The Power Grid and Complexity Science, Part 1: The Grid and Blackouts

Santa Fe Institute
Complex Systems
Summer School

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25 June 2018

This is a diverse group

- Physics
- Mathematics
- Computer Science
- Economics
- Psychology
- Anthropology

This is very good
You bring diverse perspectives to important problems

But also bad
The electricity sector is full of jargon designed to keep creative ideas out

Rule #1 for the Two Hours
If you don't understand what I am talking about:
Stop Me and Ask

Cool People

Here is a non-exhaustive list of folks that do cool stuff in this area, besides me:

- Sanya Carley (Indiana University),
- Raissa D'Sousa (UC Davis),
- Ian Dobson (Iowa State),
- Leonardo Duenas Osorio (Rice University),
- Ken Gillingham (Yale),
- Paul Hines (University of Vermont),
- Elizabeth Wilson (Dartmouth College)

Some goals for this talk

- Describe what “The Grid” is, and why it’s an interesting example of a complex system
- Describe a vexing problem where existing theory has not been helpful
- Convince you that the way to get around this vexing problem is to start over completely
- Not put you to sleep (especially right before lunch, and after three weeks of CSSS)

Three Challenges for Power Grids and Complexity

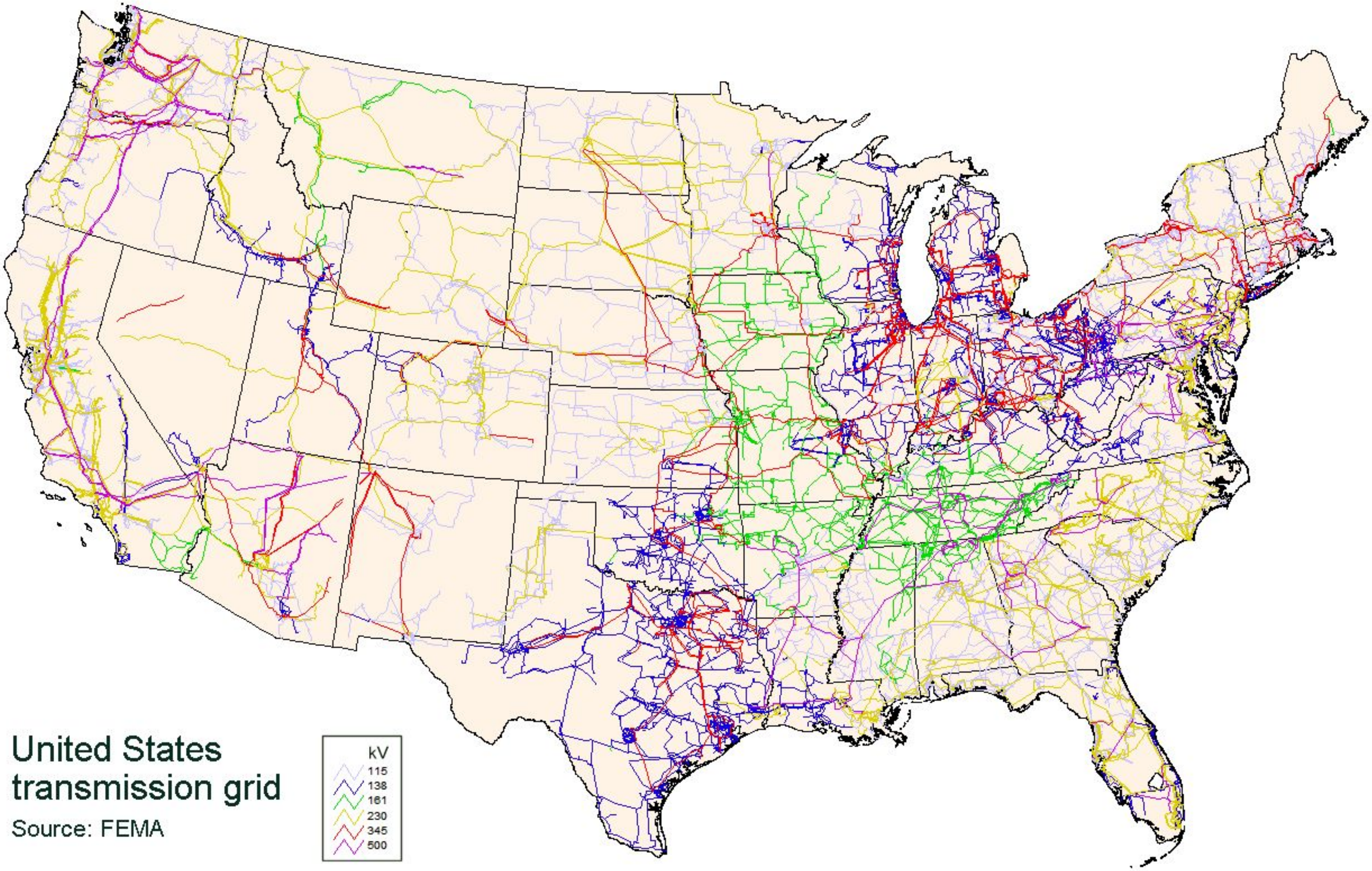
1. We can’t agree on what the “structure” of the power grid looks like.

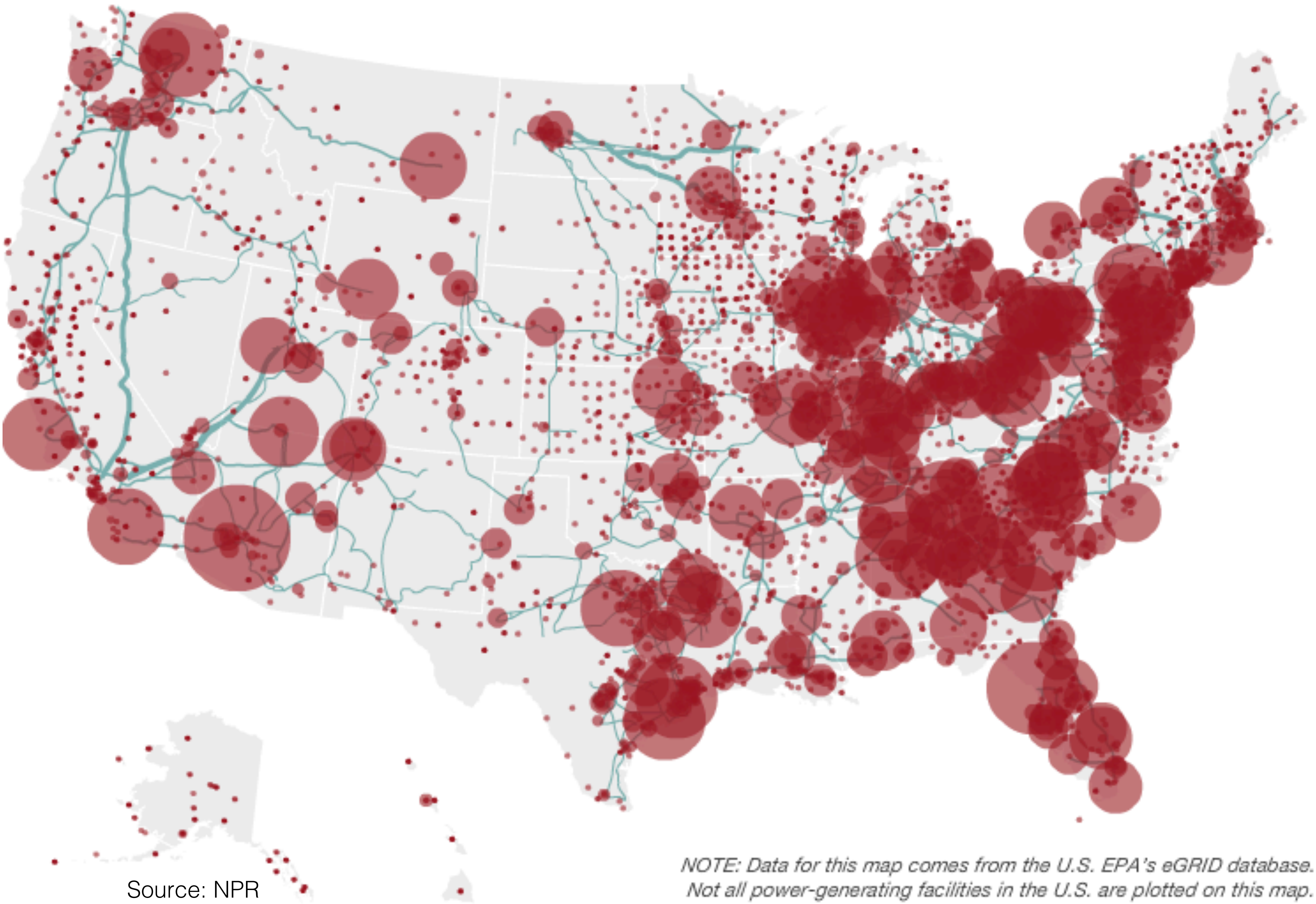
1a. This probably doesn’t matter.

2. Why not? Propagation of disturbances in power grids is not like disease, or information, or…really anything.

3. Electrons are highly social creatures.

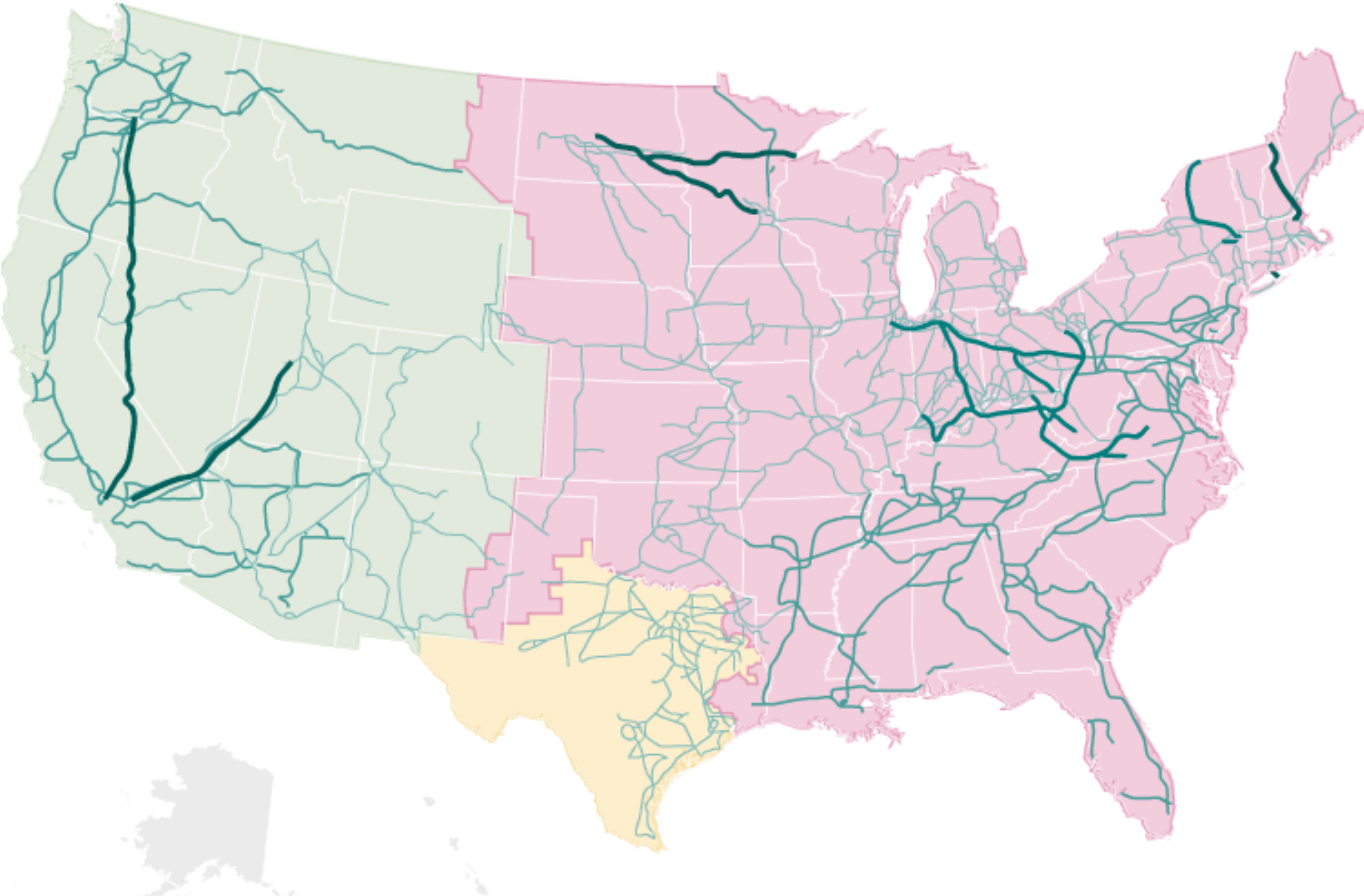

The Grid!
NY city, Nov. 9, 1965
© Bob Gomel, Life


United States
transmission grid
Source: FEMA
kV
115
138
161
230
345
500

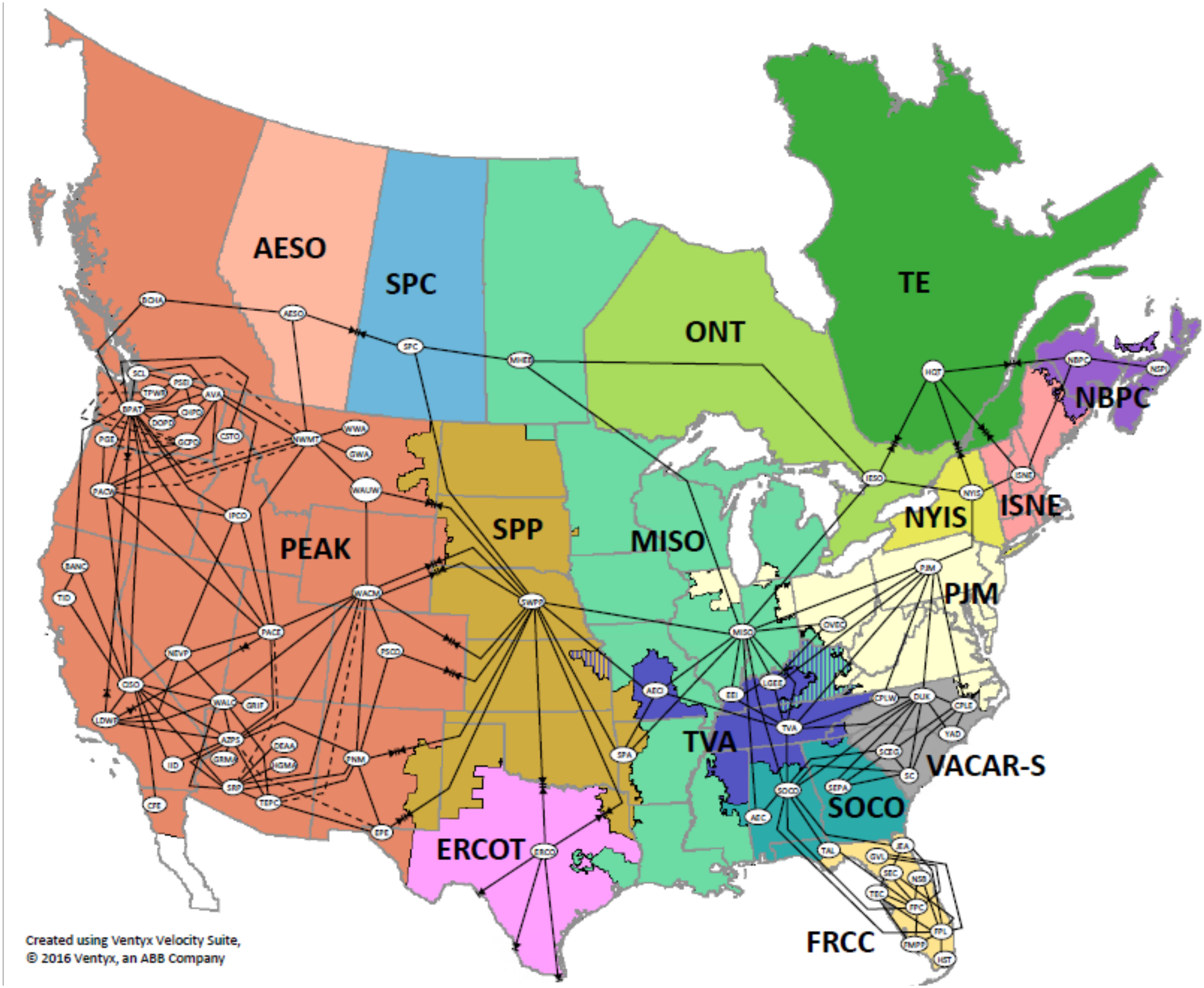


Source: NPR

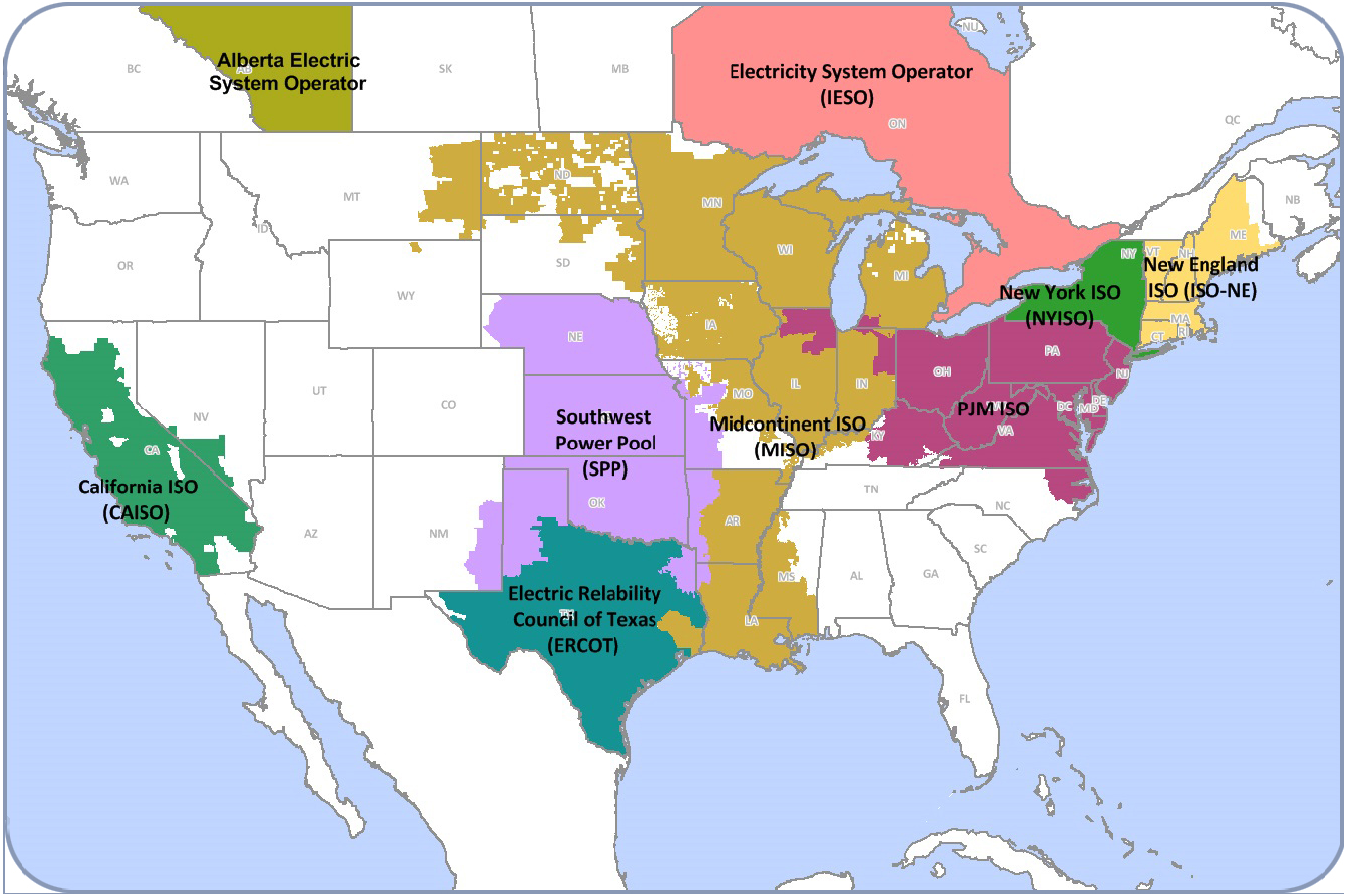
NOTE: Data for this map comes from the U.S. EPA's eGRID database. Not all power-generating facilities in the U.S. are plotted on this map.



