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

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*Views expressed in these slides are solely those of the author unless referred otherwise.*

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# Overview

**Structural Views of the Electric Power System:**

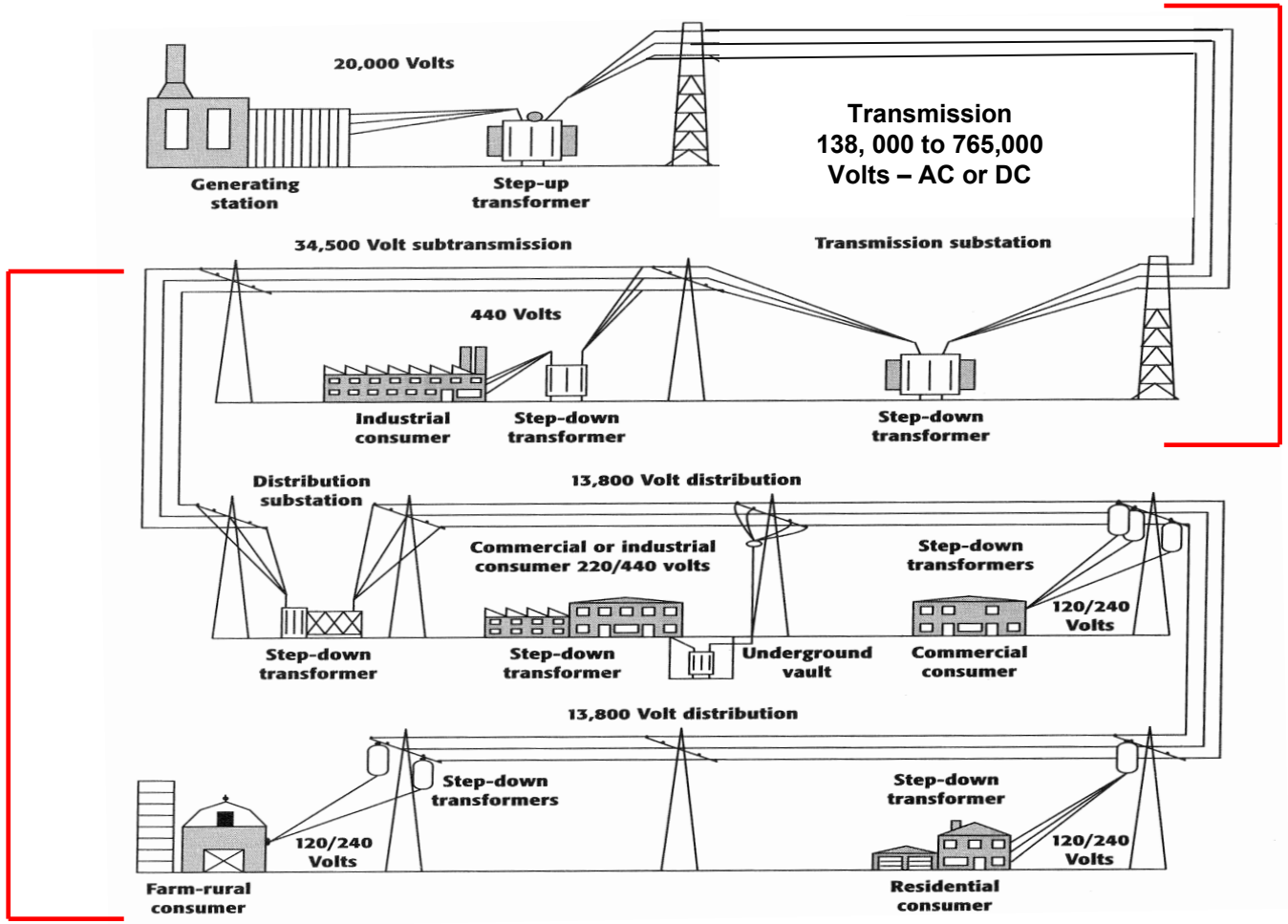
- Electromechanical Structure
  - Physical Assets
  - Fuel Supplies
- Economic and Regulatory Structure
- Organization and Ownership Structure
- Information and Control Structure

**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

**Distribution System**

6 million miles of lines

144 million meters

Source: Peter Fox-Penner, *Electric Utility Restructuring: A Guide to the Competitive Era*, Peter Fox-Penner, PUR, Inc., 1997, p. 24





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# Electricity Vs. the Internet

