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Edward J. Bloustein School of Planning and Public Policy

Climate Change, Coastal Flooding and the Electric Power Grid

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December 6, 2018

Presentation Outline

Motivation

How does the electric power grid work?

How is the grid interconnected with critical infrastructure?

What are the scientific, engineering, and public policy advances that are needed to respond to climate change?

Integrated Analysis is Required

Successful analyses – whether engineering, economic, legal/regulatory or business – requires an integrated knowledge of the industry

Electricity markets are highly regulated and only cover about a third of the supply chain

The U.S. has two major types of electricity markets, although important variations exist within each of these market types

- The U.S. has a multi-jurisdictional system that regulates different and overlapping parts of the industry

The industry is responding to major new trends; that being said, it is subject to substantial inertia. In the U.S. these trends are:

- Environmental policies (cap-and-trade, energy efficiency , renewable policies, clean up coal)
- Smart grid
- Transmission expansion with increased federal role
- Debate over the role of nuclear power
- Mandatory reliability rules

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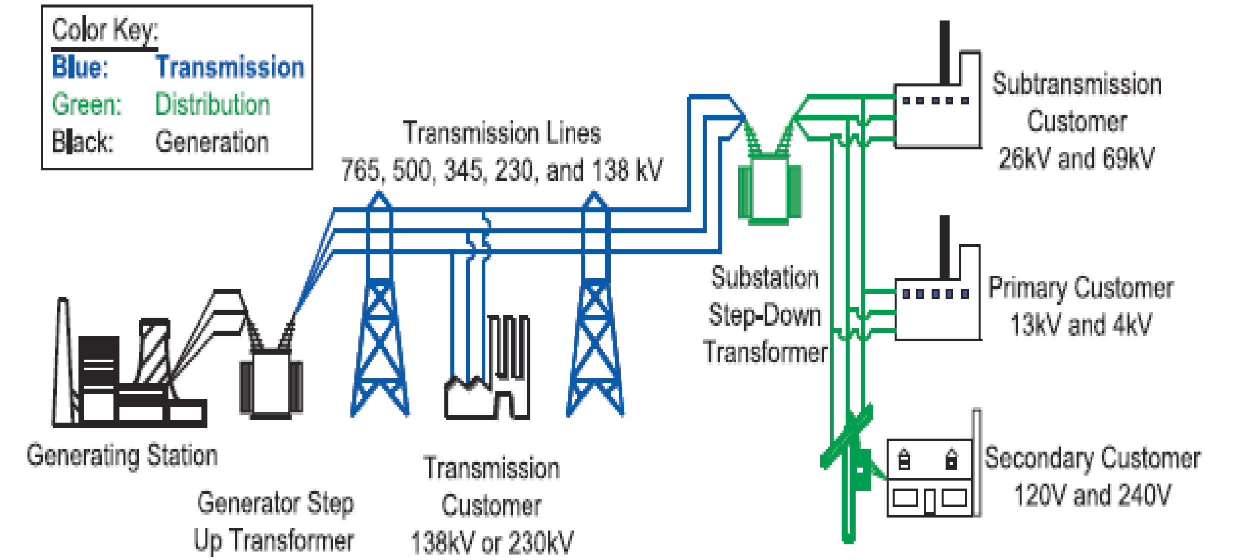


Grid's Supply Chain is Complicated

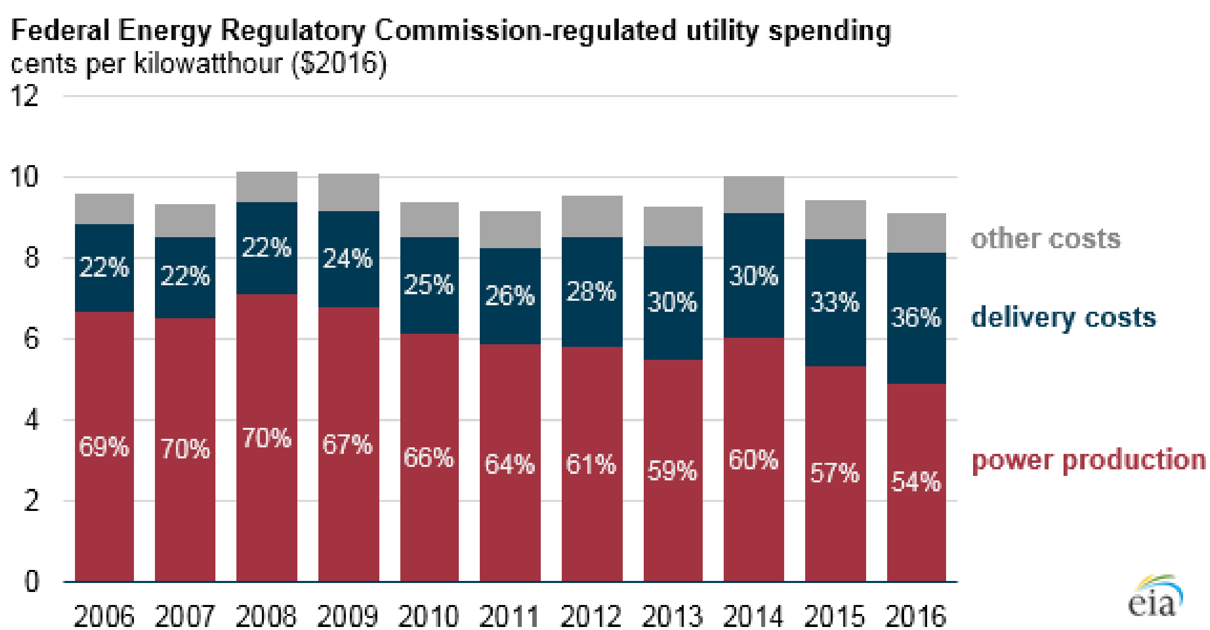
This figure does not capture the *meshed network* of the transmission system.

Distribution systems are *radial*.

Figure from the U.S.-Canadian Power System Outage Task Force final report on the 2003 Blackout, p. 5.

230 investor-owned, the largest sector in terms of assets & revenues

2,012 publicly owned
882 cooperatives
9 Federal (e.g., TVA, BPA. etc.)



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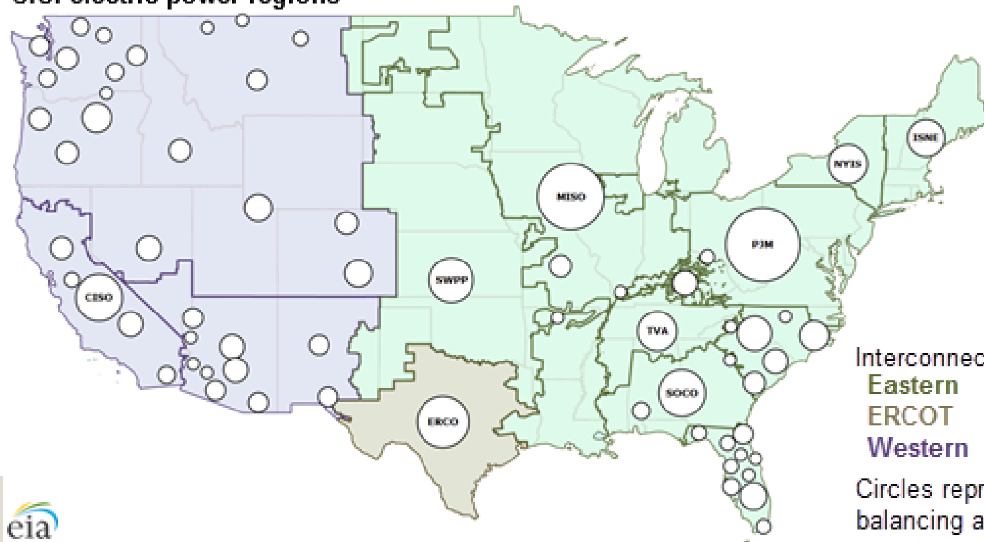
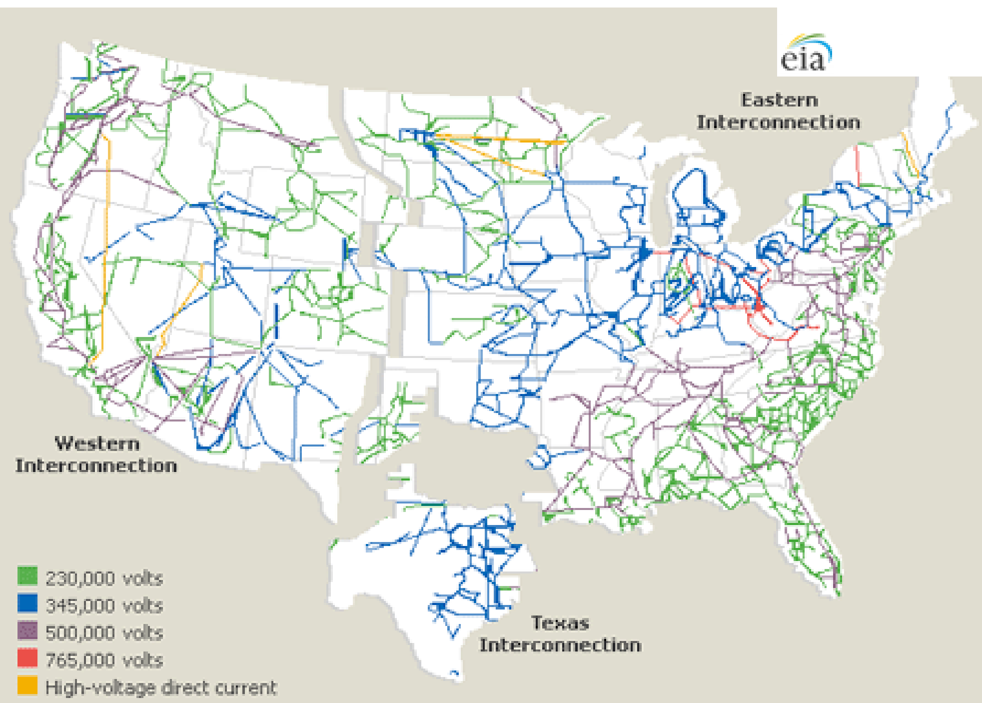
U.S. electric power regions



Interconnections
Eastern
ERCOT
Western

Circles represent the 66 balancing authorities



"The National Power Grid," Microsoft® Encarta® Encyclopedia. http://encarta.msn.com © 1993-2004 Microsoft Corporation. All rights reserved.

