The Power Grid and Complexity Science

Santa Fe Institute
Complex Systems
Summer School

Seth Blumsack,
Penn State

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26 June 2017

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 this Hour
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 (currently at Minnesota but moving to Dartmouth any day now)

Some goals for this talk

- Outline some reasons that we like to think about the power grid as a complex engineered system
- Describe what we do and do not know about engineered complexity in the grid
- Describe some research challenges, especially related to network resilience and sustainability
- Not put you to sleep (especially right before lunch, and after three weeks of CSSS)

Three Challenges for Power Grids and Complexity

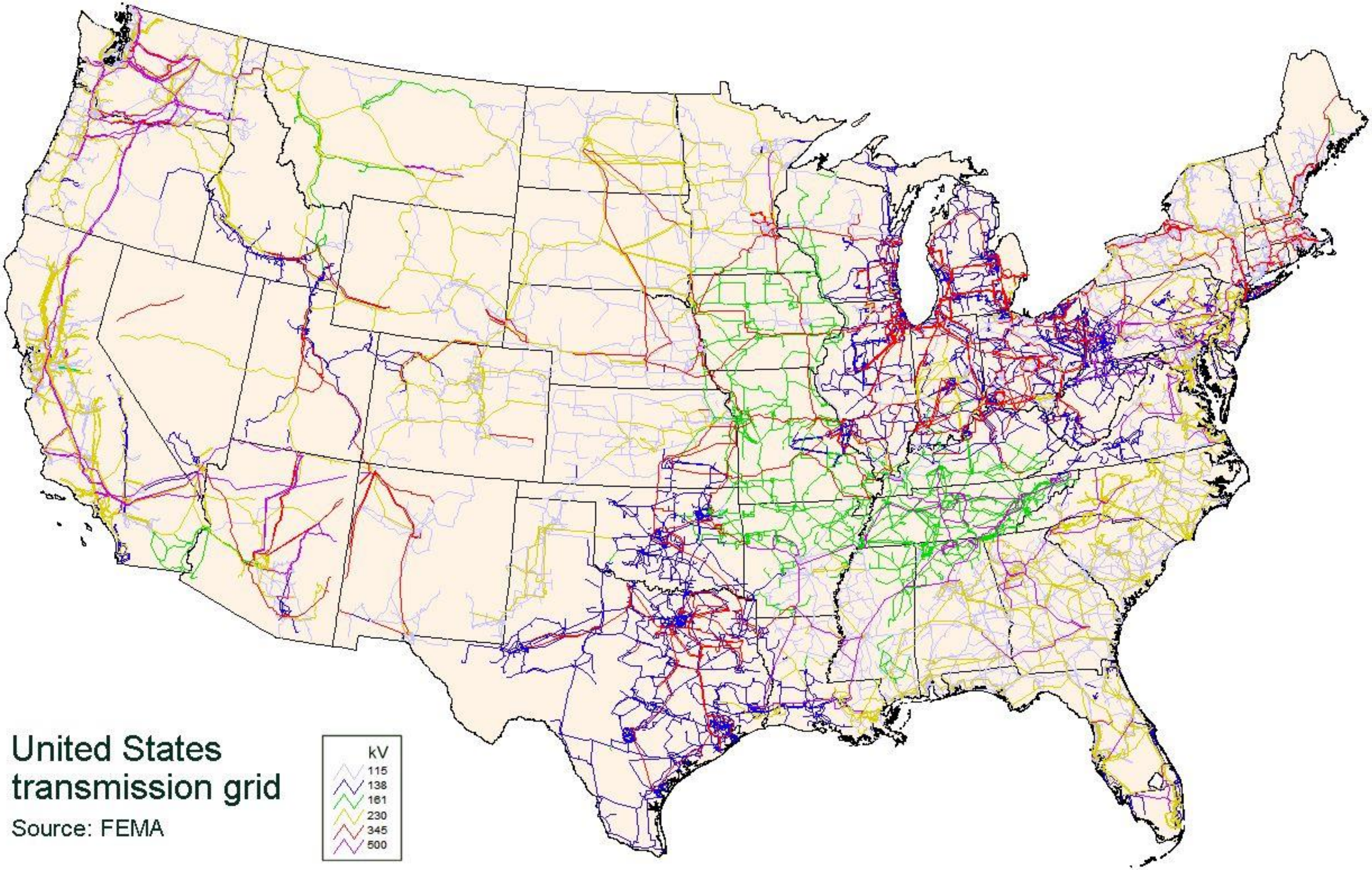
1. We can’t agree on what the “structure” of the power grid looks like.

1a. This probably doesn’t matter.

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

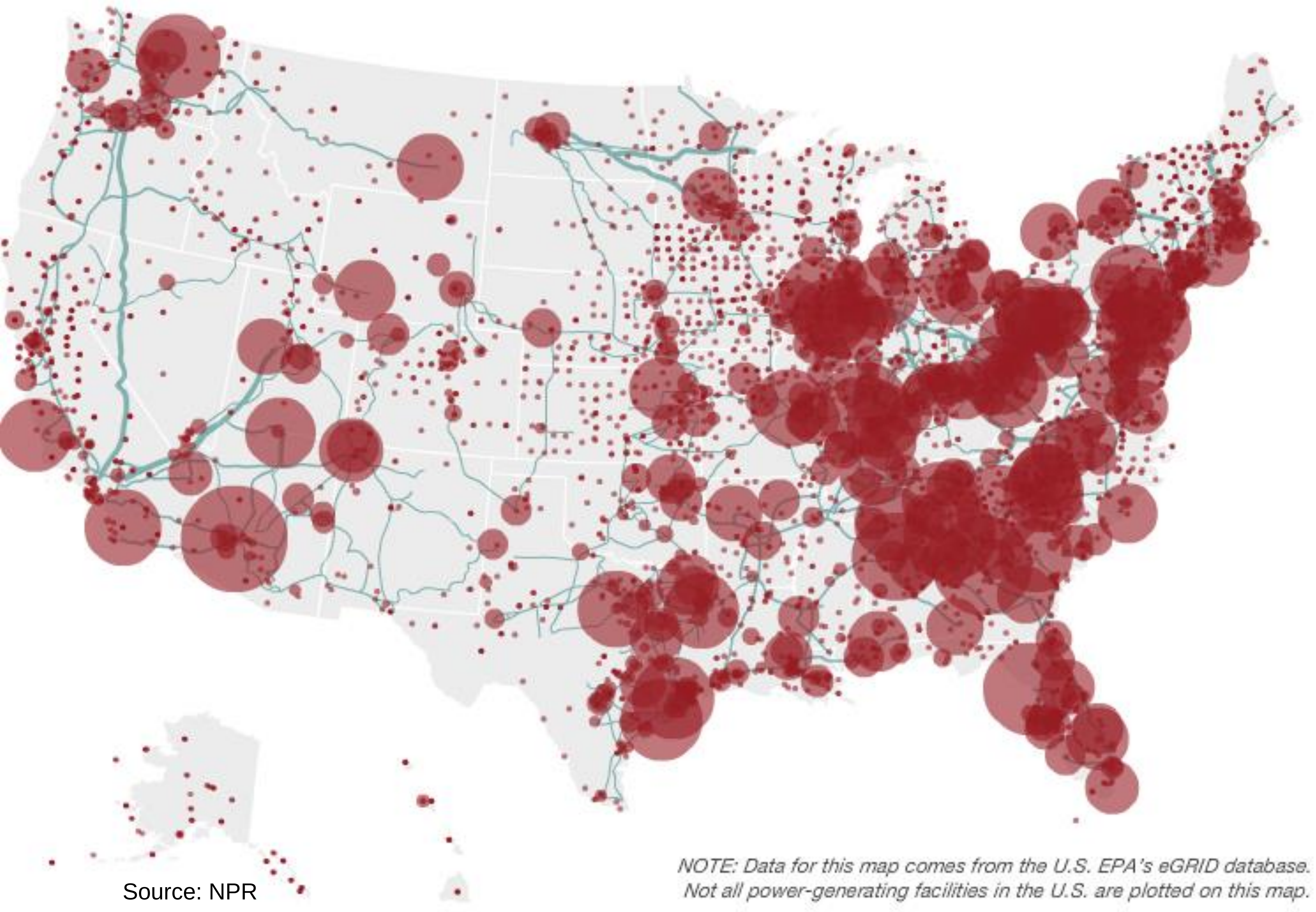
3. Electrons are highly social creatures.


