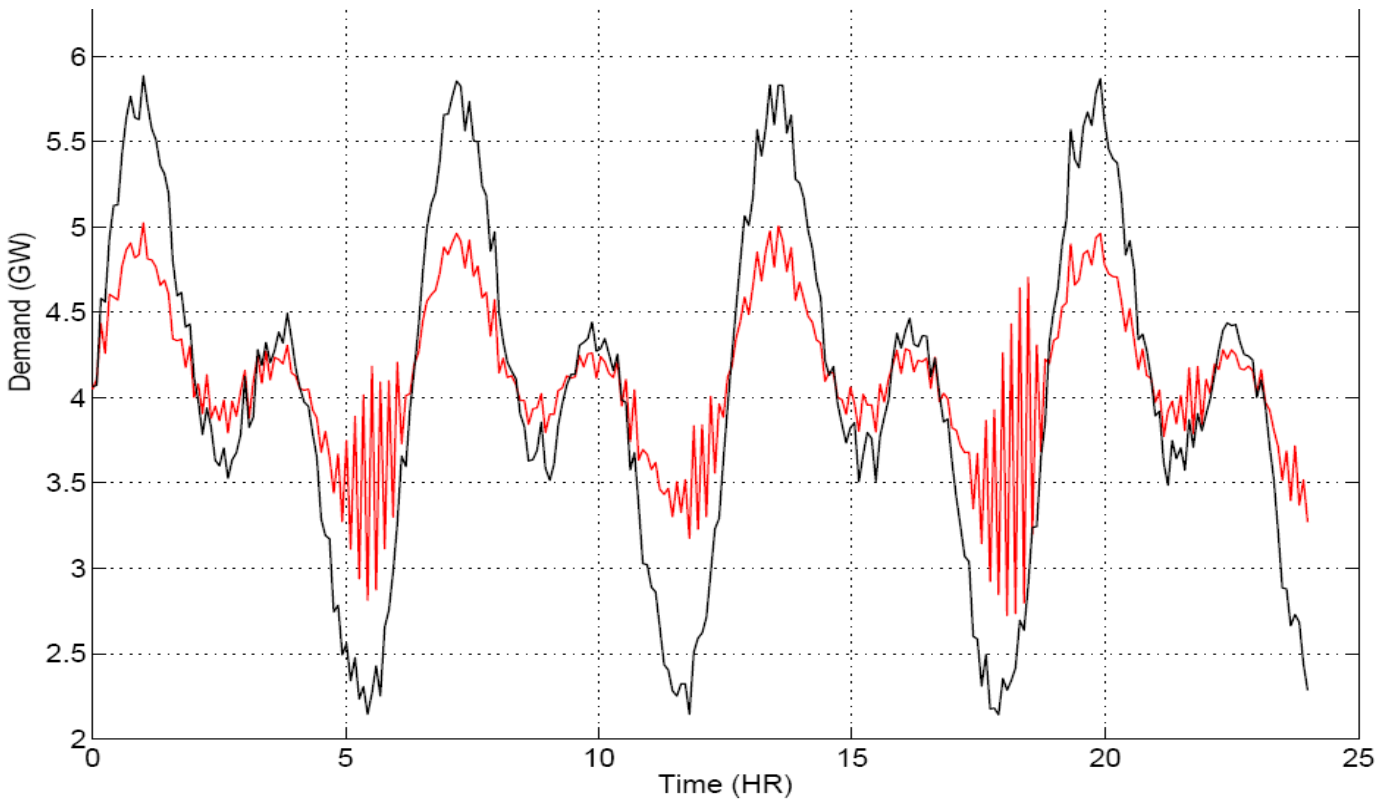
There are many examples like this.