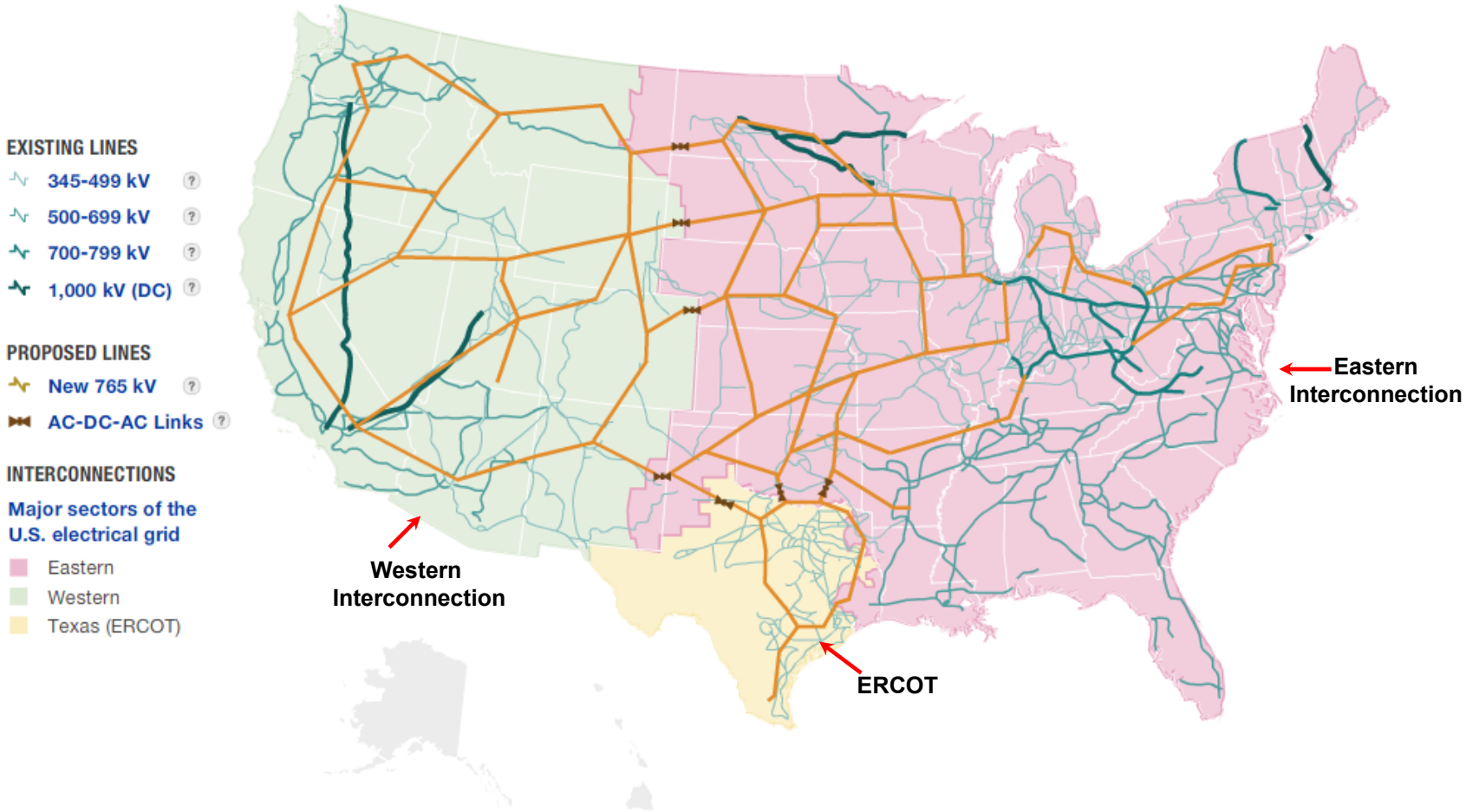
## Electric Power System

- 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




*Source: American Electric Power, American Wind Energy Association, Center for American Progress, Department of Energy, Edison Electric Institute, Energy Information Administration, Electric Power Research Institute, Federal Energy Regulatory Commission, National Renewable Energy Laboratory, U.S. Environmental Protection Agency, Western Resource Advocates*
*Credit: Producer: Andrew Prince; Designer: Alyson Hurt; Editors: Avie Schneider and Vikki Valentine; Supervising Editors: Anne Gudenkauf and Quinn O'Toole; Additional Research: Jenny Gold; Database and GIS Analysis: Robert Benincasa*

Source: "Visualizing the U.S. Power Grid," National Public Radio Webresource, Available at: http://www.npr.org/templates/story/story.php?storyId=110997398.





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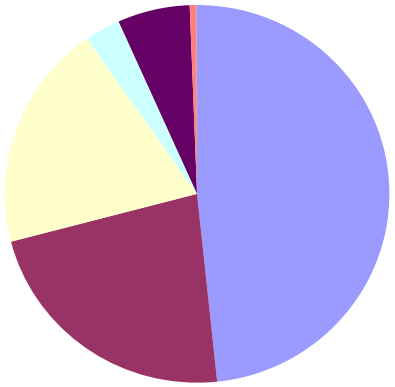
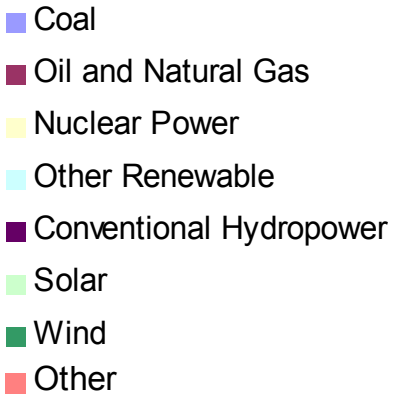
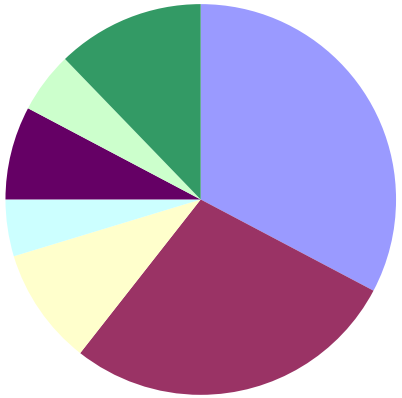
# Fuels and Water: Power Plants' "Software"