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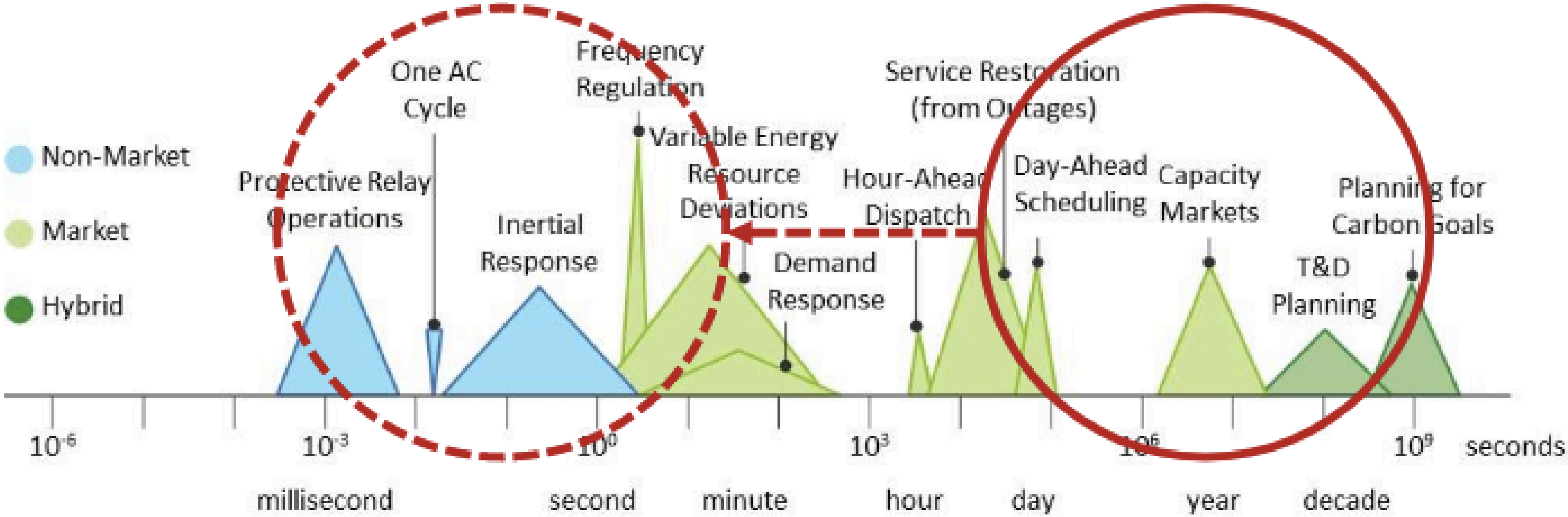
System Reliability Depends on Managing Multiple Event Speeds

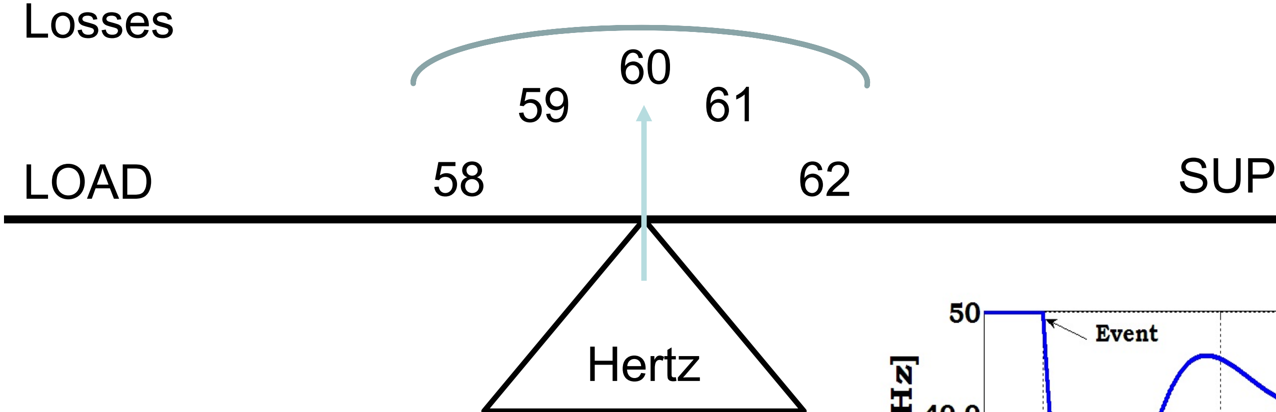


Source: von Meier, 2014

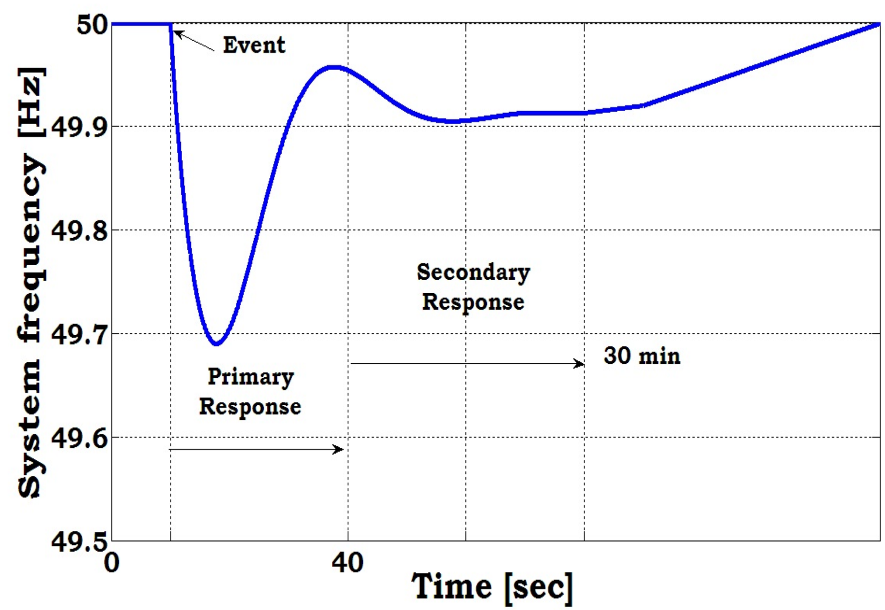
Load (Demand) and Supply must be in balance at (almost) all times

Load
Export
Losses

Generation &
Imports



Video of power plant tripping offline, https://www.youtube.com/watch?v=bdBB4byrZ6U



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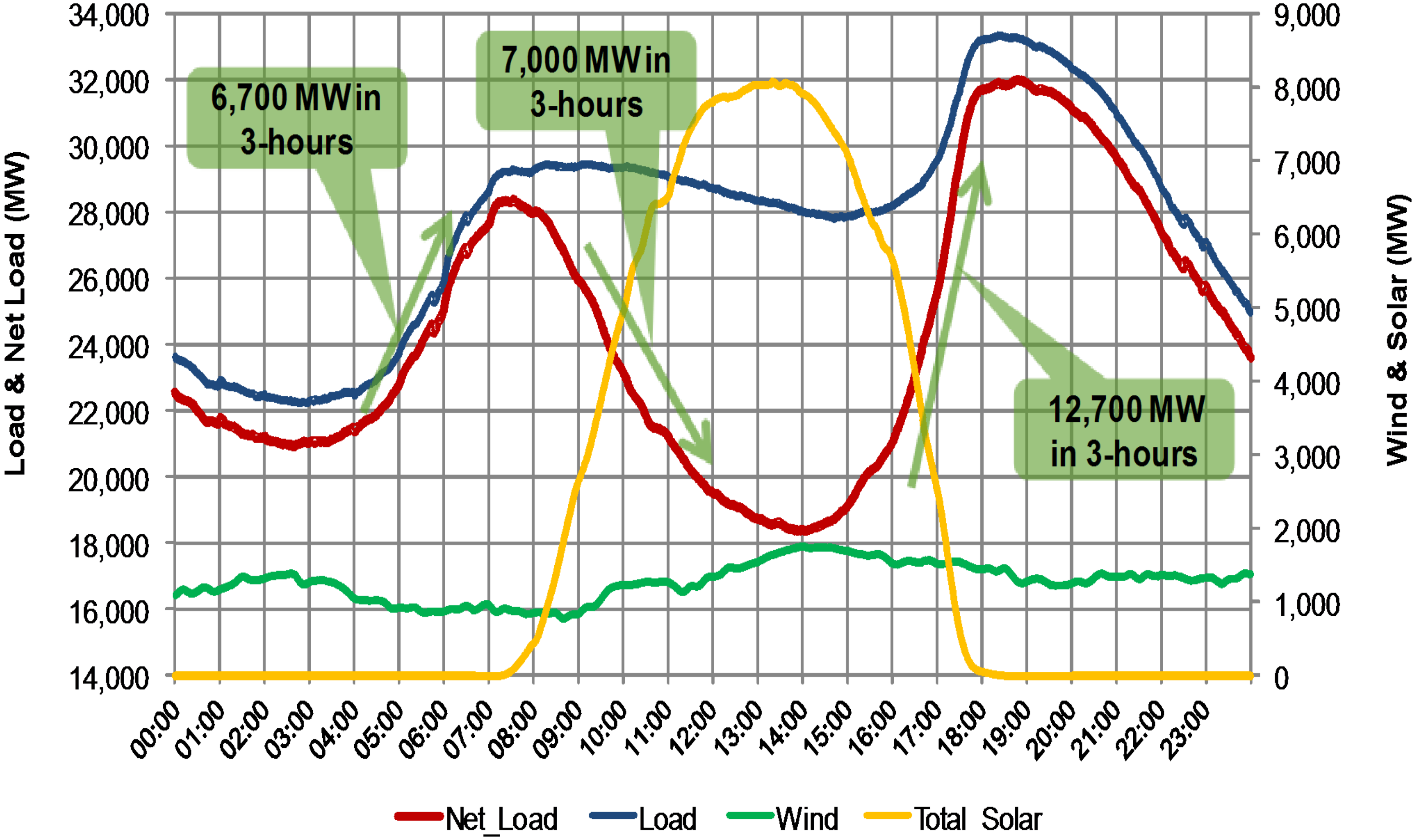

34,000
32,000
30,000
28,000
26,000
24,000
22,000
20,000
18,000
16,000
14,000
Load & Net Load (MW)
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Wind & Solar (MW)
6,700 MW in 3-hours
7,000 MW in 3-hours
12,700 MW in 3-hours
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Net_Load
Load
Wind
Total Solar