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



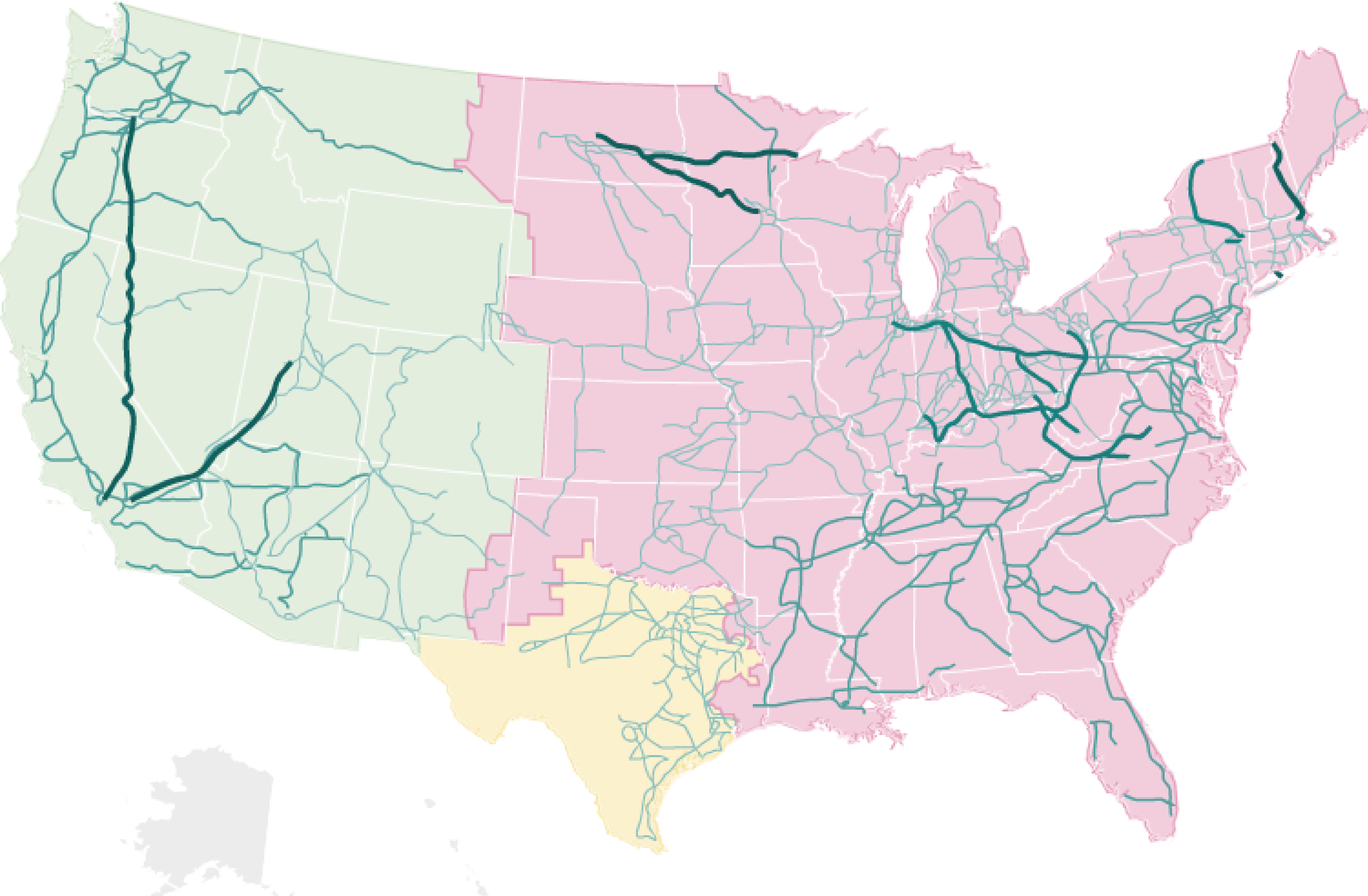
United States transmission grid

Source: FEMA

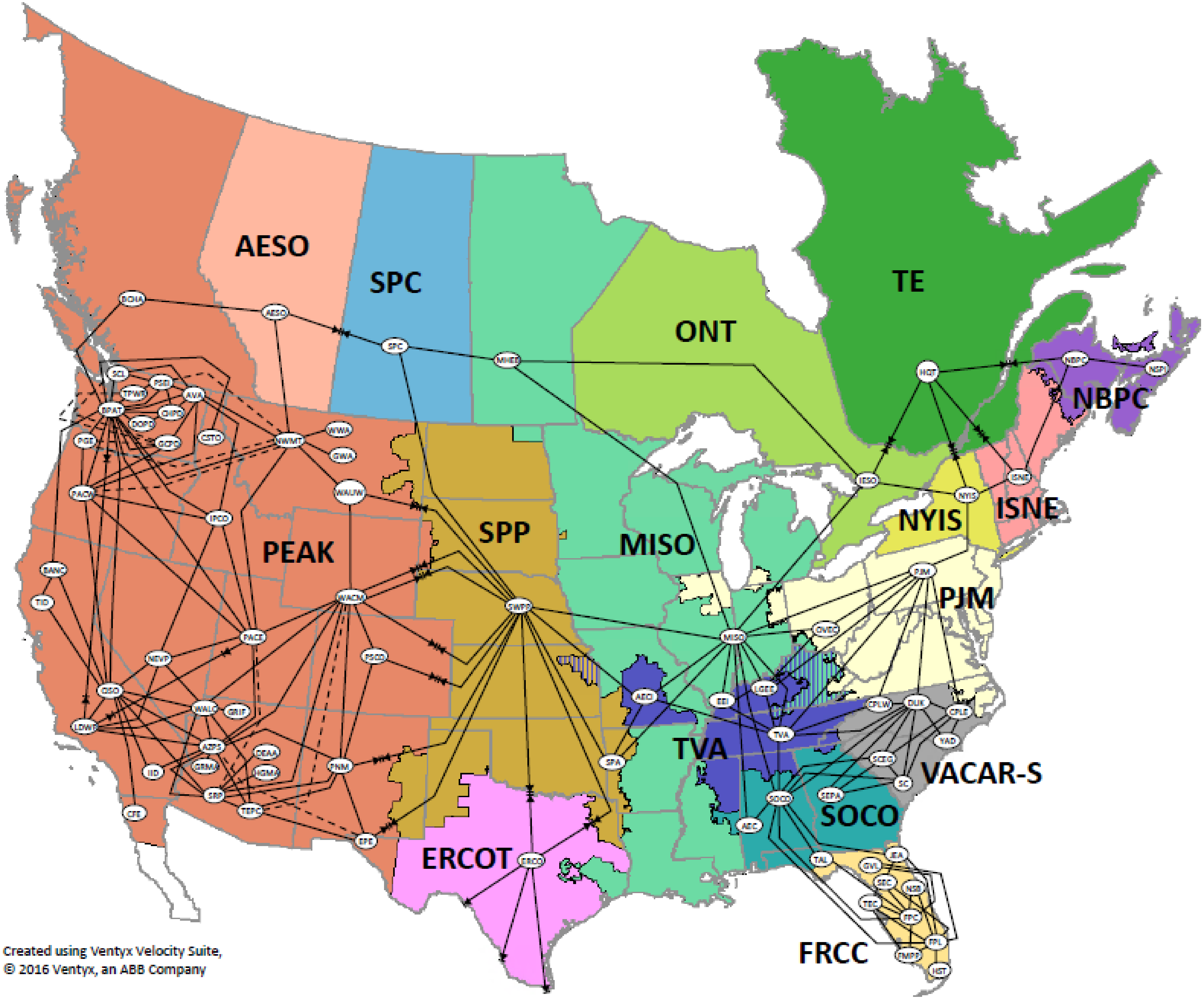


Source: NPR

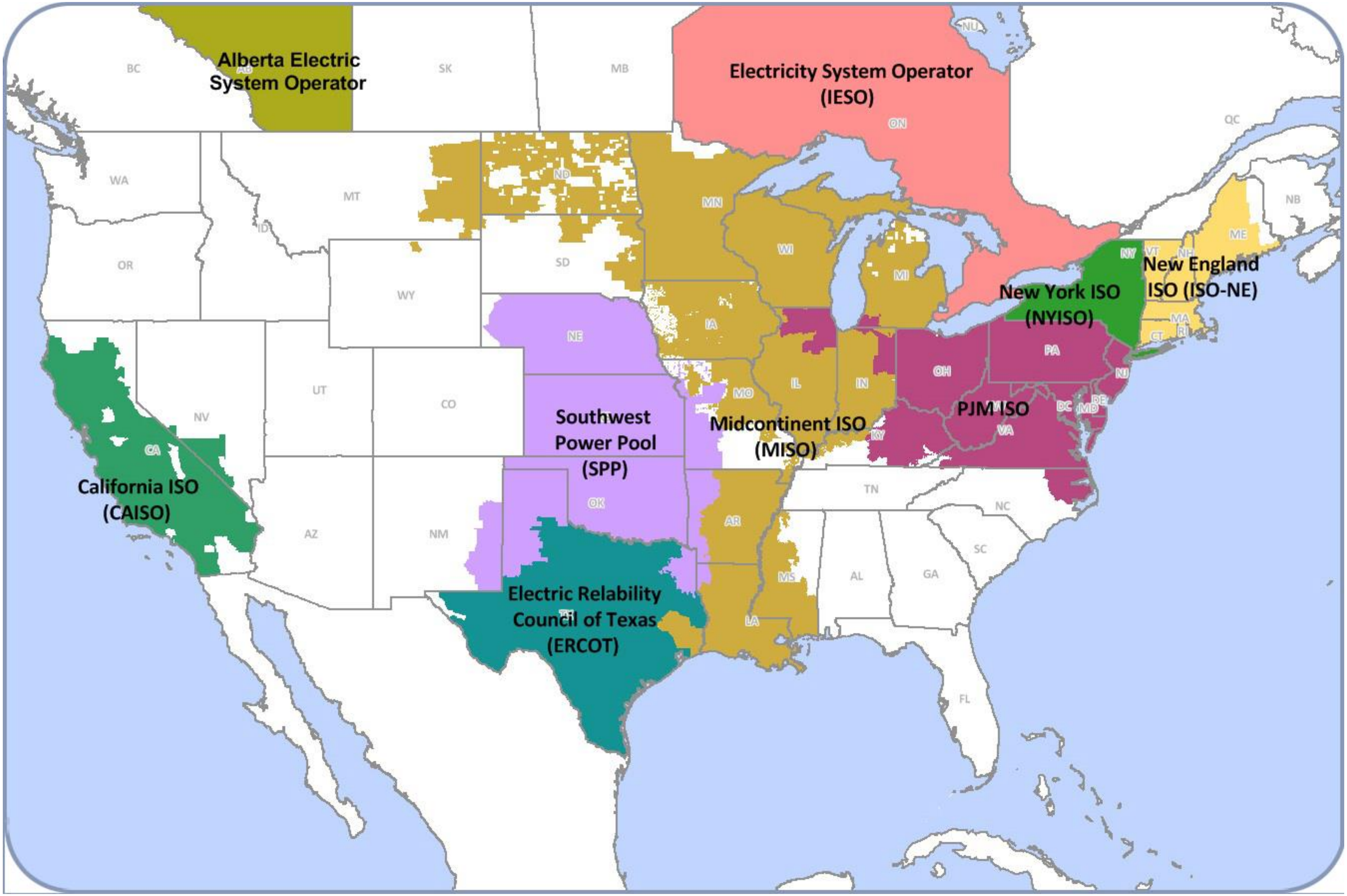
NOTE: Data for this map comes from the U.S. EPA's eGRID database. Not all power-generating facilities in the U.S. are plotted on this map.



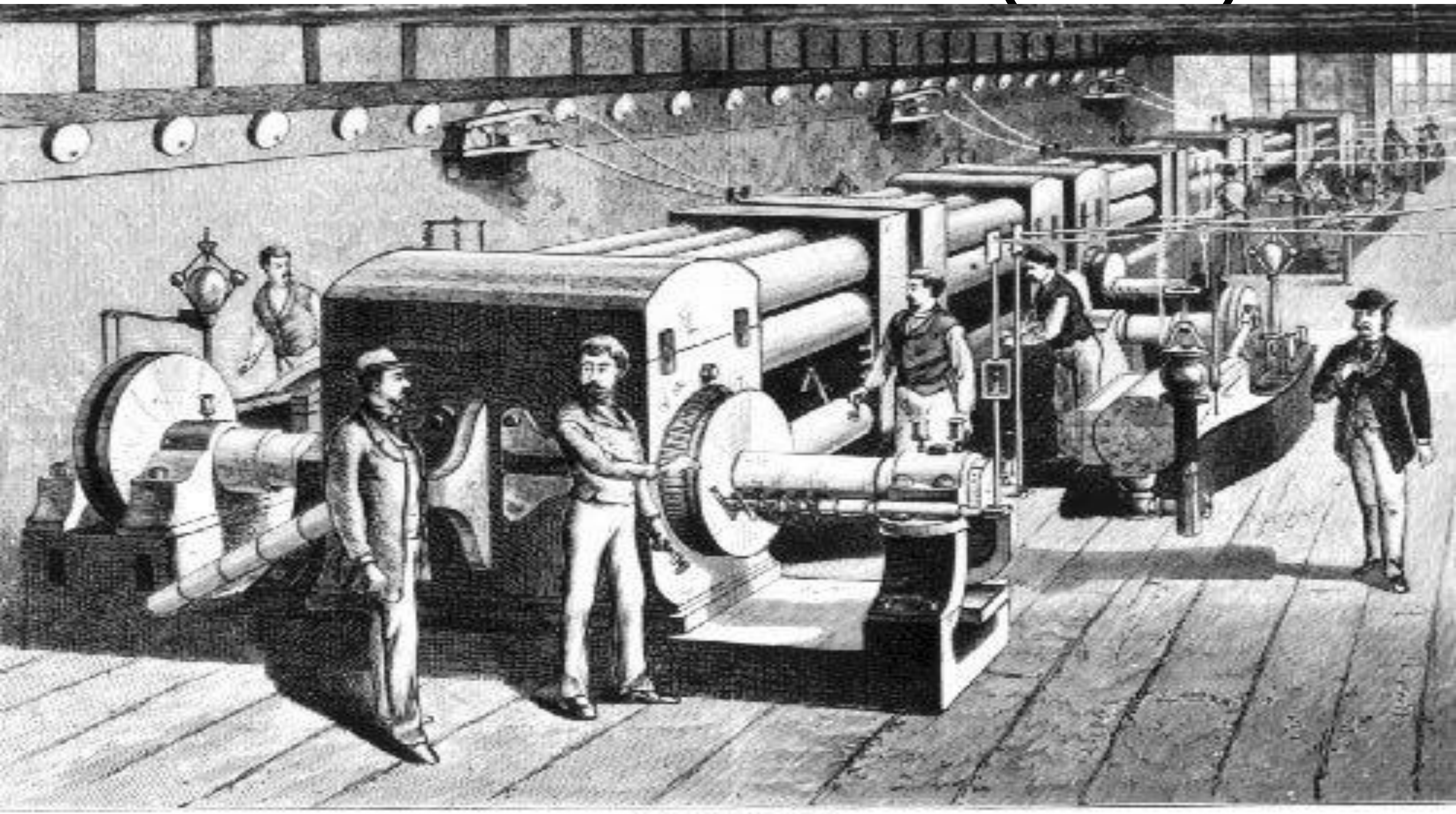
Source: NPR


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

North American Regional Transmission Organizations



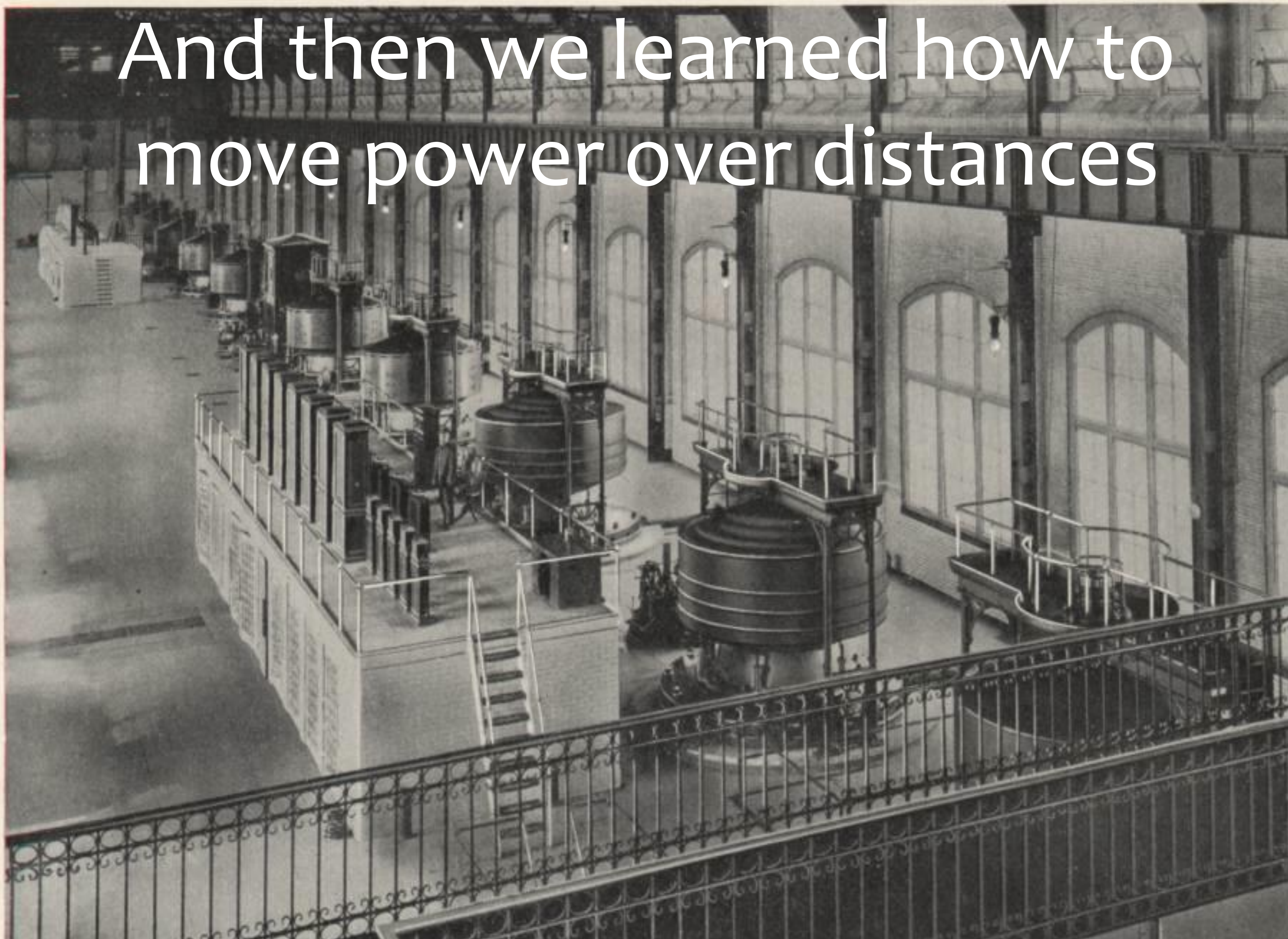
Things started decentralized: Pearl-street station (1882)