## Current Electricity Production- 2008

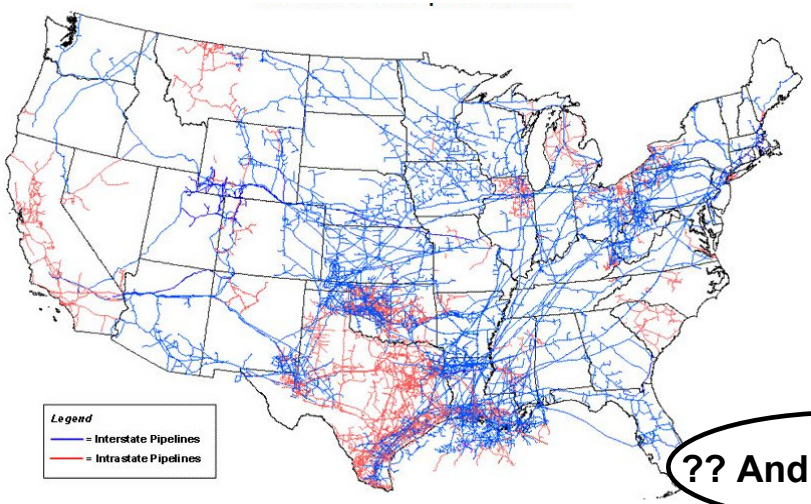





## NREL 2030- With National RES

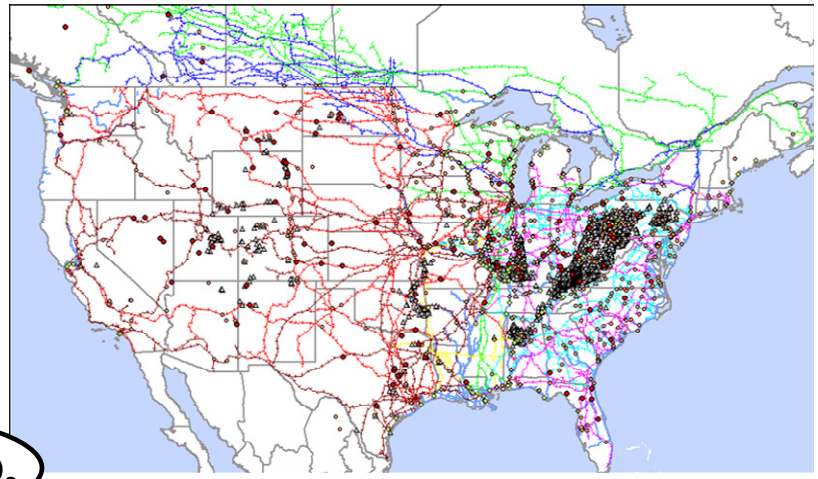


## U.S. Natural Gas Pipeline Network




?? And next – $CO_2$

## Rail Movement of Coal







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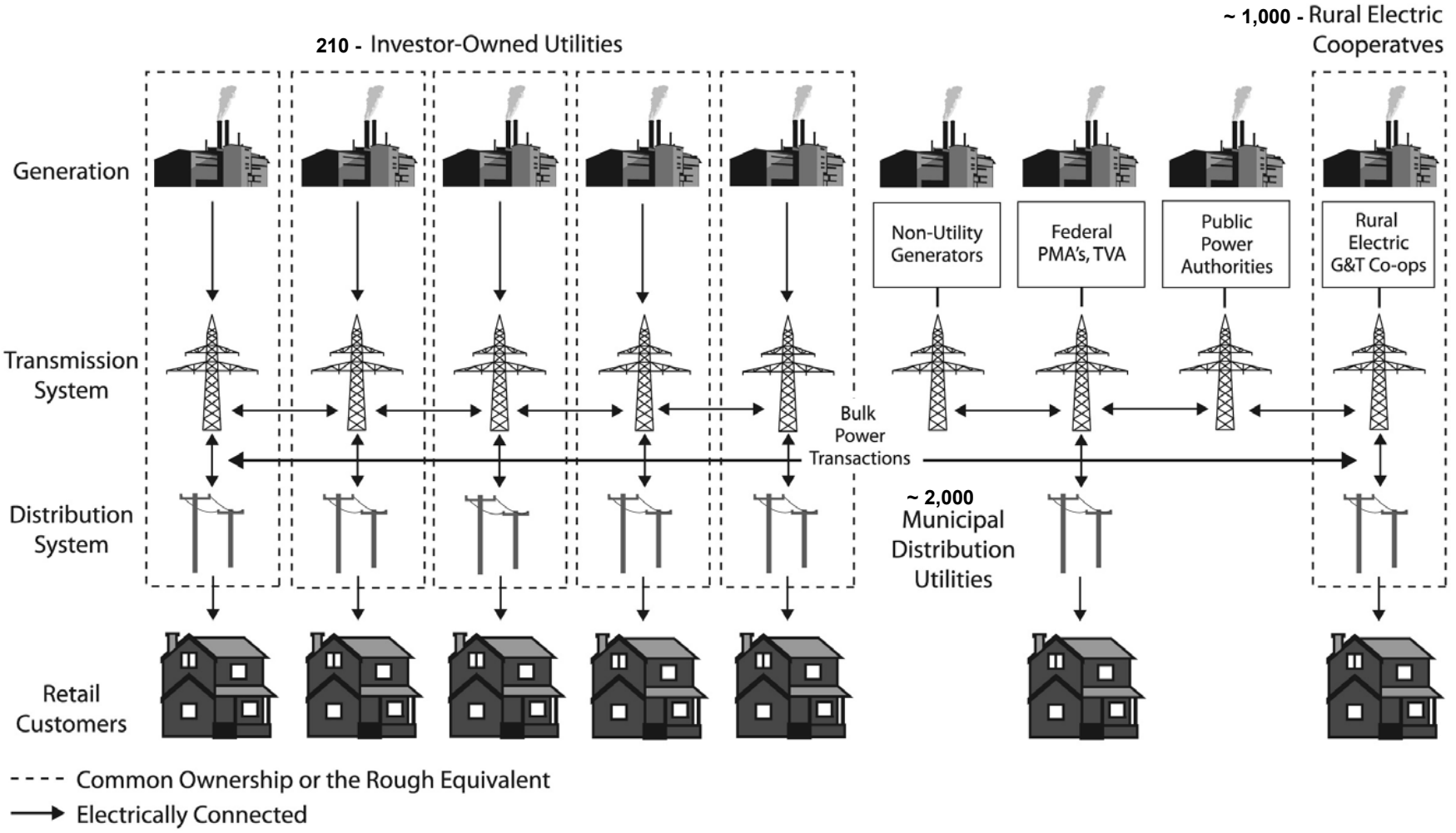
# Ownership Structure Before "Deregulation"




Source: Peter Fox-Penner, *Smart Power: Climate Change, the Smart Grid, and the Future of Electric Utilities*, Island Press, April, 2010.