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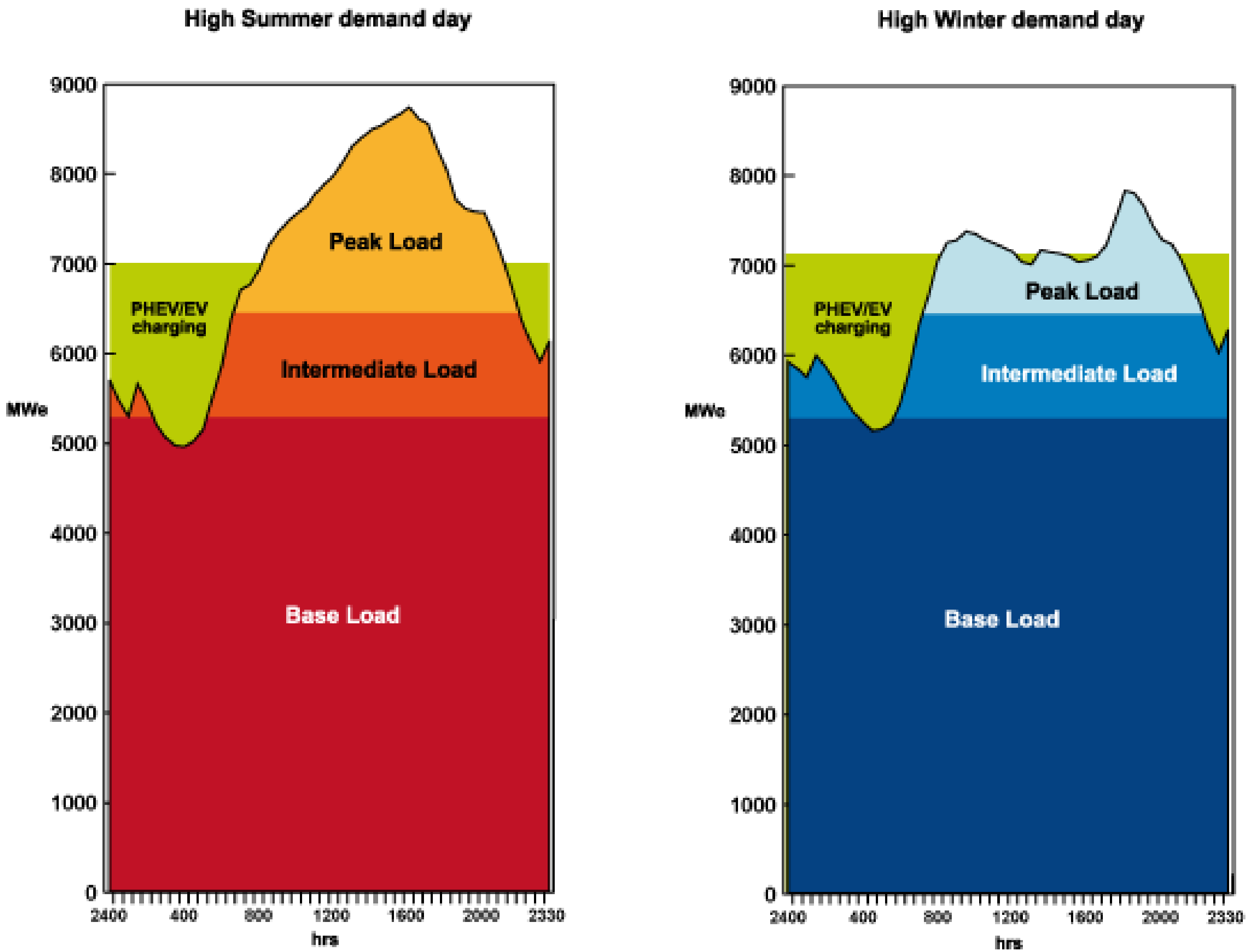
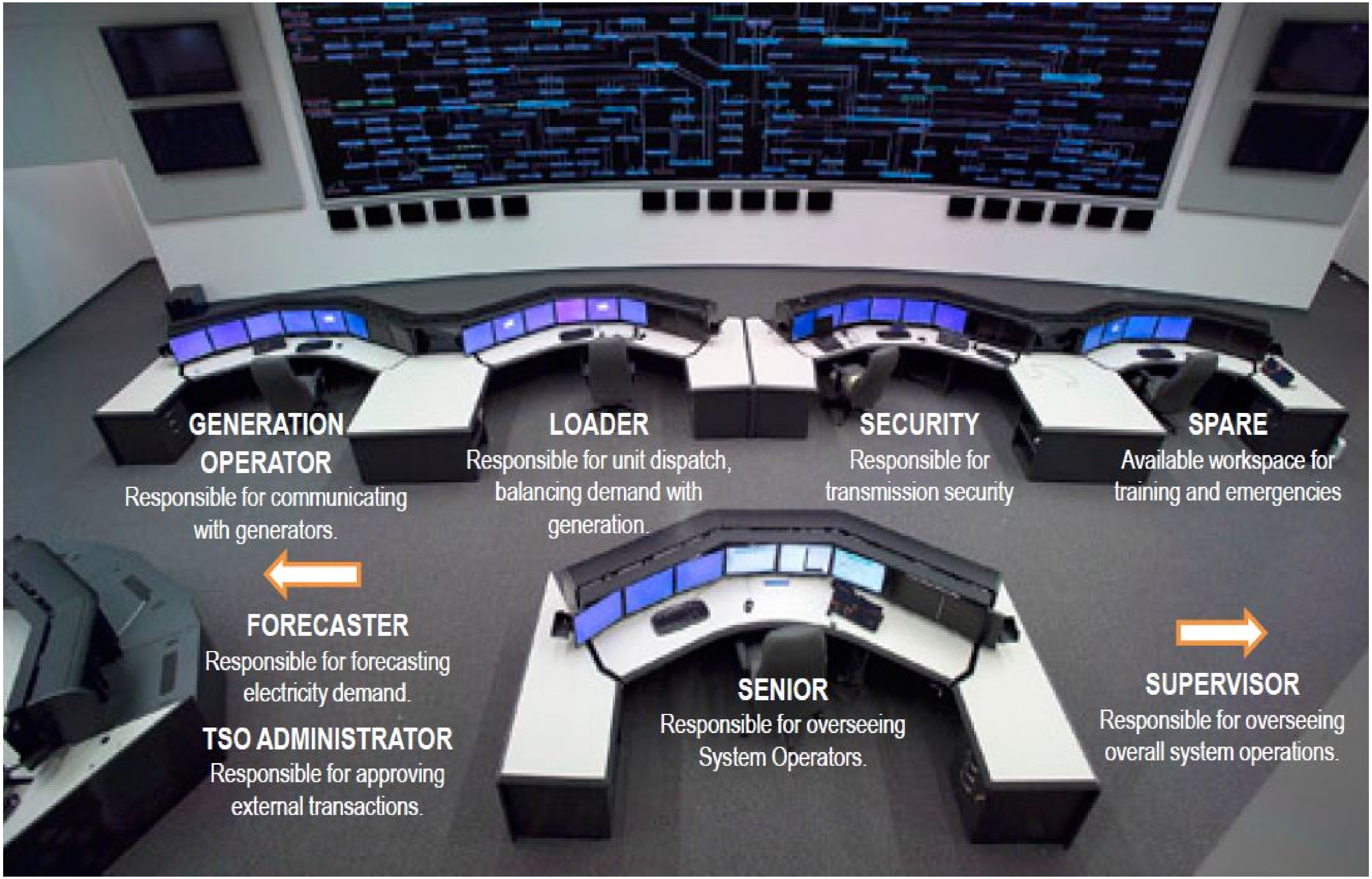
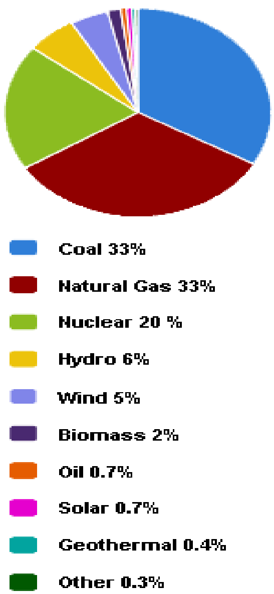
Load curves for Typical electricity grid



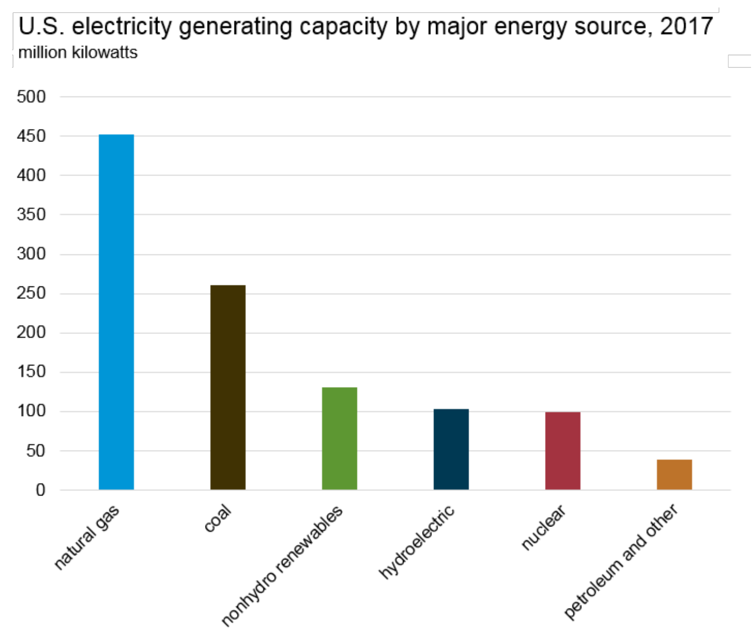


GENERATION OPERATOR
Responsible for communicating with generators.
LOADER
Responsible for unit dispatch, balancing demand with generation.
SECURITY
Responsible for transmission security
SPARE
Available workspace for training and emergencies
FORECASTER
Responsible for forecasting electricity demand.
TSO ADMINISTRATOR
Responsible for approving external transactions.
SENIOR
Responsible for overseeing System Operators.
SUPERVISOR
Responsible for overseeing overall system operations.

US Fuels for Electricity



% of MWh



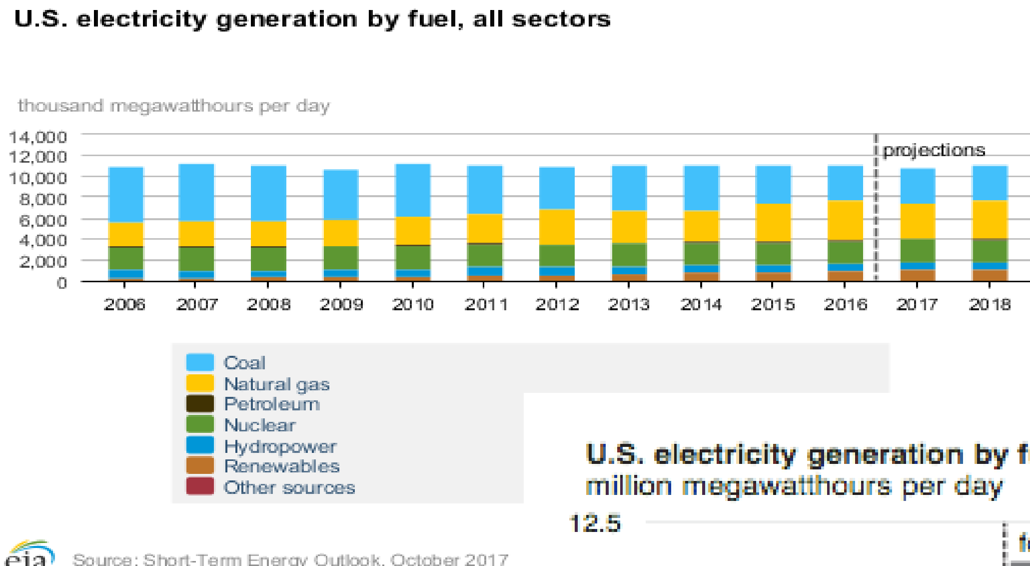
Note: Net summer capacity for utility-scale generators. Hydroelectric includes conventional and pumped storage hydropower.
Source: U.S. Energy Information Administration, *Electric Power Monthly*, Table 6.1, February 2018, preliminary data

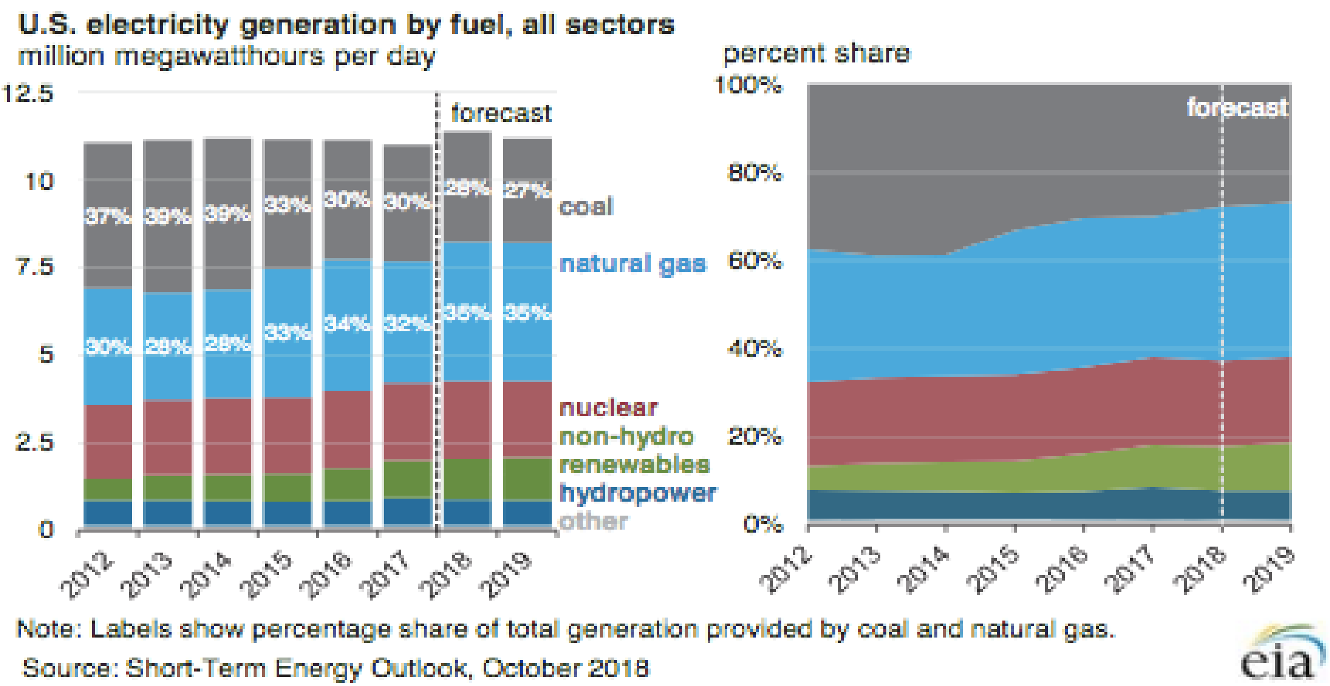
Period	Nuclear	Conventional Hydropower	Wind	Solar Photovoltaic
Annual Factors				
2013	89.9%	38.9%	32.4%	NA
2014	91.7%	37.3%	34.0%	25.9%
2015	92.3%	35.8%	32.2%	25.8%
2016	92.3%	38.2%	34.5%	25.1%
2017	92.2%	45.2%	36.7%	27.0%