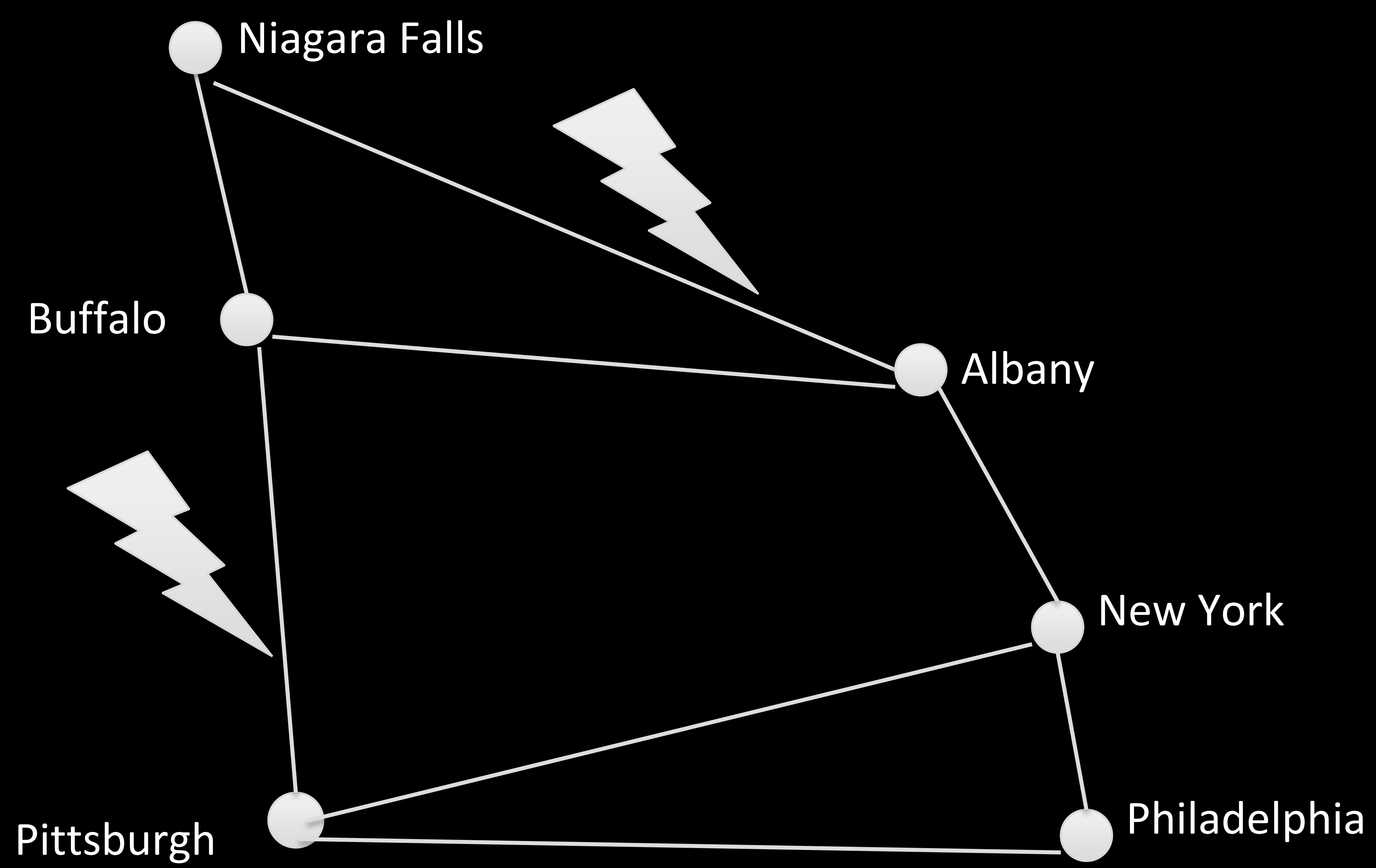
THE DYNAMO ROOM.
FIRST EDISON ELECTRIC LIGHTING STATION IN NEW YORK

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

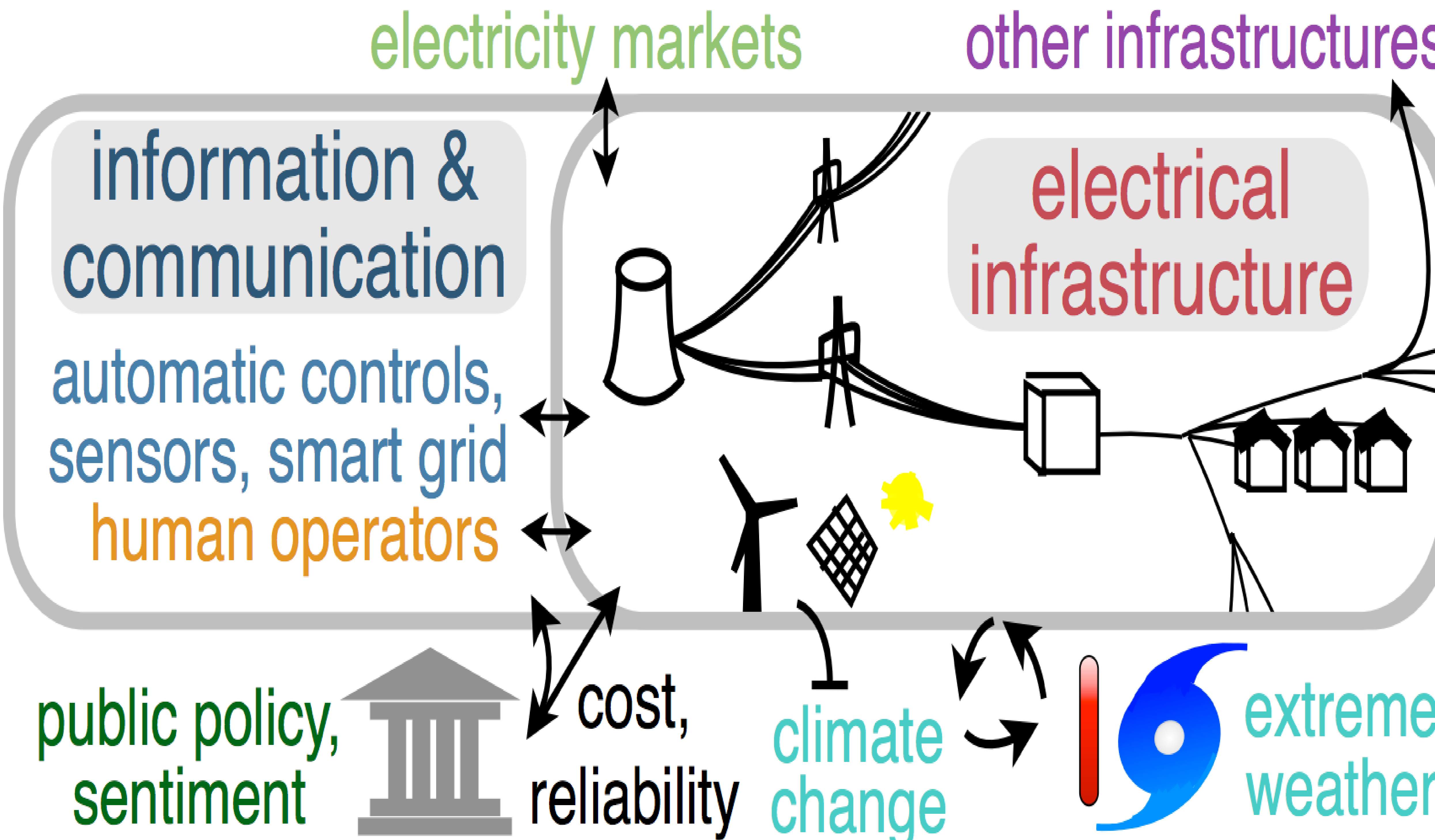
Things we know about power grids

The physics
of generation

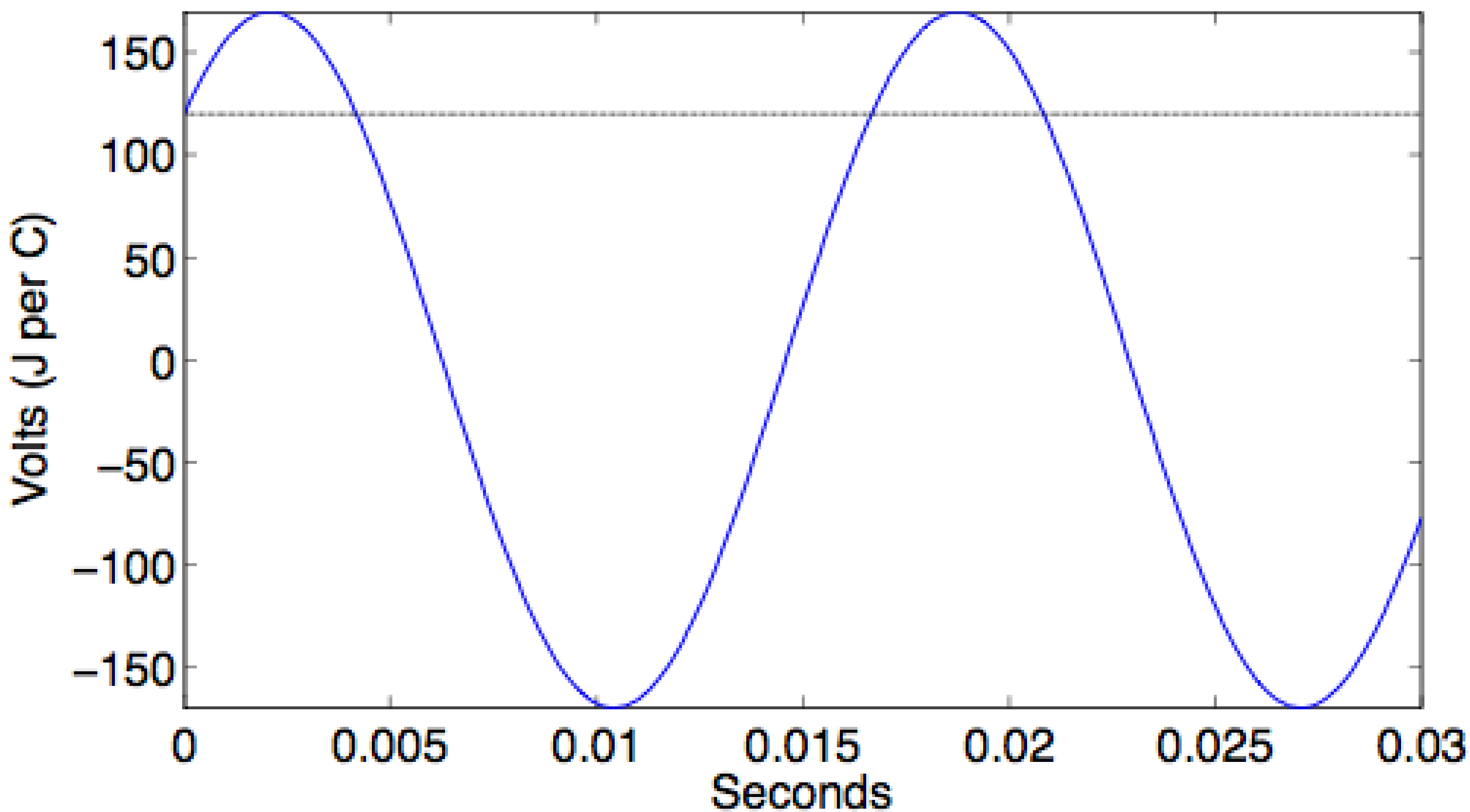
The physics of
transmission

That they
mostly work
(note the simple
interface)

Things we don't know



Key principle #1

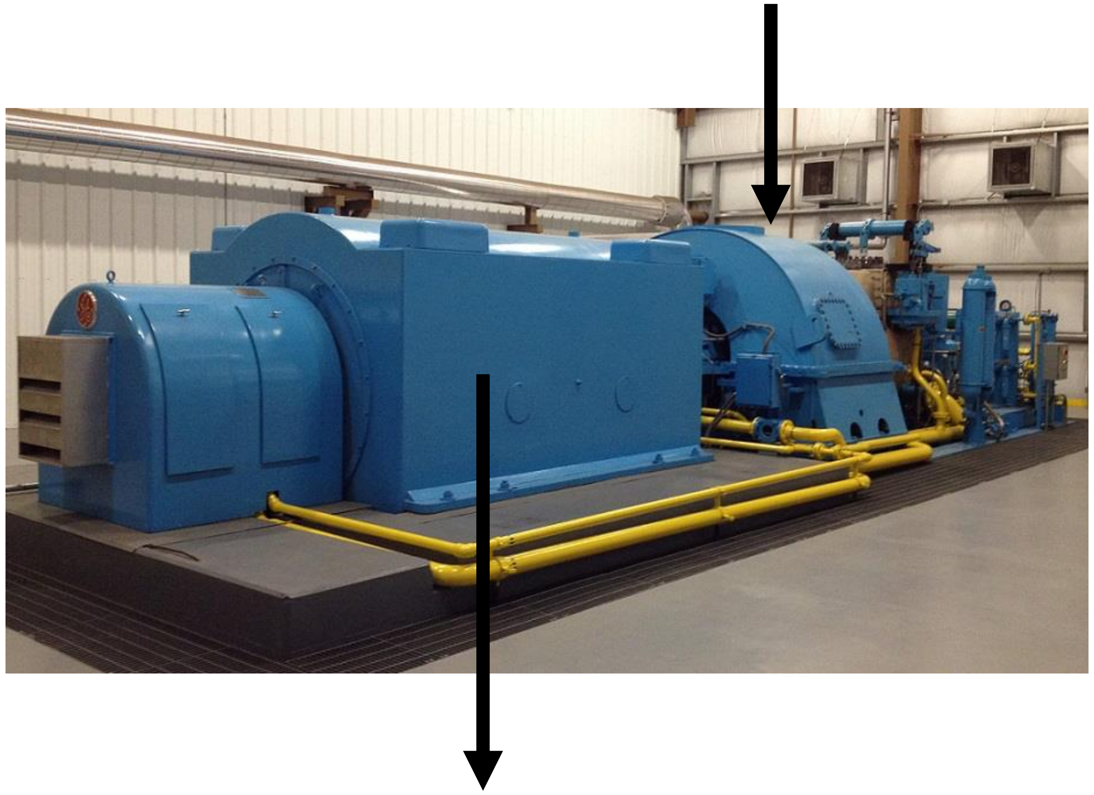


What goes in, must come out (there is no storage)

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

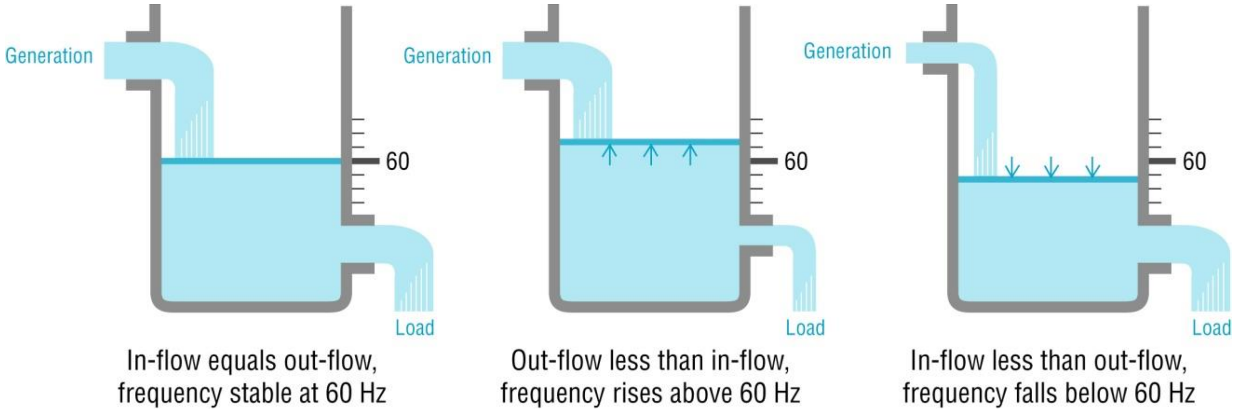
Key principle #2

P_{in}



P_{out}

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



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

We have learned some things about managing this system

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

1/10 sec	1 sec	10 sec	Minutes	Hours	Days	Months	Years
Inertia	Droop control	Auto. Gen. Control	Load following	Hourly Markets OPF	Unit Commit-ment	Seasonal Planning	Investment planning. **Policy.**

US Northeast and Canada
August 14, 2003
50 million people

California, Arizona, Mexico

September 8, 2011

5 million people

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

Bangledesh. 1 November 2014

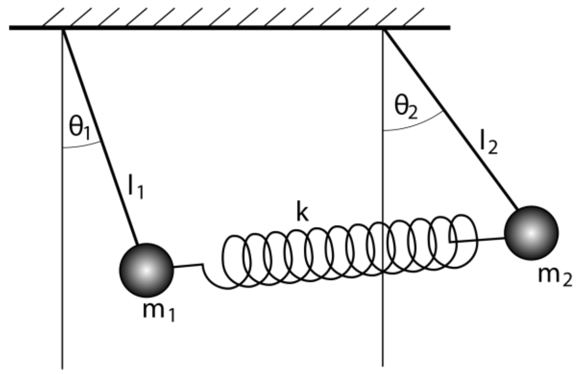
Officials said it would take at least 12 hours to repair the system and restore power to the capital Dhaka [AP]

Washington DC, April 7, 2015

washingtonpost.com

So what do we have?