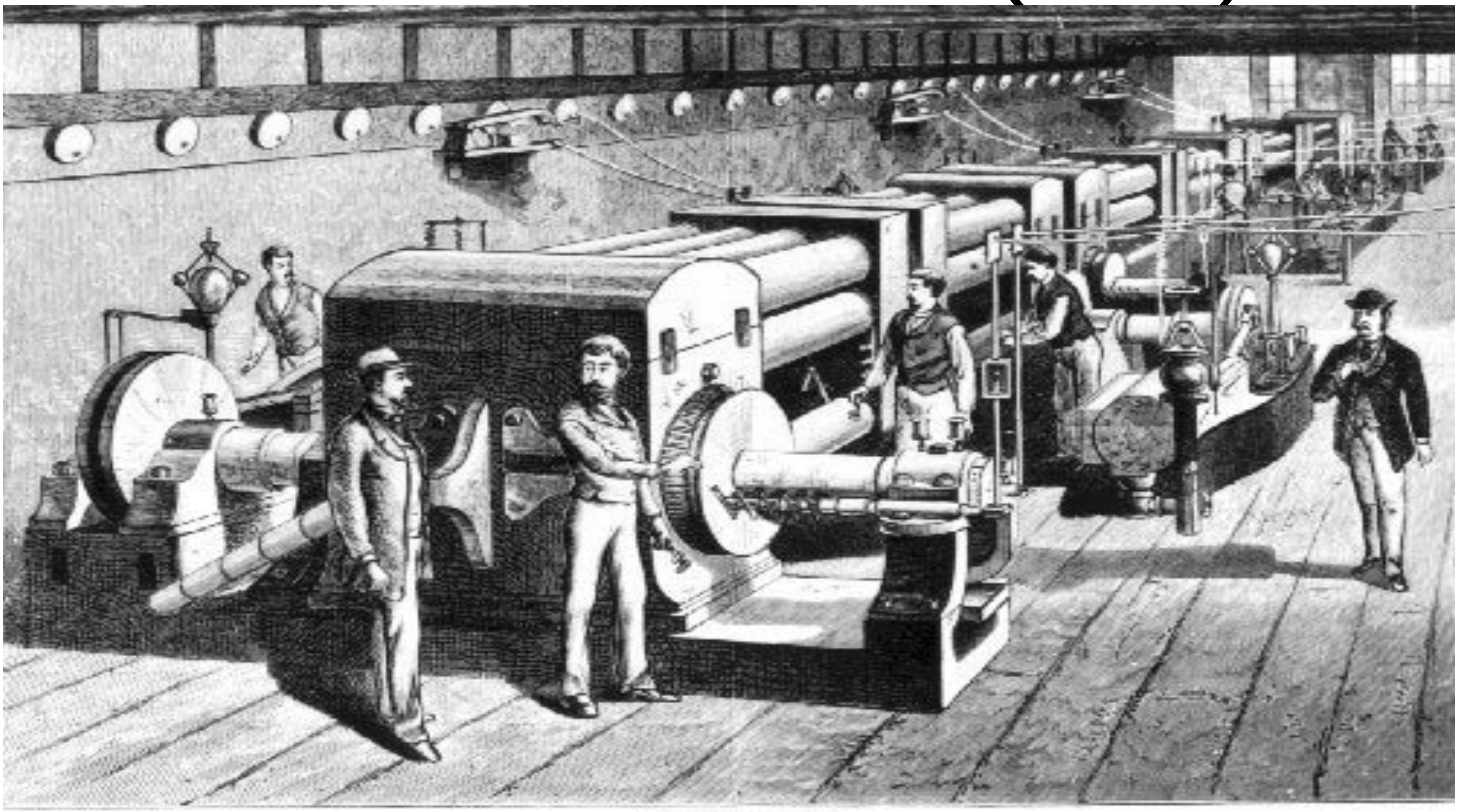
Source: NPR


AESO
SPC
ONT
TE
NBPC
ISNE
NYIS
PJM
MISO
SPP
PEAK
TVA
VACAR-S
SOCO
ERCOT
FRCC

North American Regional Transmission Organizations



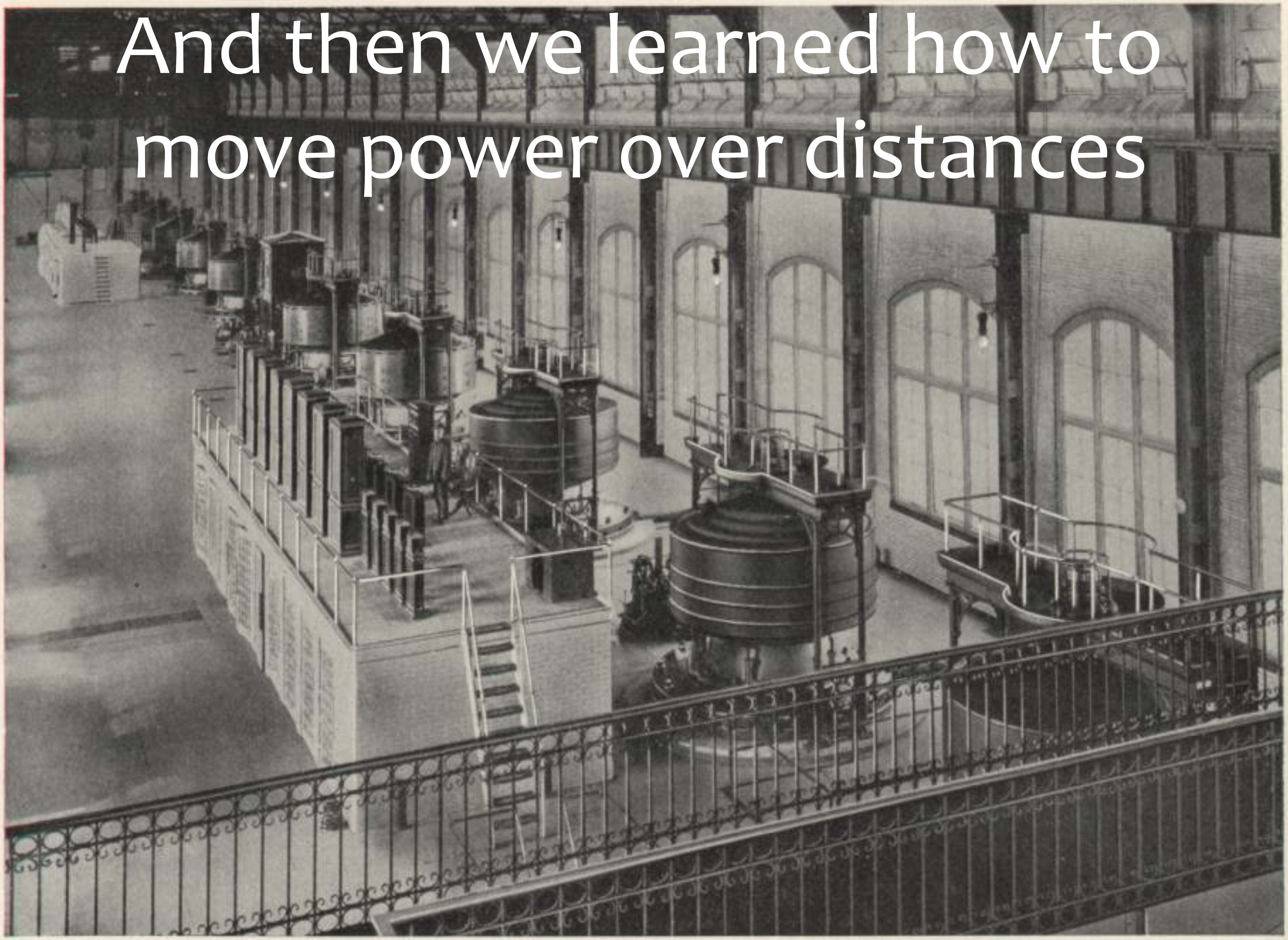
Things started decentralized: Pearl-street station (1882)



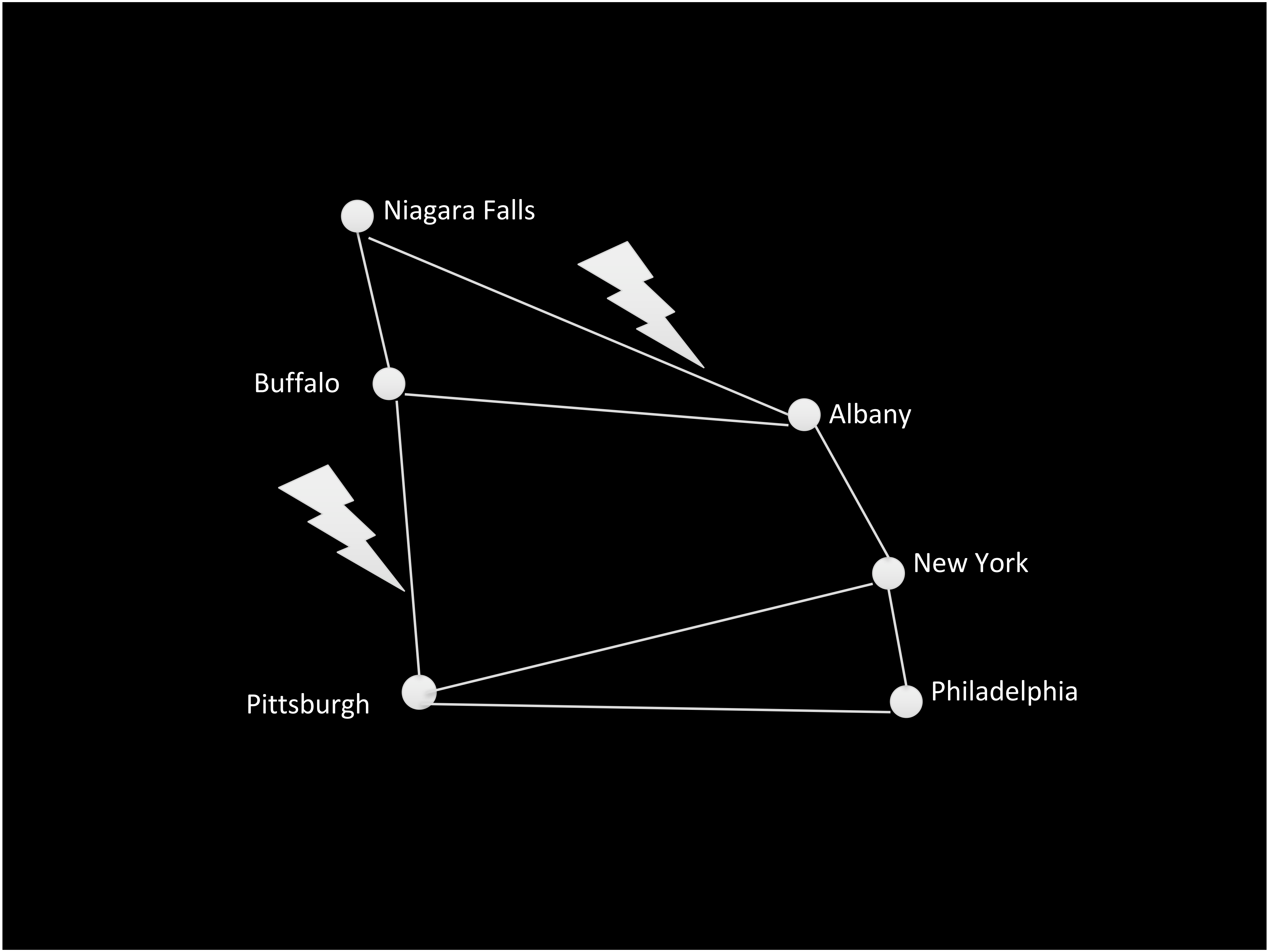
THE DYNAMO ROOM.
FIRST EDISON ELECTRIC LIGHTING STATION IN NEW YORK.

U.S. DEPARTMENT OF THE INTERIOR, NATIONAL PARK SERVICE, EDISON NATIONAL HISTORIC SITE

And then we learned how to move power over distances



GENERATING STATION OF THE NIAGARA FALLS POWER COMPANY, SHOWING THE TEN 5,000 H. P. GENERATORS



Niagara Falls
Buffalo
Albany
New York
Pittsburgh
Philadelphia

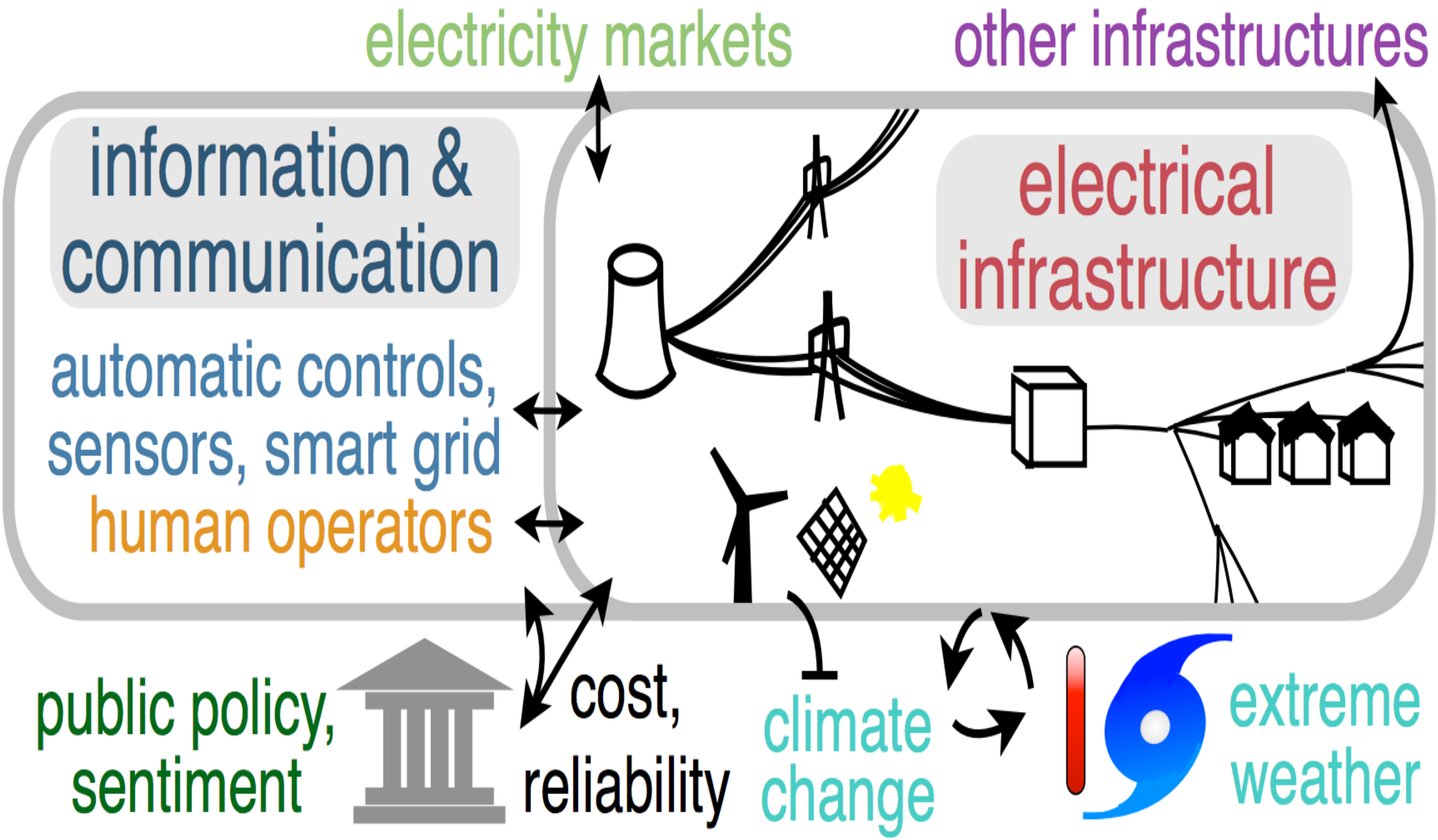
Things we know about power grids

The physics
of generation

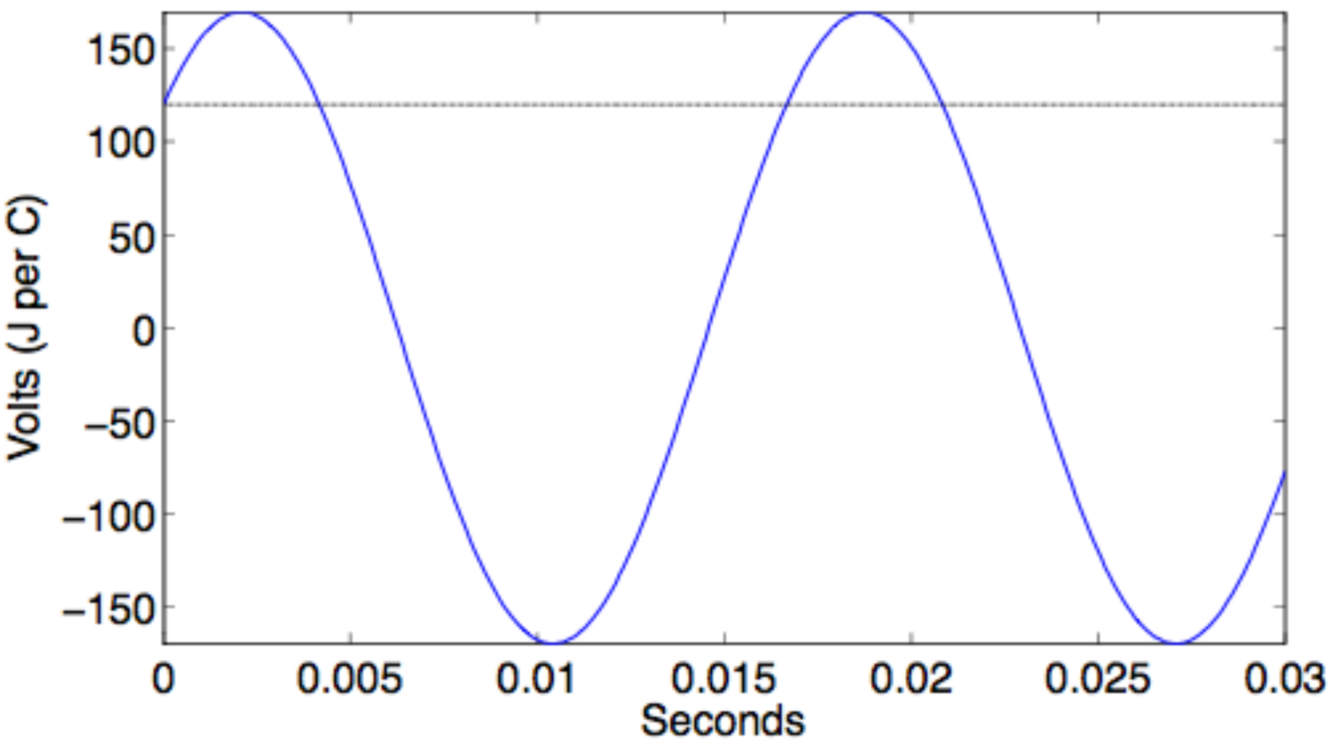
The physics of
transmission

That they
mostly work
(note the simple
interface)

Things we don’t know



Key principle #1

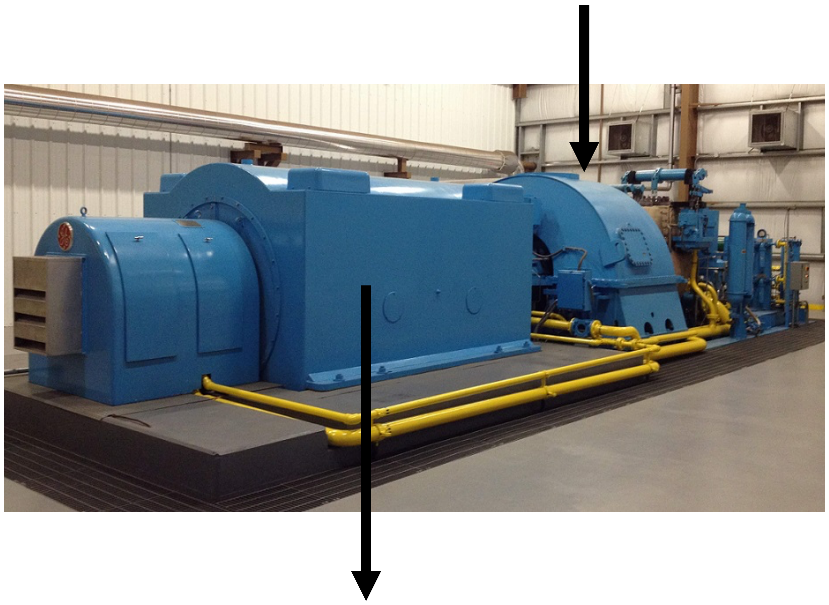


What goes in, must come out (there is no storage)

$$v(t) = 120\sqrt{2}\cos(2\pi 60t - \pi/4)$$

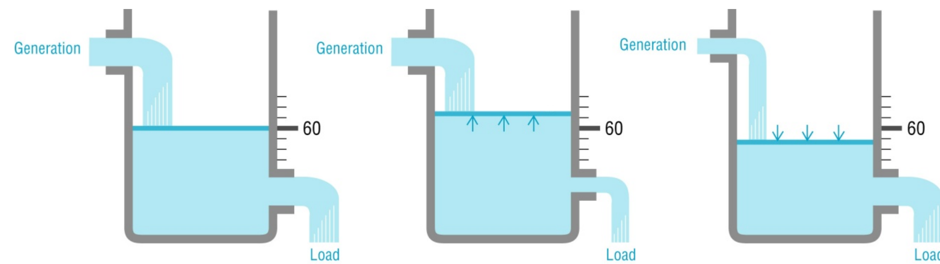
Key principle #2

P_{in}



P_{out}

$$P_m = P_g + D\omega + M\dot{\omega}$$



In-flow equals out-flow, frequency stable at 60 Hz

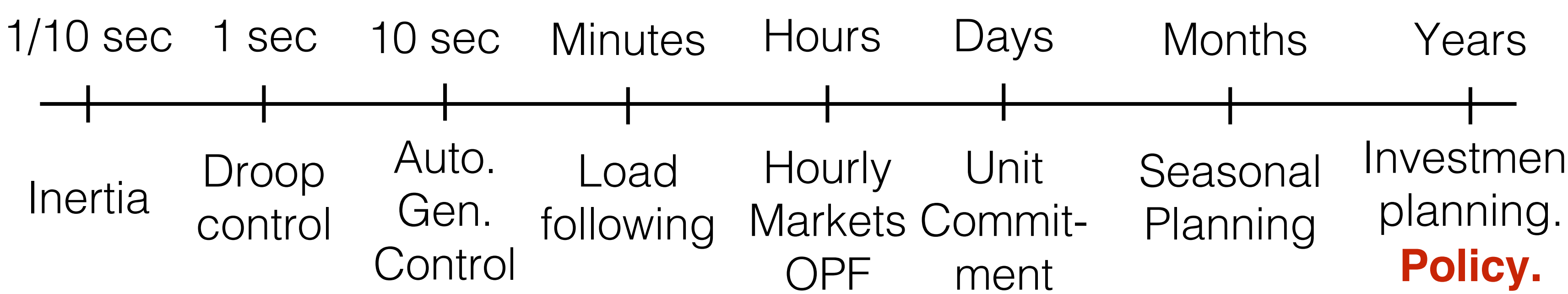
Out-flow less than in-flow, frequency rises above 60 Hz

In-flow less than out-flow, frequency falls below 60 Hz

If what goes out is not equal to what goes in generators speed up/down

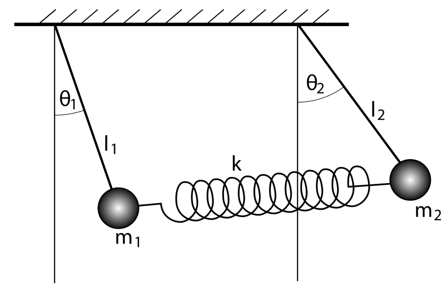
We have learned some things about managing this system

$$P_m = P_g + D\omega + M\dot{\omega}$$

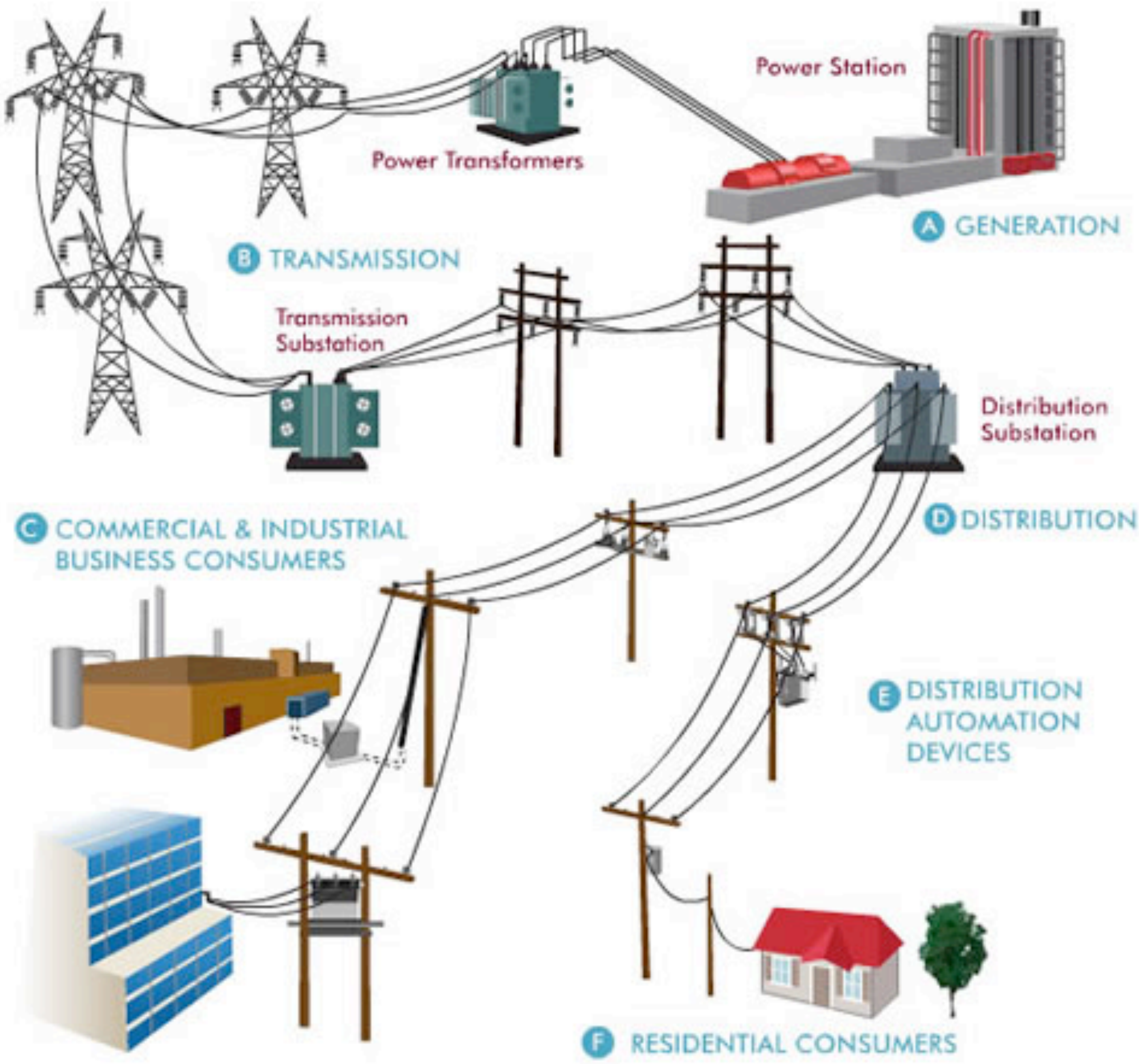


So what do we have?