	Coal	Natural Gas				Petroleum
Period		Natural Gas Fired Combined Cycle	Natural Gas Fired Combustion Turbine	Steam Turbine	Internal Combustion Engine	Steam Turbine
Annual Factors						
2013	59.8%	48.2%	4.9%	10.6%	6.1%	12.1%
2014	61.1%	48.3%	5.2%	10.4%	8.5%	12.5%
2015	54.7%	55.9%	6.9%	11.5%	8.9%	13.3%
2016	53.3%	55.5%	8.3%	12.4%	9.6%	11.5%
2017	53.5%	54.8%	9.4%	11.3%	NA	13.0%

Reference: Energy Information Agency, *Monthly Energy Review*

The US Grid is Changing





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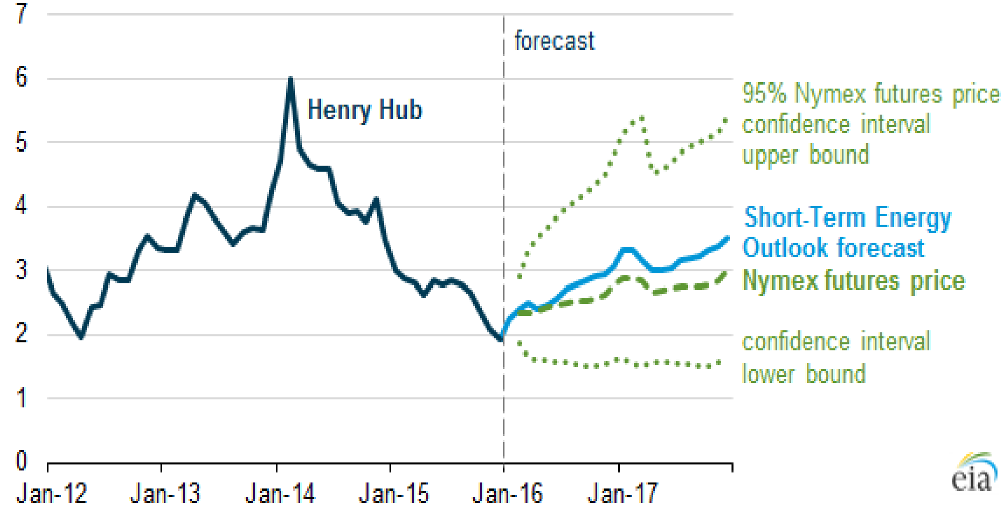
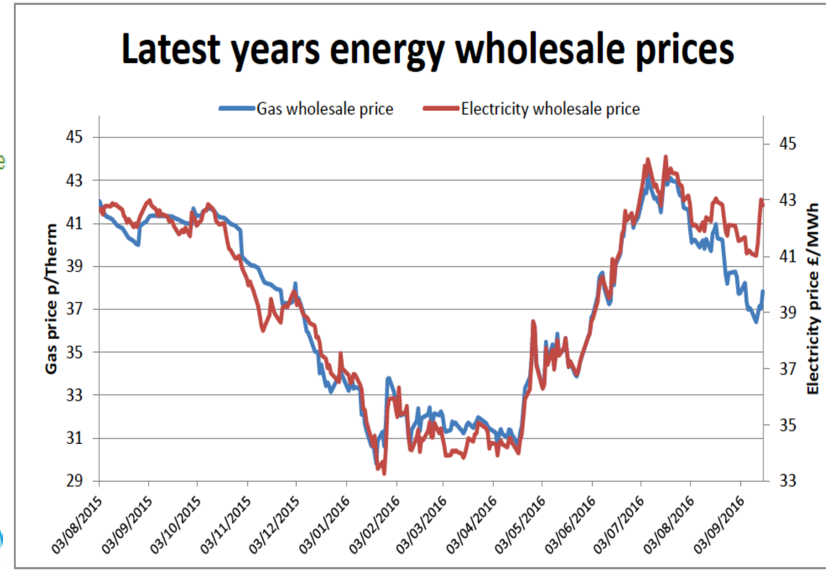
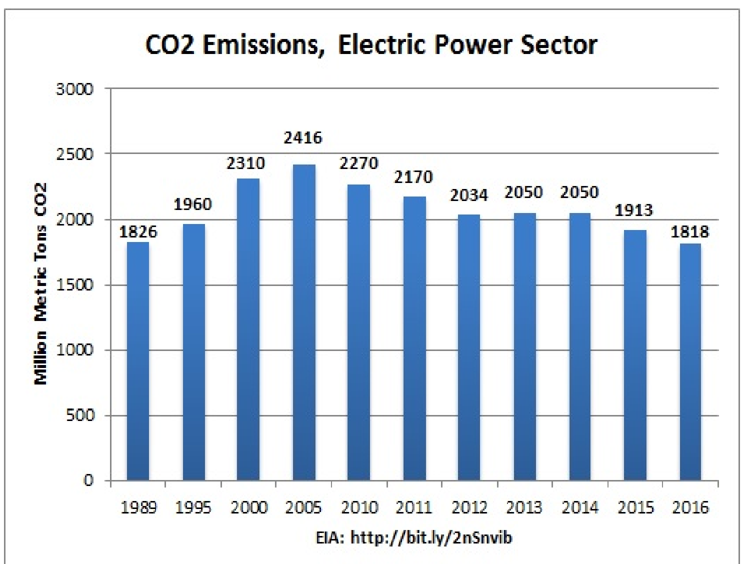
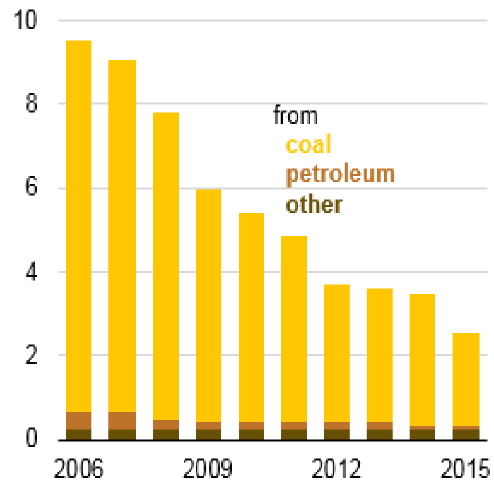
Monthly average spot price at the Henry Hub (2012–17)
dollars per million Btu



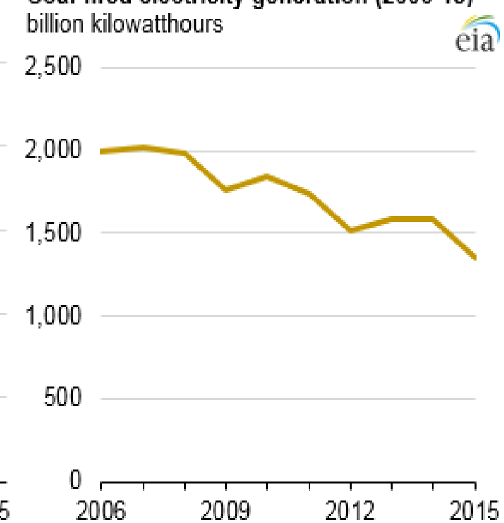




Electricity-related sulfur dioxide emissions
million metric tons



Coal-fired electricity generation (2006-15)
billion kilowatthours



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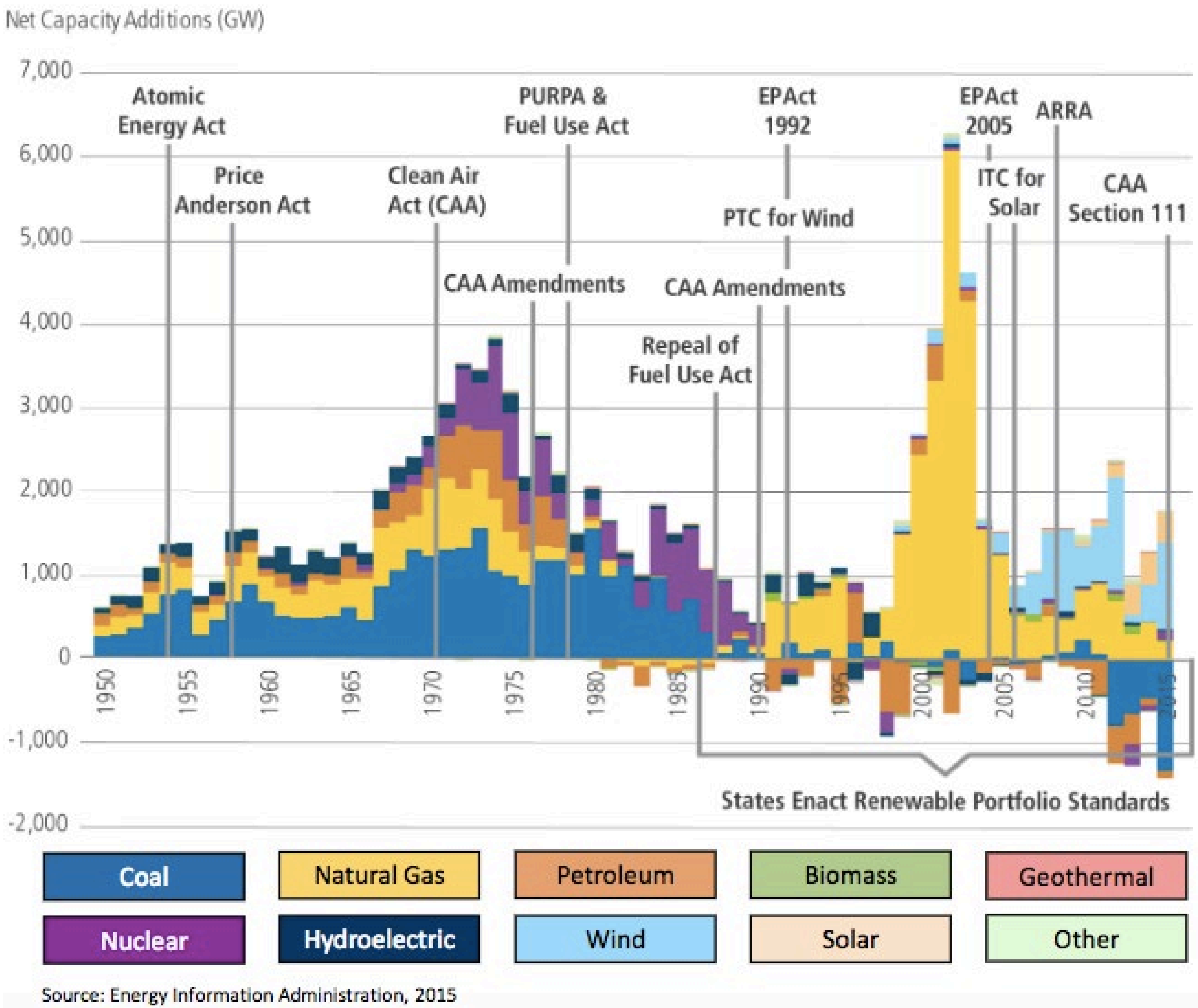
US Federal Policy Affects the Grid