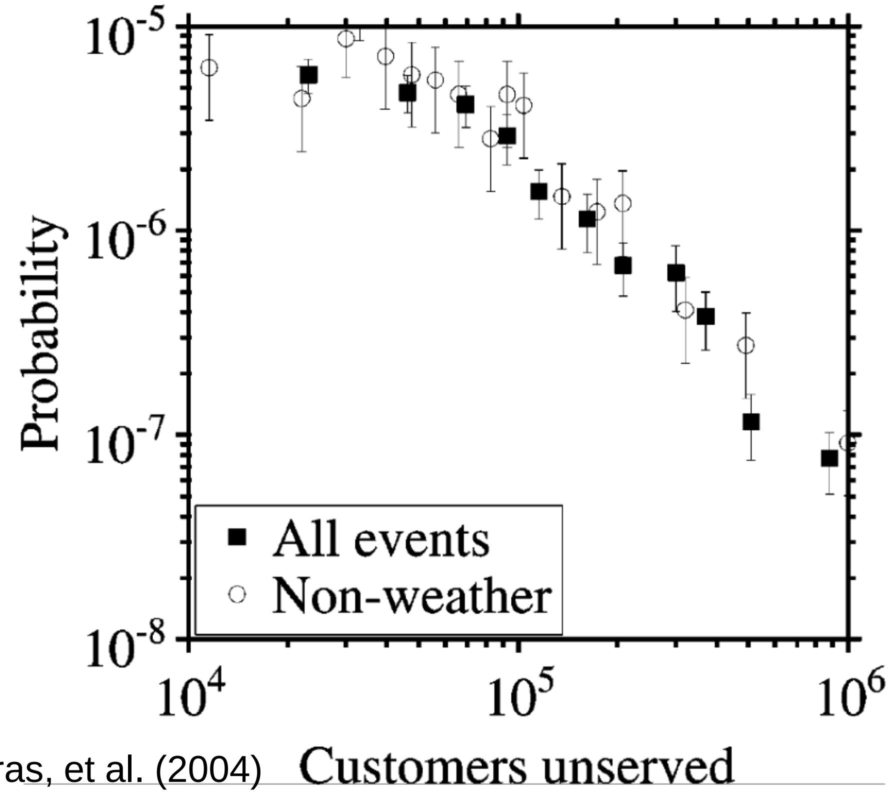
- A network of billion $ coupled pendula,
- which have a tendency to produce long chains of cascading failures every so often,
- to which we are adding millions of new stochastic sources (not to mention stochastic bad guys),
- over which no one is in charge.



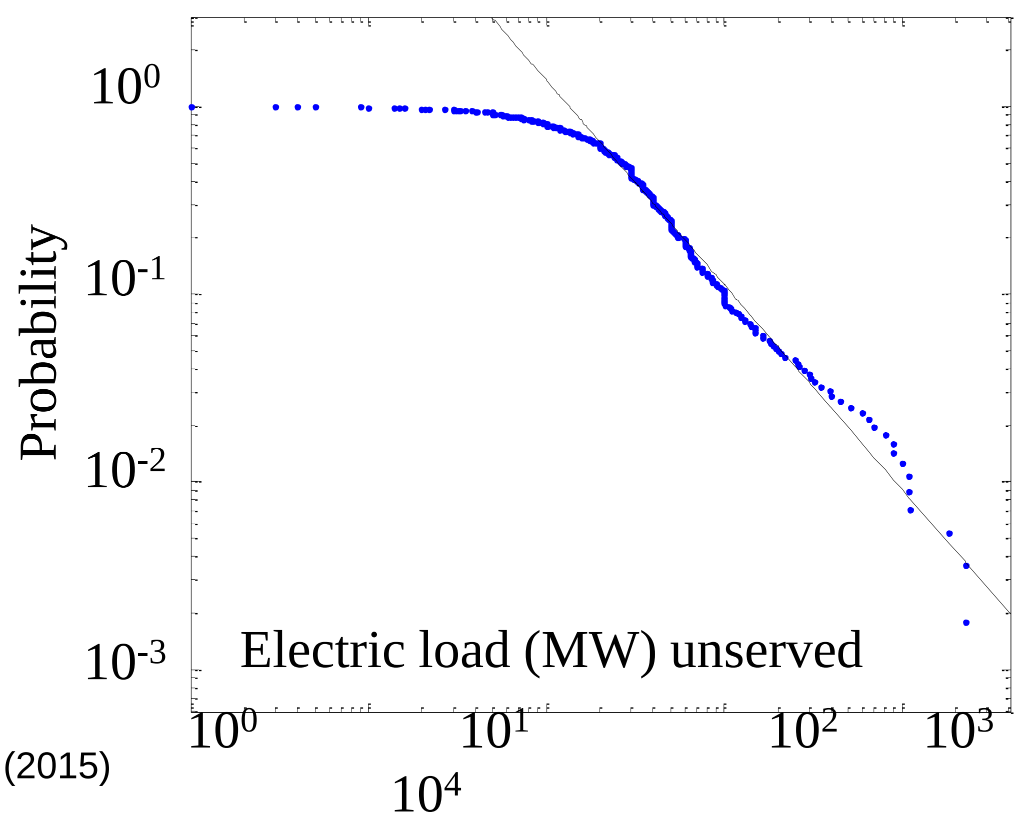
Challenge #1: Hints of Complexity and the Struggle for Structure

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

Extreme Events



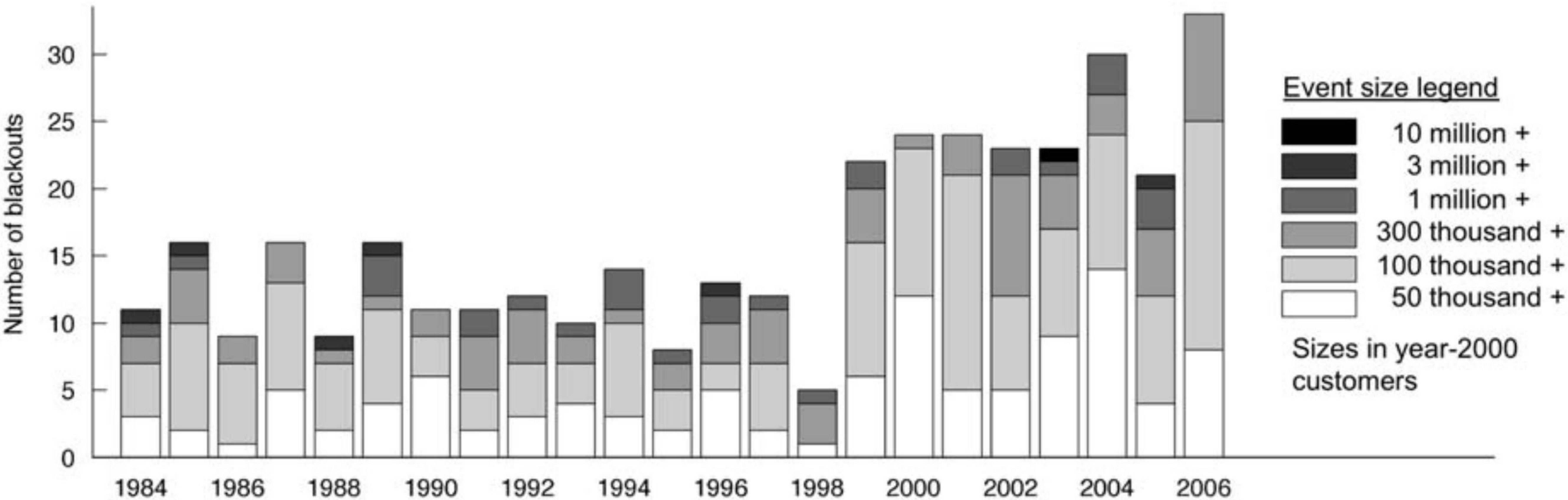
Carreras, et al. (2004)



Zhao (2015)

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

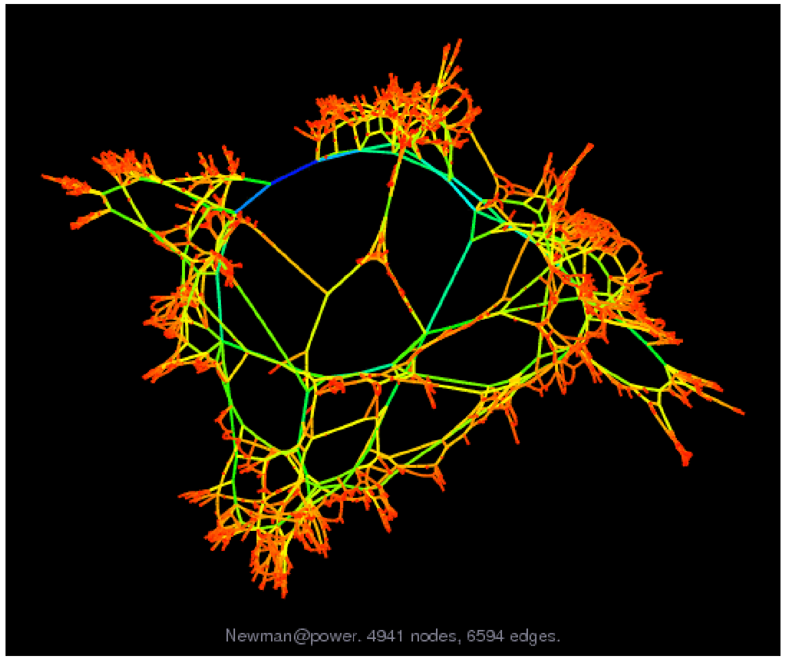
Extreme Events



Hines, et al. (2008)

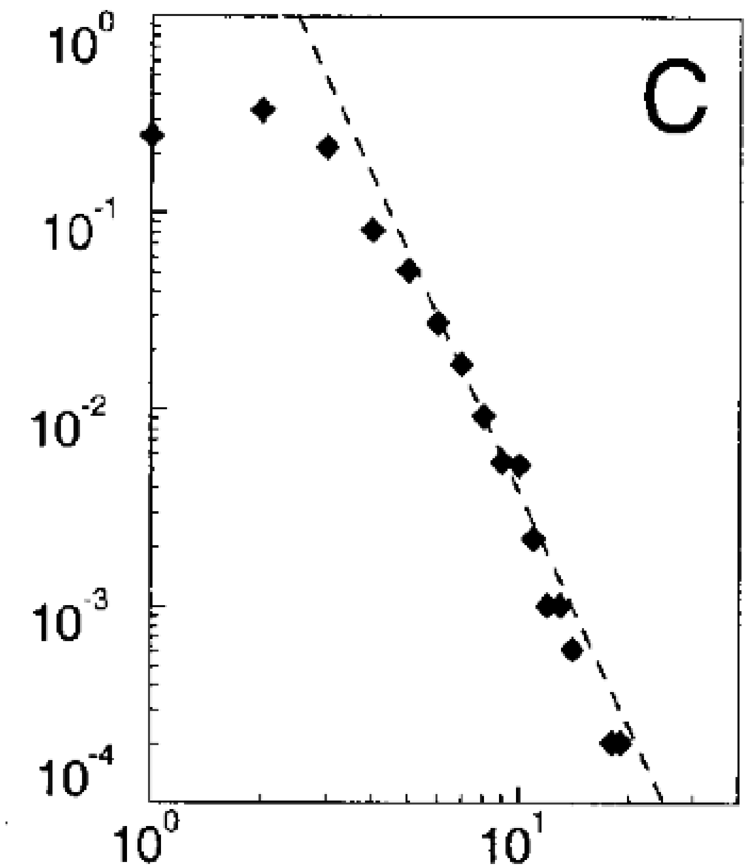
…And the frequency of large blackouts is not decreasing.

Evidence for Small-World Structure



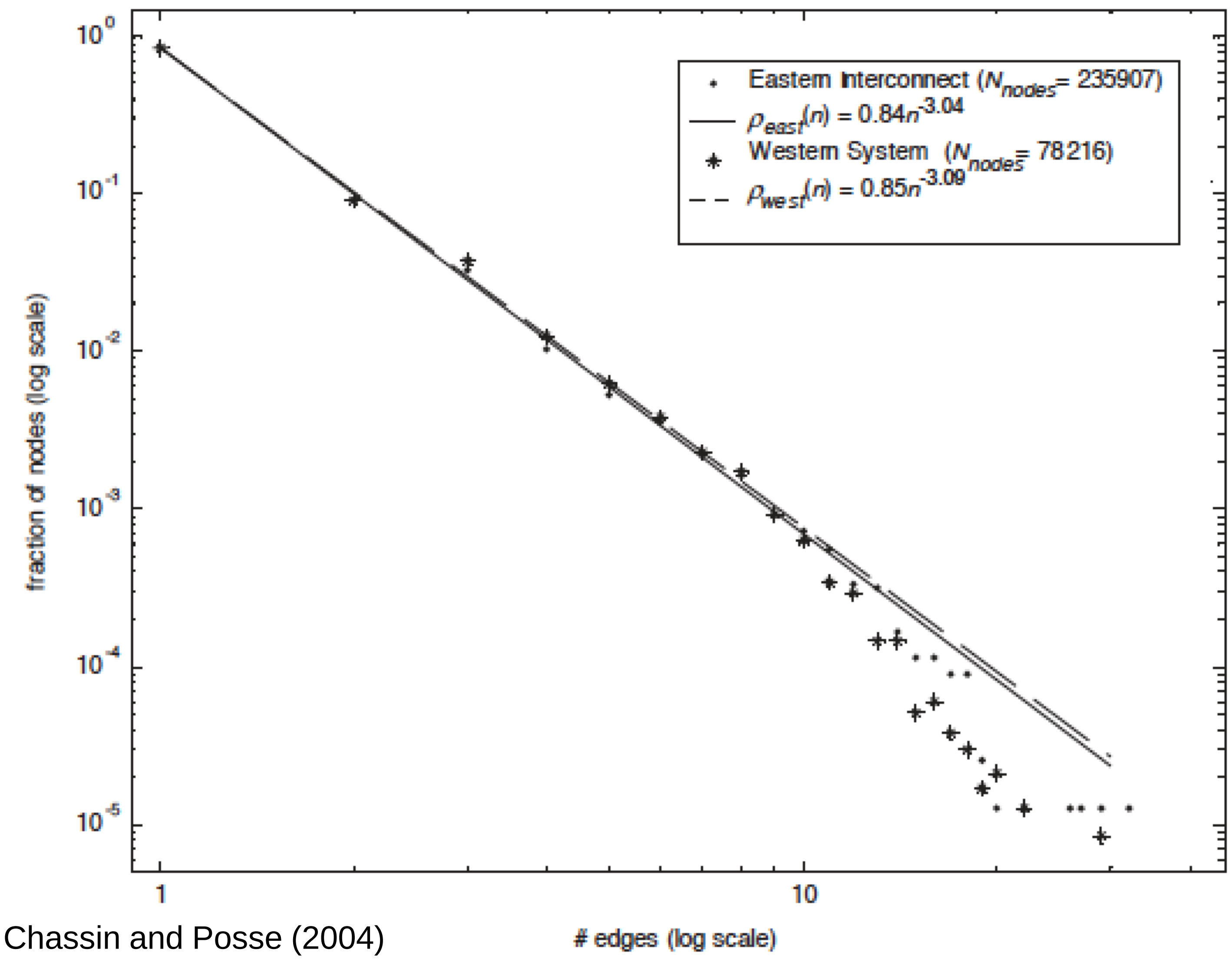
The first structural analysis (Watts and Strogatz, 1998) suggested that the Western Interconnect exhibited some properties of a small-world network.

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.