- A network of billion-dollar coupled pendula,
- which have a tendency to produce long chains of cascading failures every so often,
- to which we are adding millions of new stochastic sources (not to mention stochastic bad guys),
- over which no one is in charge.

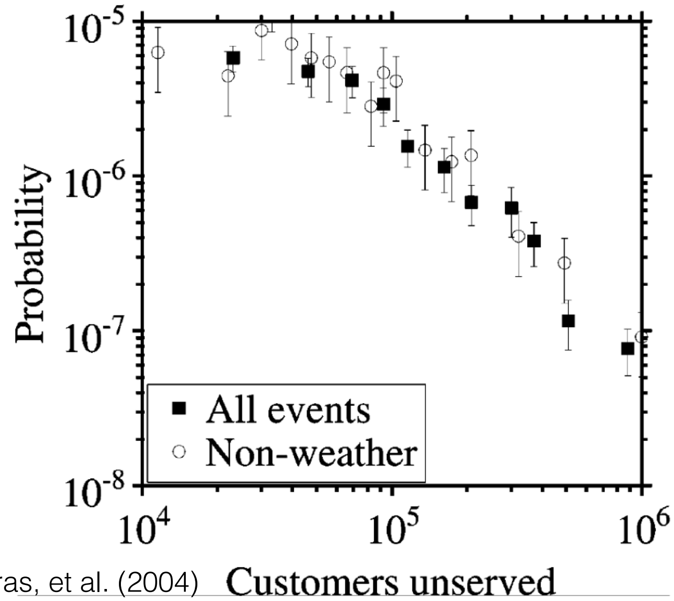


The "Smart Grid"

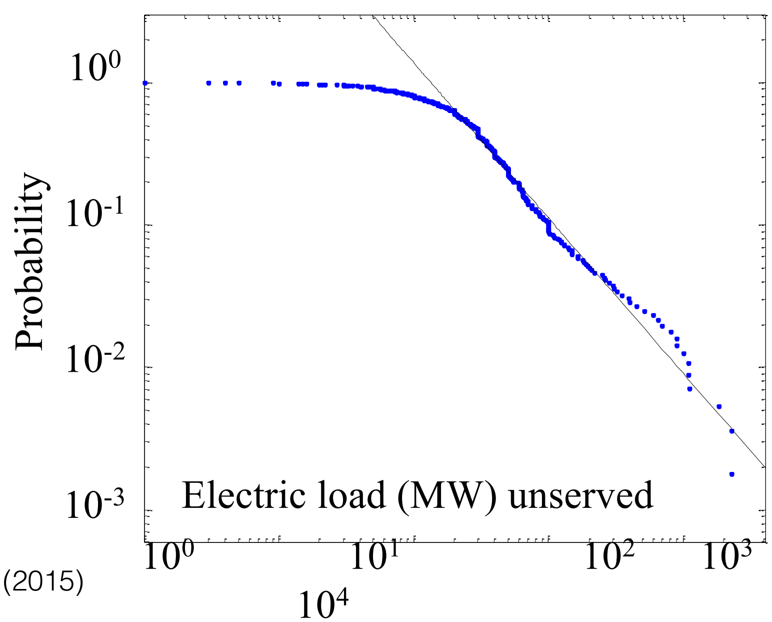



Challenge #1: Hints of Complexity and the Struggle for Structure
NY city, Nov. 9, 1965
© Bob Gomel, Life

Extreme Events



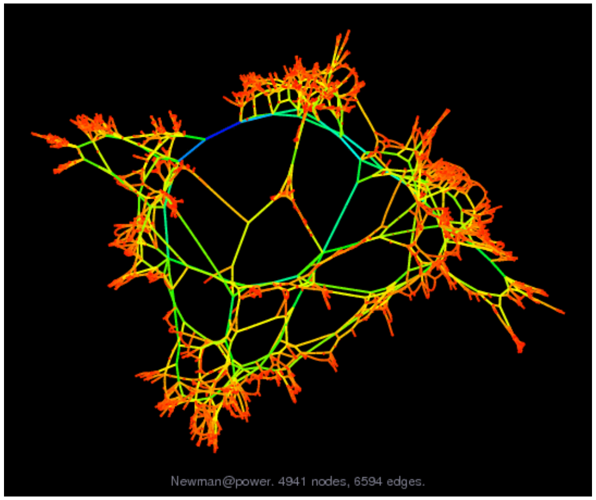
Carreras, et al. (2004)



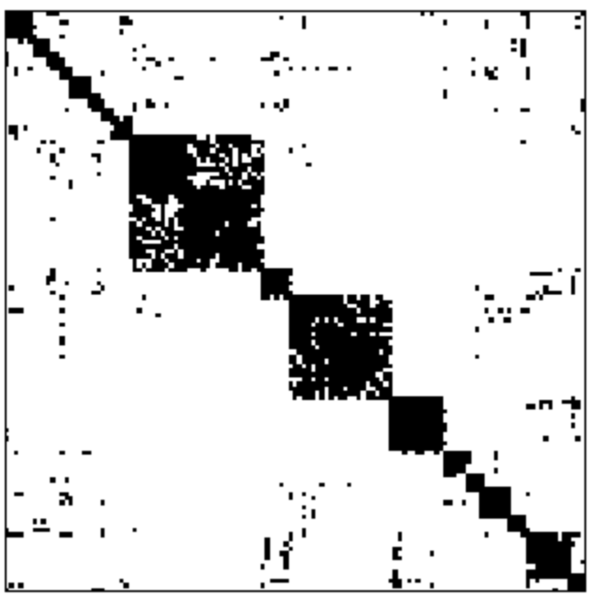
Zhao (2015)

By most measures, the size of blackouts follows a nice power law.

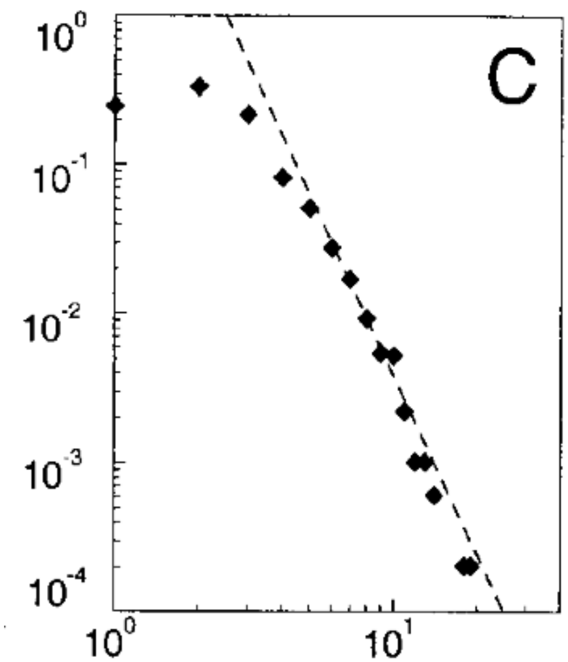
Evidence for Small-World Structure



The first structural analysis (Watts and Strogatz, 1998) suggested that the Western Interconnect exhibited some properties of a small-world network.

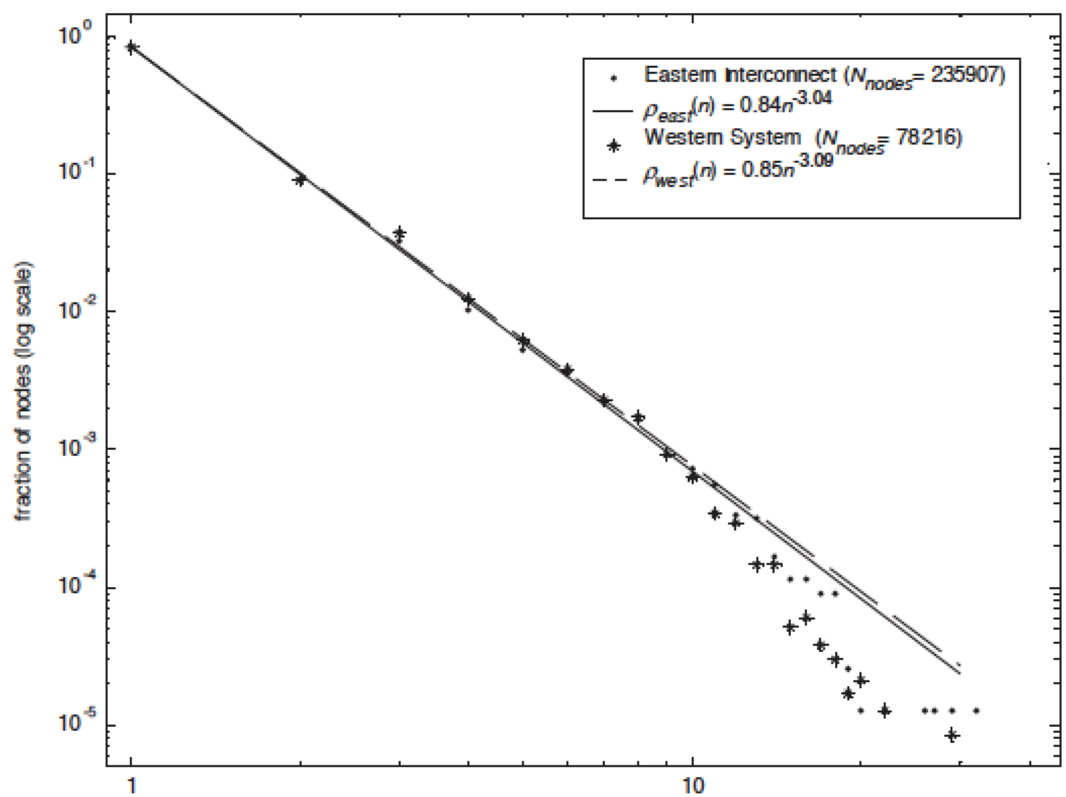


Evidence for Scale-Free Structure



Barabasi and Albert (1999)

Meanwhile, the tail of the degree distribution of the North America grid appears to follow a power law.

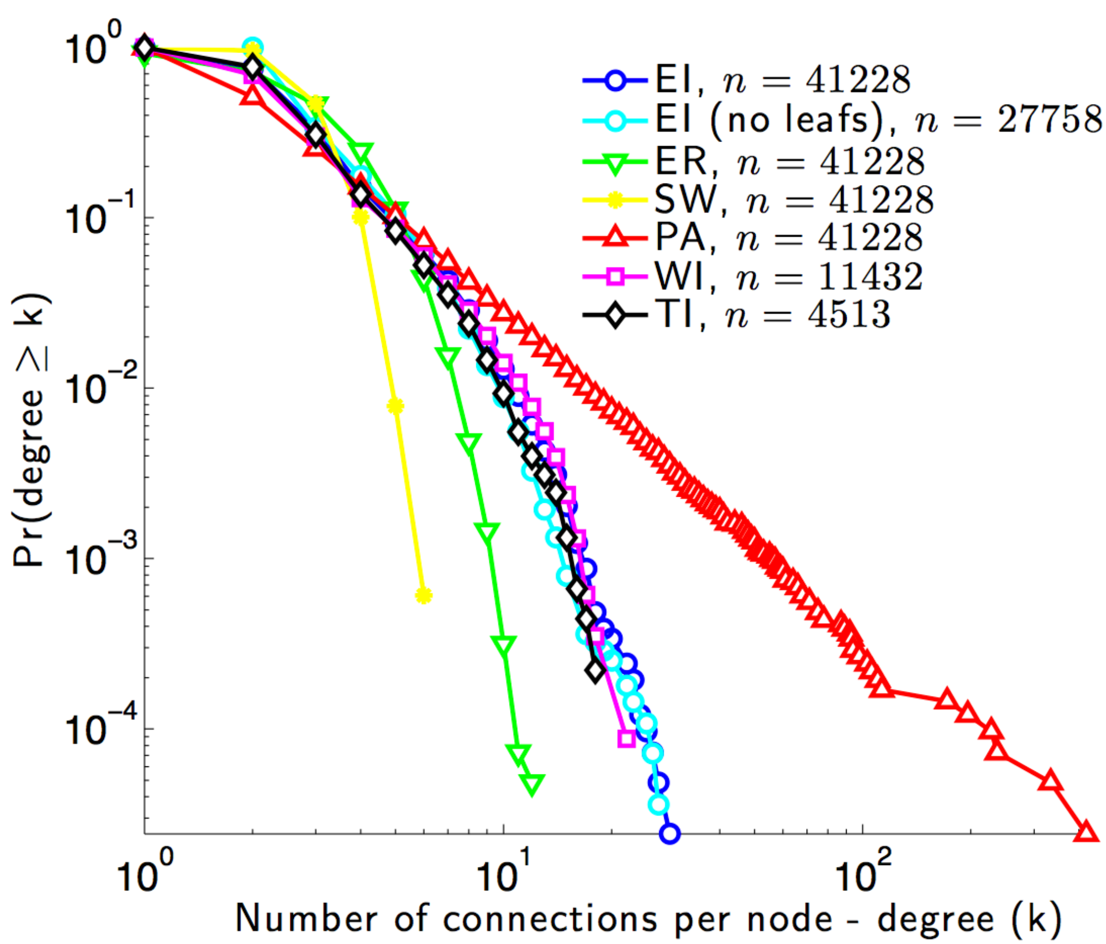


Chassin and Posse (2004)

Any Evidence for Any Structure?

Authors	Power grid data	Findings
Watts and Strogatz (1998)	Western US	Power grids are small-world
Amaral et al. (2000)	Southern California	Exponential degree
Albert et al. (2004)	North America	Exponential degree, scale-free behavior
Crucitti et al. (2004)	Italy	Power-law degree
Chassin and Possee (2005)	US East and West	Power-law degree
Holmgren et al. (2006)	Nordic, Western US	Power grids fail in ways similar to scale-free nets
Blumsack et al. (2007)	IEEE 118	Wheatstone motifs
Wang, et al. (2008)	Various	Synthetic power grids
Bompard et al. (2009)	Italy	“Net-ability”

What We Don't Really Understand: Structure of the Power Grid



The three North American grid interconnections share topological similarities with one another…but not with canonical graph models.

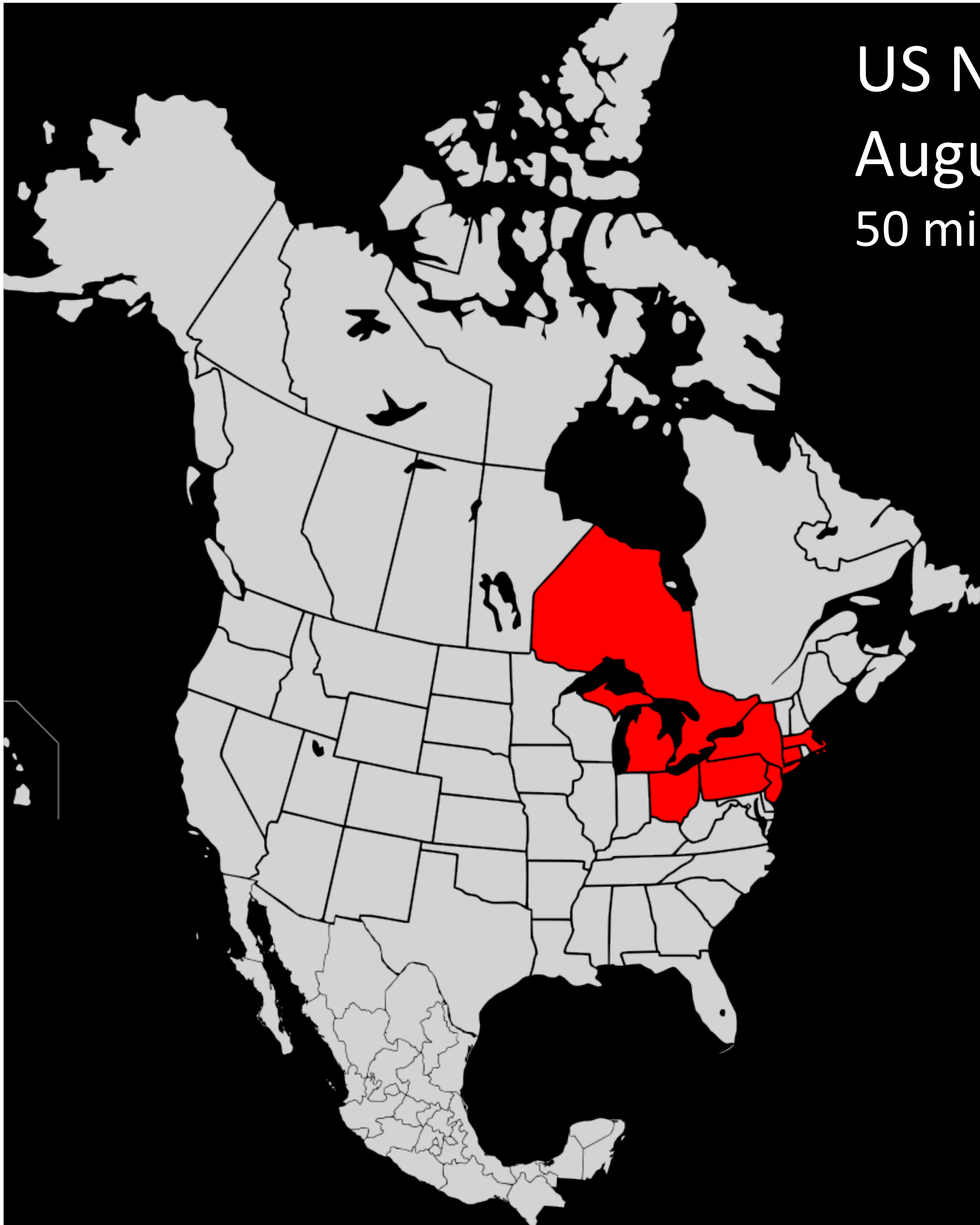
Cotilla Sanchez et al, 2012

Challenge #2: The Nature and Propagation of Failures in the Power Grid

NY city, Nov. 9, 1965
© Bob Gomel, Life

US Northeast and Canada
August 14, 2003

50 million people




California, Arizona, Mexico
September 8, 2011
5 million people
Hines, 25 Jan 2013

Northern India

July 30, 2012: 350 million people

July 31, 2012: 700 million people

Photo: Bikas Das/AP Photo
IEEE Spectrum, Oct. 2012

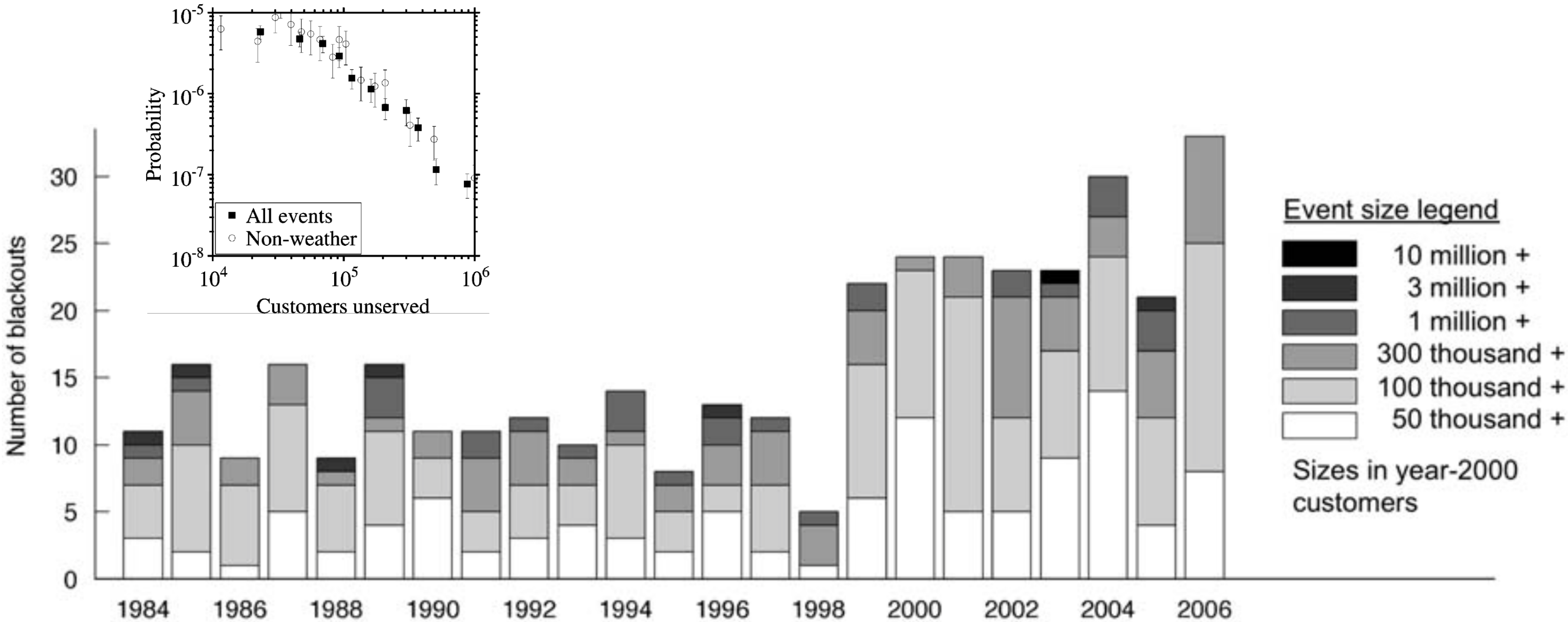
Bangledesh. 1 November 2014

Officials said it would take at least 12 hours to repair the system and restore power to the capital Dhaka [AP]

Washington DC, April 7, 2015

washingtonpost.com

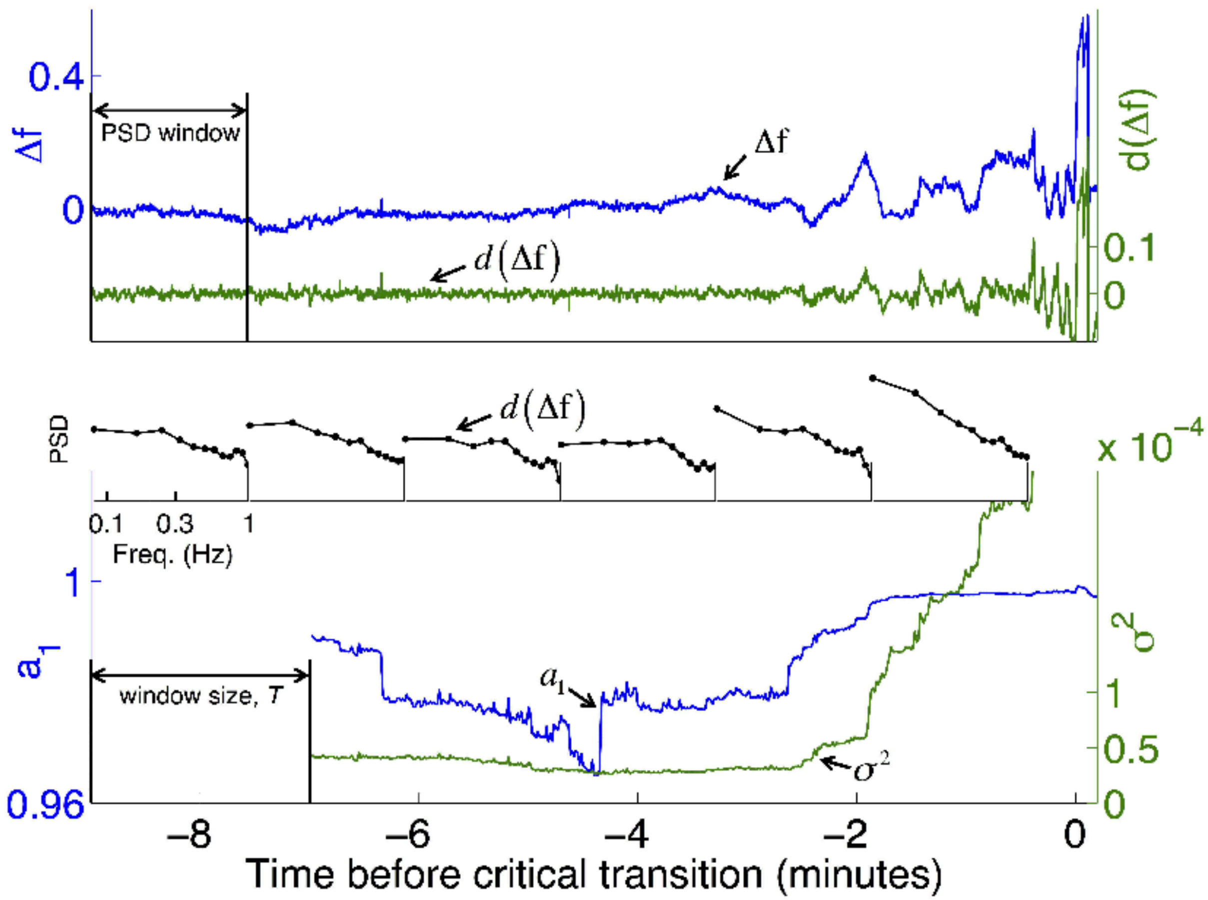
What We Understand: Blackout Frequency



Hines, et al. (2008)

Remember the power law? Despite many billions of dollars in “hardening,” the frequency of large blackouts is not decreasing.