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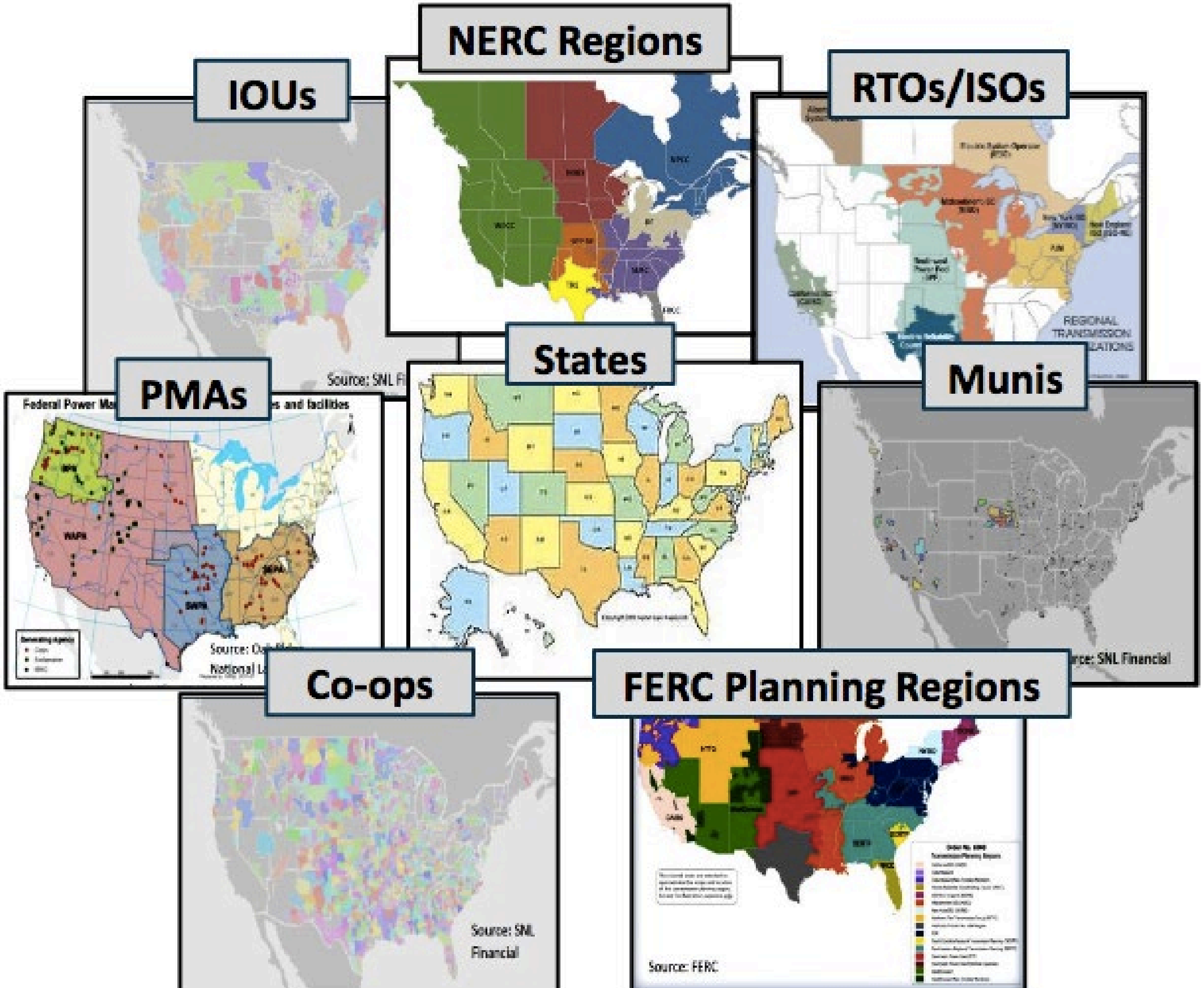
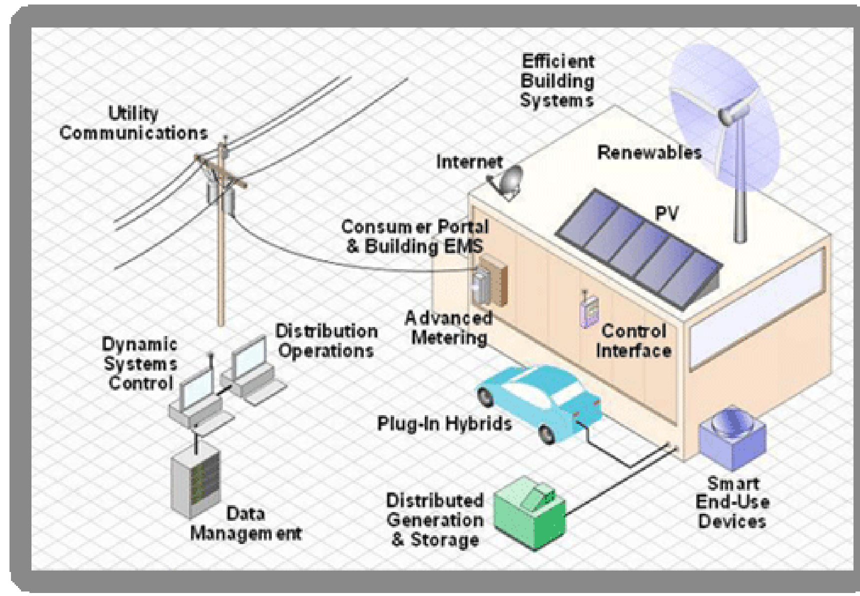
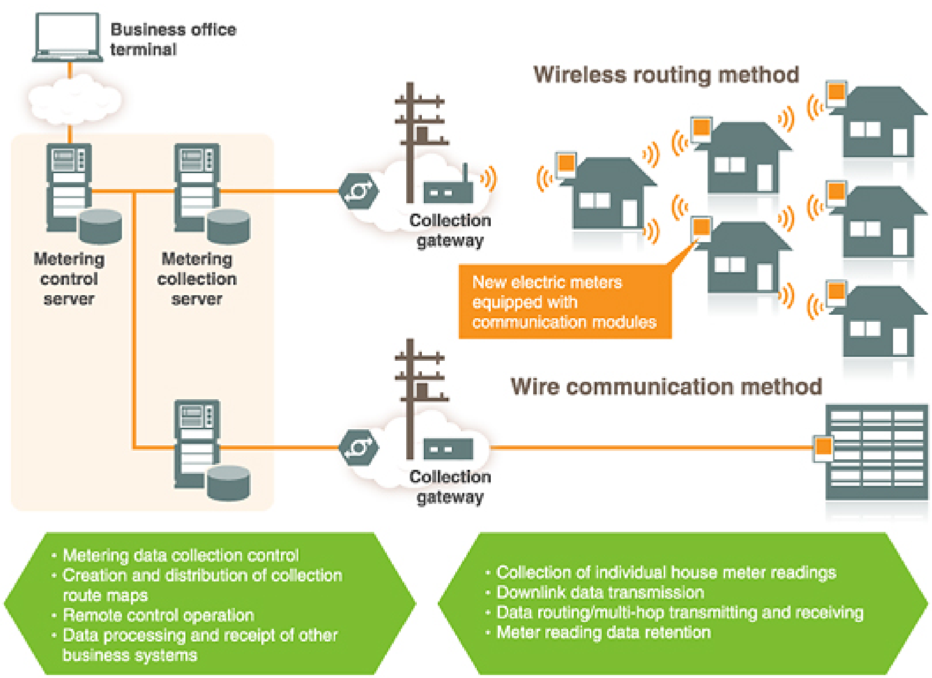
Grid Governance is Overlapping and Layered



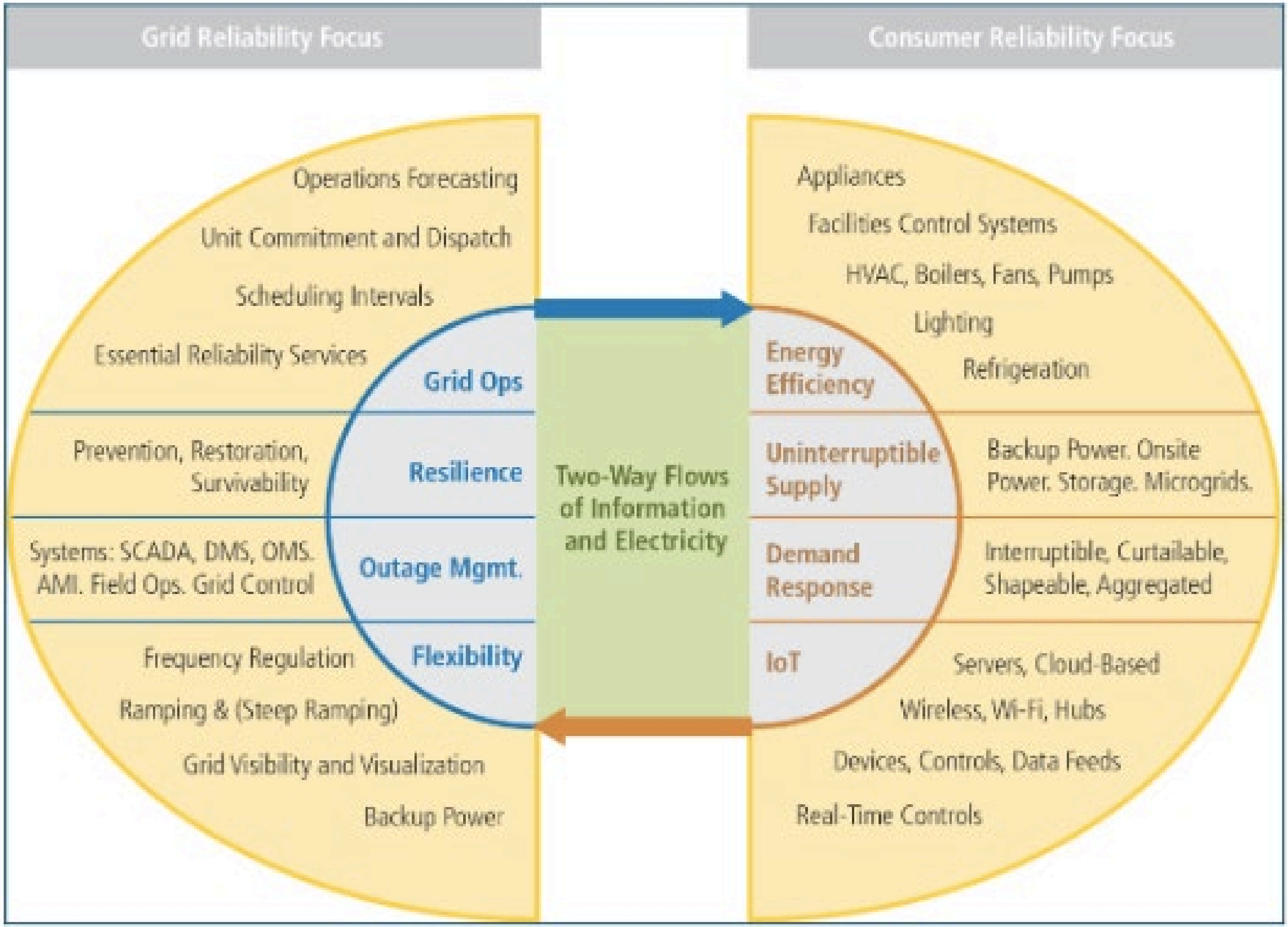
Grid's Technological Structure is Changing