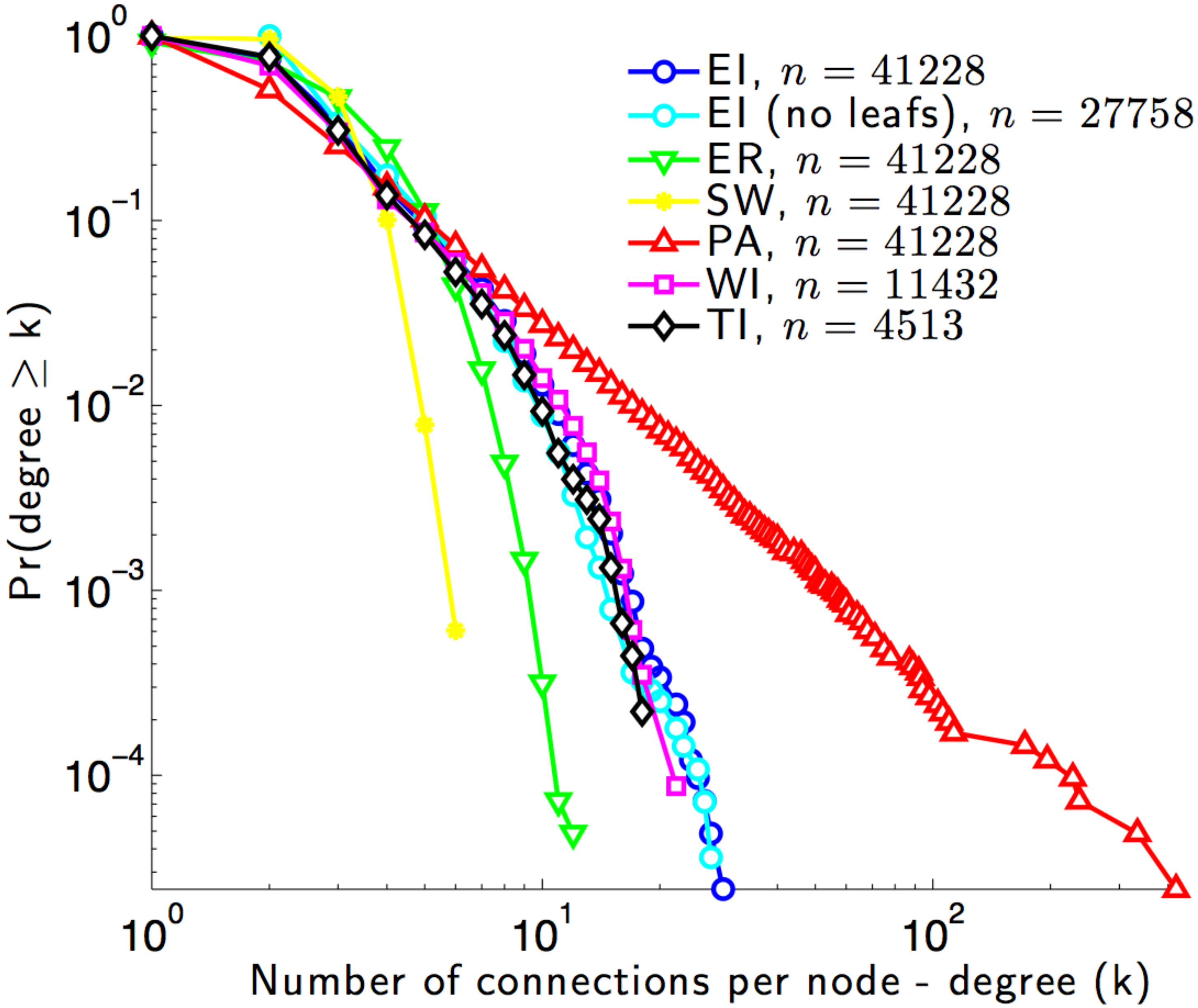


Chassin and Posse (2004)

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”

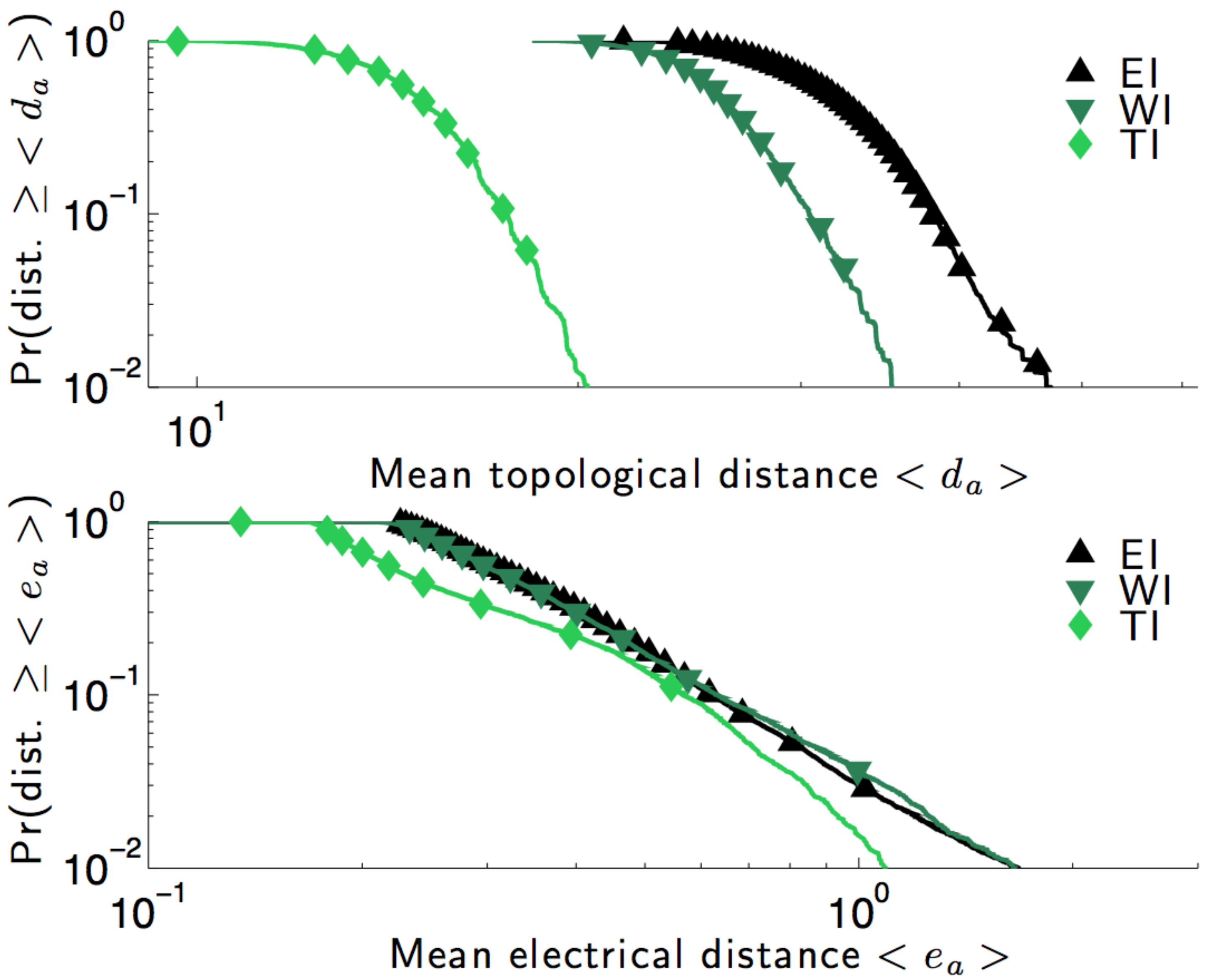
What We Don't Really Understand: Structure of the Power Grid



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

Cotilla Sanchez et al, 2012

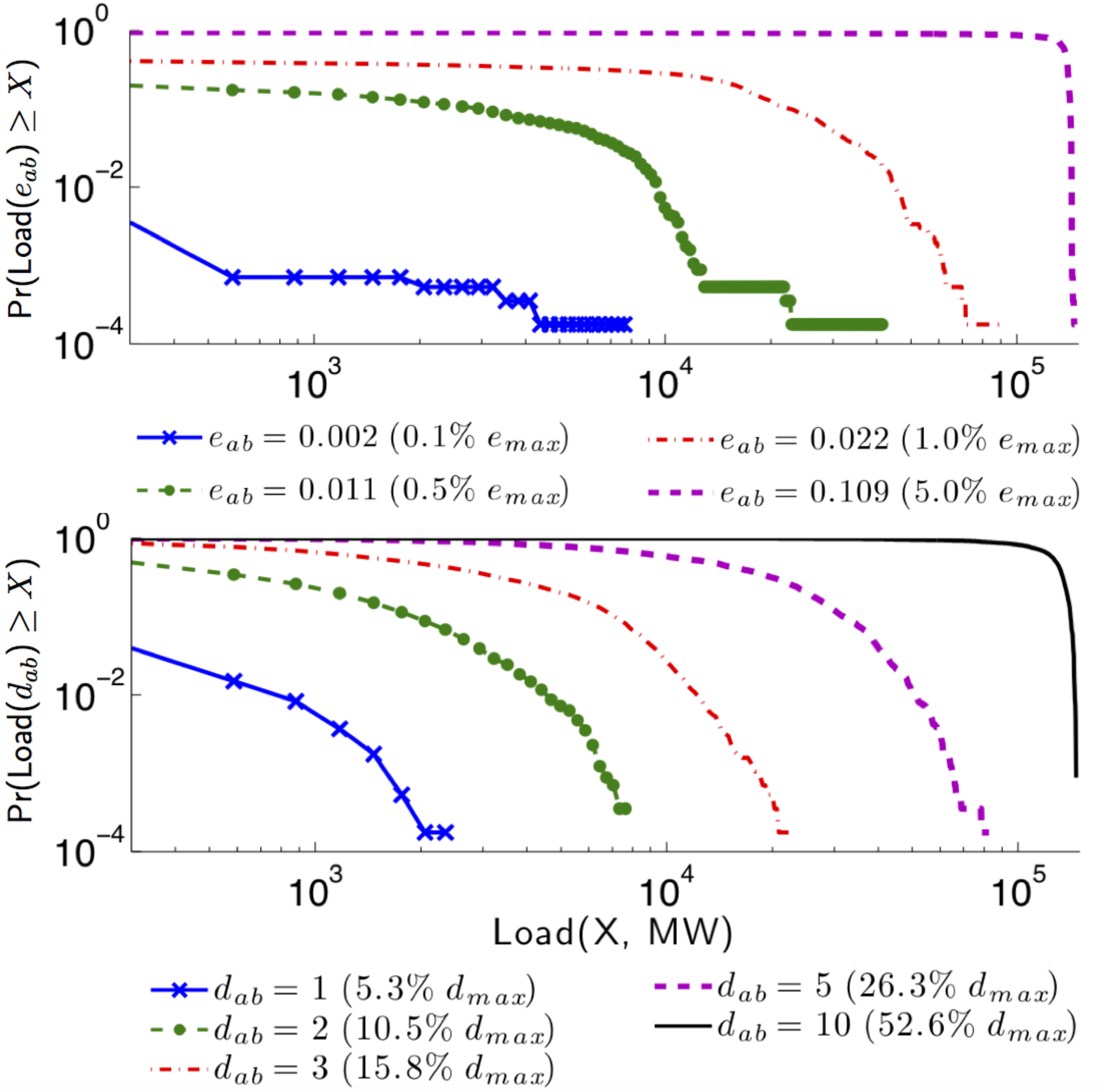
What We Don't Really Understand: Structure of the Power Grid



What does 'distance' even mean for the power grid? A topological or electrical concept?

Cotilla Sanchez et al, 2012

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



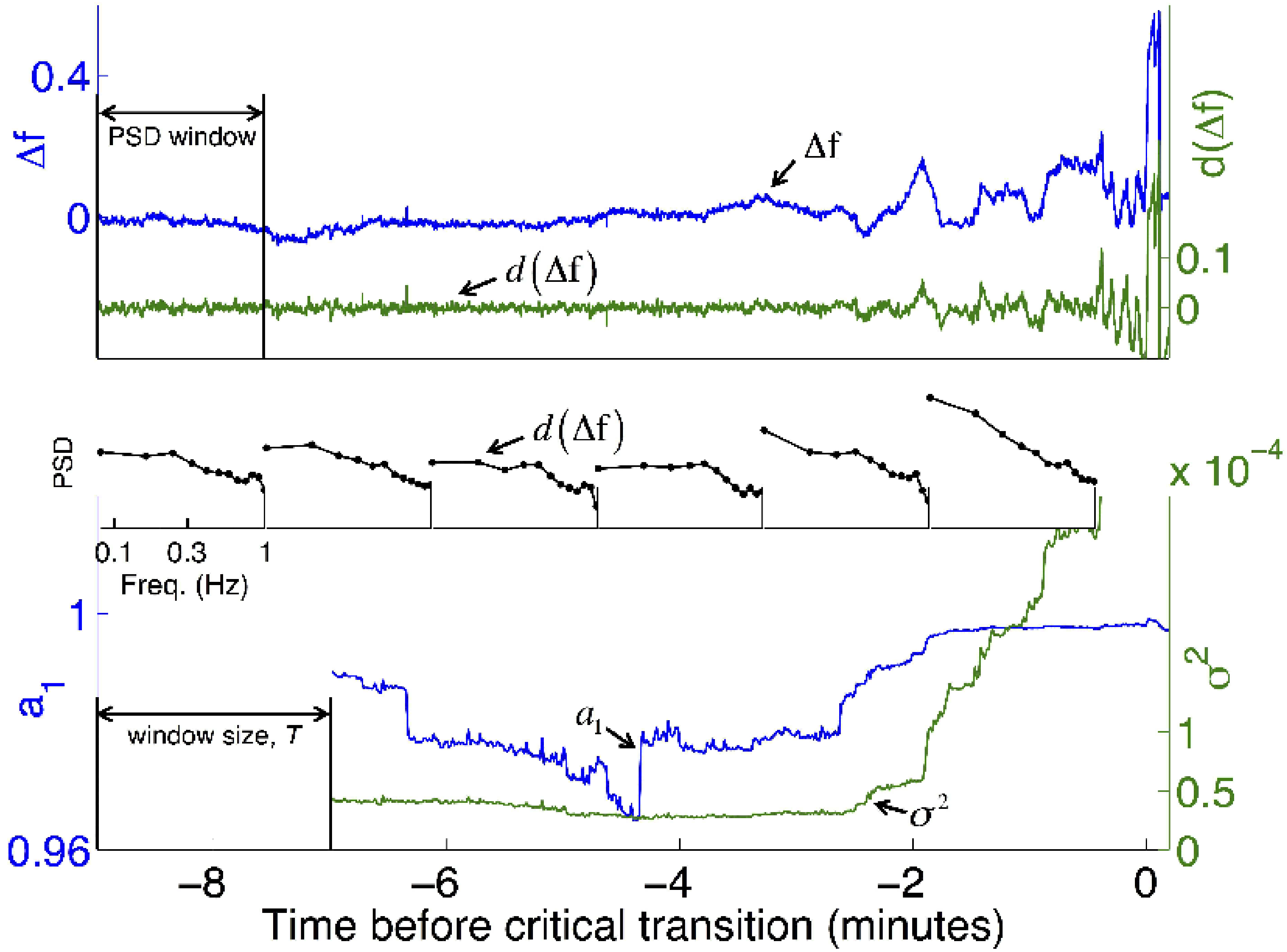
Electrical (top) and topological (bottom) connectivity to demand centers in the Mid-Atlantic US power grid