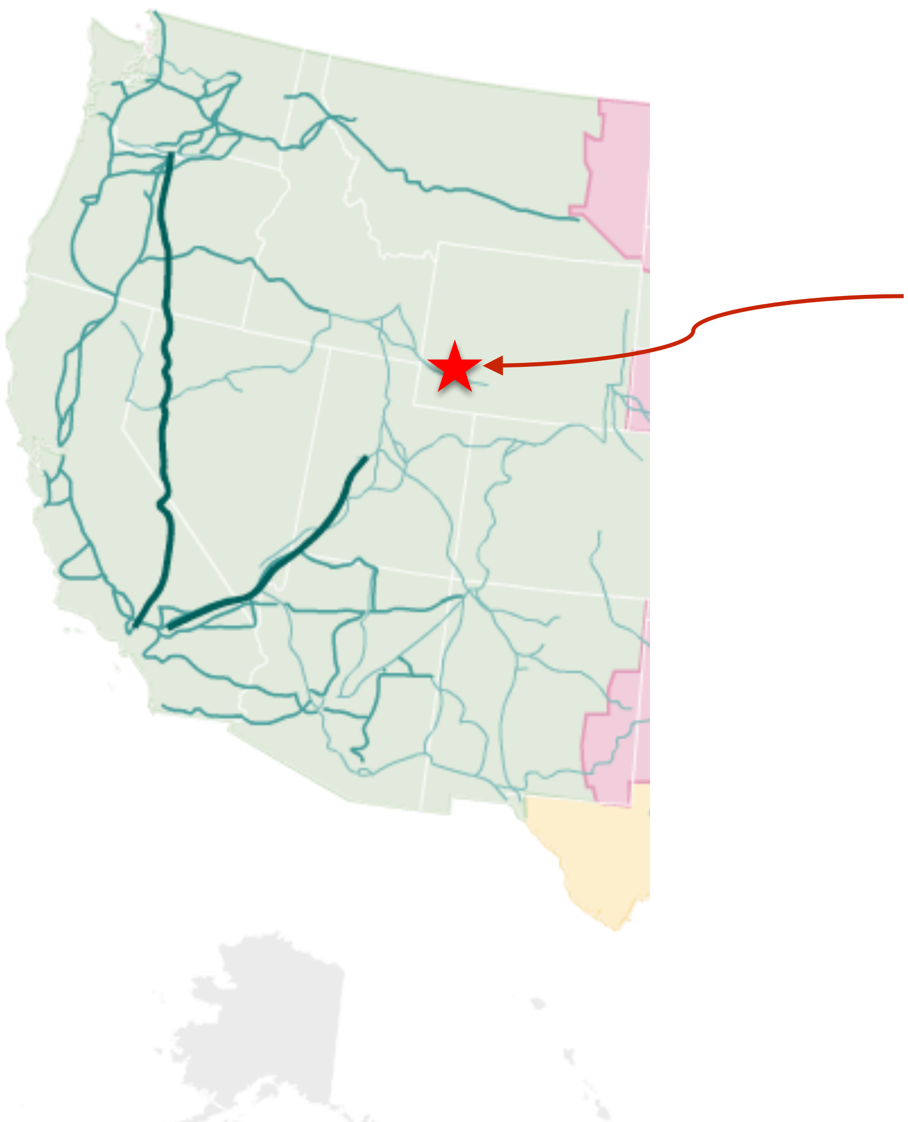
What We (Kind of) Understand: Oscillations and Instability



Time series signatures in the rotational frequency of the grid can serve as early-warning precursors for instability and blackouts.

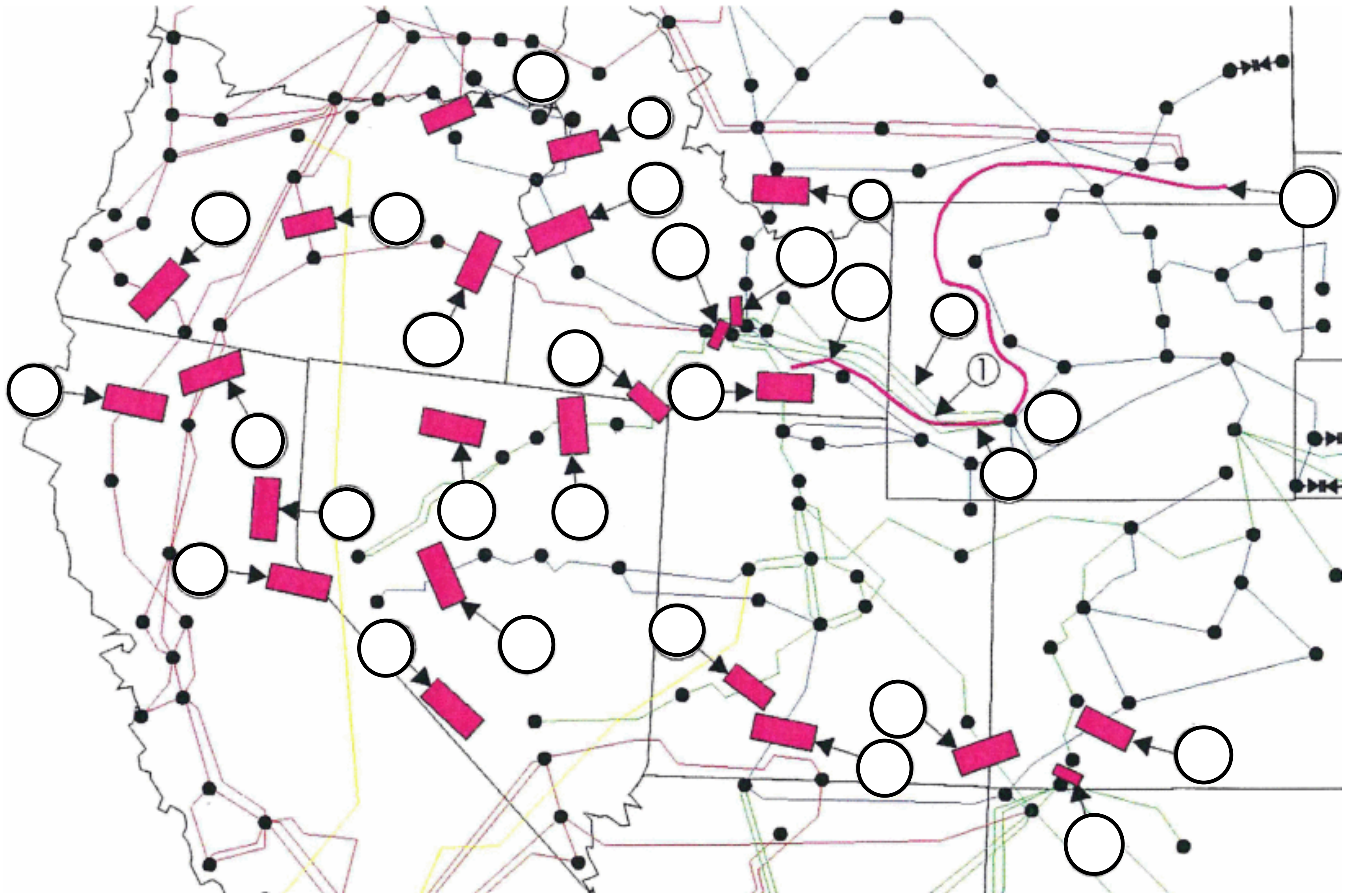
Cotilla Sanchez et al (2012)

What We Don't Really Understand: The Nature of Propagation

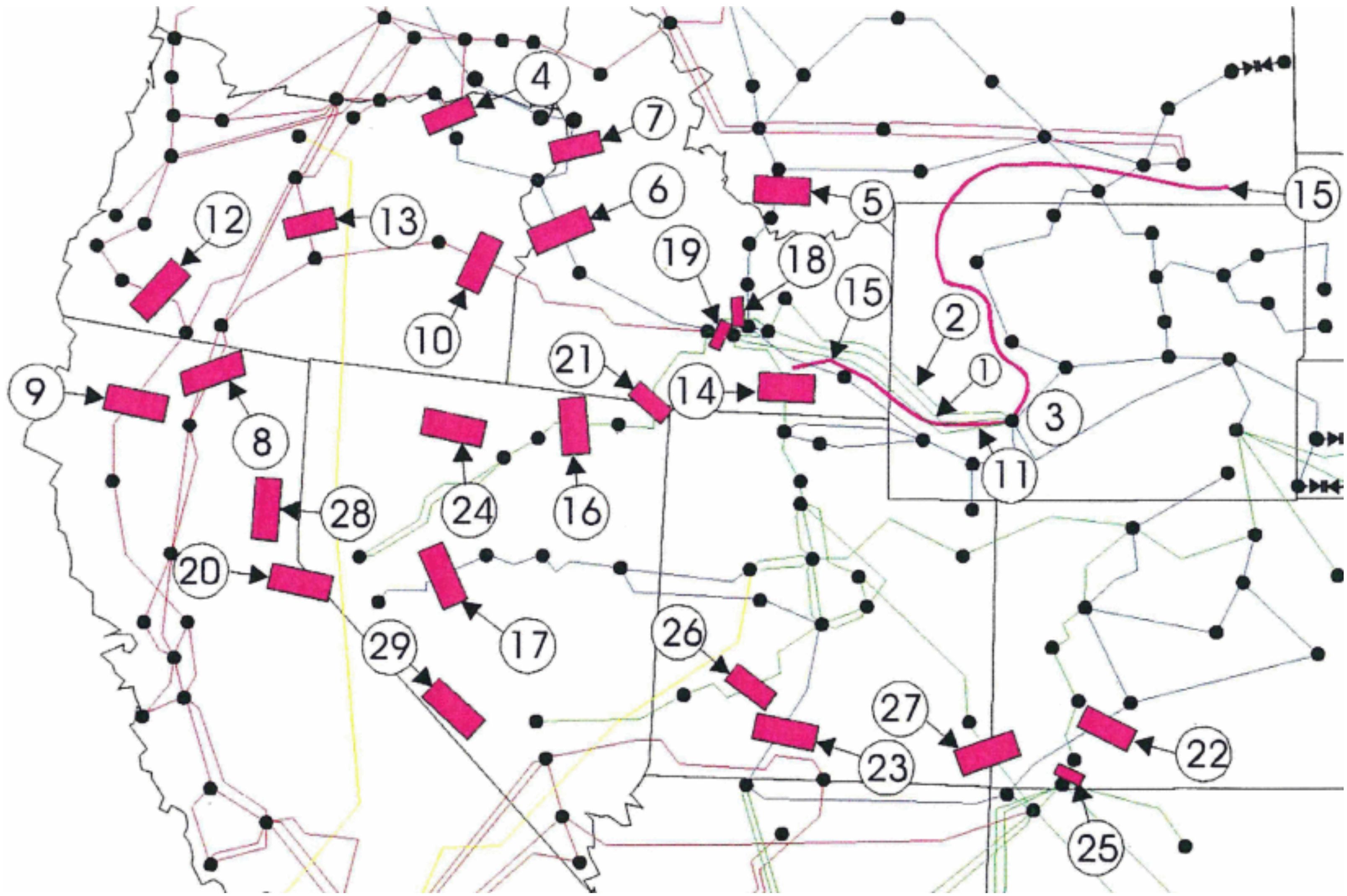


One of the worst power grid failures in the Western US started right here. Based on what you have learned about networks, how do you think it propagated through the system?

What We Don't Really Understand: The Nature of Propagation



What We Don't Really Understand: The Nature of Propagation



We Know that Propagation is More than Topology

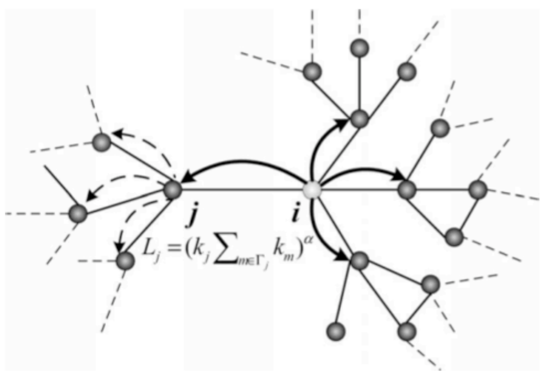


Fig. 2. The scheme illustrates the load redistribution triggered by an node-based attack. Node *i* is removed and the load on it is redistributed to the neighboring nodes connecting to node *i*. Among these neighboring nodes, the one with the higher load will receive the higher shared load from the broken node.

Wang and Rong (2009)

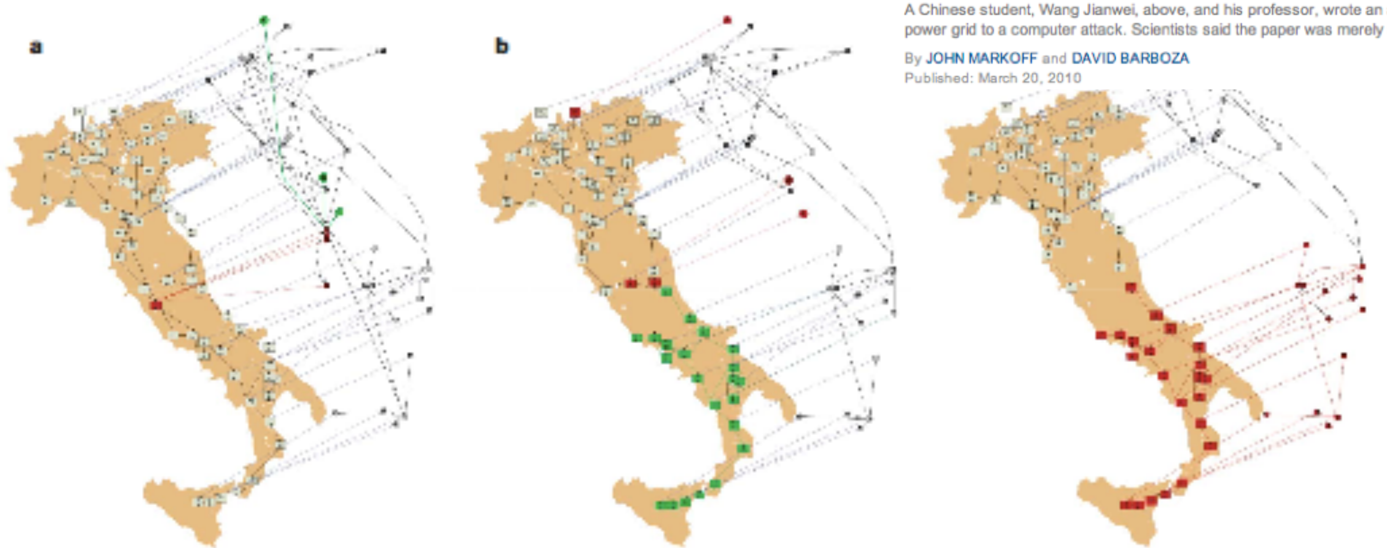
Academic Paper in China Sets Off Alarms in U.S.

Du Bin for The New York Times

A Chinese student, Wang Jianwei, above, and his professor, wrote an academic paper on the vulnerability of the American power grid to a computer attack. Scientists said the paper was merely a technical exercise.

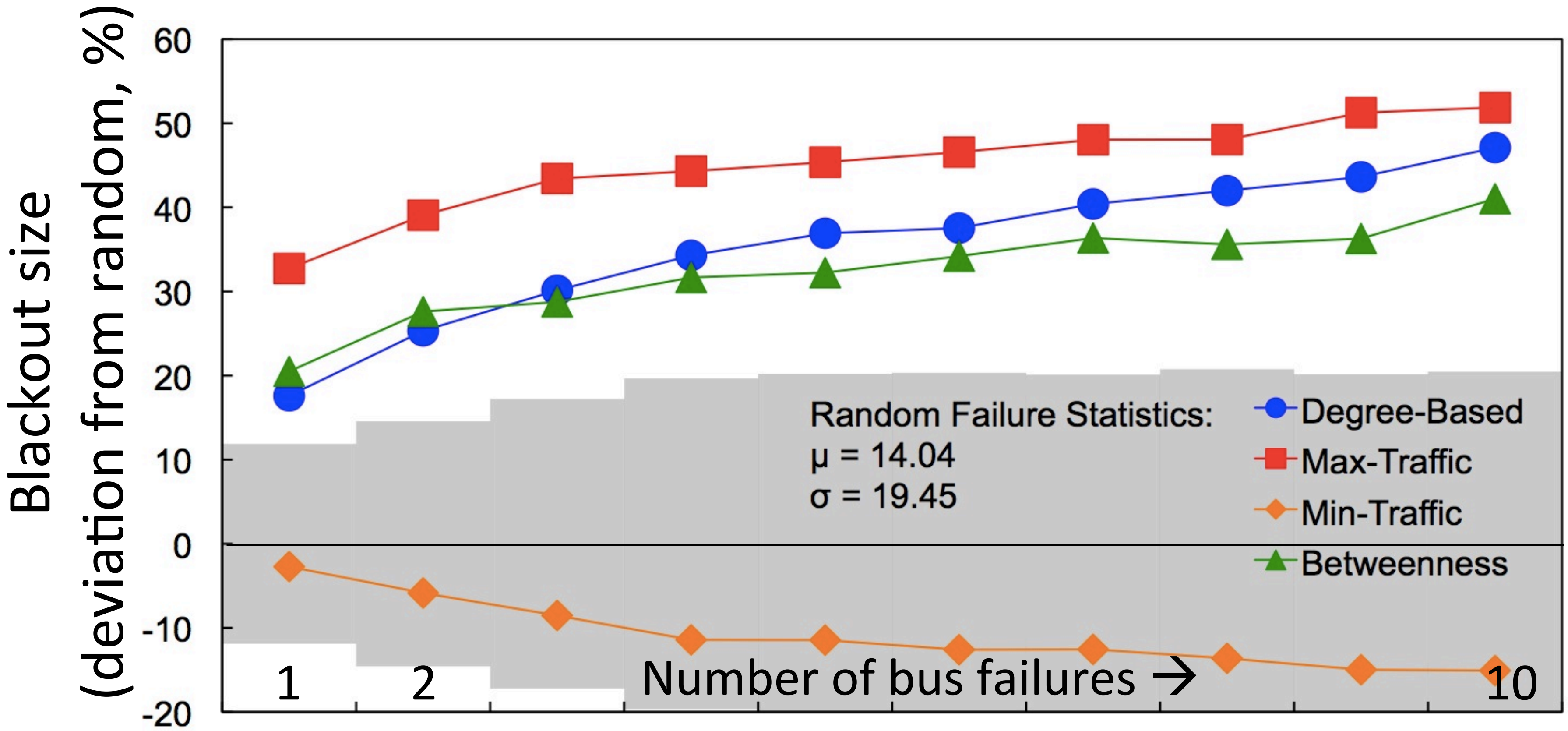
By JOHN MARKOFF and DAVID BARBOZA

Published: March 20, 2010



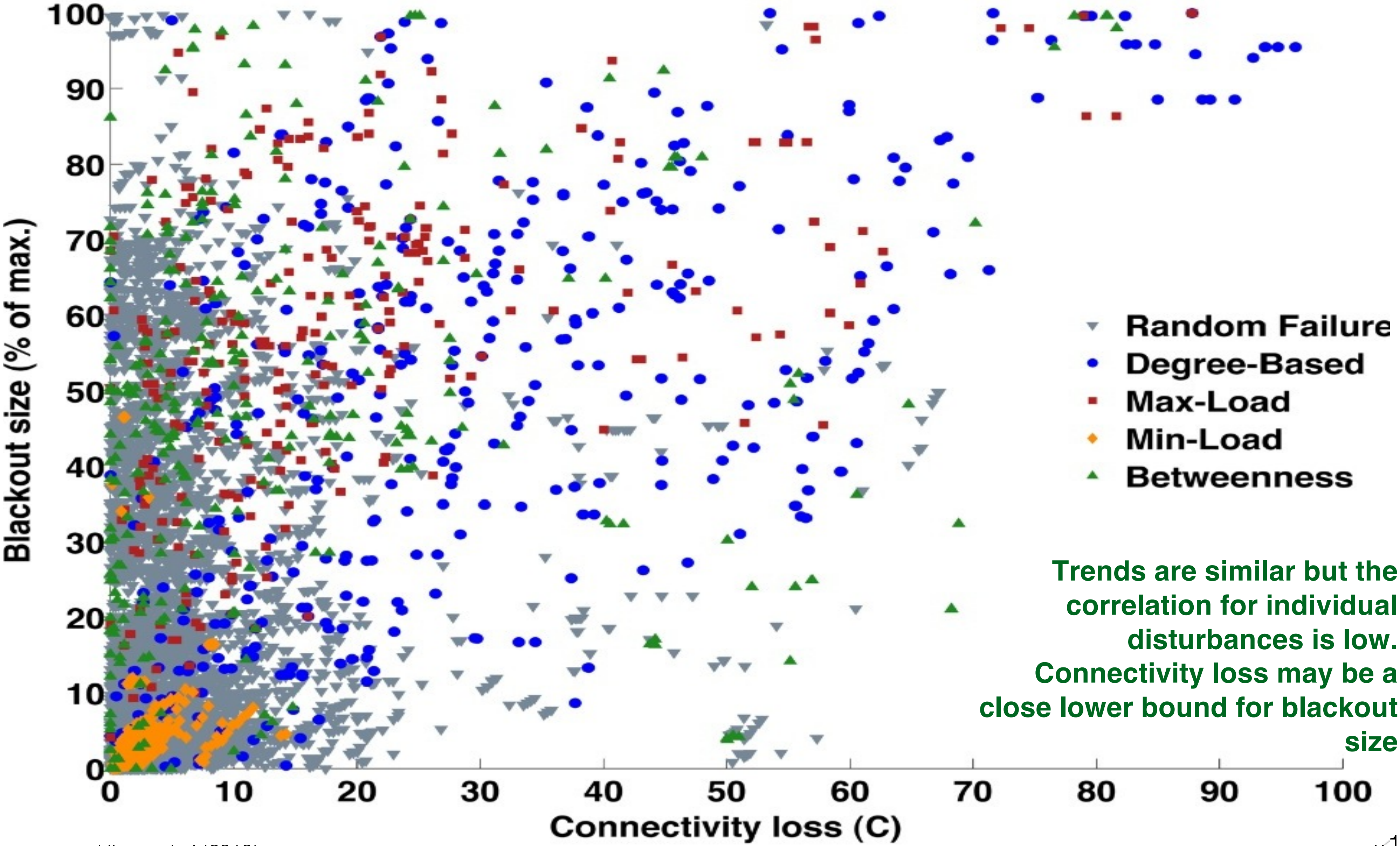
Buldyrev, et al (2010)