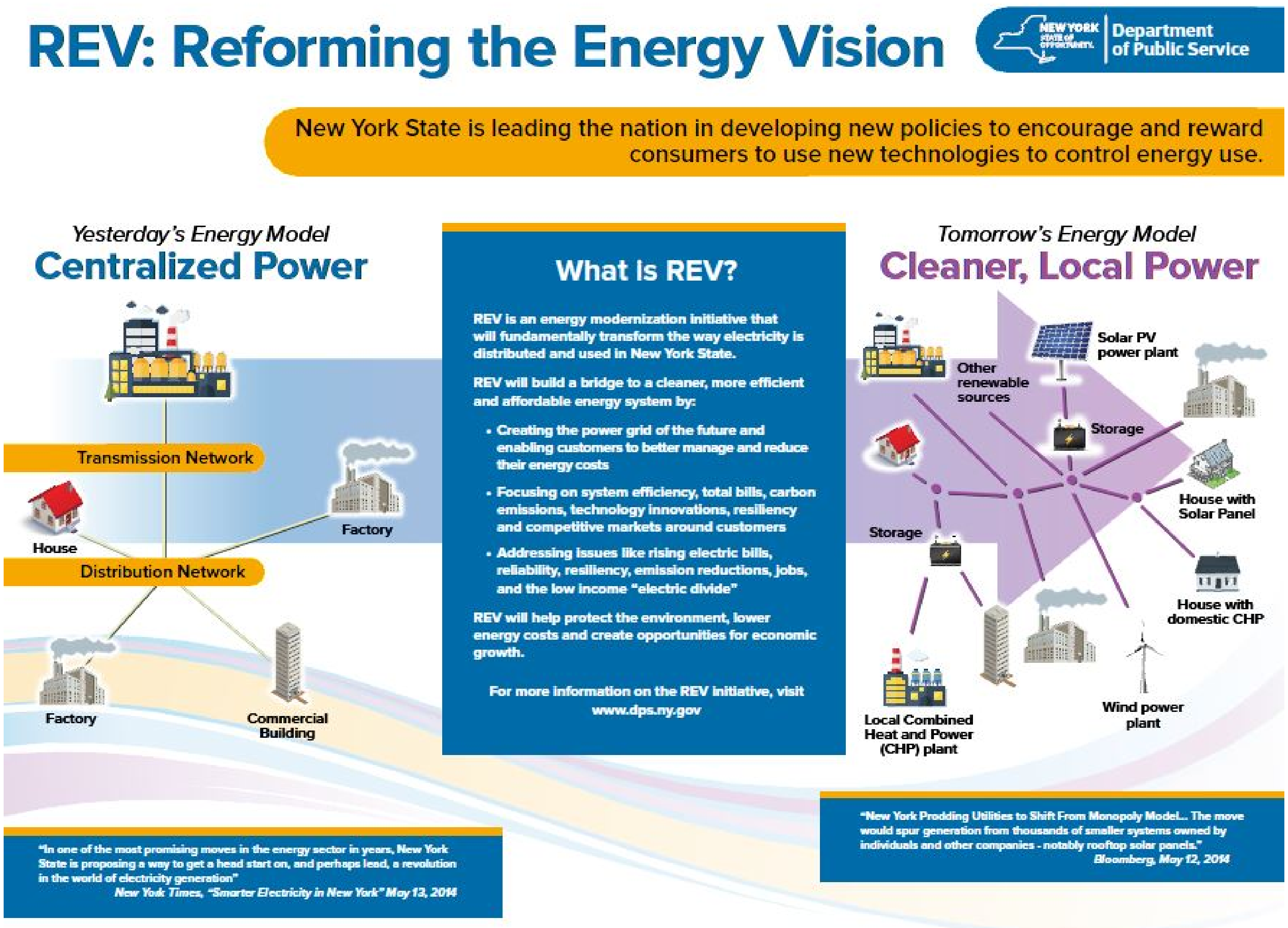


Tekiner-Mogulkoc*, H., Coit, D., & Felder, F. (2012). Electric Power System Generation Expansion Plans Considering the Impact of Smart Grid Technologies. *International Journal of Electrical Power and Energy Systems*, 42(1), 229–239.

Electric Service Reliability Increasingly Interactive between Grid and Consumer

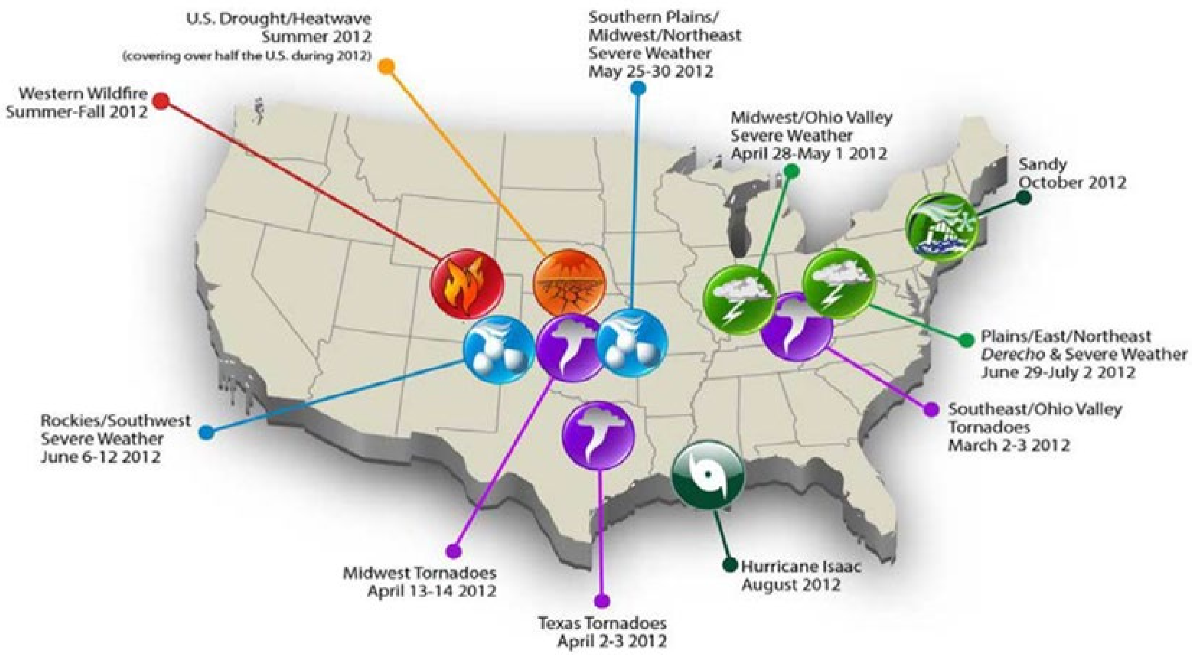


Source: Department of Energy, 2016



Felder, F., & R. Athawale. (2016). Optimizing New York's Reforming the Energy Vision. *Utilities Policy*, 41C, 160-162.

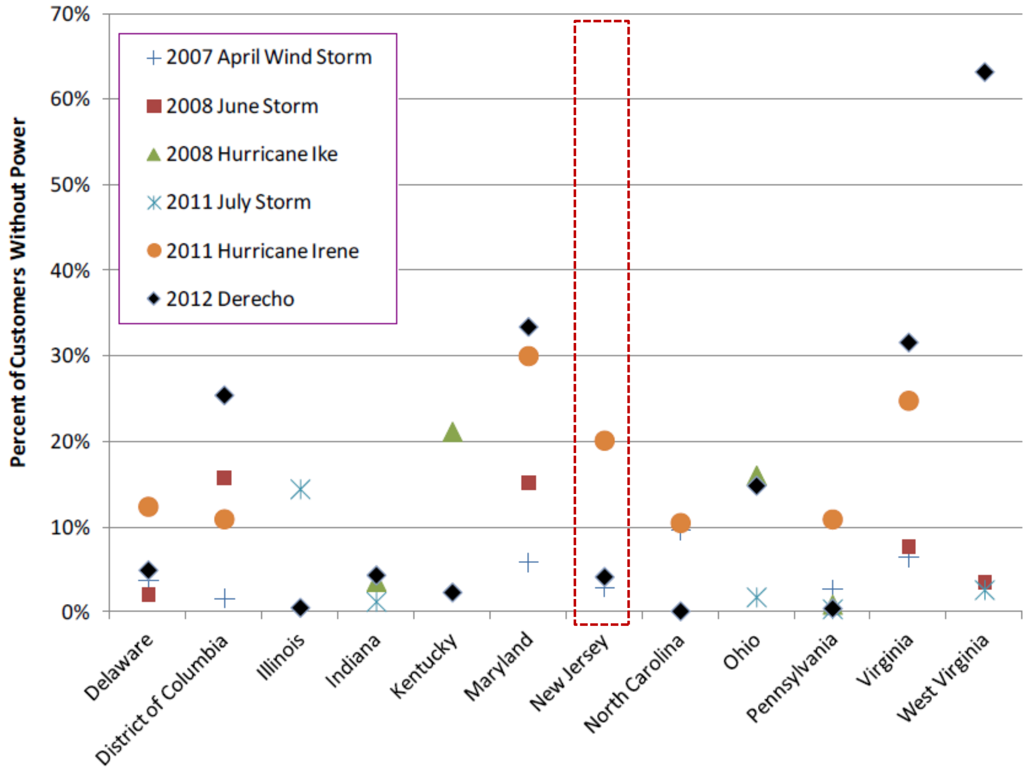
The United States Suffered Eleven numbers of Billion-Dollar Weather Disasters in 2012



Source: National Oceanic and Atmospheric Administration (NOAA)

Between 2003 and 2012, roughly 679 power outages, each affecting at least 50,000 customers, occurred due to weather events (U.S. DOE)

The State of New Jersey has Some of the Worst Storms in the Last Few Years



Source: OE/ISER Situation Reports and Energy Assurance Daily, A Review of Power Outages and Restoration Following the June 2012 Derecho – U.S. DOE, August 2012

New Jersey electric customers were severely impacted by Hurricane Irene and Superstorm Sandy (U.S. DOE)

Reliability/Resiliency: More than Severe Weather

"NY Regulators are building a more Distributed, Reliable, Transactive Grid" Sept 2014

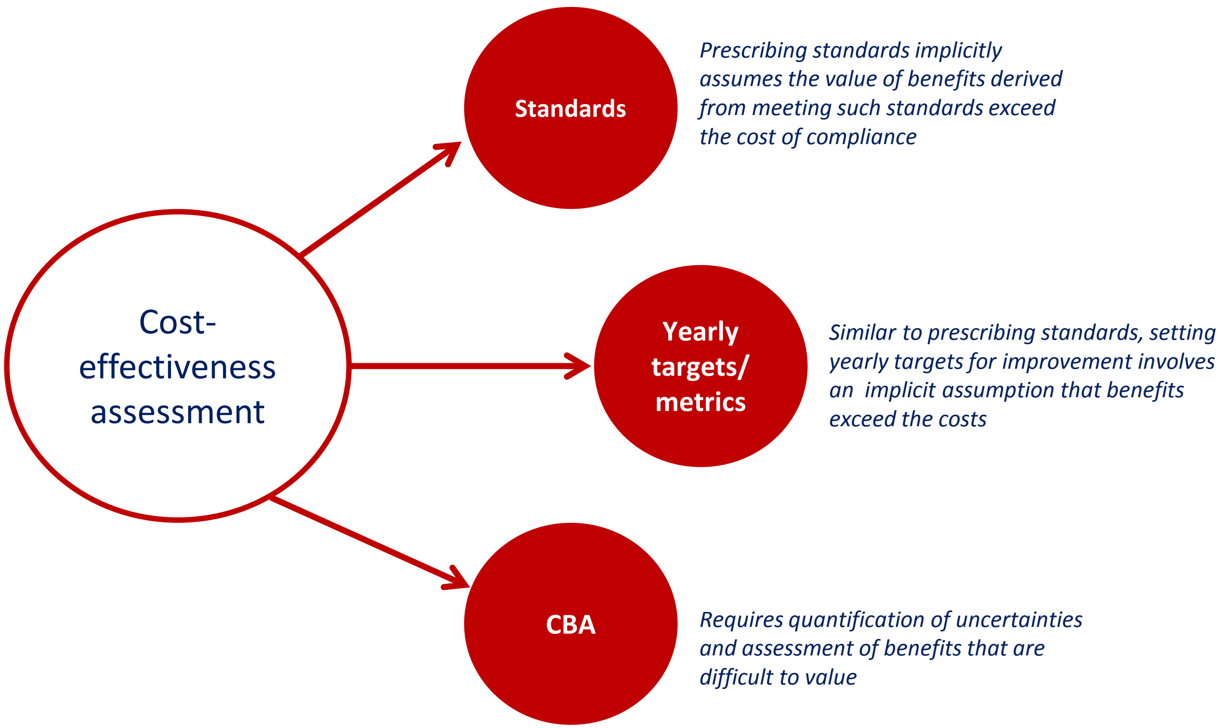
Solar storms add to growing list of pressing issues for reliability, Sept 2014