Cotilla Sanchez et al, 2012

Challenge #2: The Nature of Complex Grid Behaviors

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

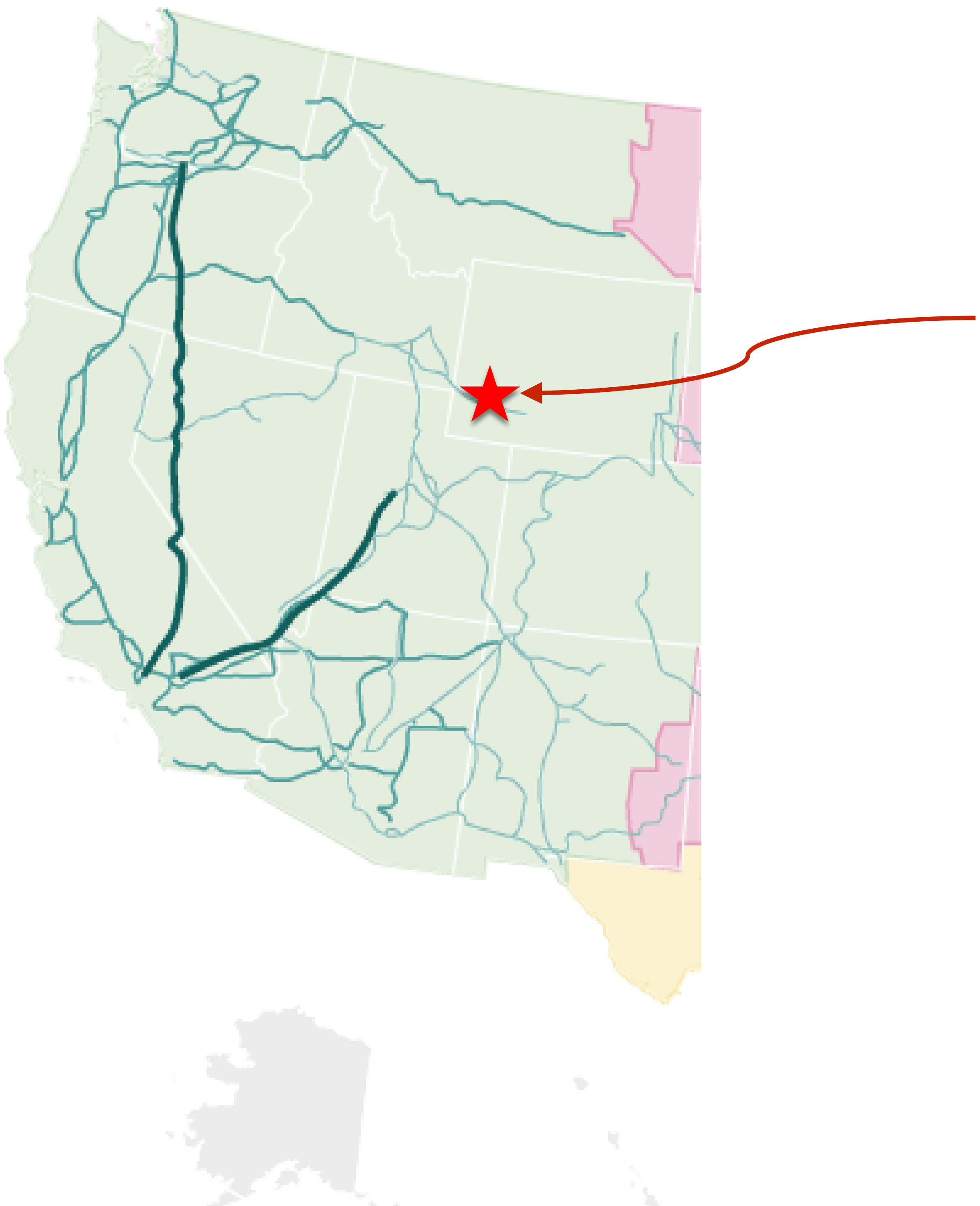
What We (Kind of) Understand: Oscillations and Instability



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

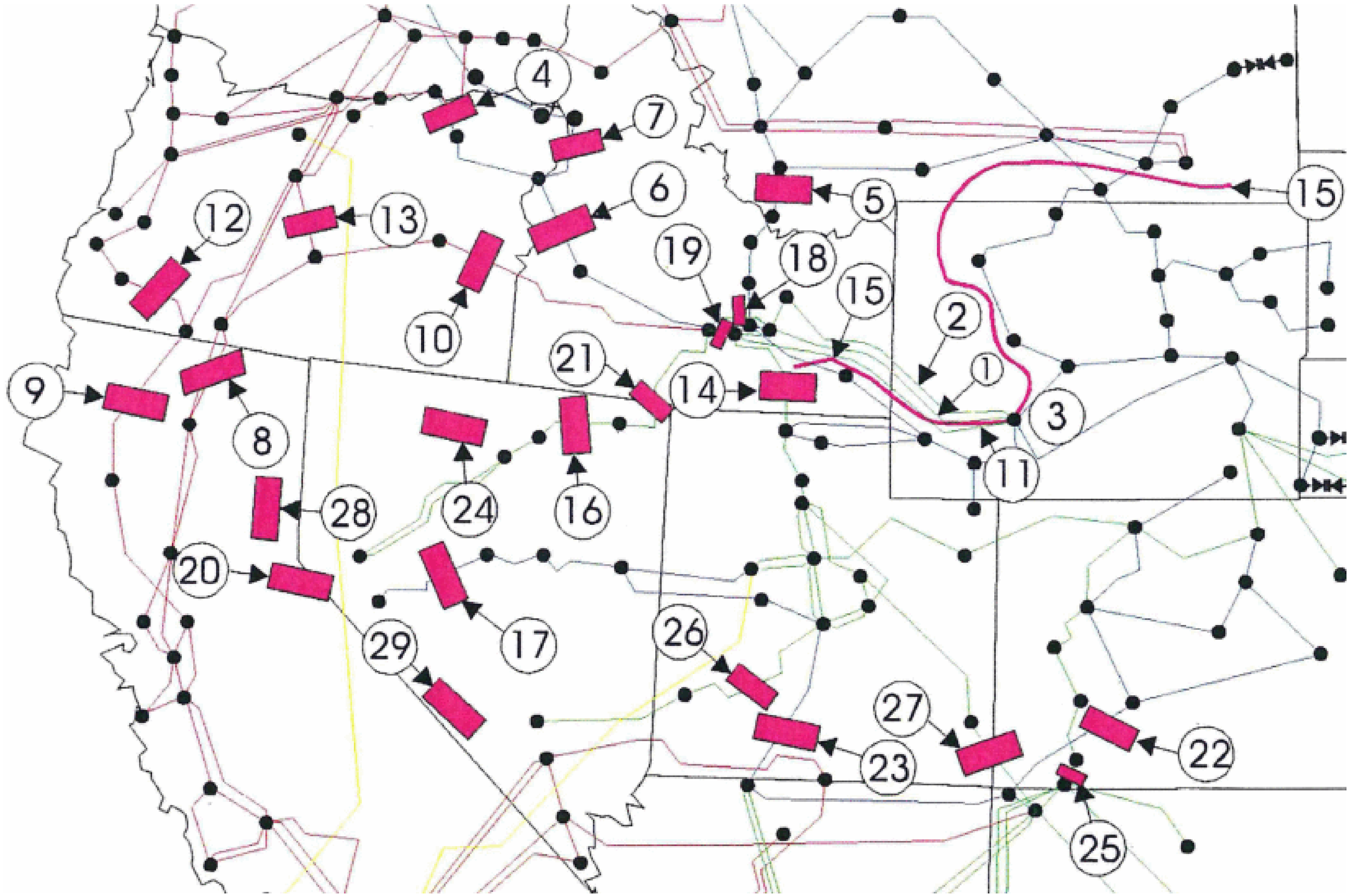
Cotilla Sanchez et al (2012)

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



We Know that Propagation is More than Topology

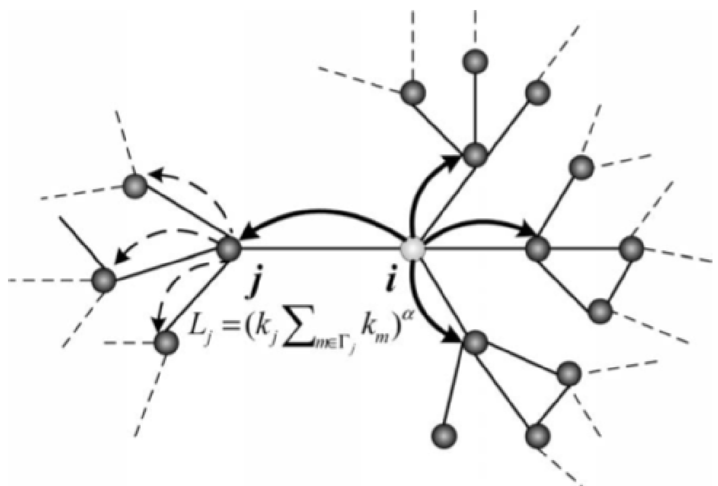


Fig. 2. The scheme illustrates the load redistribution triggered by an node-based attack. Node *i* is removed and the load on it is redistributed to the neighboring nodes connecting to node *i*. Among these neighboring nodes, the one with the higher load will receive the higher shared load from the broken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

Wang and Rong (2009)

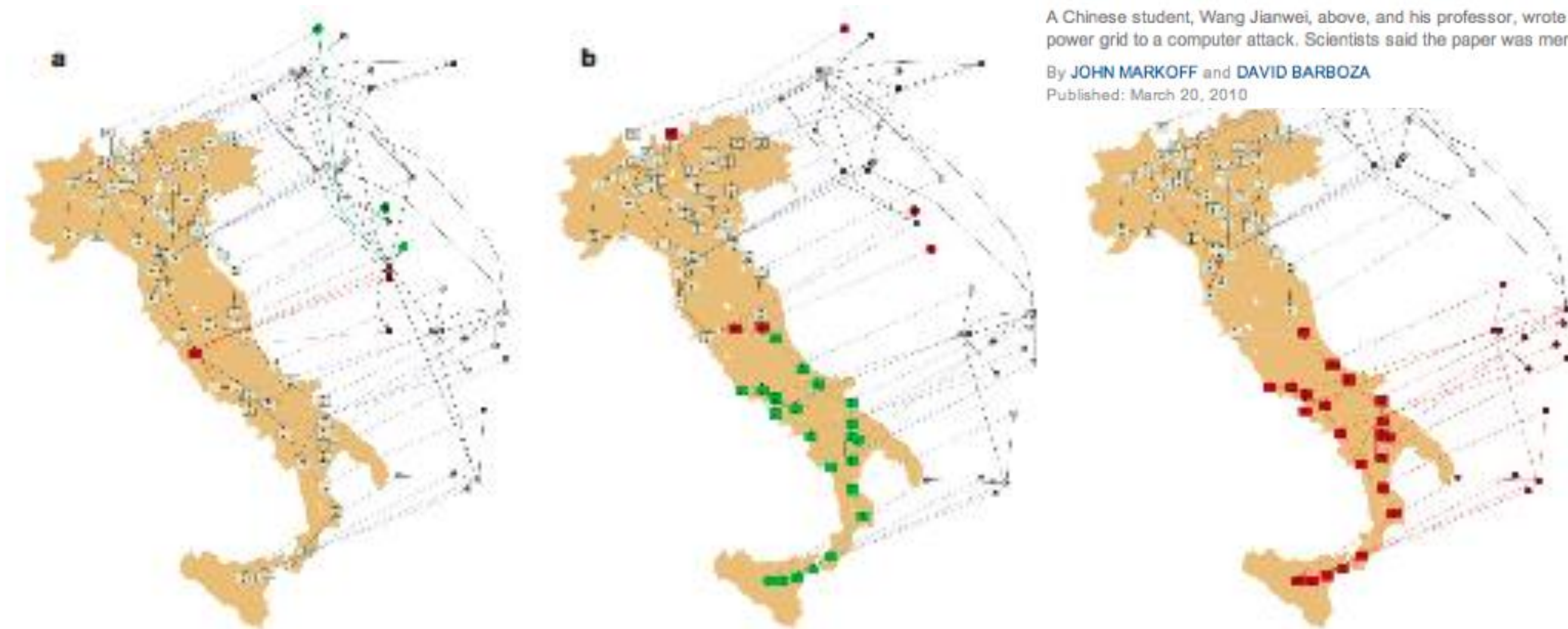
Academic Paper in China Sets Off Alarms in U.S.

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.