Real-Time Demand Response

Closing the Loop



RTP Increases Volatility



Price of Coordination

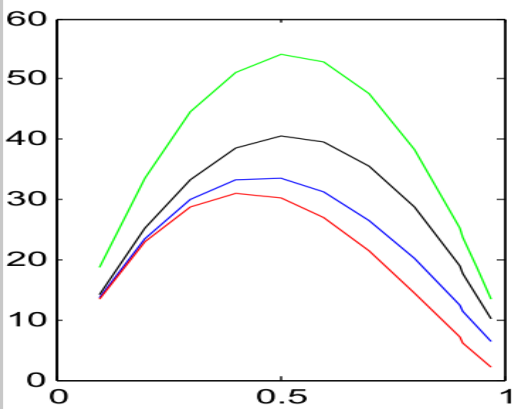
- Price of Anarchy: Loss in efficiency due to strategic interactions in contrast to a coordination
- Simple model: one agent with shiftable demand and another with instantaneous demand
- Contrast optimal efficient solution to a Stackelberg game of strategic behavior
- A new tradeoff: Cooperation can increase endogenous risk

Price of Anarchy: what about risk?

Aggregate demand

Cooperative
Strategic

Variance



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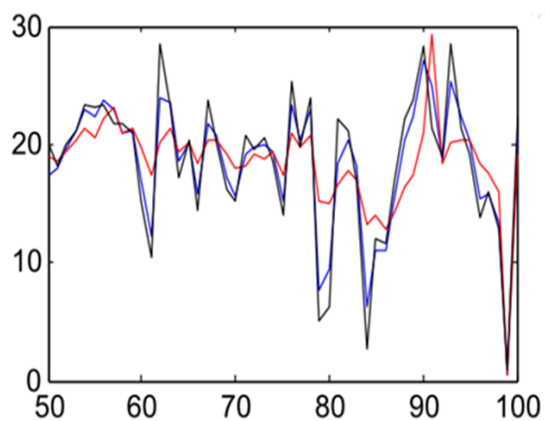
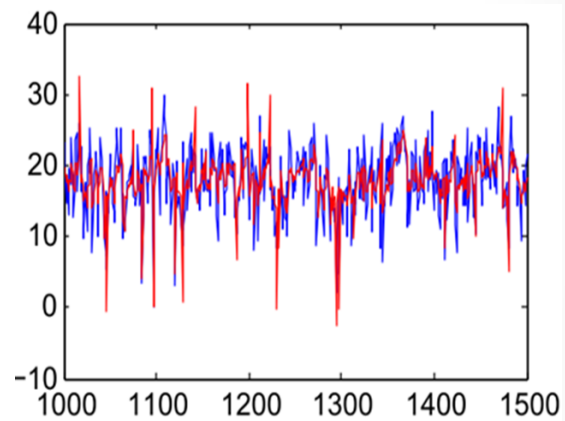
Sample path