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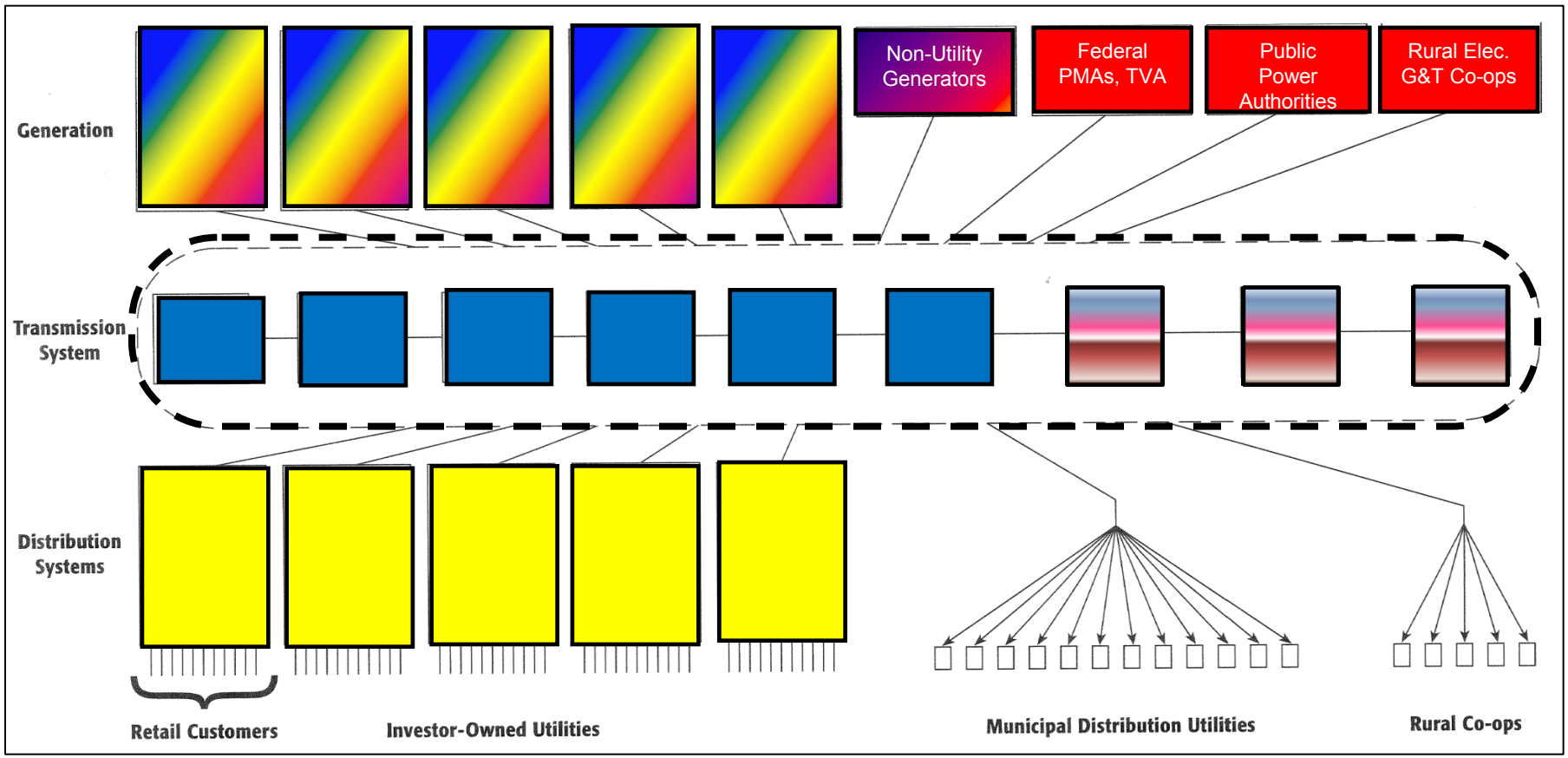
# The Regulatory Landscape with "Deregulation"

Full FERC Regulation

Partial FERC Jurisdiction

Federal & State Environmental Regulations

State Rate and Planning Regulation




Source: Peter Fox-Penner, *Electric Utility Restructuring: A Guide to the Competitive Era*, Peter Fox-Penner, PUR, Inc., 1997, p. 24.