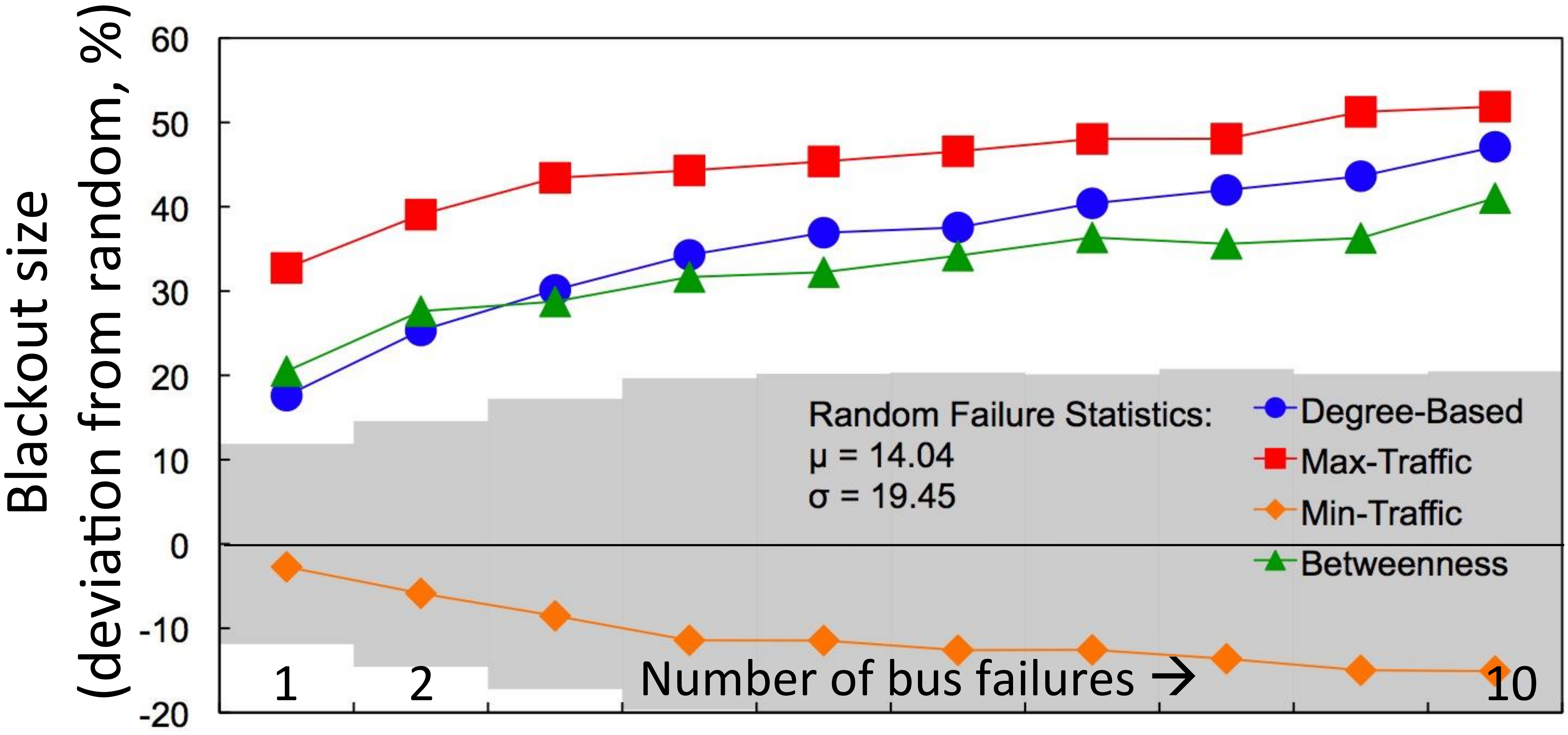
By JOHN MARKOFF and DAVID BARBOZA

Published: March 20, 2010



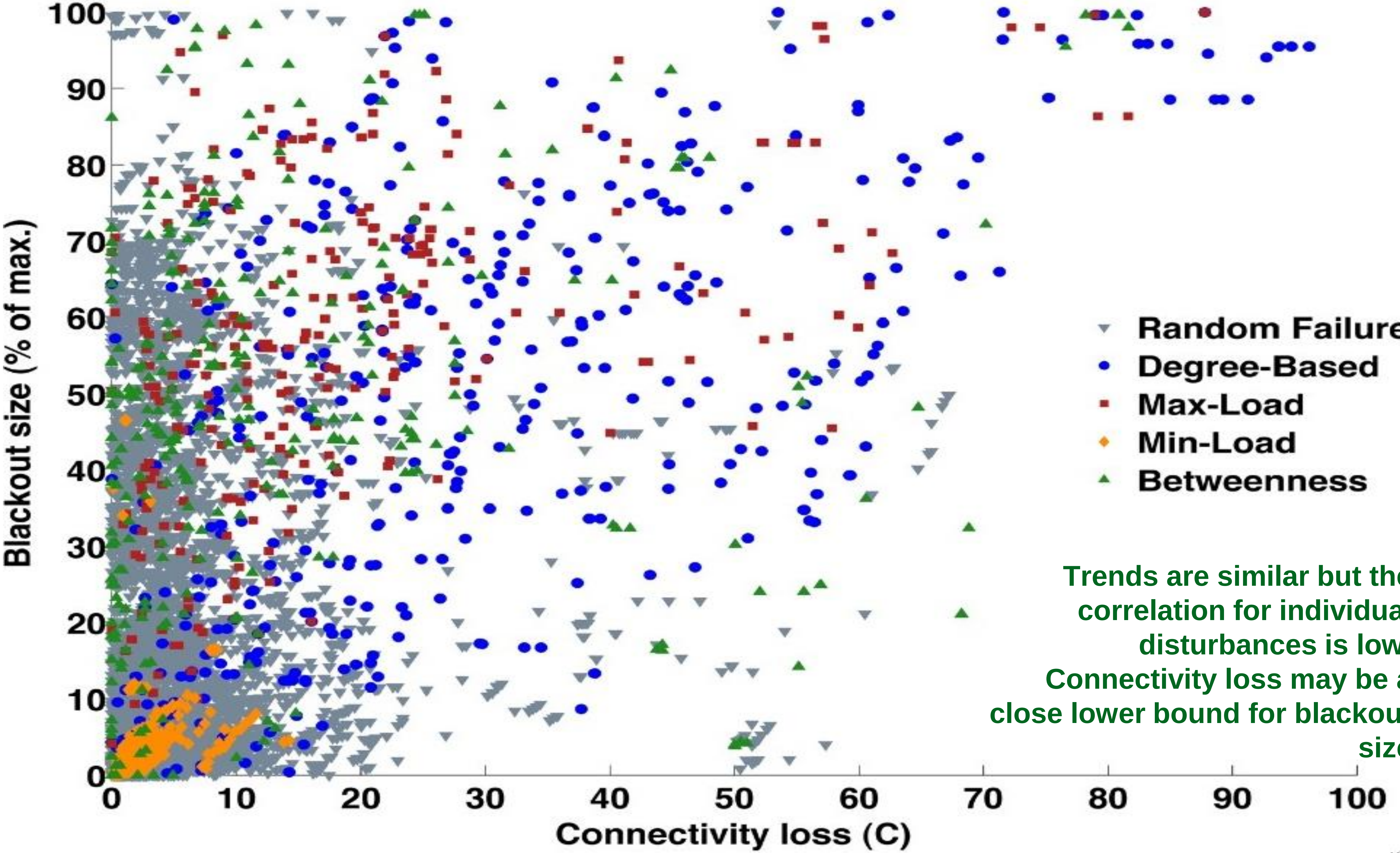
Buldyrev, et al (2010)

The Value of Topological Models



Hines, et al (2010)

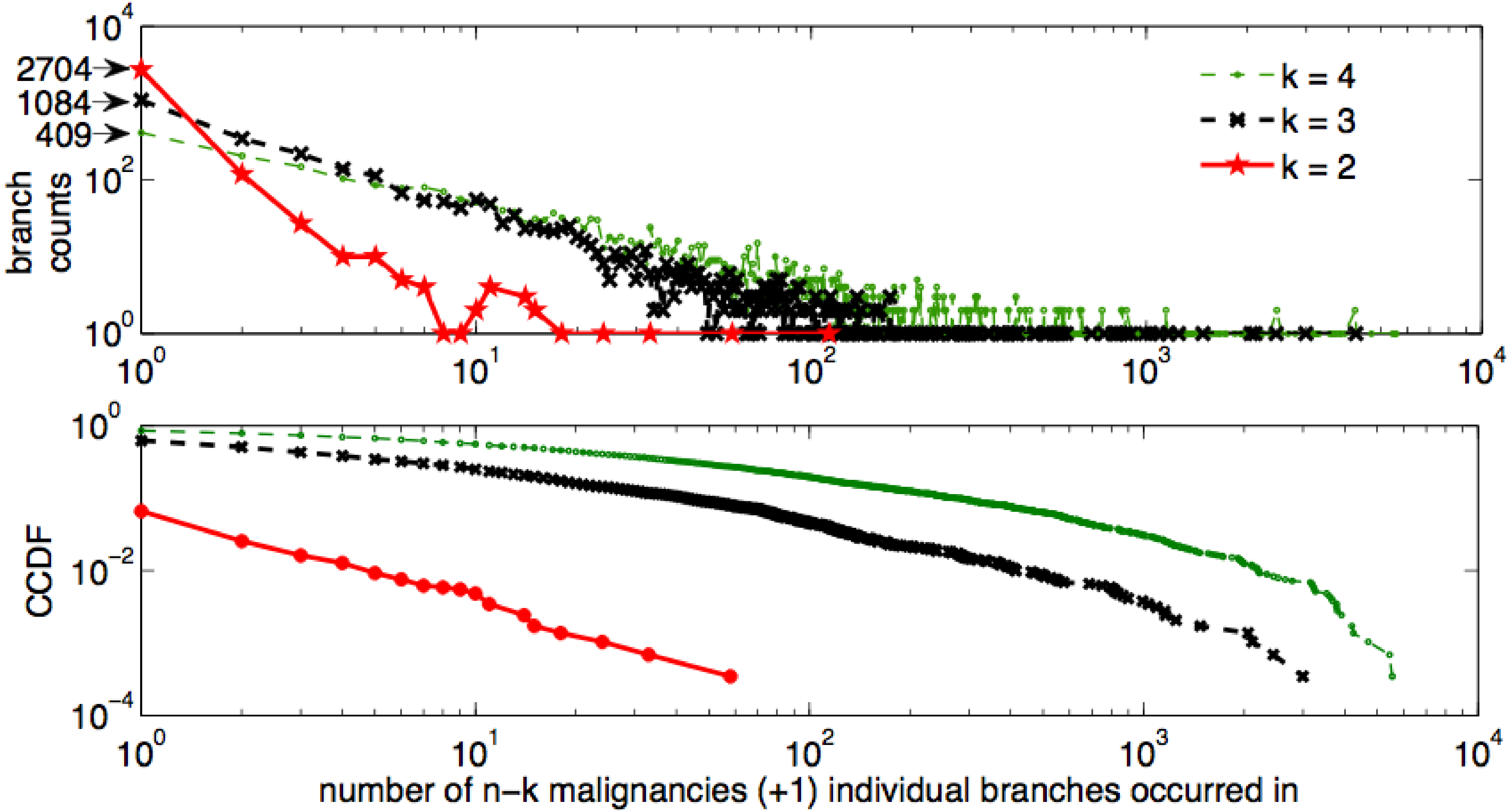
The Value of Topological Models



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

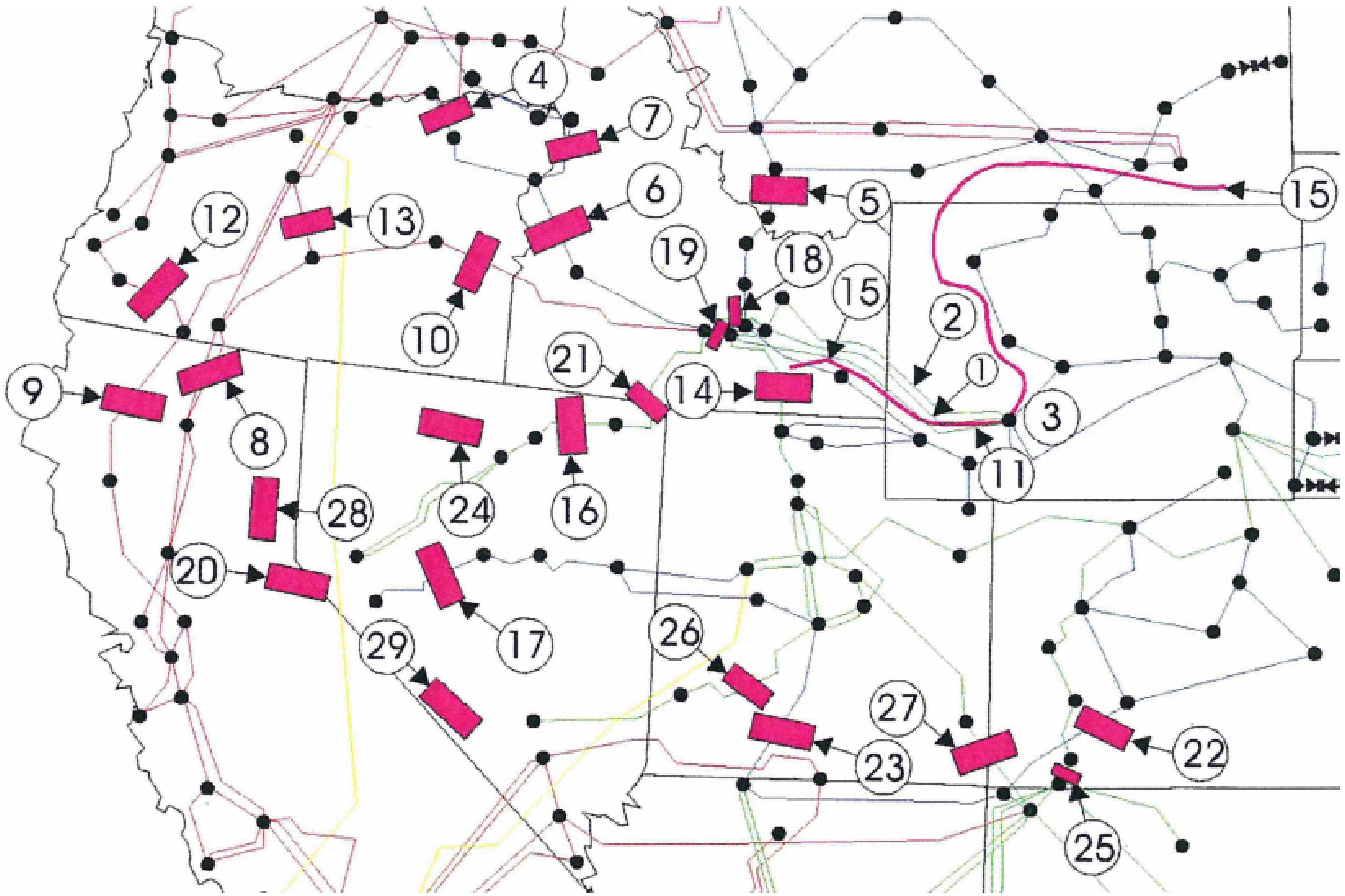
Hines, et al (2010)

Yet, Power Grids do have Critical Elements



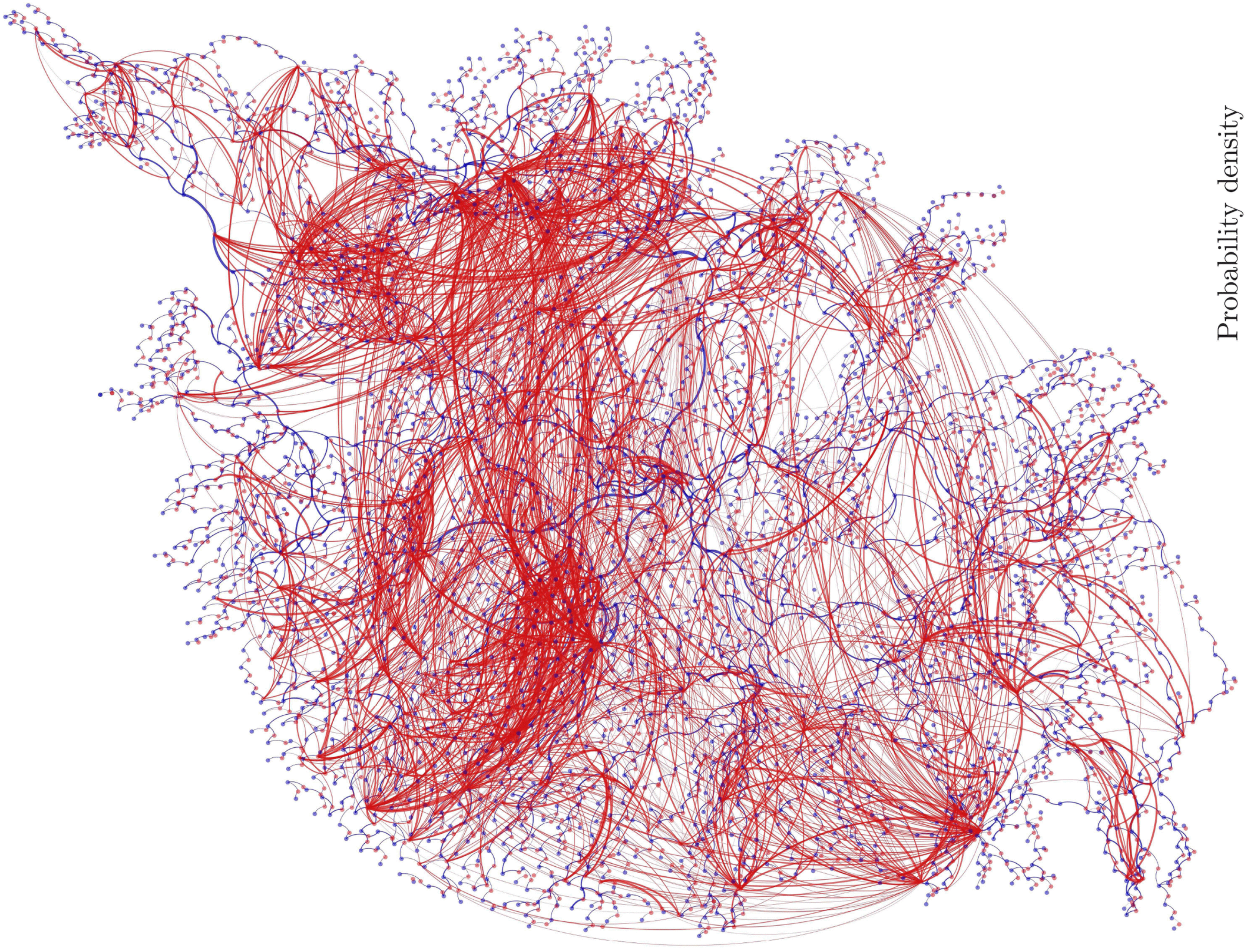
Eppstein and Hines (2012)