small time scale



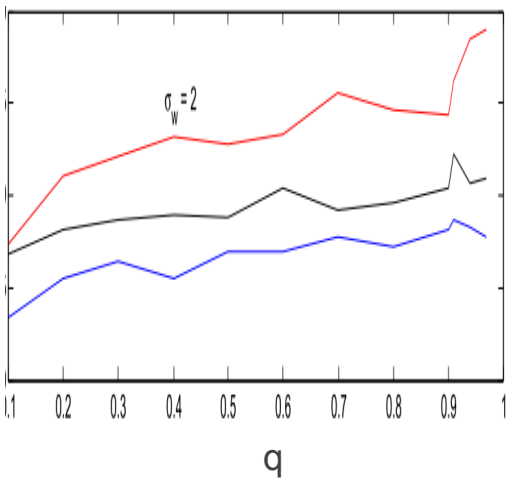
large time scale

Example I: L = 2

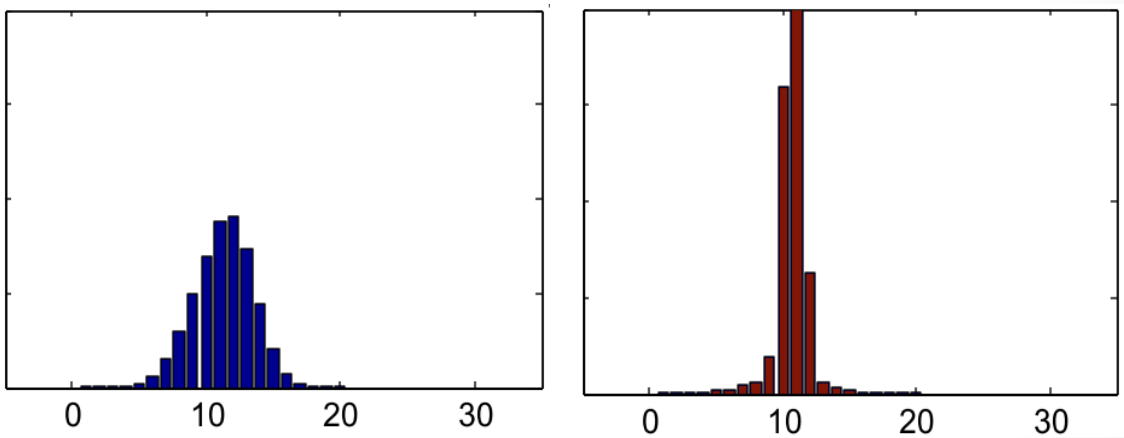
Aggregate demand

Cooperative
Strategic

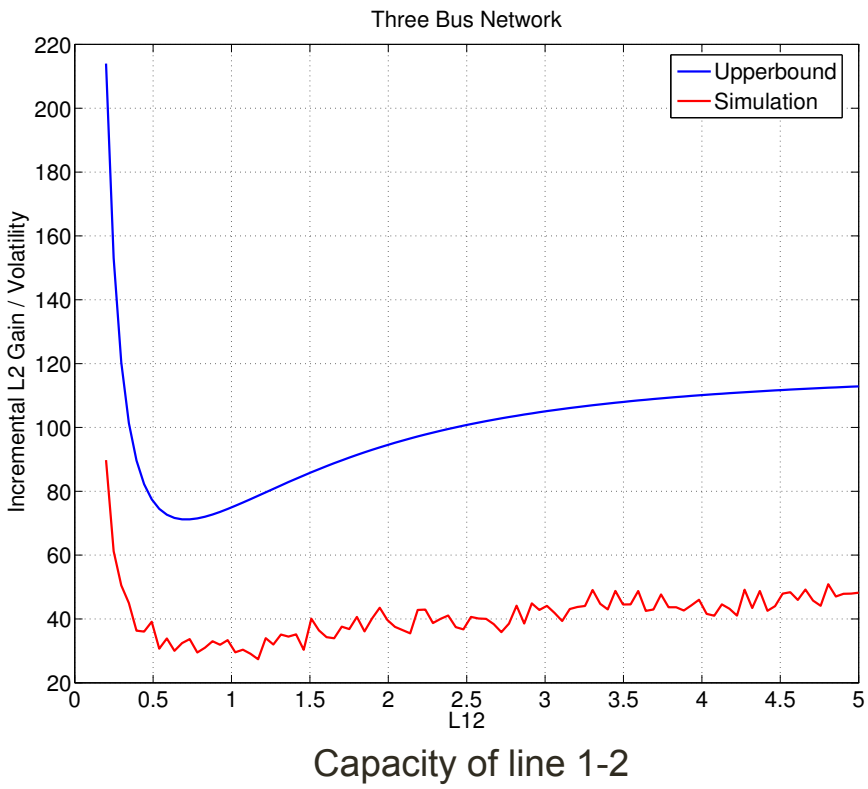
95% percentile



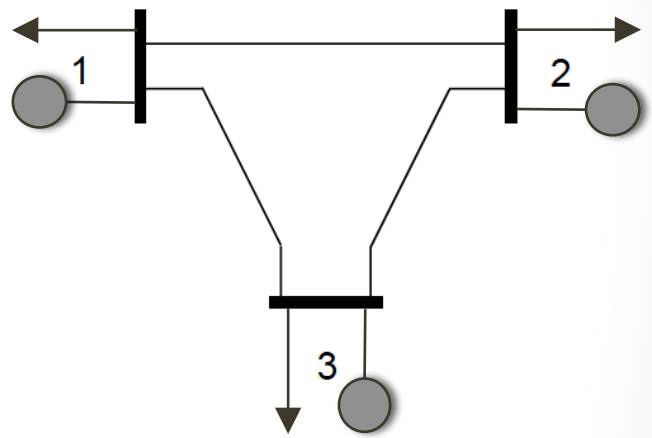
Stationary distribution



Network example



- **Heterogeneity amplifies the "network effects"**
- **"More interconnection" can lead to more volatility**