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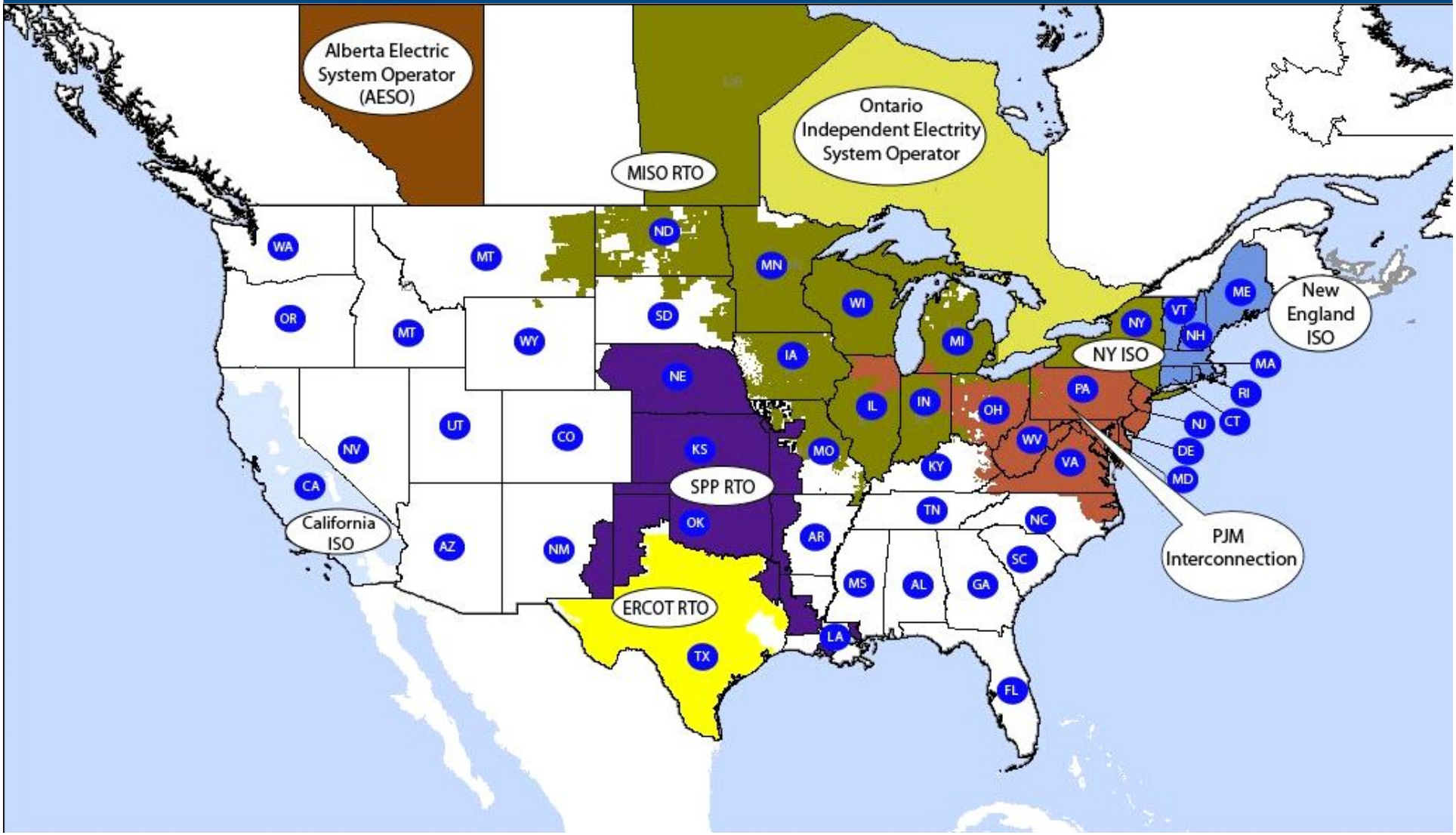
# Regional Transmission Organizations (RTOs)




Source: "Electric Market National Overview," The Federal Energy Regulatory Commission, October 20, 2009.





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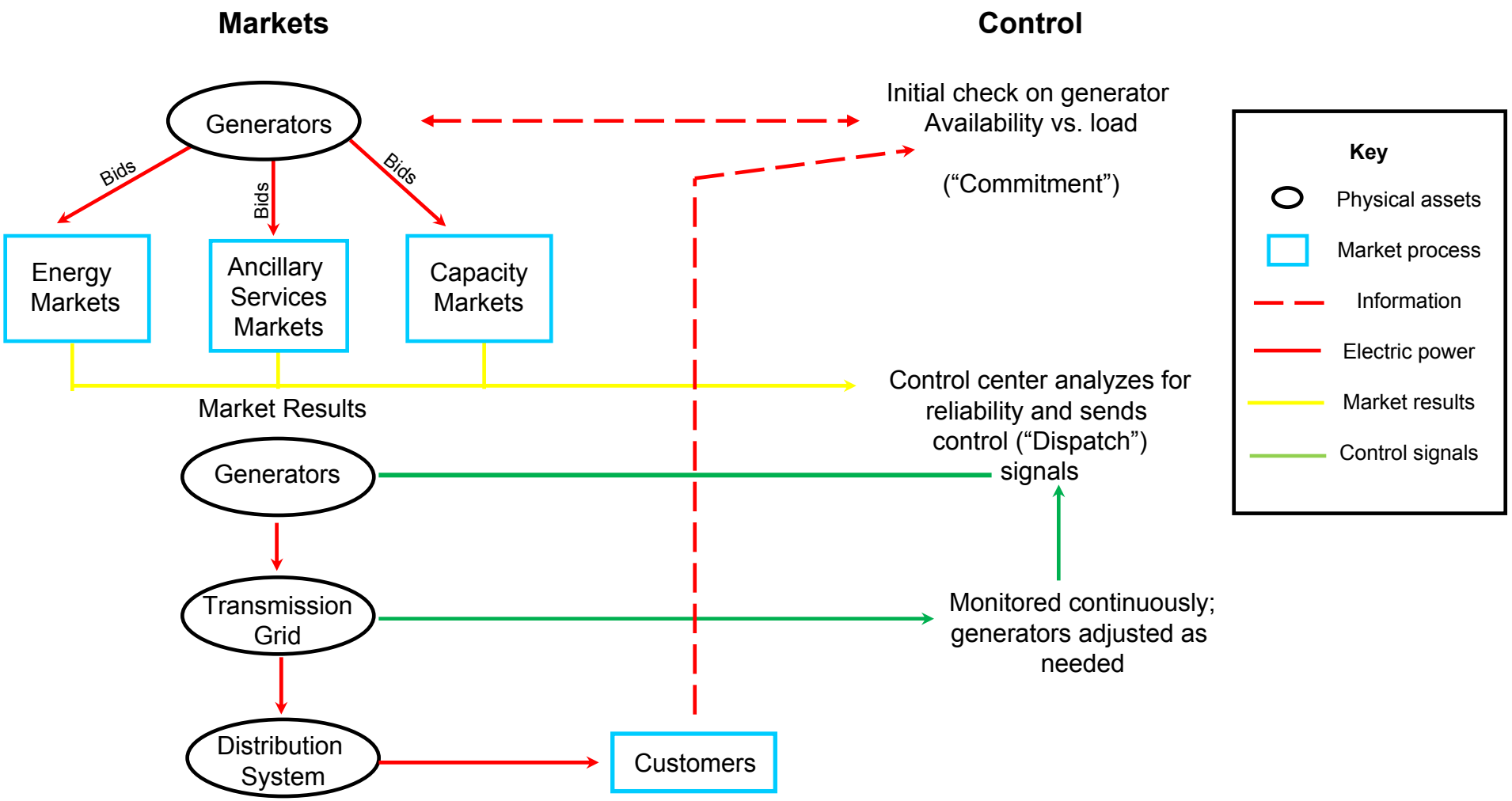
# Market and Control Mechanics within RTOs





