An Introduction to Electricity Grid Infrastructure:
System Complexity in a Rapidly Changing Industry

By:
Peter Fox-Penner
The Brattle Group
1850 M Street, NW Suite 1200
Washington, DC 20036
202.955.5050

August 31, 2010
Overview

Structural Views of the Electric Power System:

♦ Electromechanical Structure
  • Physical Assets
  • Fuel Supplies

♦ Economic and Regulatory Structure

♦ Organization and Ownership Structure

♦ Information and Control Structure

Power System Crisis and Threats – Initial Thoughts and Examples
Electromechanical Production: Generator to Customer

**Generation**
- 6,137 plants

**Transmission System**
- 365,000 miles
- 45,000 Transformers etc

**Transmission**
- 138,000 to 765,000 Volts – AC or DC

**Distribution System**
- 6 million miles of lines
- 144 million meters

## Electricity Vs. the Internet

### Electric Power System

- To prevent physical destruction, load and generation must balance precisely at all times.

- AC power generators on one grid must synchronize frequency within fractions of a second.

- Power cannot be directed over the grid, it must be operated to prevent overloads on the weaker links.

- These attributes create gigantic cascading failure modes.

### Internet

- No comparable requirement; latency is flexible within limits.

- Common communication protocols are necessary but ubiquitous.

- No comparable constraint; packets easily rerouted around constraints (Most similar non-electric system is Air Traffic Control).

- Closest analog is rapidly spreading computer viruses or Air Traffic Control system – not the internet.
The Physical Topology of the High Voltage Electric Grid

EXISTING LINES
- 345-499 kV
- 500-699 kV
- 700-799 kV
- 1,000 kV (DC)

PROPOSED LINES
- New 765 kV
- AC-DC-AC Links

INTERCONNECTIONS
Major sectors of the U.S. electrical grid:
- Eastern
- Western
- Texas (ERCOT)


Views expressed in these slides are solely those of the author unless referred otherwise.
Fuels and Water: Power Plants’ “Software”

Current Electricity Production- 2008

- Coal
- Oil and Natural Gas
- Nuclear Power
- Other Renewable
- Conventional Hydropower
- Solar
- Wind
- Other

NREL 2030- With National RES

U.S. Natural Gas Pipeline Network

Rail Movement of Coal

?? And next – CO₂
Ownership Structure Before “Deregulation”

The Regulatory Landscape with “Deregulation”

Regional Transmission Organizations (RTOs)

Market and Control Mechanics within RTOs

Markets

Generators

Energy Markets

Ancillary Services Markets

Capacity Markets

Control

Initial check on generator availability vs. load ("Commitment")

Control center analyzes for reliability and sends control ("Dispatch") signals

Monitored continuously; generators adjusted as needed

Key

- Physical assets
- Market process
- Information
- Electric power
- Market results
- Control signals

- Generators

- Transmission Grid

- Distribution System

- Customers
Systems Ecology of the Grid

Information Smart Grid Standards and Domains

What is the Smart Grid?

- Advanced Digital Communications, Sensors, and Control
- Predictive & Self-Healing
- Smart Meters
- Interactive, Real-time Info
- Incorporates Small Local Generators, Storage, and Electric Vehicles
Power System Crises and Threats: Some Initial Thoughts
Vulnerability Catalog*

Physical attacks – local or cascading
- Generators, including nuclear
- Lines
- Hubs
- Substations
- Fuel/water/chemical supplies/effluents

Unintentional Failures
- Accidents within system facilities
- Acts of God – storms, lighting, etc.
- Black swans

Cyber Attacks

Market-led disruptions

*The seminal work is Brittle Power, A. and H. Lovins, 1982 (www.rmi.org)
Power Industry Vulnerabilities Are Multifaceted

♦ Operating controllers must prevent or remediate local or large cascading blackouts; many failure modes/physical points of vulnerability and diverse remedial needs.

♦ The ownership structure is diverse and complex: the regulatory jurisdictional landscape is even more complex.

♦ Complex markets have been embedded within the generation and transmission control segments, intermixing financial, regulatory, and operational issues. The multiple layers of regulation create complex authority chains.

♦ Several key aspects of the industry are changing rapidly, notably the vulnerability to cyber disruption.
California Energy Crisis 2000-2001

Poor market design, bad fundamentals, manipulation

Power prices rise 200 to 1000%

Political-regulatory reactions begin – lawsuits and price caps

May 22, 2000

 Buyers begin to lose financial strength

July-September 2000

Sellers raise price further

November 2000

Stronger regulation and new supplies stabilize market prices

June 2001

Buyers become Non-creditworthy

December 2000 – January 2001

• State of California becomes the buyer of power
• Environmental rules relaxed

Spring 2001

Periodic blackouts as state conserves power and entire region grows wary

Spring 2001

January 21, 2001

Copyright © 2010 The Brattle Group, Inc.
Views expressed in these slides are solely those of the author unless referred otherwise.
Conclusion

♦ The electric power system is a vast and complex network with layers of physical, regulatory and market structure. It has a uniquely demanding operating environment that is highly vulnerable to many types of physical and cyber disruptions and the ability to cascade from local to large-scale failures.

♦ Current change drivers (climate change, smart grid, market complexity) will add to the vulnerabilities in the short term.

♦ The long term changes underway towards greater local generation, greater renewable generation, and smart grid will eventually make the grid much less vulnerable to widespread failures.