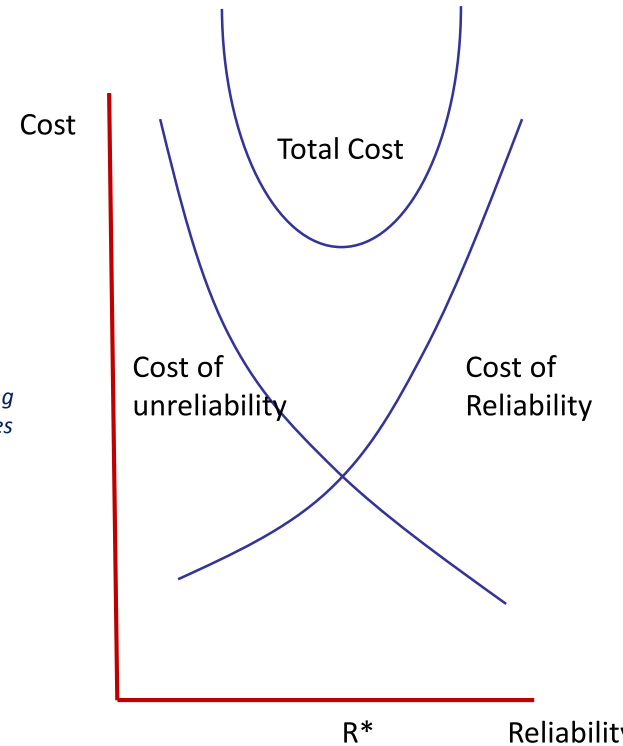
Repeat Physical attack on California power station, Sept 2014

Strom Arthur Outages, "It took Nova Scotia Power a week to restore service to everyone." Aug 2014

Facing Climate Change, Cities embrace resiliency, Sept 2014

Difficult Task of Evaluating Cost-effectiveness of Utility Hardening Investments





=> Cost effectiveness does not mean efficient

Figueroa-Candia, M., Felder, F. and Coit, D. (2018). Resiliency-Based Optimization of Restoration Policies for Electric Power Distribution Systems, *Electric Power Systems Research*, 161, 188-198.

Cost-effectiveness Needs to Be Put in Context

Policy Considerations

- How to measure reliability and resiliency?
- What should be the hierarchy of planning documents for efforts to increase reliability and resiliency?
- How does changes in business environment (microgrid, increased penetration of RE) changes need for reliability and resiliency planning?

Governance Considerations

- Who is responsible for advocating standards for reliability and resiliency?
- Who is responsible for maintaining reliability and resiliency (especially when large-scale events disrupt interdependent infrastructure)?
- Who is responsible for monitoring reliability and resiliency?

Economic Considerations

- What is the optimal cost for maintaining reliability and resiliency at the desired level?
- Who pays for such costs?
- How to avoid/ minimize cost shifting among ratepayers?
- How to measure benefits (individual and society) from investments in increasing and maintaining reliability?

Felder, F., & Haut, R*. (2008). Balancing Alternatives and Avoiding False Dichotomies to Make Informed U.S. Electricity Policy. *Policy Sciences*, 41, 165-180.

Cost-Benefit Analysis of Utility Hardening is a Hard problem

Formally, it involves decision-making under uncertainty involving low probability, high consequence events

Standard heuristics that we use do not apply and in fact can lead to poor decisions when applied to these types of decisions

Data and models are evolving and incomplete

Understandably, there is public and political calls for immediate action – and much can be done right away – but analysis of the efficacy of costly options is a challenging undertaking

CBA assumes all benefits can be quantified – such as aesthetics value to a community as a result of undergrounding

Hardening measures may interact in complex and unforeseen ways

CBA becomes complex because the "uncertainty itself is uncertain"

The probabilities, magnitudes and durations of the initiating events (i.e., severe weather) are themselves uncertain

Overtime (many years), with more data collection, these uncertainties can be updated with new information

Aleatory vs. epistemic

Li, S., Coit, D., & Felder, F. (2016). Stochastic optimization of electric power generation expansion planning with discrete climate change scenarios. *Electric Power Systems Research*. 140, 401-412.

Tekiner-Mogulkoc, H., Coit, D., & Felder, F. (2015). Mean-Risk Stochastic Electricity Generation Expansion Planning Problems with Demand Uncertainties Considering Conditional-Value-at-Risk and Maximum Regret as Risk Measures. *International Journal of Electrical Power and Energy Systems*, 73, 309-317.

Predictions of Future Severe Weather from Other Studies

- WRF control simulation 2012
- Observed 2012 (National Hurricane Center (NHC))
- WRF simulation 2050

Figure 14. Comparison of observed (2012), modelled (2012) and simulated 2050 track of Superstorm Sandy (Base map: © 2014 OpenStreetMap Data CC-By-SA)

Source: DNV GL: Adaptation to a changing climate, Hovik, 2014

Chandramowli, S., & Felder, F. (2014). Impact of Climate Change on Electricity Systems - A Review of Models and Forecasts. *Sustainable Energy Technologies and Assessments*, 5, 62-74.

Quantification of benefits is complex

VOLL
for a customer who faces outage

DURATION
of outage

MAGNITUDE
of severe weather event

FREQUENCY
of severe weather event

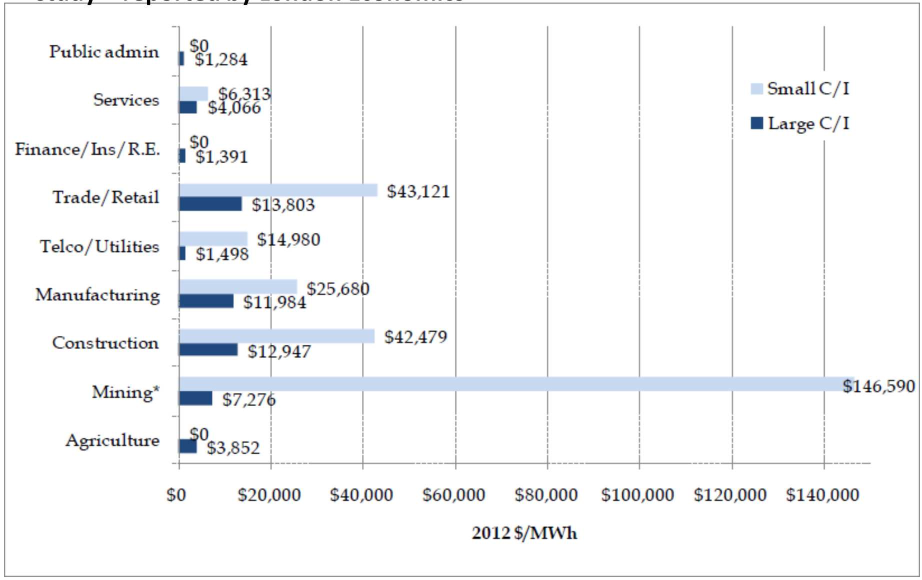
More recent estimates of VOLL from various national and regional studies

Costs per Avg. kWhr of a 1 hour interruption for Medium & Large C&I (2008$)	
Interruption Characteristics	**Mean (Ratio)**
Season	
Winter	$13.8
Summer	$22.8
Day	
Weekend	$30.6
Weekday	$21.4
Region	
Midwest	$19.8
Northwest	$19.9
Southeast	$18.2
Southwest	$37.0
West	$28.5

Costs per Avg. kWhr of a 1 hour interruption for Medium & Large C&I (2008$)		**Costs per event – 1 hour interruption duration Medium & Large C&I (Summer Weekday Afternoon) (2008$)**
Interruption Characteristics	**Mean (Ratio)**	
Industry		
Agriculture	$43.6	$8,049
Mining	$7.6	$16,366
Construction	$62.9	$46,733
Manufacturing	$22.0	$37,238
Telco. & Utilities	$19.0	$20,015
Trade & Retail	$34.2	$13,025
Fin., Ins. & RE	$32.7	$30,834
Services	$18.7	$14,793
Public Admin	$14.8	$16,601

Source: Estimated Value of Service Reliability for Electric Utility Customers in the United States, Lawrence Berkeley National Laboratory (LBNL), 2009

Estimated VOLLs by sector (median value, $/MWh) – based on the LBNL 2009 study – reported by London Economics

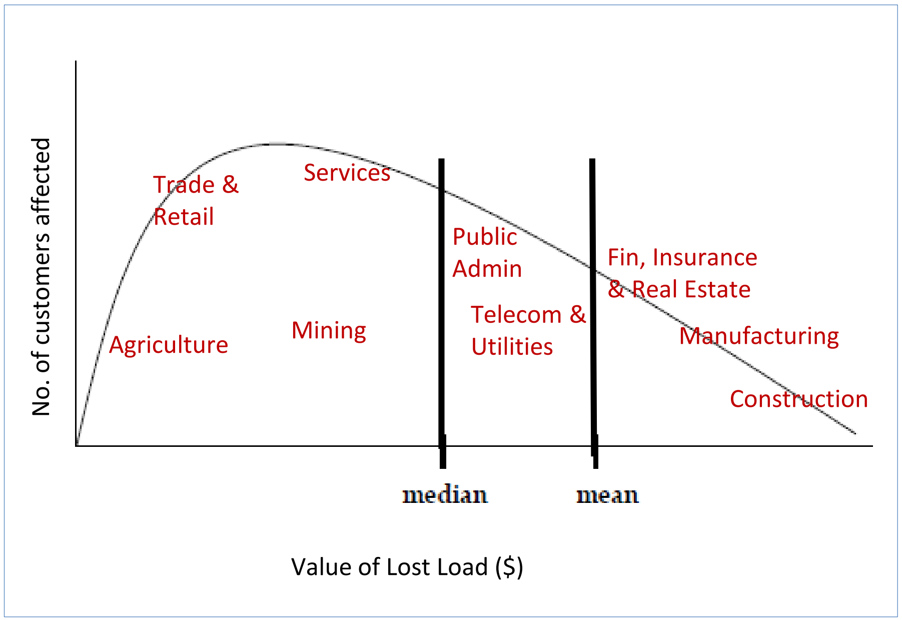


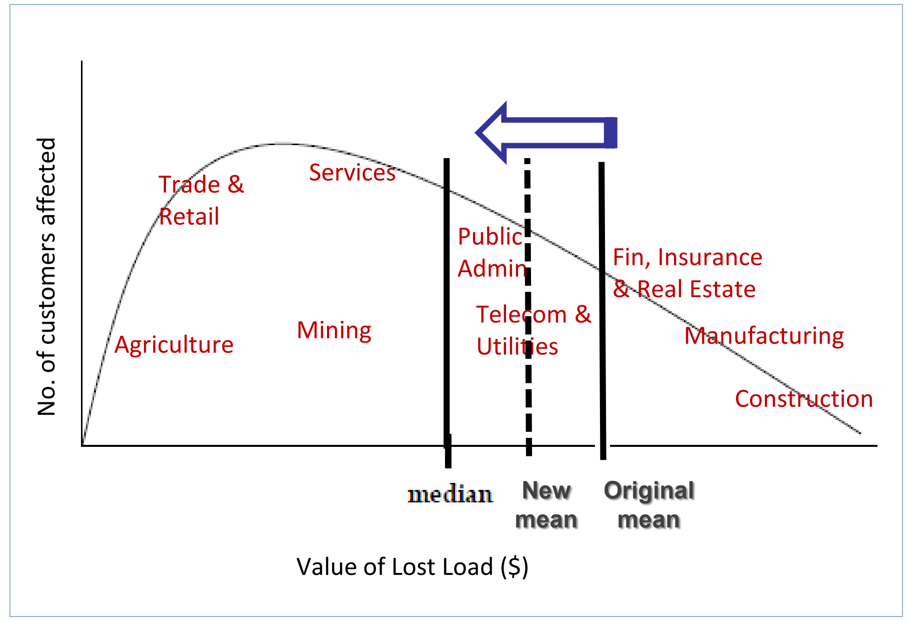
Source: Estimating the Value of Lost Load, London Economics, 2013