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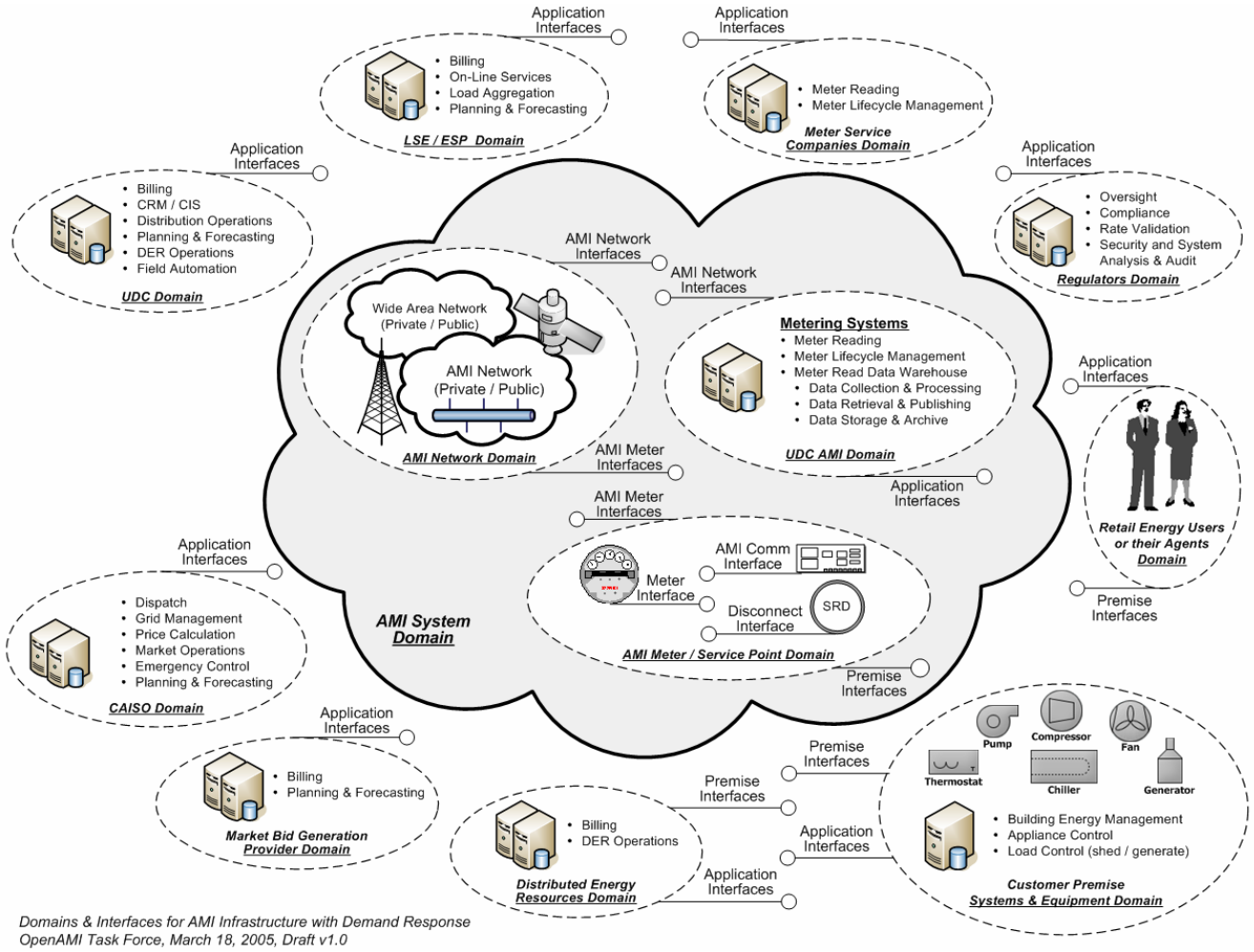
# Systems Ecology of the Grid




*Domains & Interfaces for AMI Infrastructure with Demand Response*
*OpenAMI Task Force, March 18, 2005, Draft v1.0*

Source: "Advanced Metering And Demand Responsive Infrastructure: A Summary Of The PIER/CEC Reference Design, Related Research And Key Findings " Enerex and California Energy Commission, June 1, 2005.