The Value of Topological Models



Hines, et al (2010)

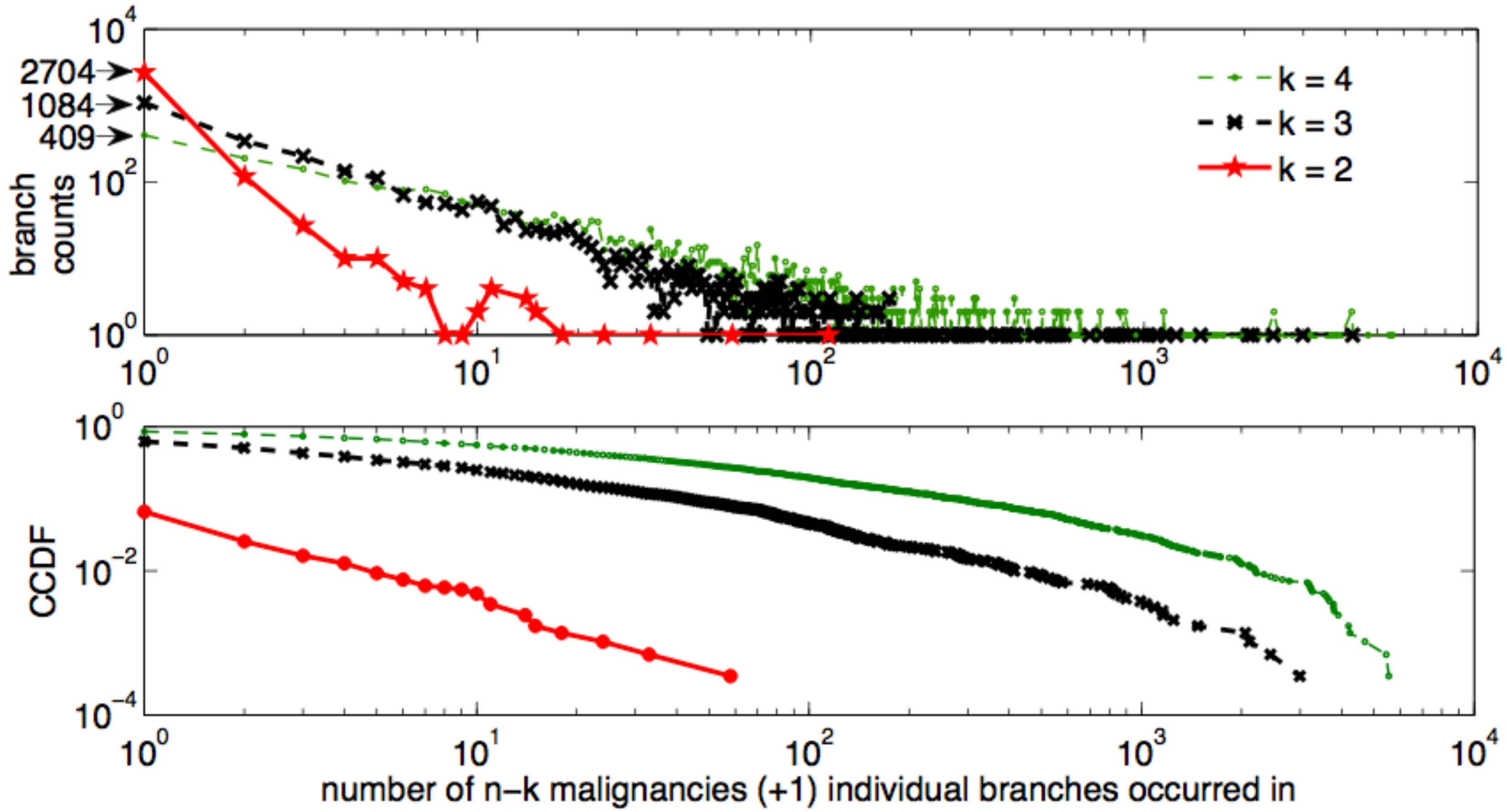
The Value of Topological Models



Trends are similar but the correlation for individual disturbances is low. Connectivity loss may be a close lower bound for blackout size

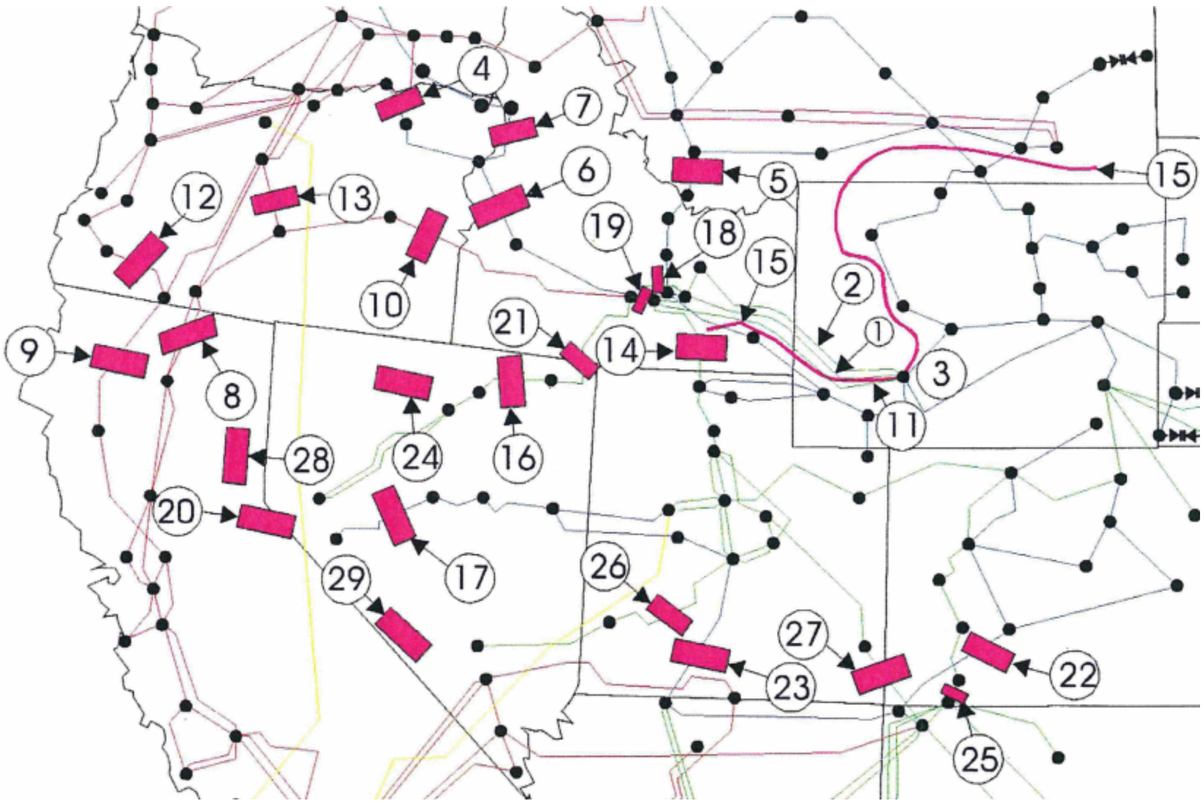
Hines, et al (2010)

Yet, Power Grids do have Critical Elements



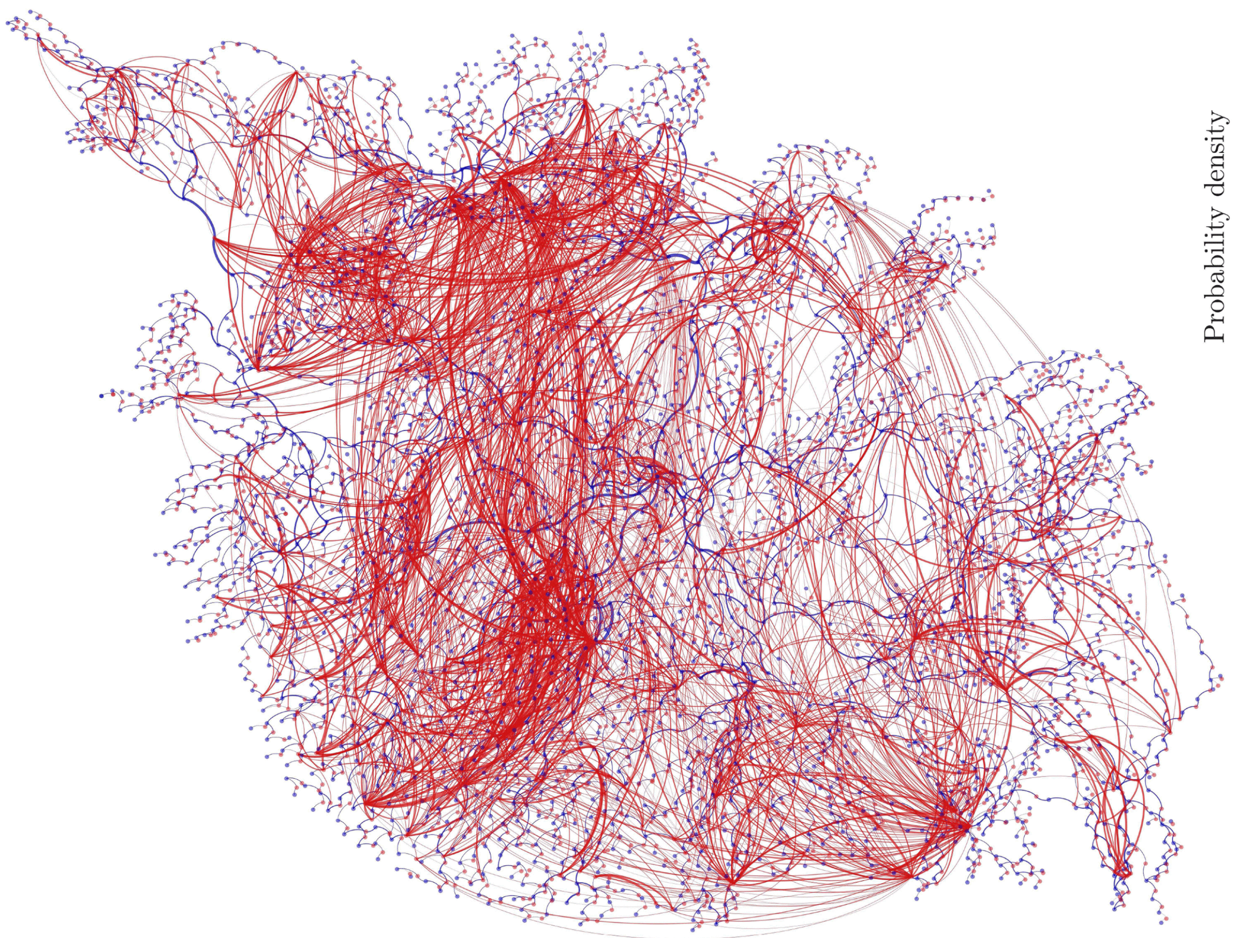
Eppstein and Hines (2012)

Challenge 1: Rethinking Propagation and Connectivity

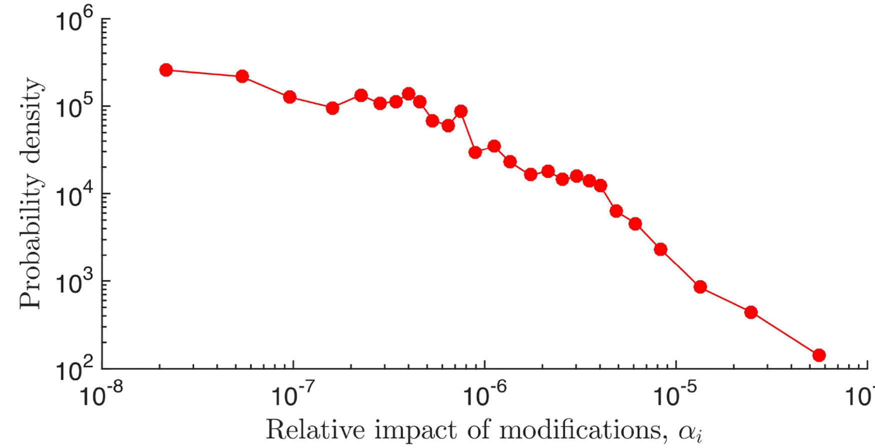


Let's forget about network structure, or even topology. Reverse the question: Suppose that there were a network structure under which disturbances would propagate in a way that we think we understand. What would such a network look like?

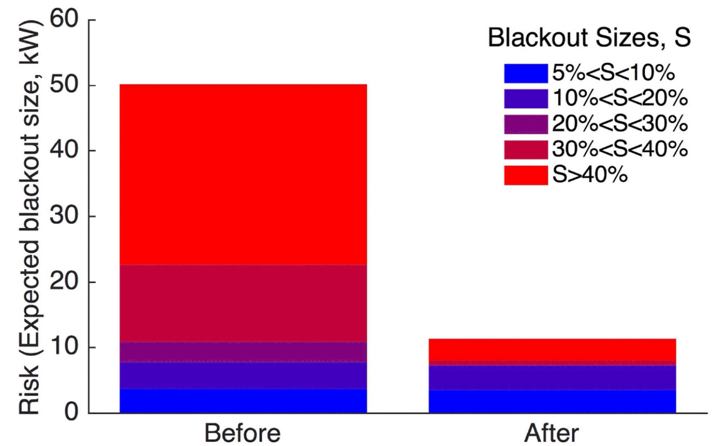
Lesson 1: Rethinking Propagation



(a)



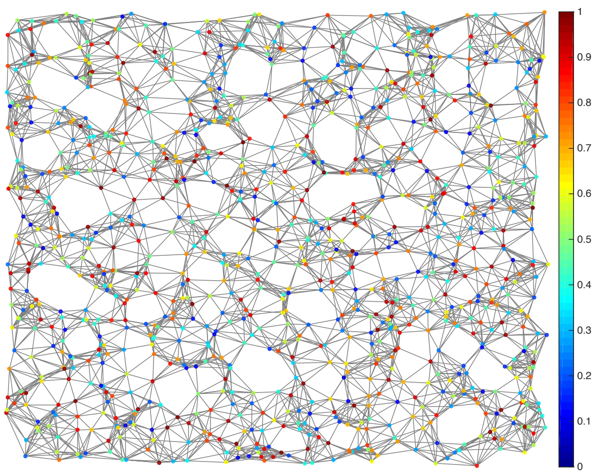
(b)

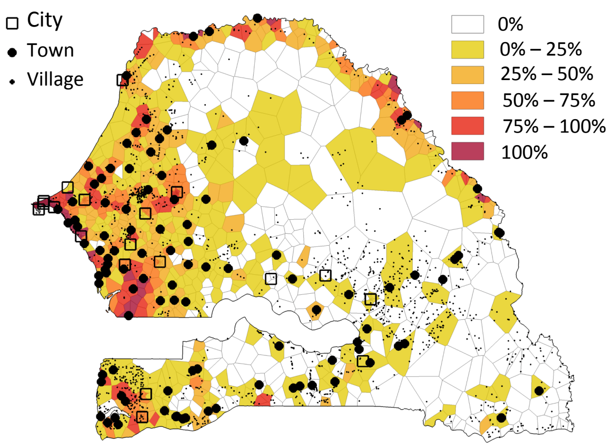


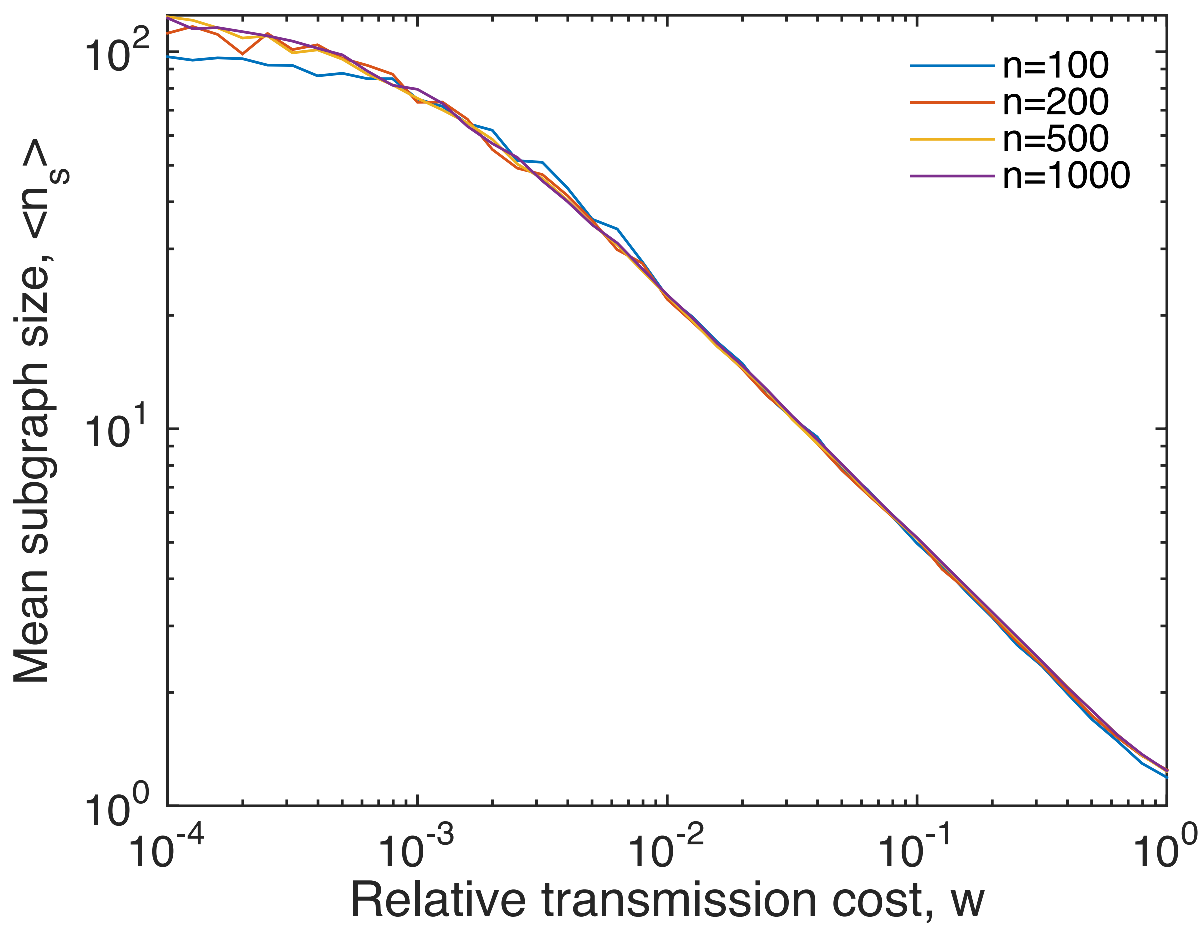
(c)

Hines, Dobson, Rezai (2017)

Lesson 2: "Centralized" vs "Decentralized" is a False Dichotomy








Questions?
Seth Blumsack: blumsack@psu.edu
NY city, Nov. 9, 1965
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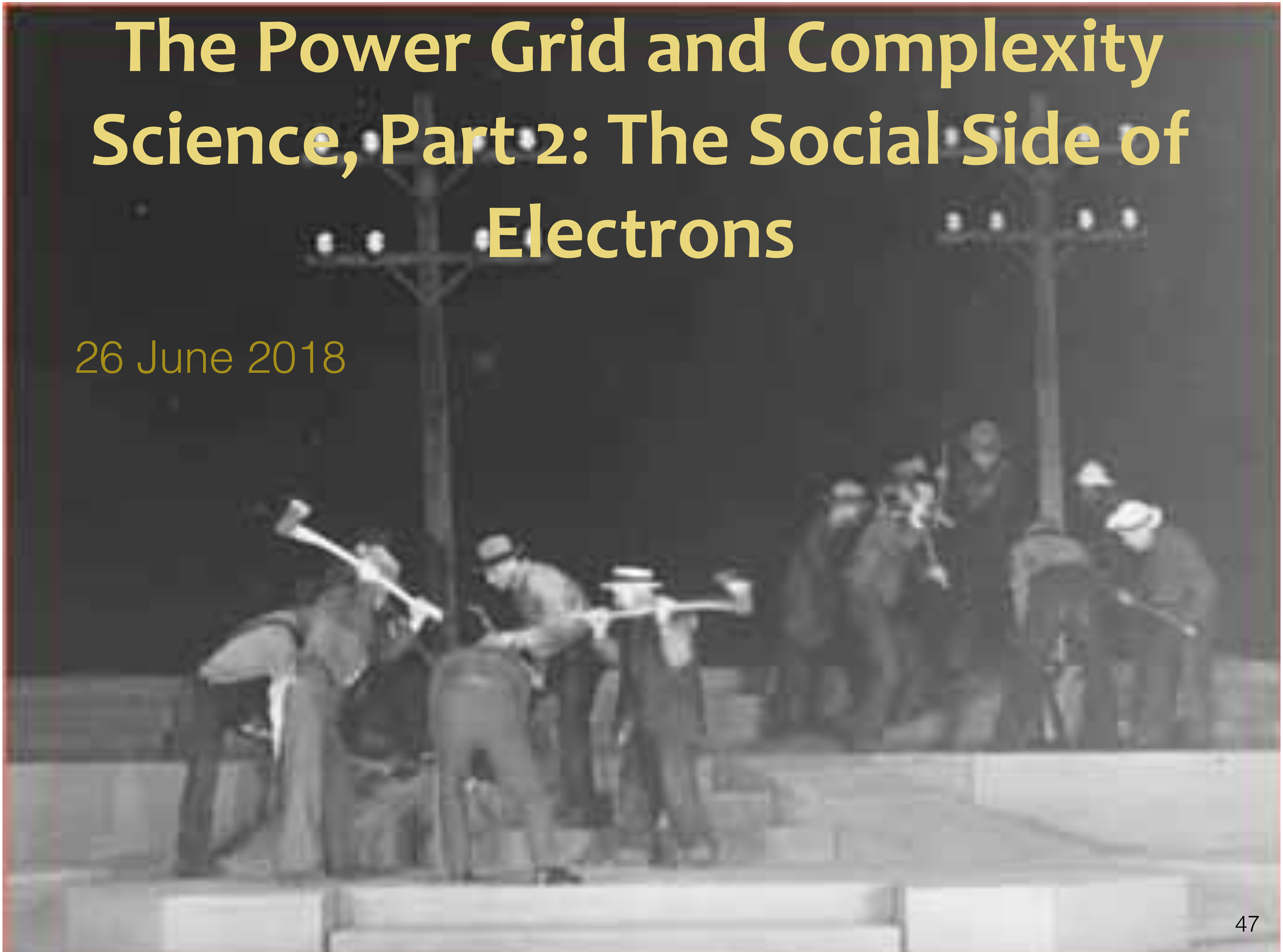
The Power Grid and Complexity Science, Part 2: The Social Side of Electrons