- The elasticity of consumers and producers is such that the interactions at each node are very stable.
- Due to heterogeneity, interactions between a consumer and a producer at a different bus may be unstable or “less stable”.
- Increasing the transmission capacity between 1 and 2 amounts to interconnecting dynamical systems.

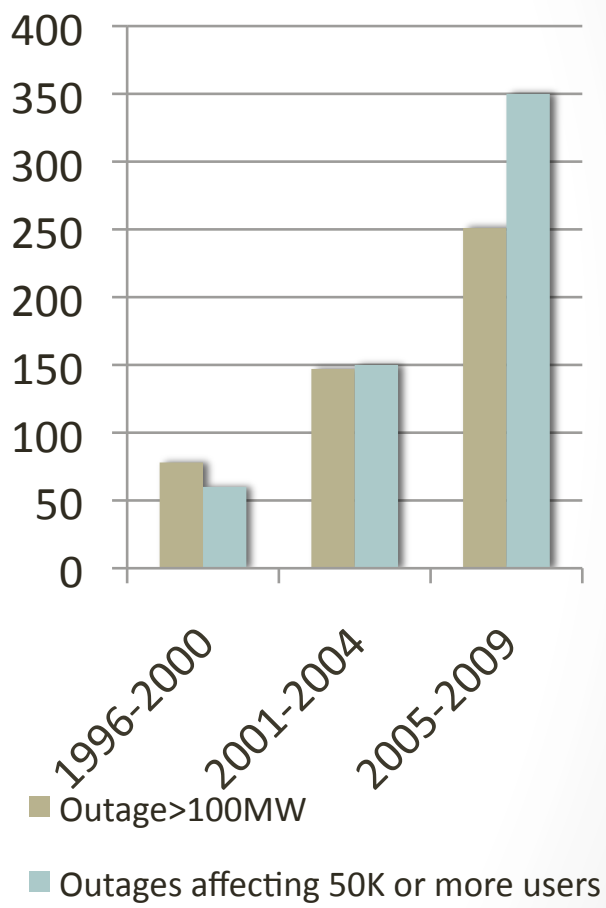
Innovation

- Robust Architecture (Distributed vs decentralized)
  - Robust Feedback
  - Distributed computing, Strategic decisions
  - Network effects and Resilience
- Degree of Regulation and Centralization
- Incentives
  - Who owns what?
  - Can renewables be penalized?
  - Storage
- Electrification of cars