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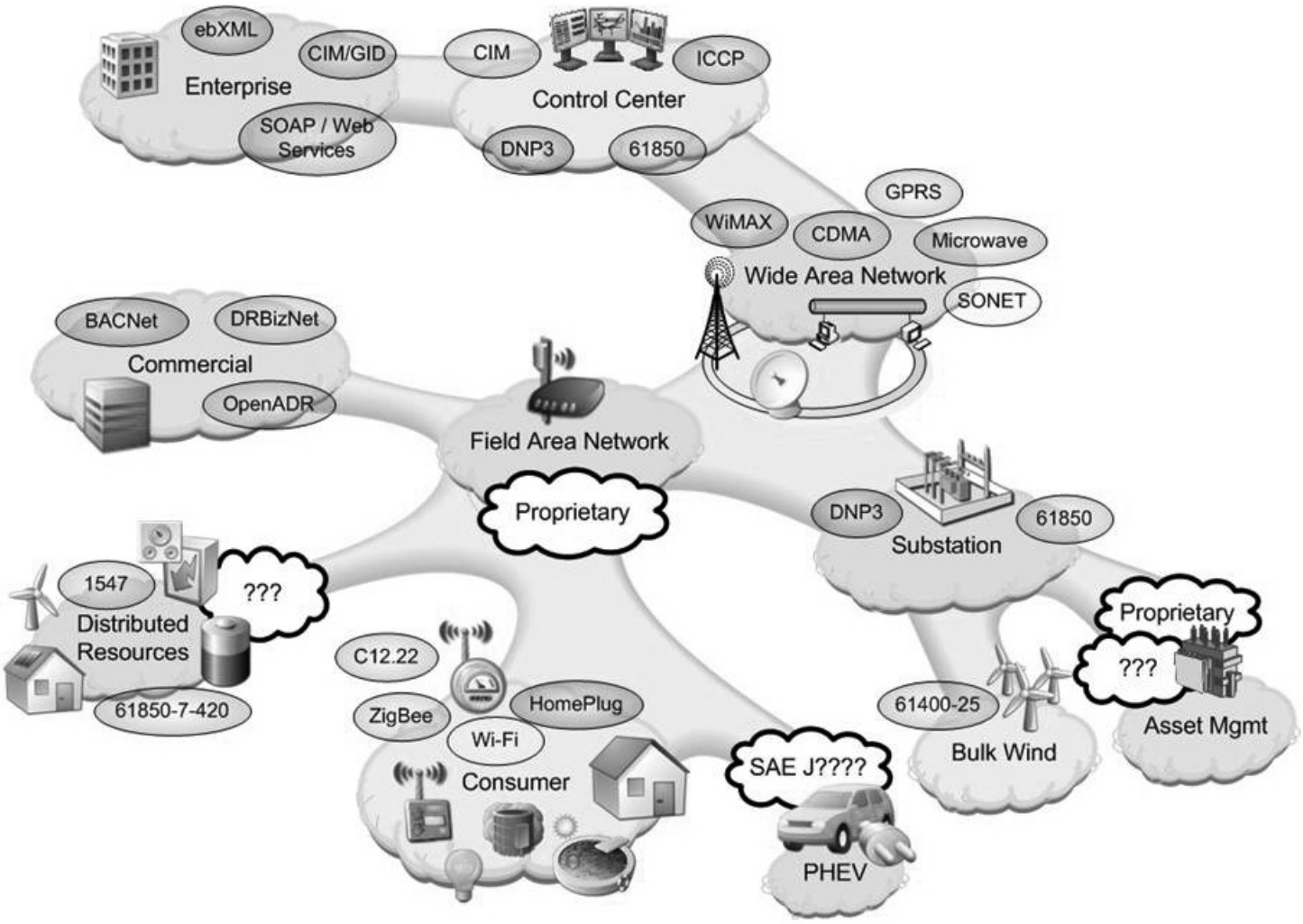
# Information Smart Grid Standards and Domains




Source: "Advanced Metering And Demand Responsive Infrastructure: A Summary Of The PIER/CEC Reference Design, Related Research And Key Findings " Enerex and California Energy Commission, June 1, 2005.