26 June 2018



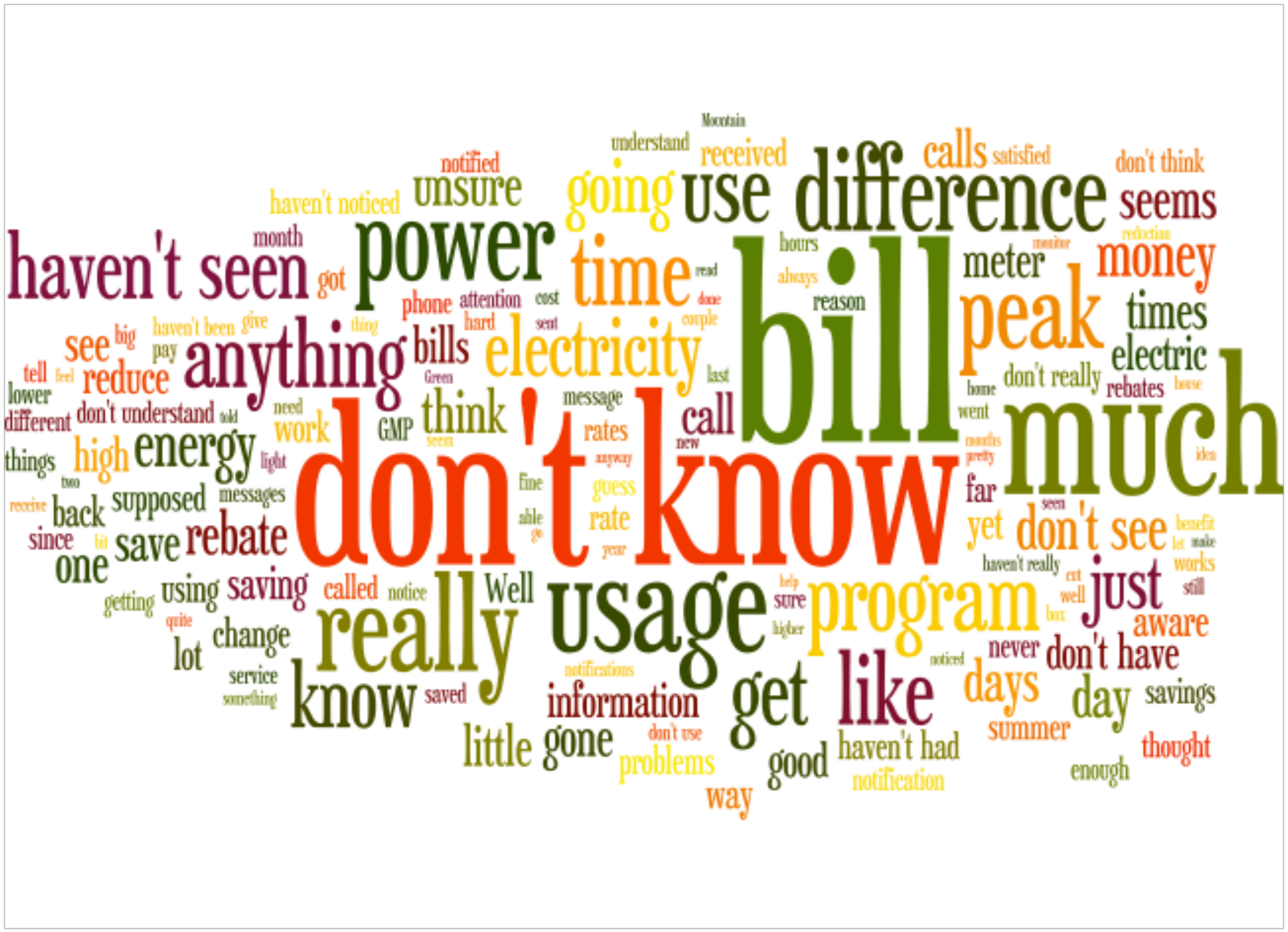
“Look, dear. I'm just one little consumer. How can I fight a utility?”

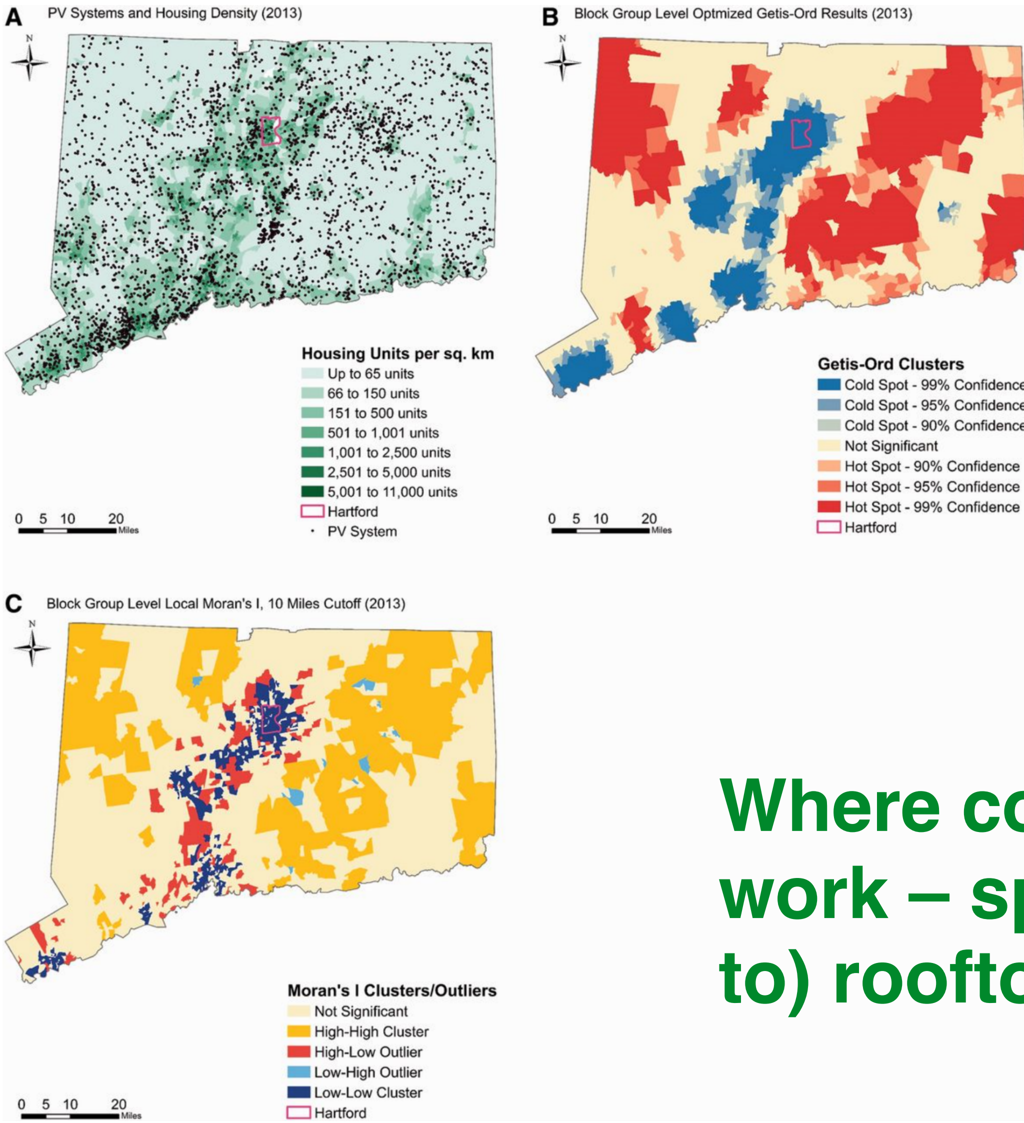
Power, 1937 http://newdeal.feri.org/power/pwr1-15.htm

Some goals for this talk

- Describe some challenges in aligning individual behavior with sustainable energy or efficiency goals
- Describe some challenges in emergent organizational behavior related to governing sustainable power grids
- Hope that you continue to stay awake.

Challenge #3: Engaging (but not confusing, exacerbating) energy users

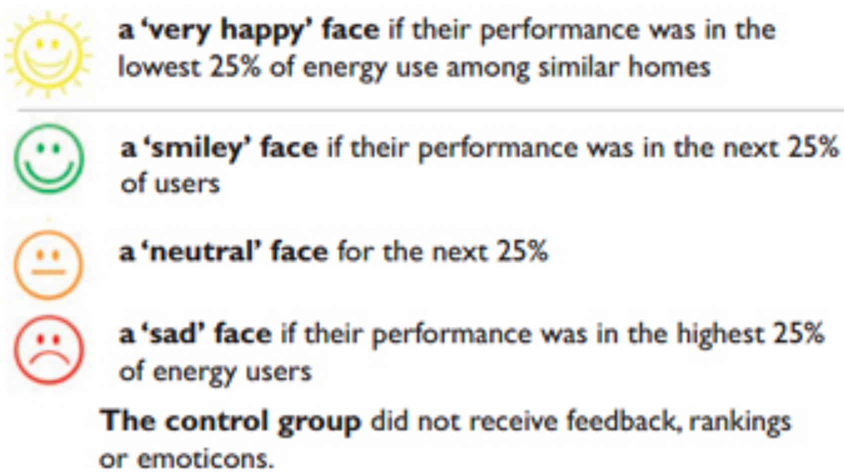




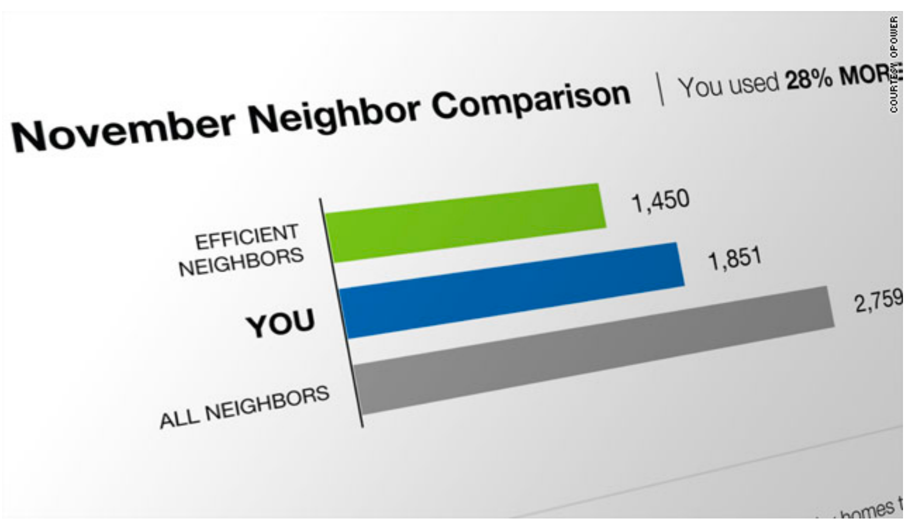
Where contagion models DO work – spread of (or resistance to) rooftop solar power.

Source: Graziano and Gillingham

Conservation Paradox: Reinforcement vs Reversion



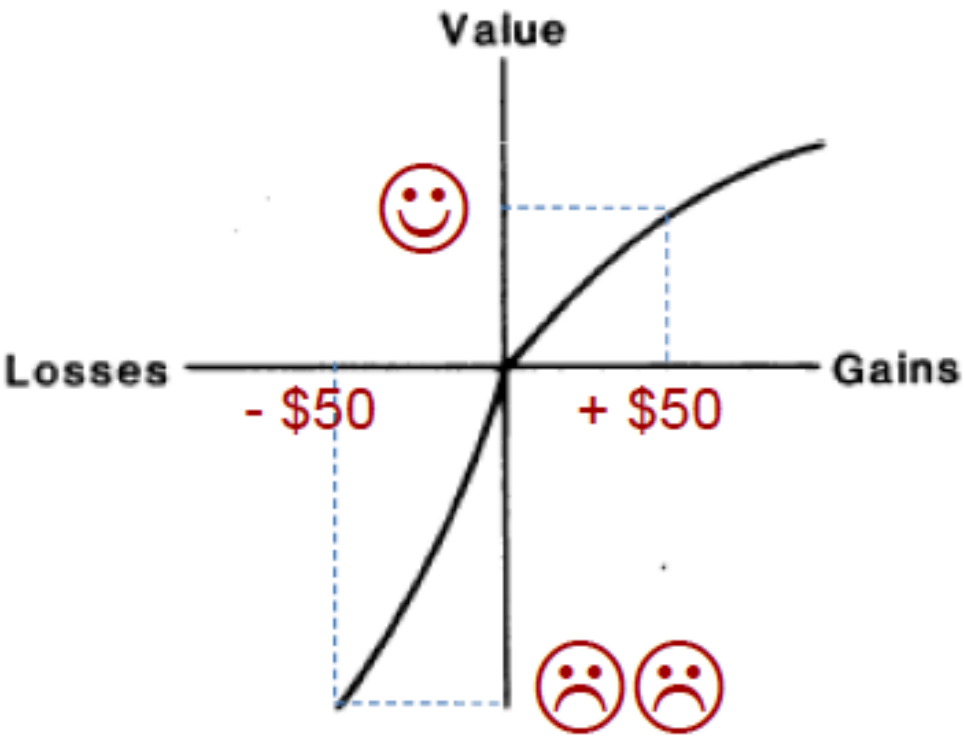
One of the perplexing mysteries of energy economics is the irrationality of efficiency behaviors – people systematically leave money on the table by failing to take actions for which benefits >> costs



Question: Would it be effective to give everyone frowny faces every month? Would it be ethical?

Framing Gains and Losses

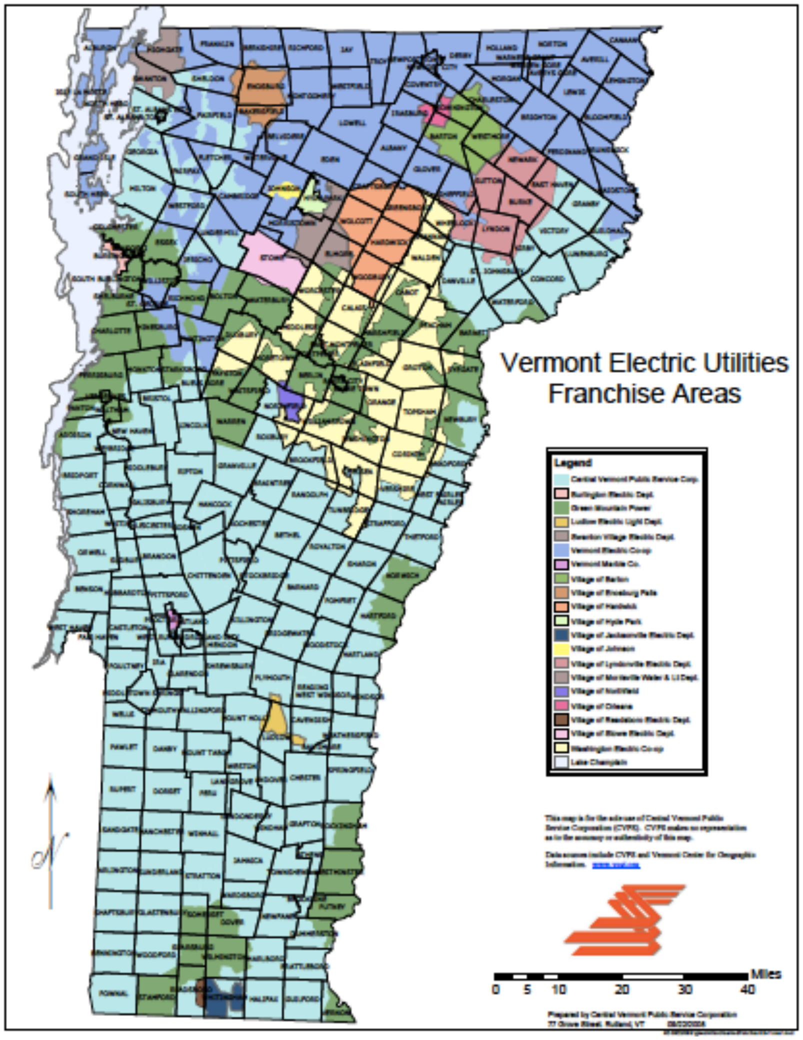
"The aggravation that one experiences in losing a sum of money appears to be greater than the pleasure associated with gaining the same amount." - Kahneman and Tversky, 1979



Graphic: Annika Todd, LBNL

- Avoiding a loss is somehow preferred to achieving a gain that is identical in magnitude.
- Suggests that we should expect greater conservation behaviors from "sticks" than "carrots"

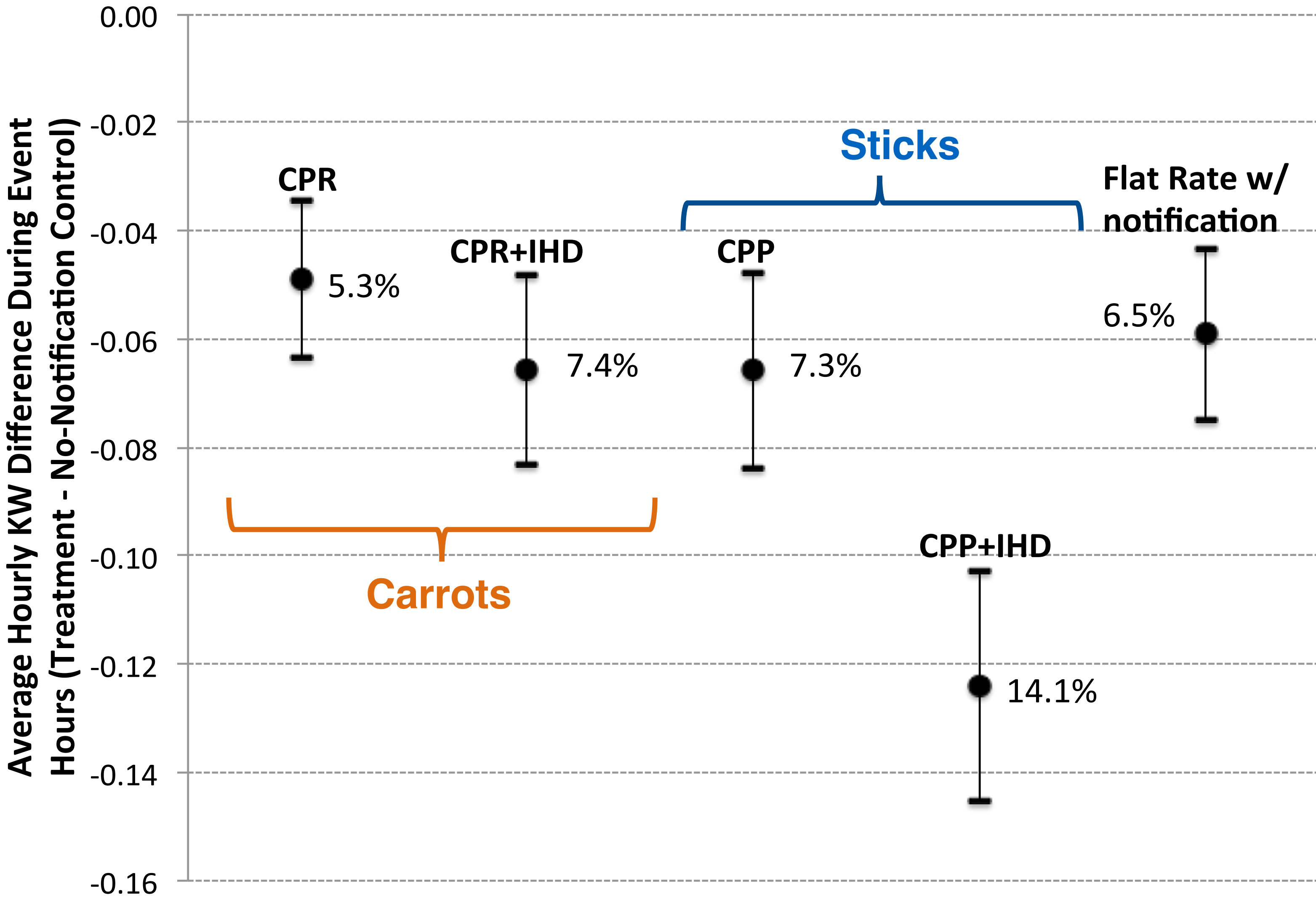
A Framing Experiment



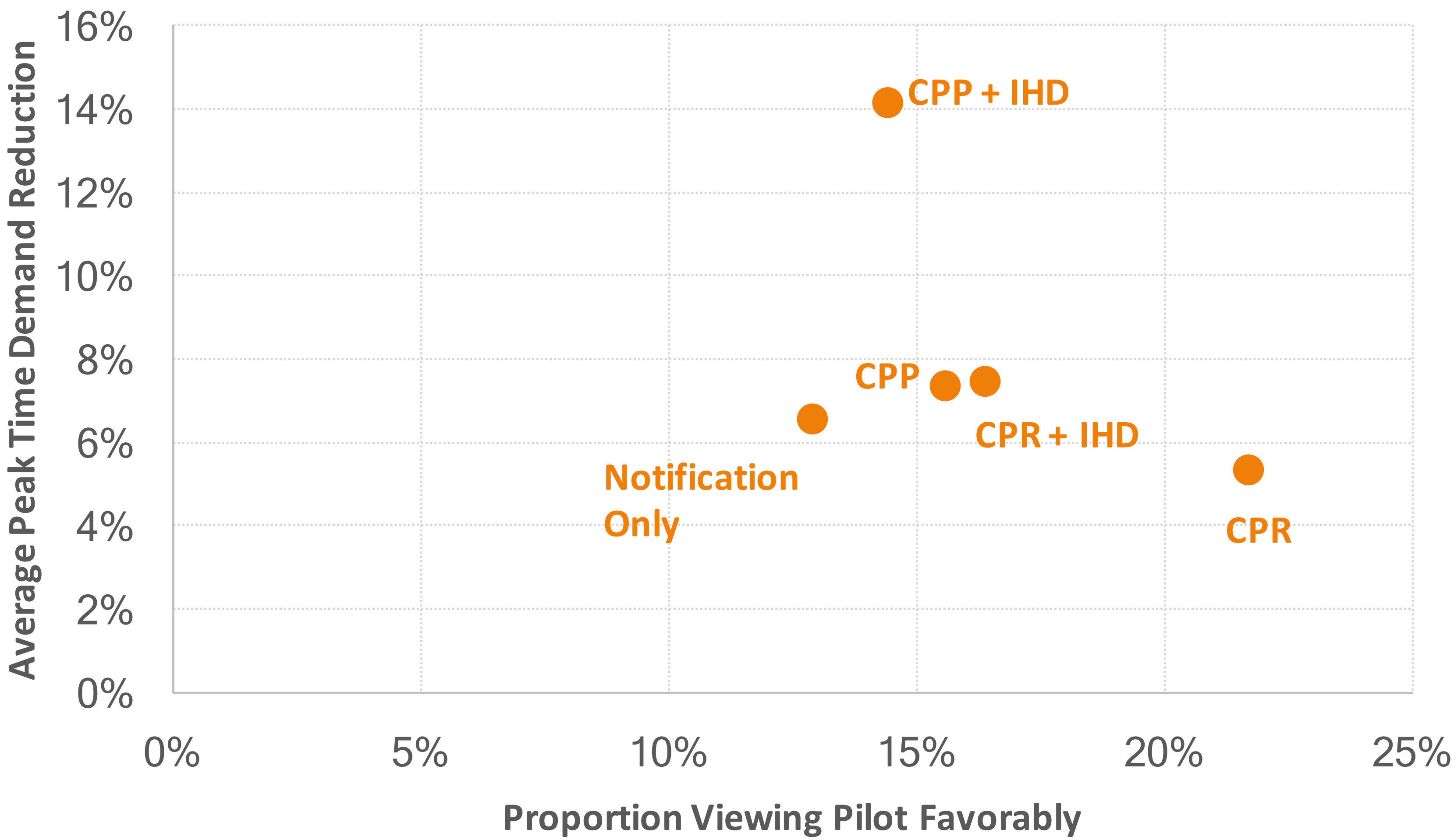
- Several thousand utility customers in Vermont were randomly assigned to “carrot” (rebate) or “stick” (high price) treatments to encourage energy conservation during summertimes.