Caveats:

- *LBNL does **not** report median VOLL*
- *LBNL does **not** report NJ specific or Northeast specific VOLL*
- *London Economics does not study NJ specific or Northeast specific VOLL*
- *London Economics quotes a 2003 Northeast specific study by ICF ("The Economic Cost of the Blackout" which uses an assumed VOLL (as a multiple of retail electricity price) to calculate total economic cost of outage*

VOLL Also Depends upon Existing Backup Arrangements Are Present, i.e., Strategic Behavior





Source:

- *Estimated Value of Service Reliability for Electric Utility Customers in the United States, Lawrence Berkeley National Laboratory, 2009*
- *Estimating the Value of Lost Load, London Economics, 2013*

Possibly customers with high VOLL shall have some back up arrangements; thereby shifting the mean towards left

Shan*, X., Felder, F., & Coit, D. (2017). Game-theoretic Models for Electric Distribution Resiliency/Reliability from a Multiple Stakeholder Perspective. *IIE Transactions*, 49(2), 159-177.

Athawale, R., Felder, F., & Goldman, L. (2016). Do CHPs Perform? Case Study of NYSERDA Funded Projects. *Energy Policy*, 97, 618-627.

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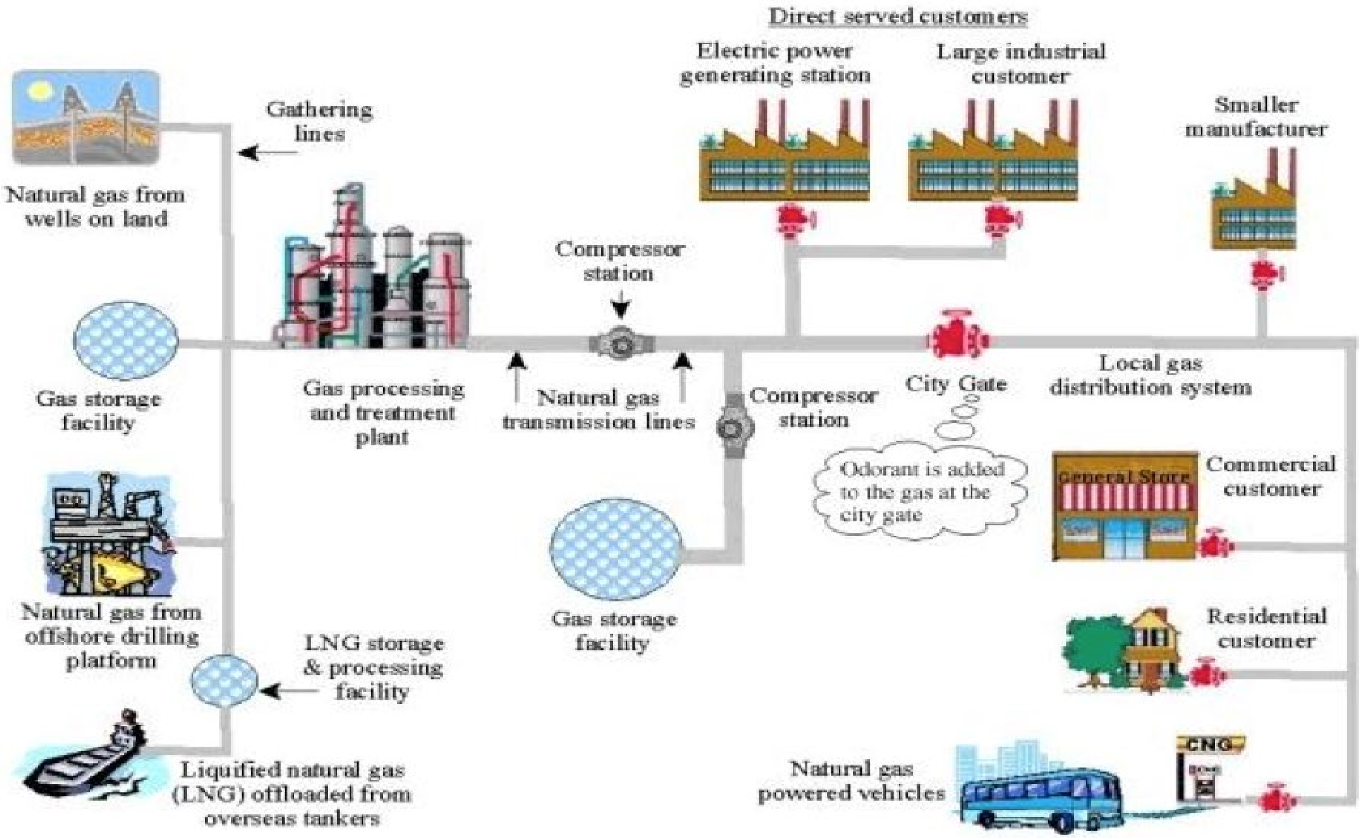
The Grid is Susceptible to Other Dependent Failures besides Severe Weather



Felder, F. (2004). Incorporating Resource Dynamics to Determine Generation Adequacy Levels in Restructured Bulk Power Systems. *KIEE International Transactions on Power Engineering*, 4A(2), 100-105.

Zhou, J., Huang, N., Coit, D. W., & Felder, F. A. (2018). Combined effects of load dynamics and dependence clusters on cascading failures in network systems. *Reliability Engineering & System Safety*, 170, 116-126.

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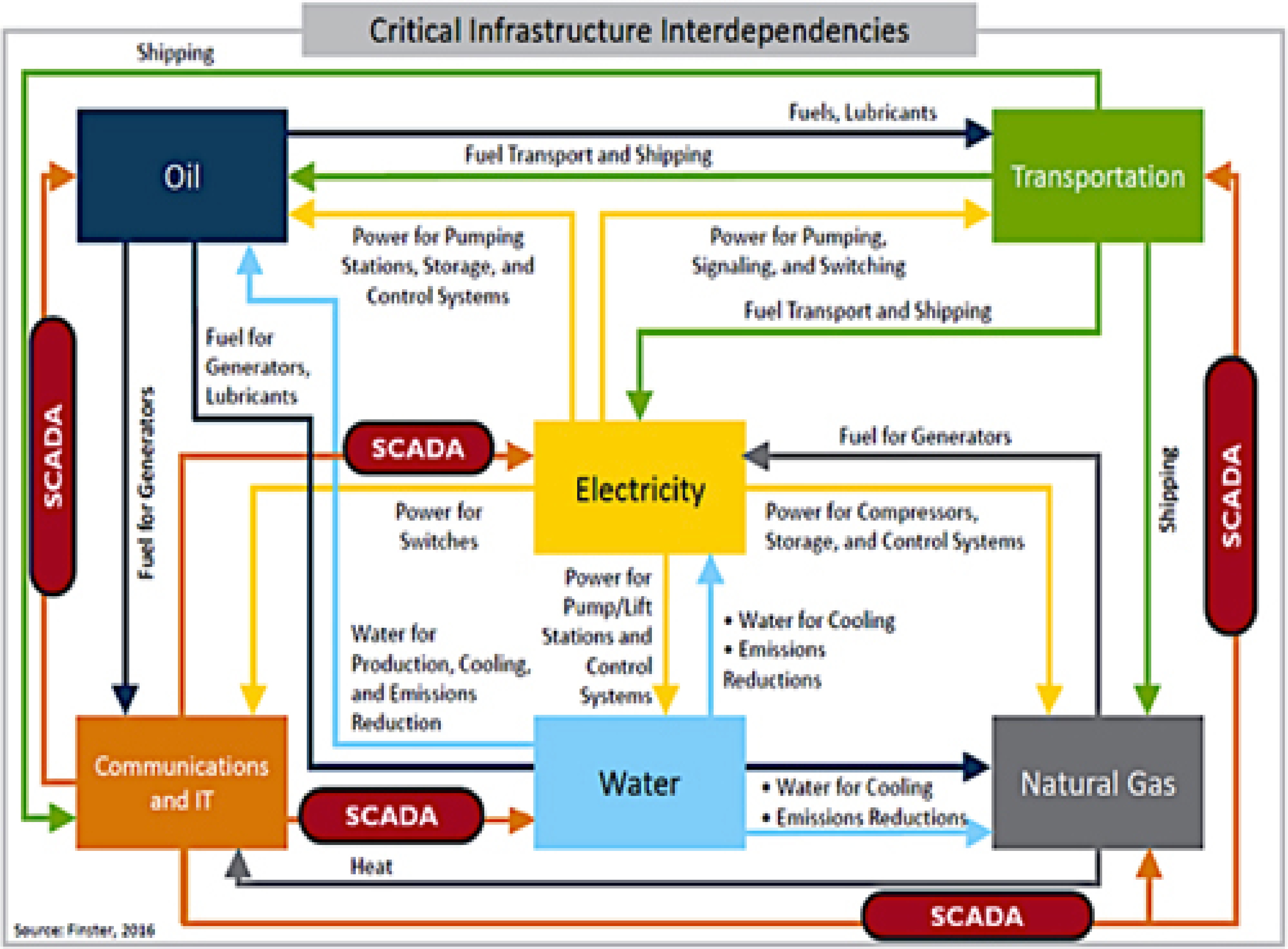
Critical Infrastructure Interdependencies
Shipping
Fuels, Lubricants
Fuel Transport and Shipping
Oil
Transportation
Power for Pumping Stations, Storage, and Control Systems
Power for Pumping, Signaling, and Switching
Fuel Transport and Shipping
Fuel for Generators, Lubricants
SCADA
Fuel for Generators
SCADA
Electricity
Fuel for Generators
Power for Switches
Power for Compressors, Storage, and Control Systems
Shipping
SCADA
Power for Pump/Lift Stations and Control Systems
Water for Production, Cooling, and Emissions Reduction
• Water for Cooling
• Emissions Reductions
Communications and IT
Water
Natural Gas
SCADA
• Water for Cooling
• Emissions Reductions
Heat
SCADA
Source: Finster, 2016

Findings Re: Electric Grid and Coastal Flooding

1. The technological, economic and policy structures must be considered in an integrated manner
2. Government and private actors behave strategically
3. Better data and quantitative models are needed
    1. Quantifying probabilities of low-probability events
    2. Severe weather predictions given the changing global climate
    3. Interaction of large-scale wind farms on regional and global climates
    4. Better data, models and theory regarding reliability and resiliency