# 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

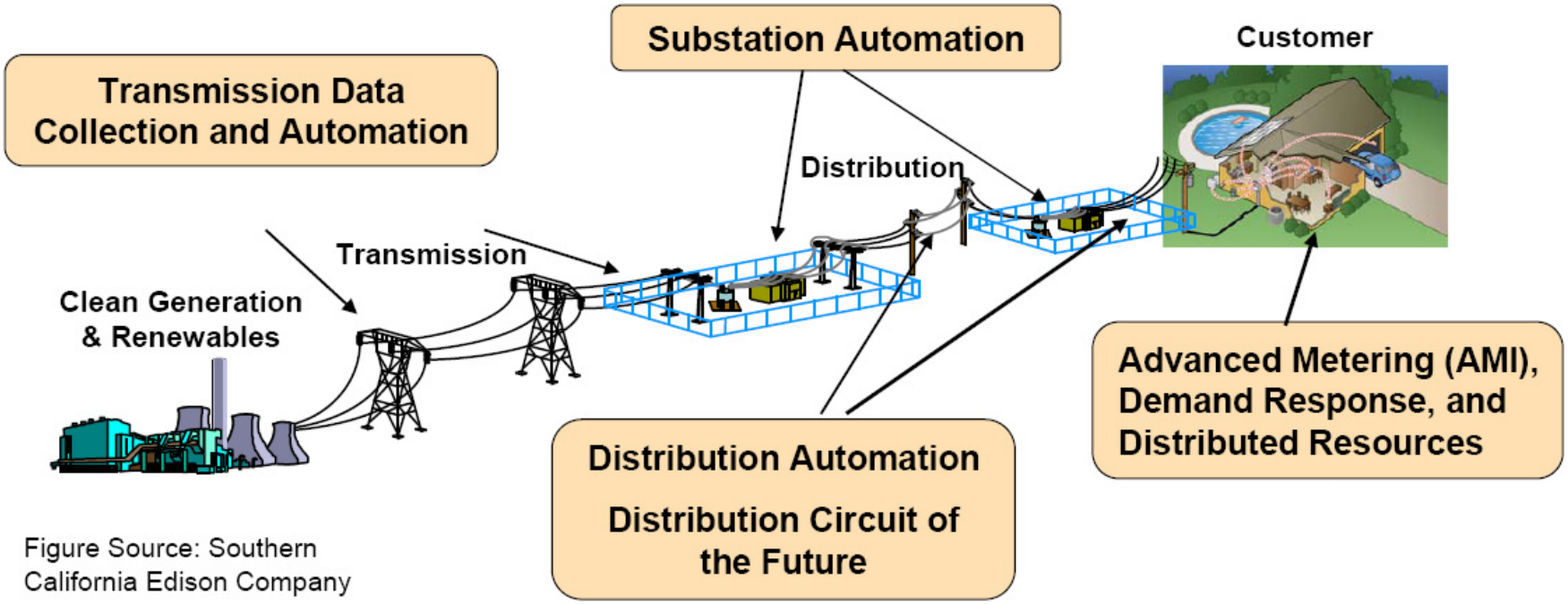



Figure Source: Southern California Edison Company





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# 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

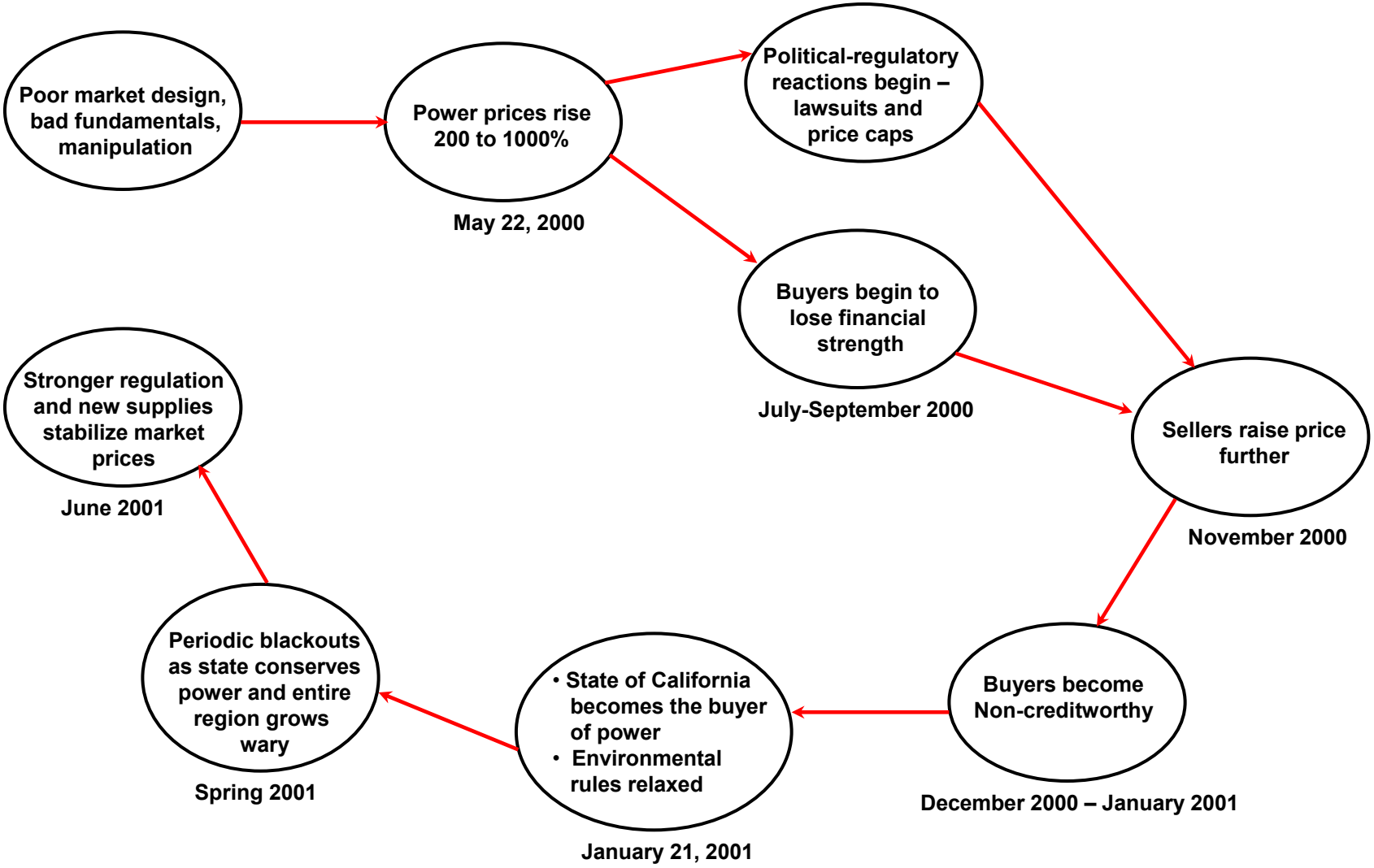
## Market-led disruptions

***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 vulernability 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



# 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.