- The carrot and stick were basically of the same magnitude (but different sign).

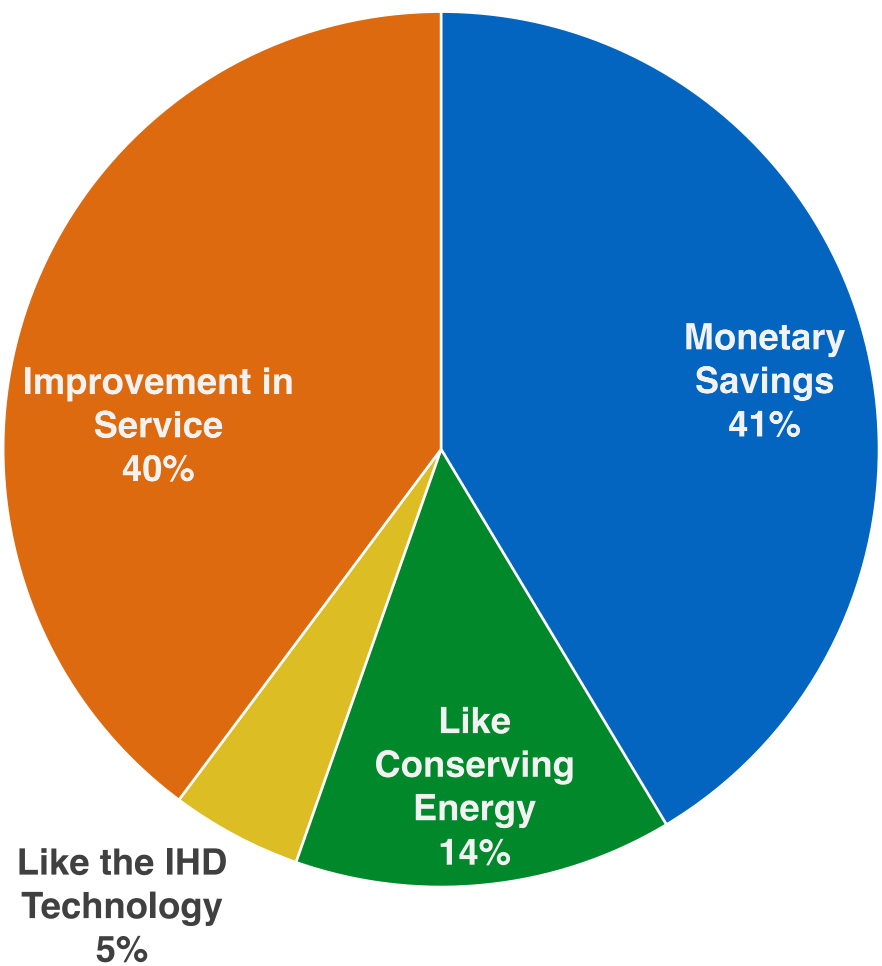
The Boring Result



Do People Know What is Good for Them?



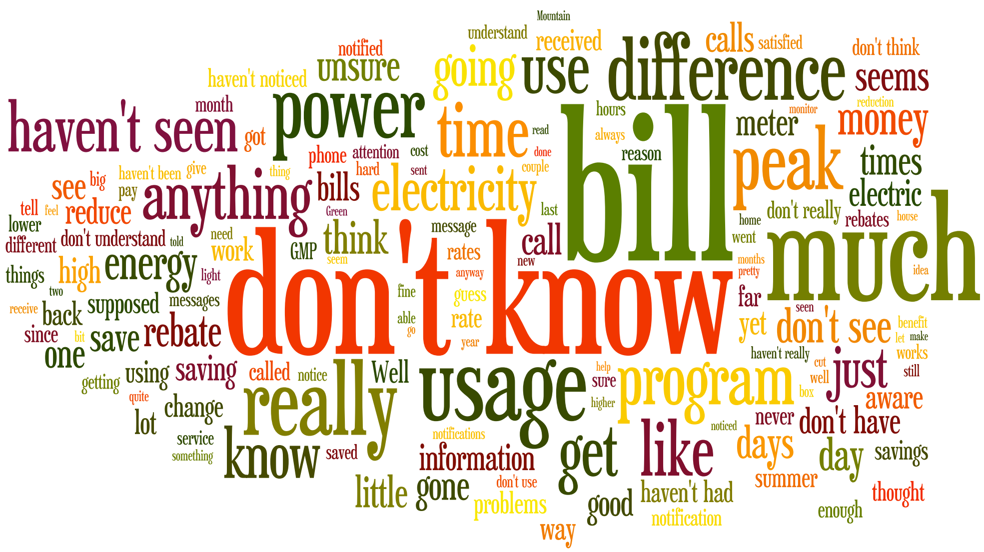
What do People Value?



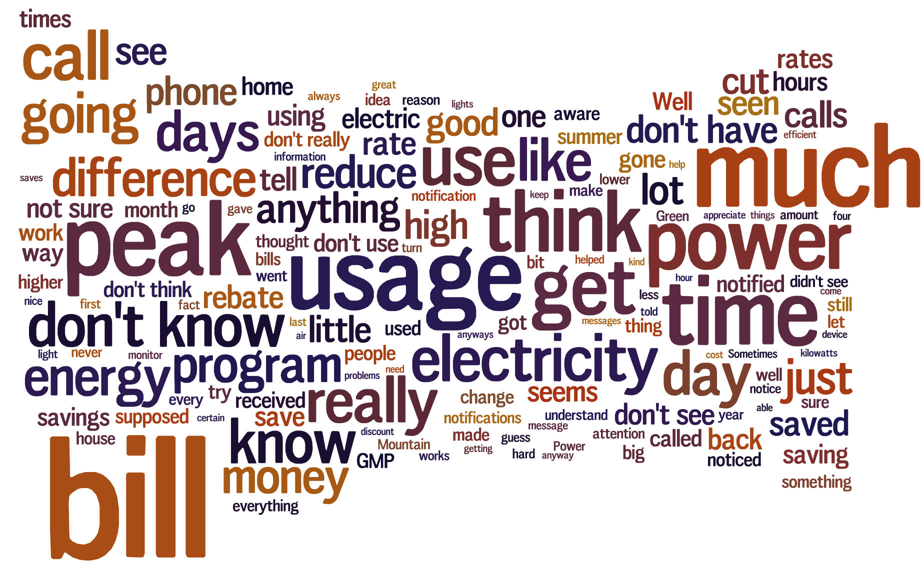
"They knew where we were when we had power outages"

--GMP customer (without IHD)

Words Are Worth A Thousand Pictures



"Carrot" Customers

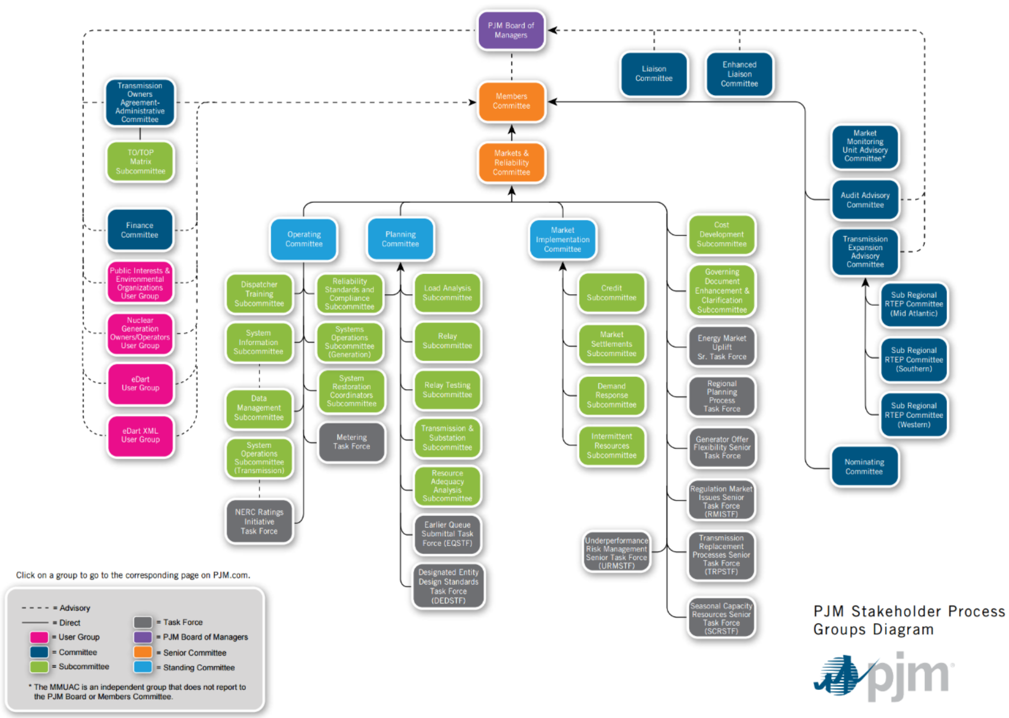


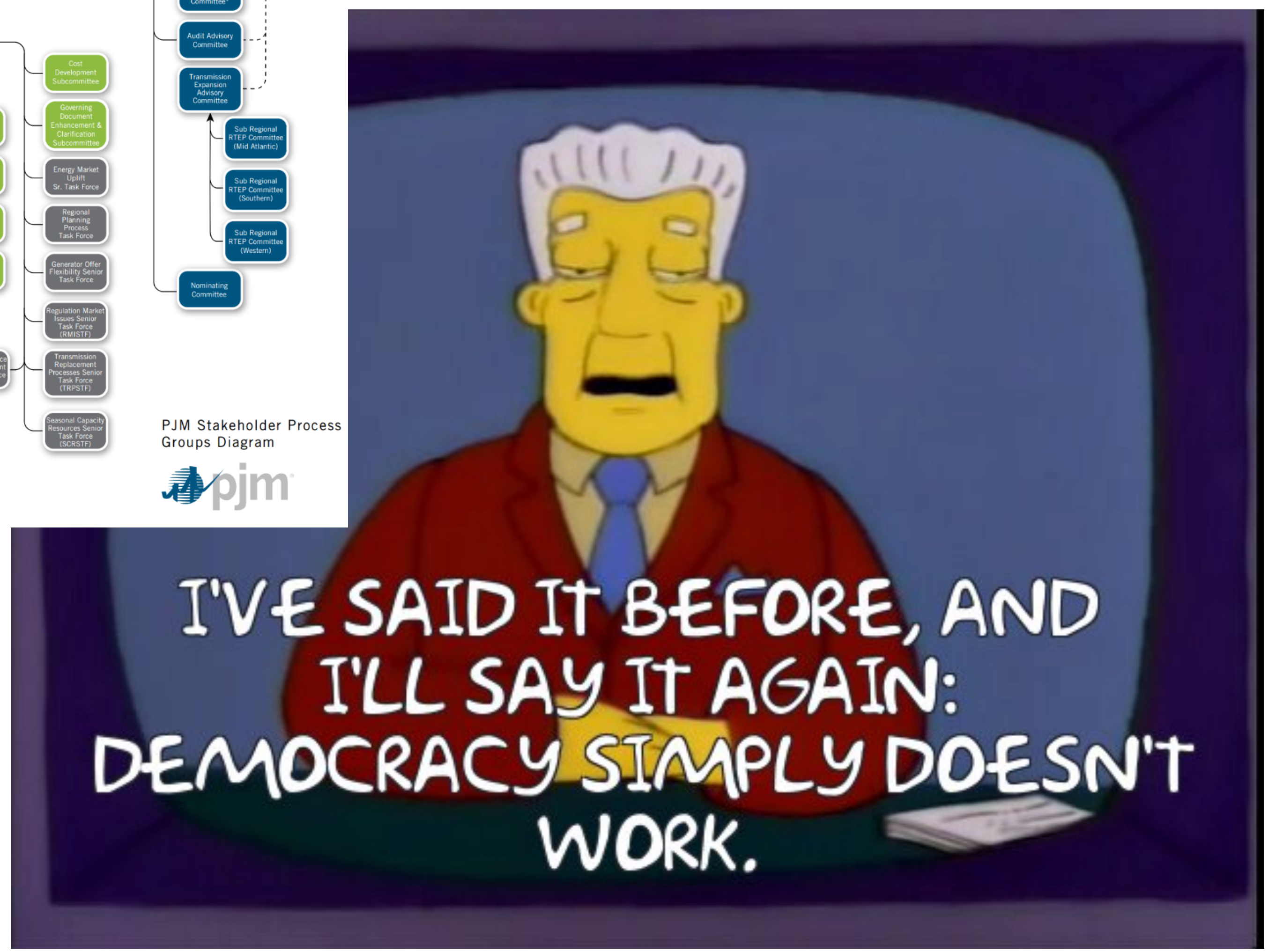
"Stick" Customers

What Motivates Conservation?

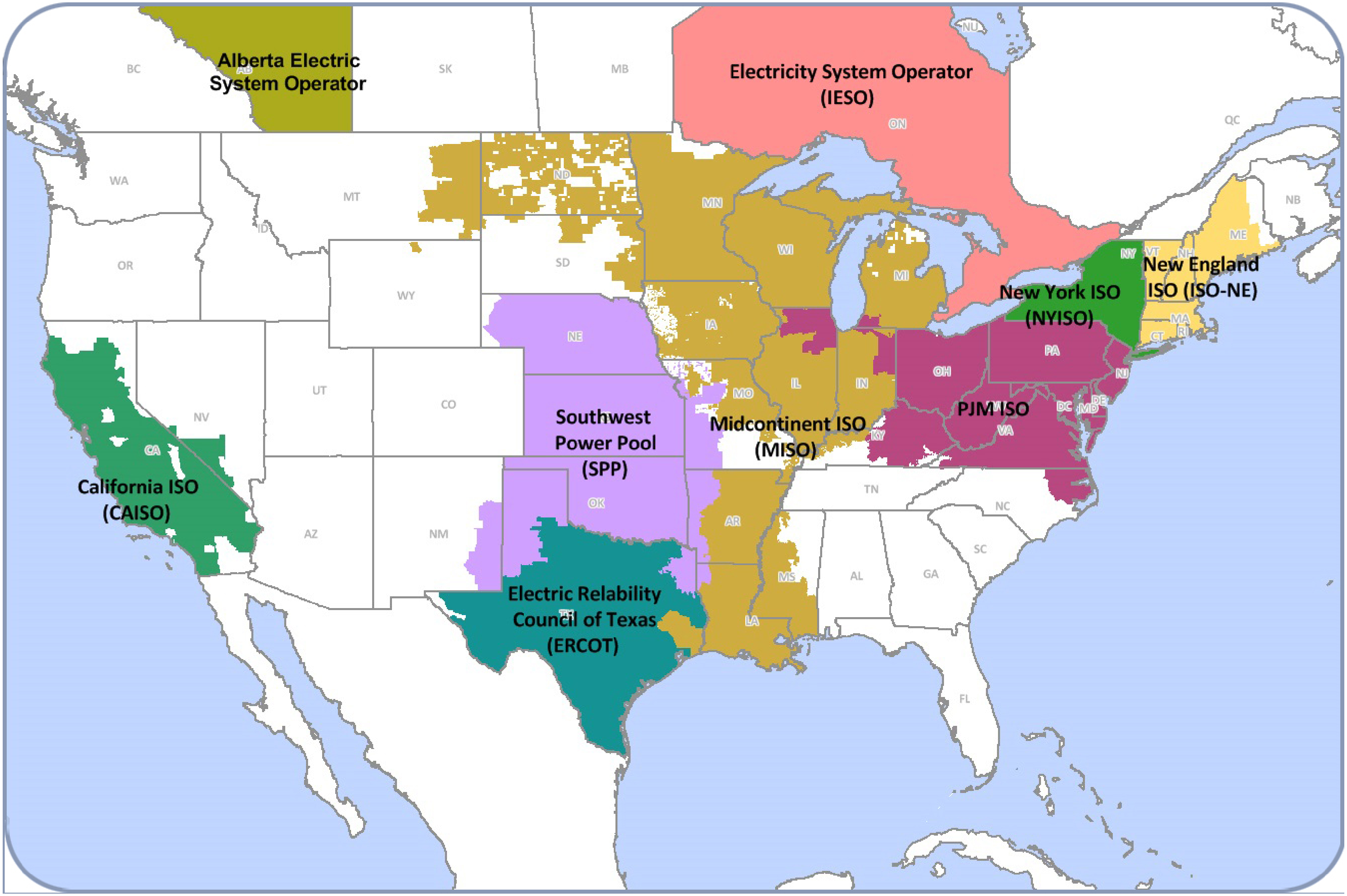
- Why do *households* care about the carrot or the stick?
- GMP customers each saved *tens of cents* during every peak event!
- What motivates customers? Does the penny make the conservation choice more or less complicated?

Challenge #4: Organizational Behavior and Governance



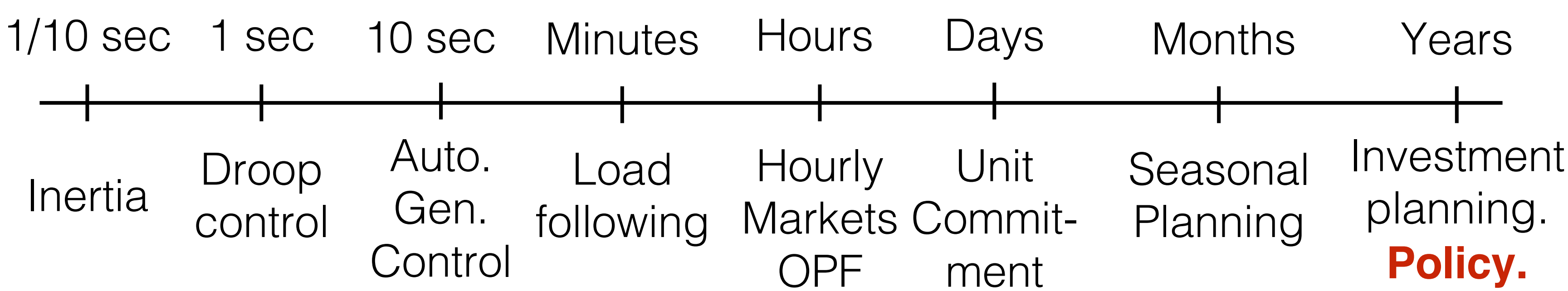


North American Regional Transmission Organizations

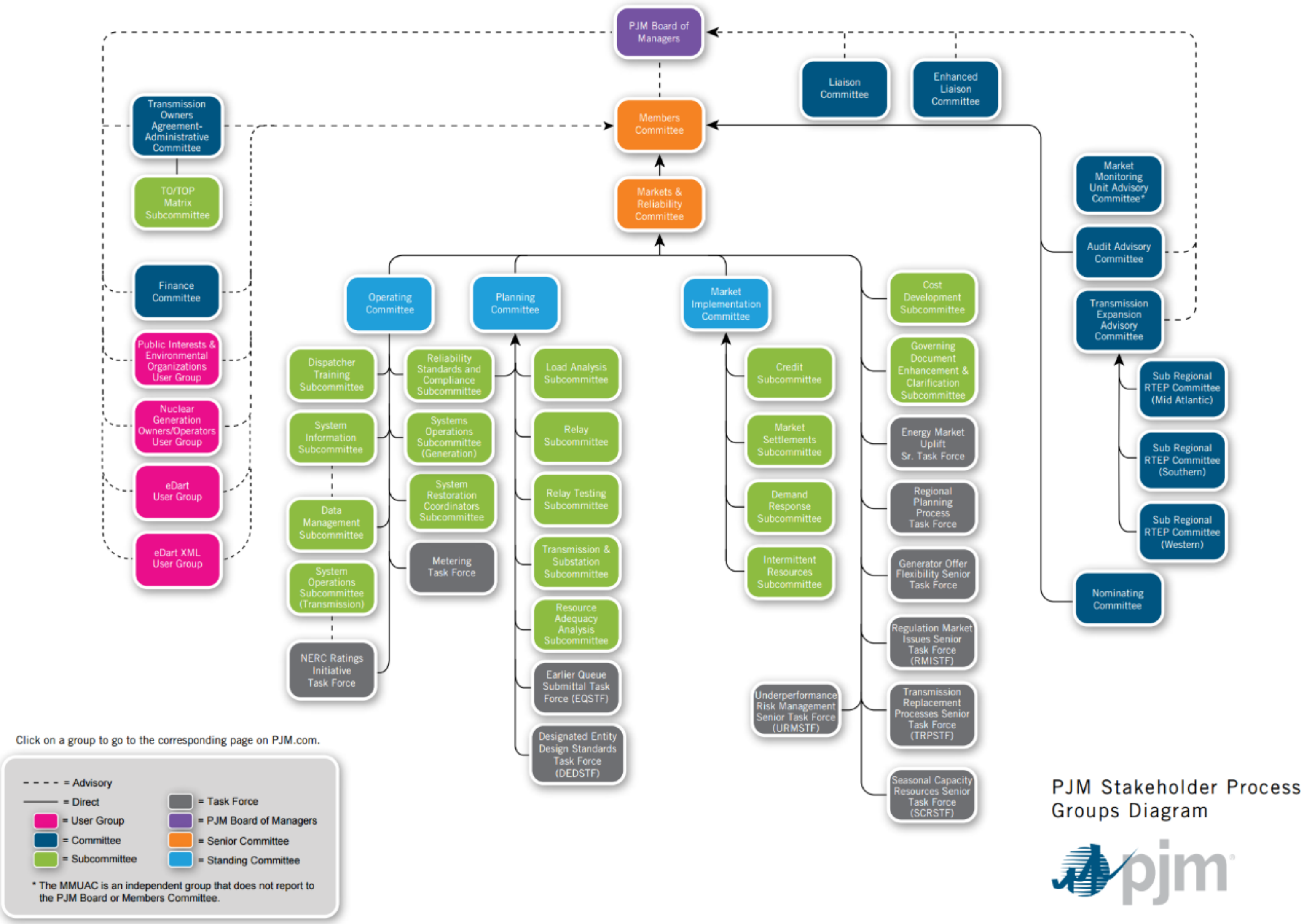


What Kind of Organizations are RTOs?