Thank You

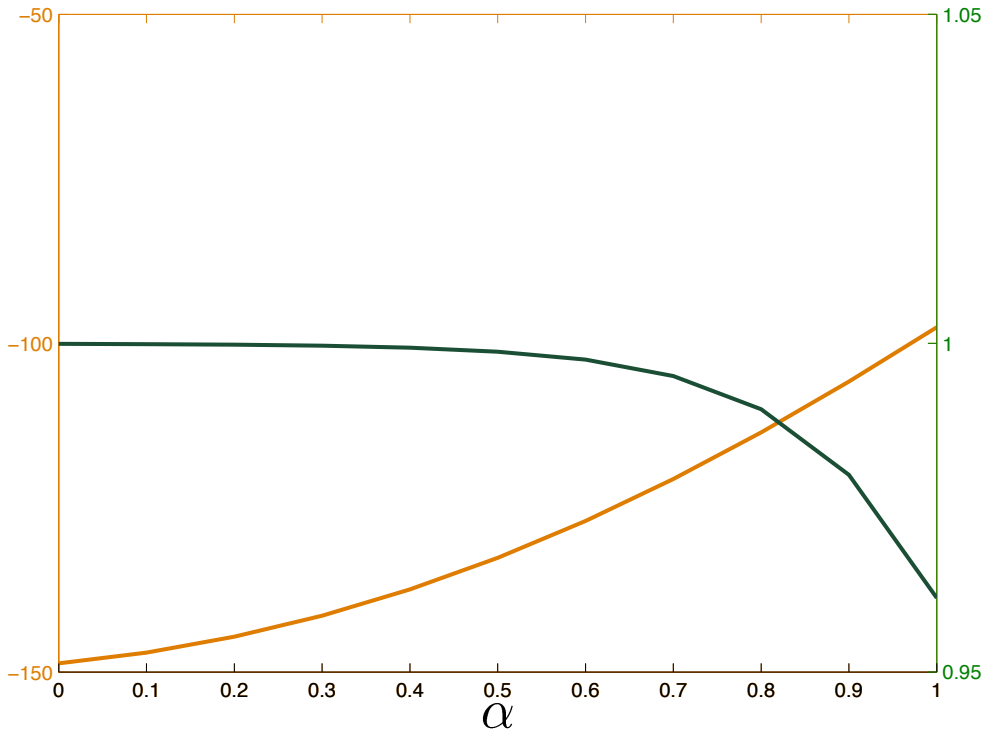
Economics

- Power outages cost US economy $80B -150B annually (0.01 % of GDP)
  - The number of outages of 100 MW or larger is up from **78** during 1995-1999 to **147** during 2000 -2004, and to **250** during 2005-2009.
  - The number of outages affecting 50000 or more customers has a similar pattern of steady increase.
  - Other surprising risks: Network effects and coupled infrastructures (The Germany Case).



Tradeoff

Efficiency
(- variance)



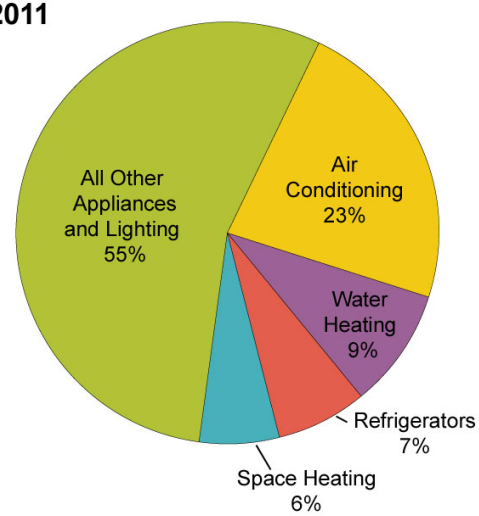
Robustness
(1- tail probability)

strategic ← ↑ complementarity ↓ → cooperative

Electrical Energy Usage in the USA

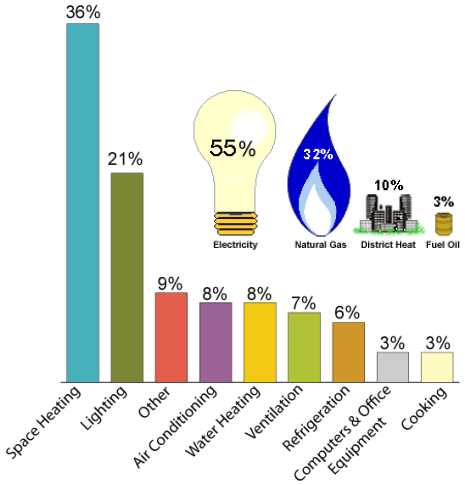
- Energy usage divided among sectors
  - Residential ~ 37%
  - Commercial ~34%
  - Industrial ~26%
  - Transportation ~ (currently) small

How Electricity Is Used in Homes, 2011



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2012, Early Release,* Table 4.

Energy Use in Commercial Buildings, 2003



Source: U.S. Energy Information Administration, *2003 Commercial Building Energy Consumption Survey,* Table E1A (September 2008).