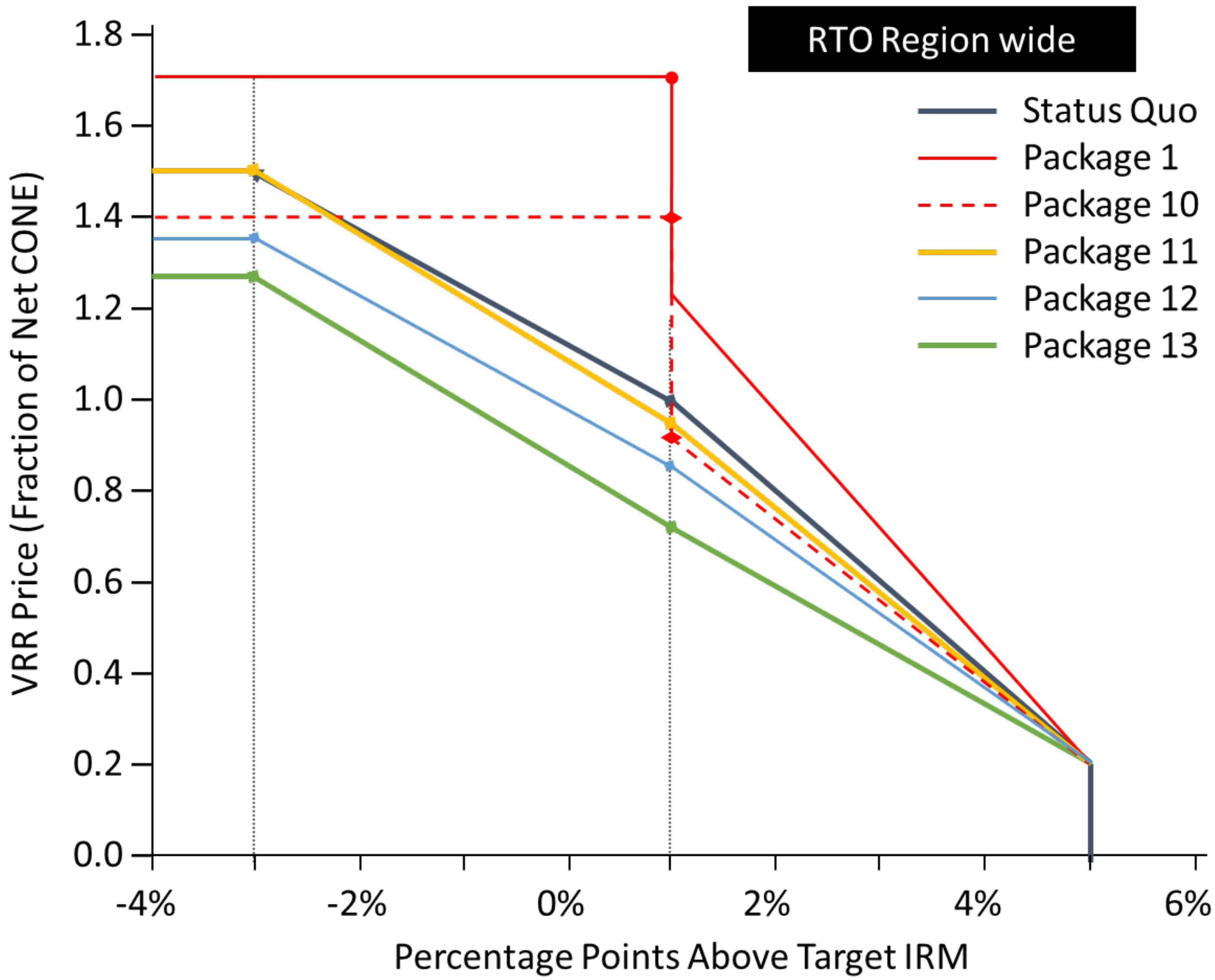
- RTOs are responsible for grid reliability (no blackouts) but they own no physical assets.
- They generally rely on market mechanisms.
- The rules for markets and planning are devised via a highly stakeholder-driven process.



Stakeholder Processes



A “Demand Curve” for Power Plants



Making the Rules = Blood Sport

"We could sit down with crayons and write on a map a few lines that would make all kinds of sense to make stuff move around. Then we would take 20 years to figure out who pays for it."

--CAISO Stakeholder

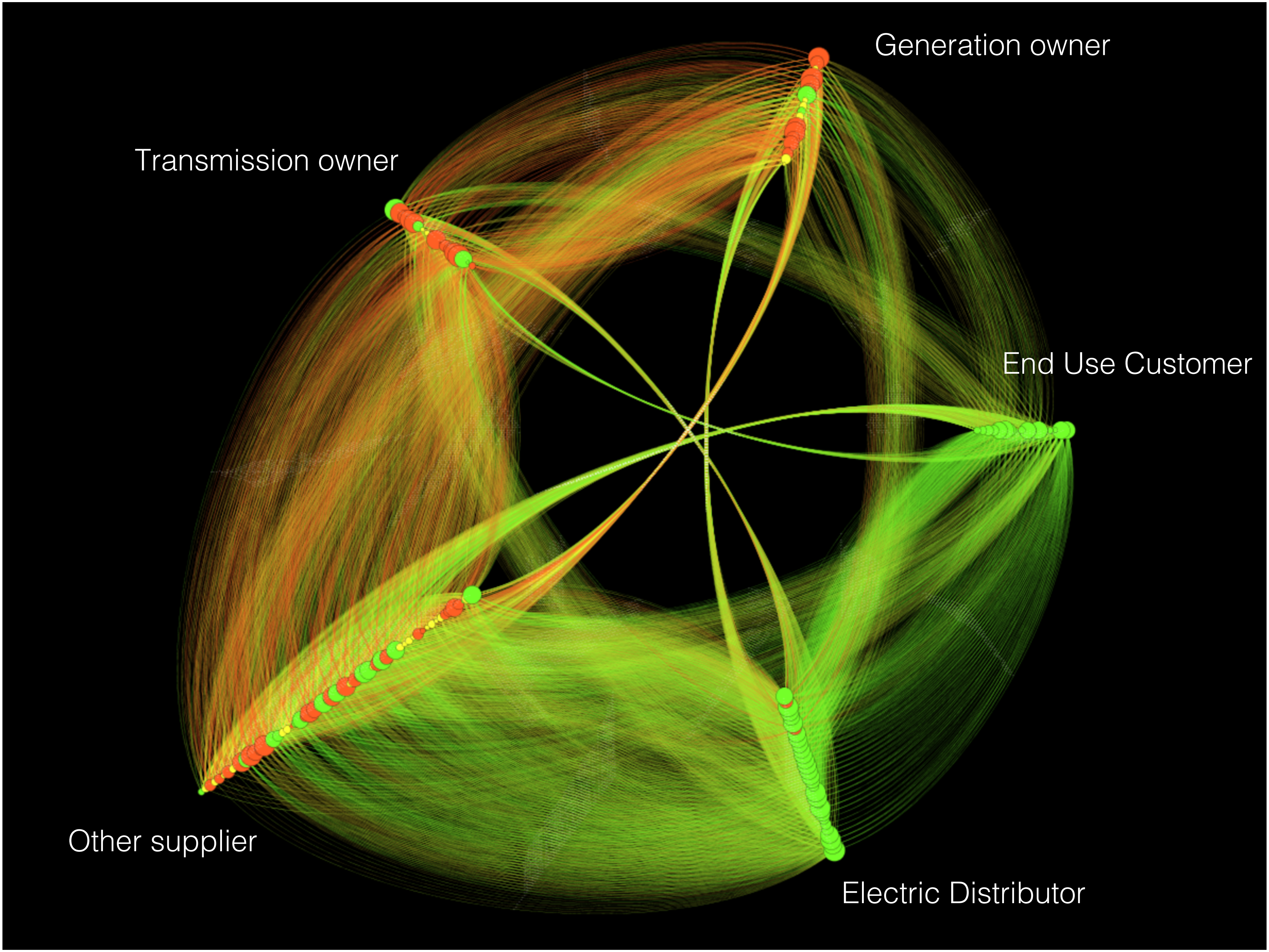
But the rules (and the psychology of who makes them) matters a lot!

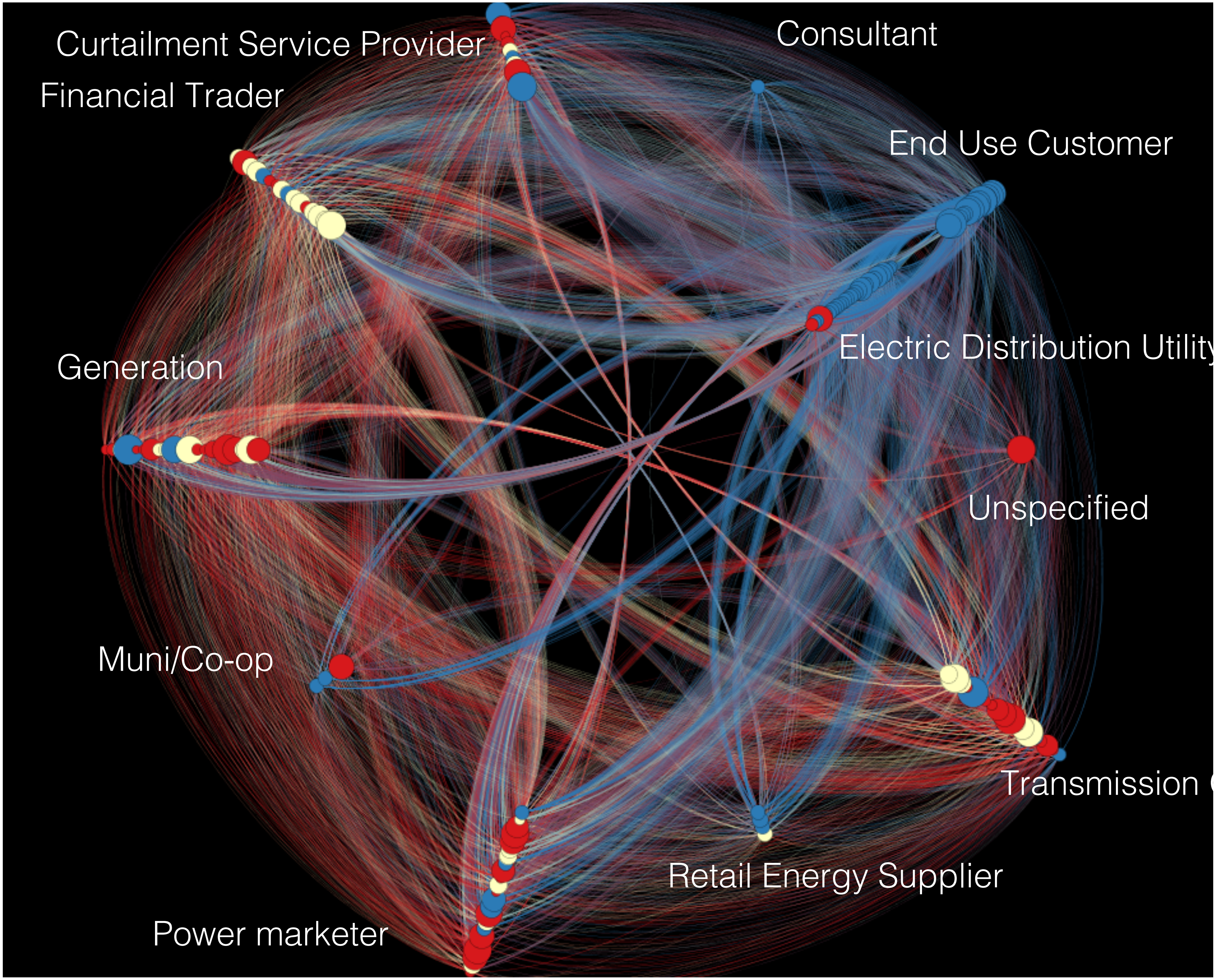
Who Has Power to Make the Rules?

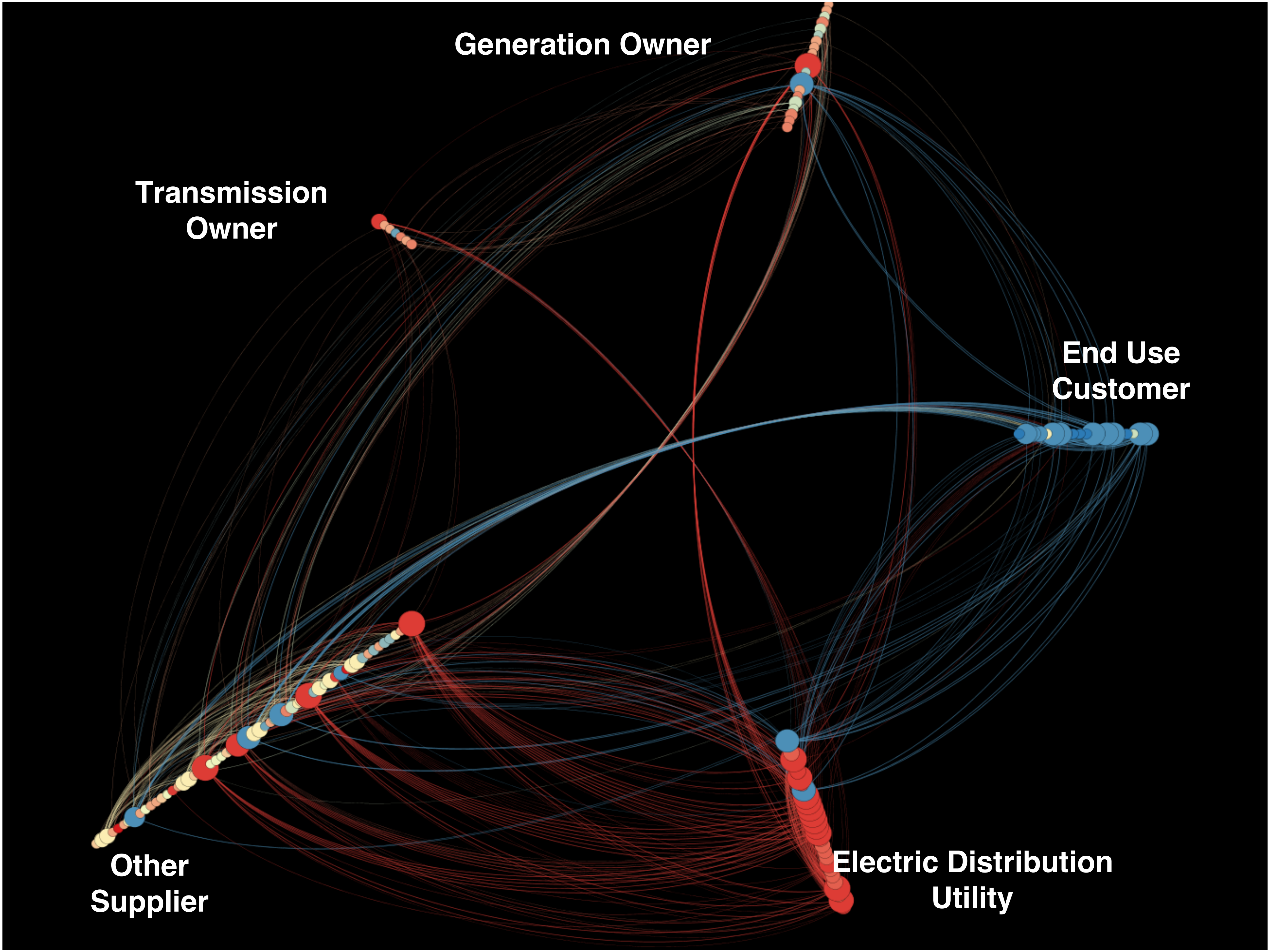
"The problem that some people find is that one side can stymy the other. You have generation, transmission, load, and so on. Generation's always worried that load can stop them from doing things. Load is worried about generation."
-- PJM Employee

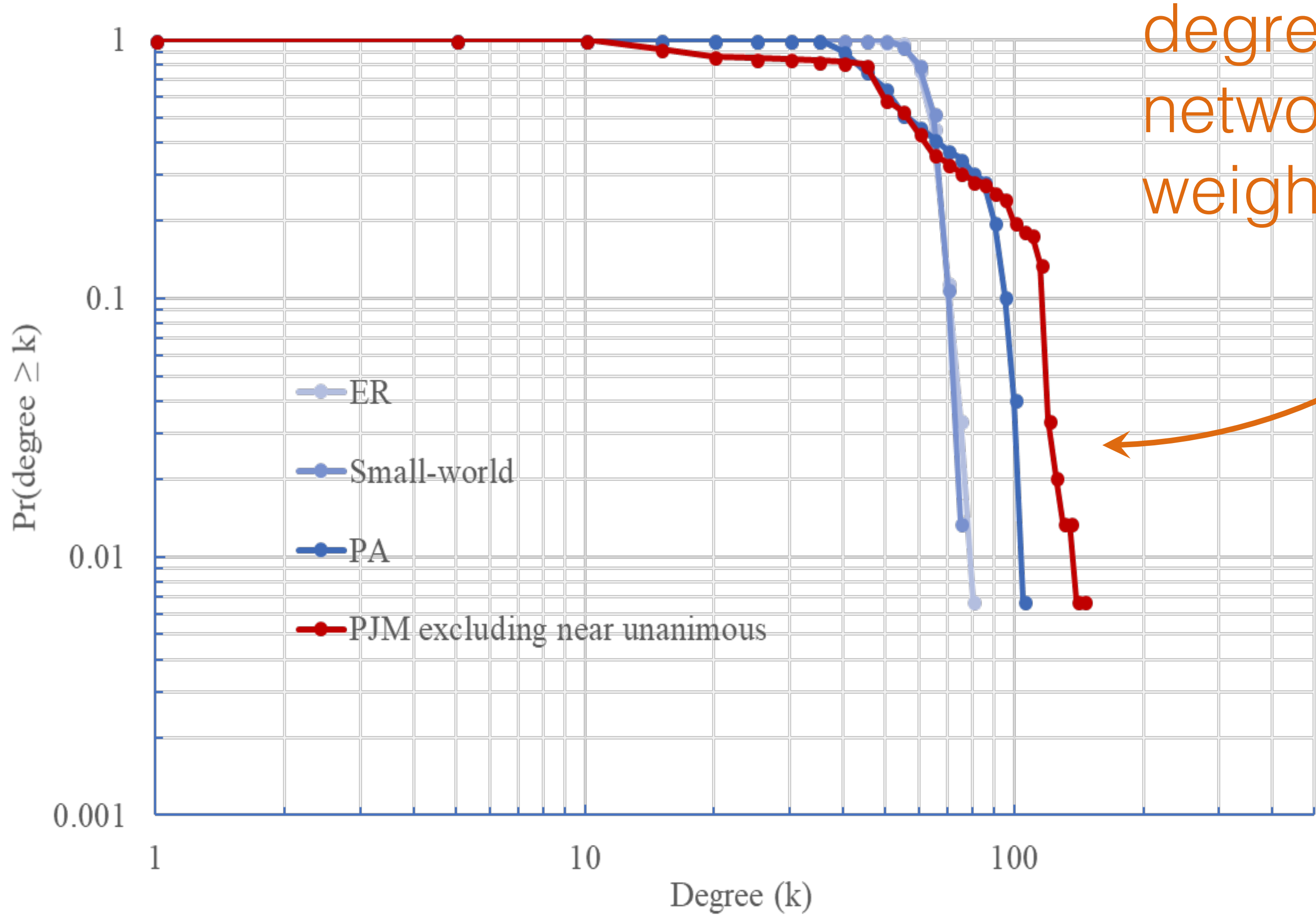
"What you actually find now is the load interest, where it used to be they had about 50 percent of the vote, they now have 65 percent of the vote."
-- Power Plant Owner

"The process is tilted towards the supplier side"
-- Consumer advocate


Generation owner
Transmission owner
End Use Customer
Other supplier
Electric Distributor

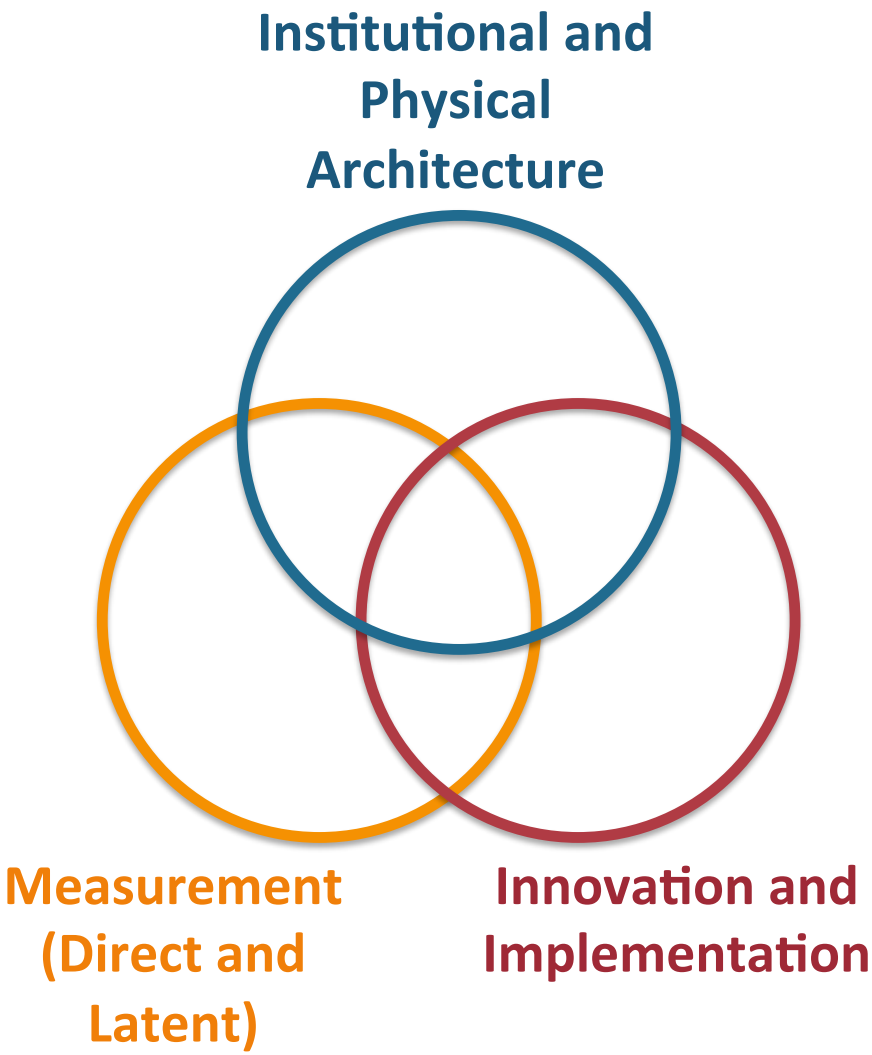

Curtailment Service Provider
Consultant
Financial Trader
End Use Customer
Electric Distribution Utility
Generation
Unspecified
Muni/Co-op
Transmission
Retail Energy Supplier
Power marketer


Generation Owner
Transmission Owner
End Use Customer
Other Supplier
Electric Distribution Utility



The stakeholders in the tail have atypically large degree in the voting network but very low weighted degree

The Science of Complex Power Grids



Transdisciplinary Needs
Not just an engineering problem

Creative Thinking
Bring the spirit of complexity science…but many of the models can stay at home

Not Just the Grid
Couplings with other physical, natural and social infrastructure


Questions?
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NY city, Nov. 9, 1965
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