Challenge 1: Rethinking Propagation

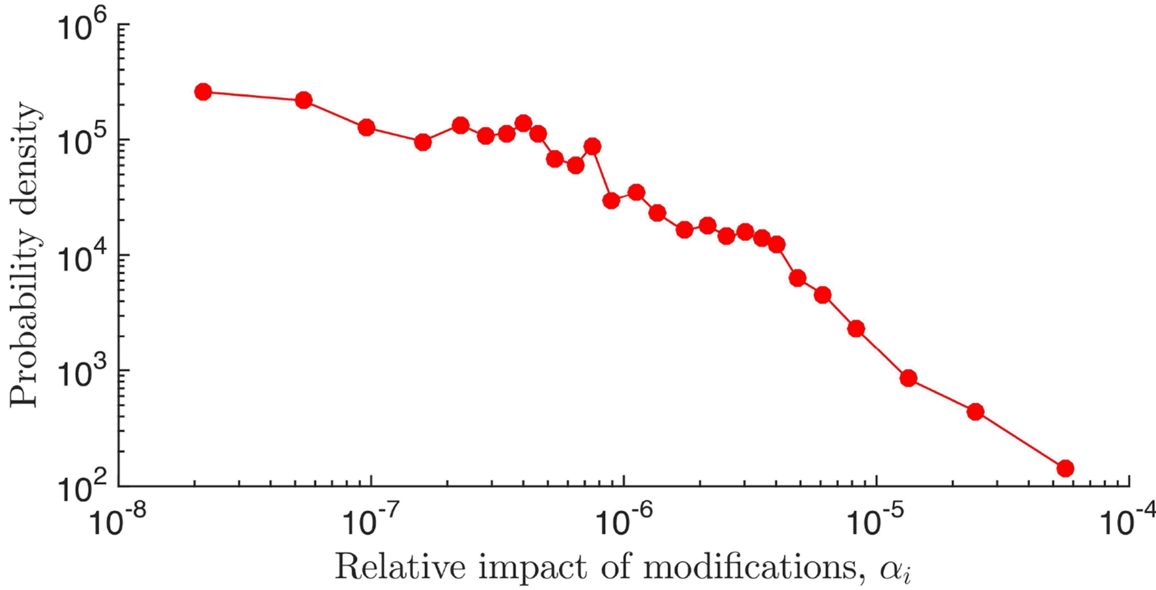


Let's forget about network structure, or even topology. Reverse the question: Suppose that there were a network structure under which disturbances would propagate in a way that we think we understand. What would such a network look like?

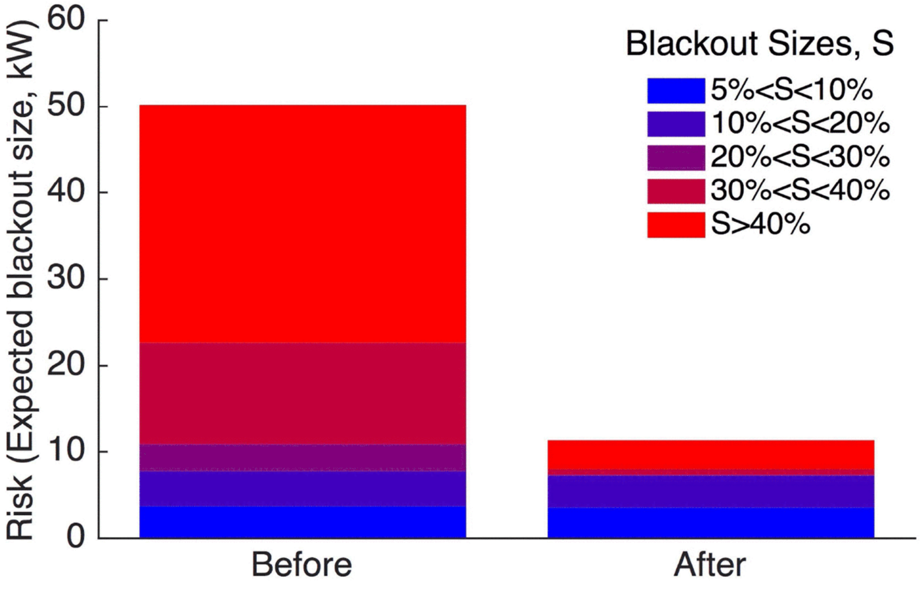
Lesson 1: Rethinking Propagation



(a)



(b)



(c)

Hines, Dobson, Rezai (2017)

Challenge #3: Sustainability and the Social Side of Electrons

So, You Want Renewable Power?

Institution: Santa Fe Institute

Proceedings of the National Academy of Sciences of the United States of America

CURRENT ISSUE // ARCHIVE // NEWS & MULTIMEDIA // AUTHORS // ABOUT | COLLECTED ARTICLES // BROWSE BY TOPIC

> Current Issue > vol. 112 no. 49 > Mark Z. Jacobson, 15060–15065, doi: 10.1073/pnas.1510028112

Check for updates

Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes

Mark Z. Jacobson[a,1], Mark A. Delucchi[b], Mary A. Cameron[a], and Bethany A. Frew[a]

Author Affiliations

Edited by Stephen Polasky, University of Minnesota, St. Paul, MN, and approved November 2, 2015 (received for review May 26, 2015)

Abstract | Full Text | Authors & Info | Figures | SI | Metrics | Related Content | PDF | PDF + SI

Significance

PNAS

Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar

Christopher T. M. Clack[a,b,1,2], Staffan A. Qvist[c], Jay Apt[d,e], Morgan Bazilian[f], Adam R. Brandt[g], Ken Caldeira[h], Steven J. Davis[i], Victor Diakov[j], Mark A. Handschy[b,k], Paul D. H. Hines[l], Paulina Jaramillo[d], Daniel M. Kammen[m,n,o], Jane C. S. Long[p,3], M. Granger Morgan[d], Adam Reed[q], Varun Sivaram[r], James Sweeney[s,t], George R. Tynan[u], David G. Victor[v,w], John P. Weyant[s,t], and Jay F. Whitacre[d]

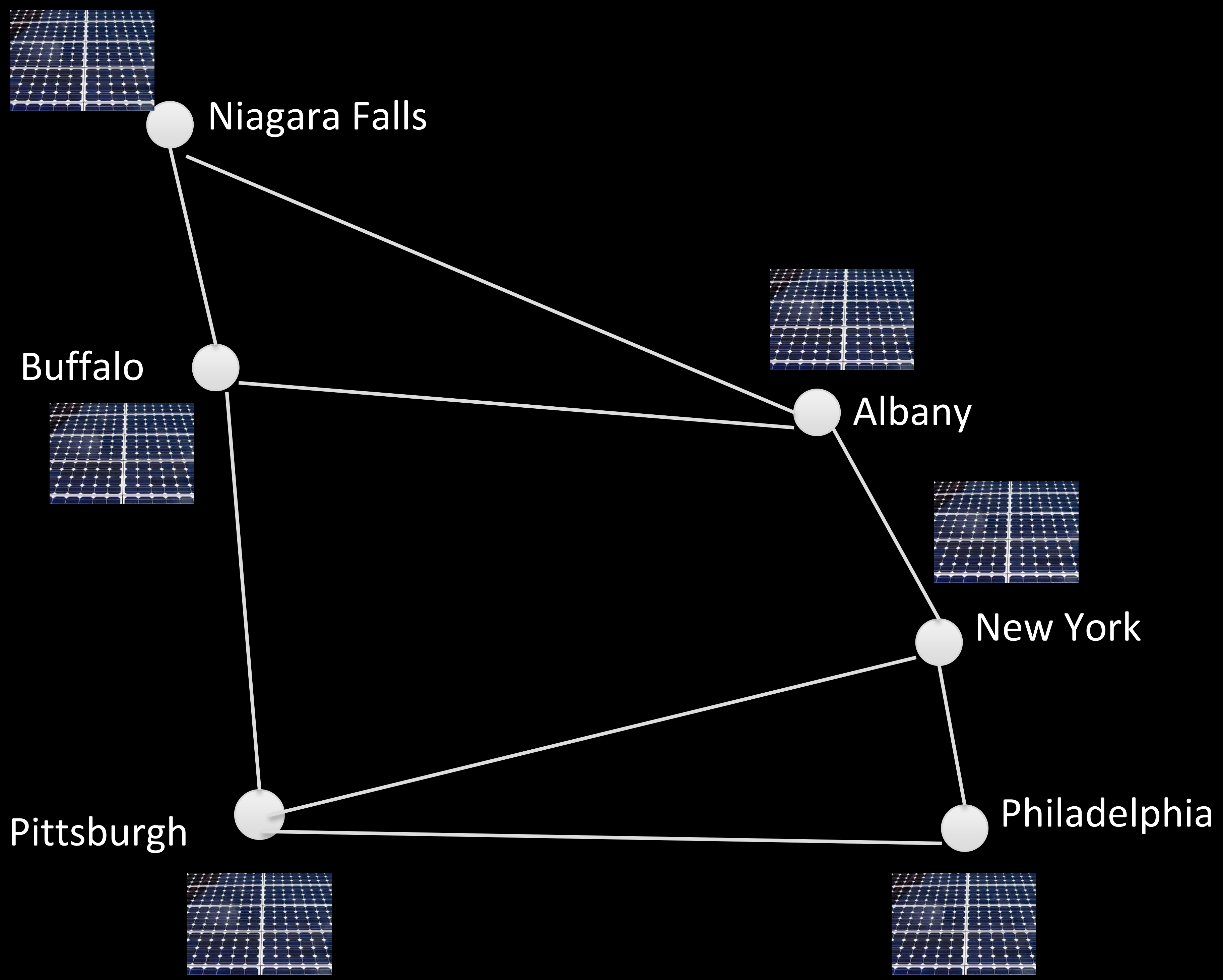
Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved February 24, 2017 (received for review June 26, 2016)

A number of analyses, meta-analyses, and assessments, including those performed by the Intergovernmental Panel on Climate Change, the National Oceanic and Atmospheric Administration, the National Renewable Energy Laboratory, and the International Energy Agency, have concluded that deployment of a diverse portfolio of clean energy technologies makes a transition to a low-carbon-emission energy system both more feasible and less costly than other pathways. In contrast, Jacobson et al. [Jacobson MZ, Delucchi MA, Cameron MA, Frew BA (2015) Proc Natl Acad Sci USA 112(49):15060–15065] argue that it is feasible to provide "low-cost solutions to the grid reliability problem with 100% penetration of WWS [wind, water and solar power] across all energy sectors in the continental United States between 2050 and 2055", with only electricity and hydrogen as energy carriers. In this paper, we evaluate that study and find significant shortcomings in the analysis. In particular, we point out that this work used invalid modeling tools, contained modeling errors, and made implausible and inadequately supported assumptions. Policy makers should treat with caution any visions of a rapid, reliable, and low-cost transition to entire energy systems that relies almost exclusively on wind, solar, and hydroelectric power.

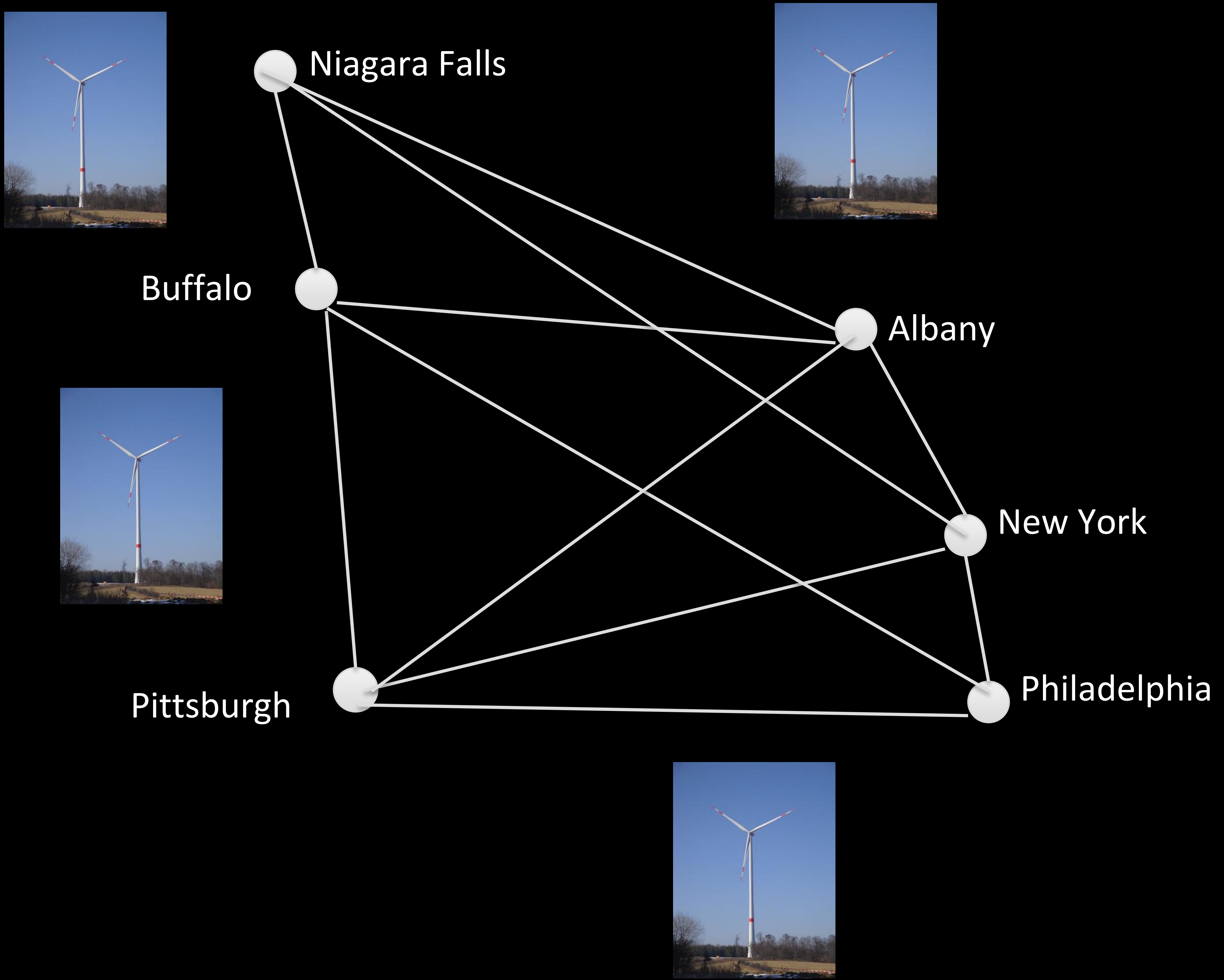
energy systems modeling | climate change | renewable energy | energy costs | grid stability

A number of studies, including a study by one of us, have concluded that an 80% decarbonization of the US electric grid could be achieved at reasonable cost (1, 2). ...

Maybe the transition should look like this

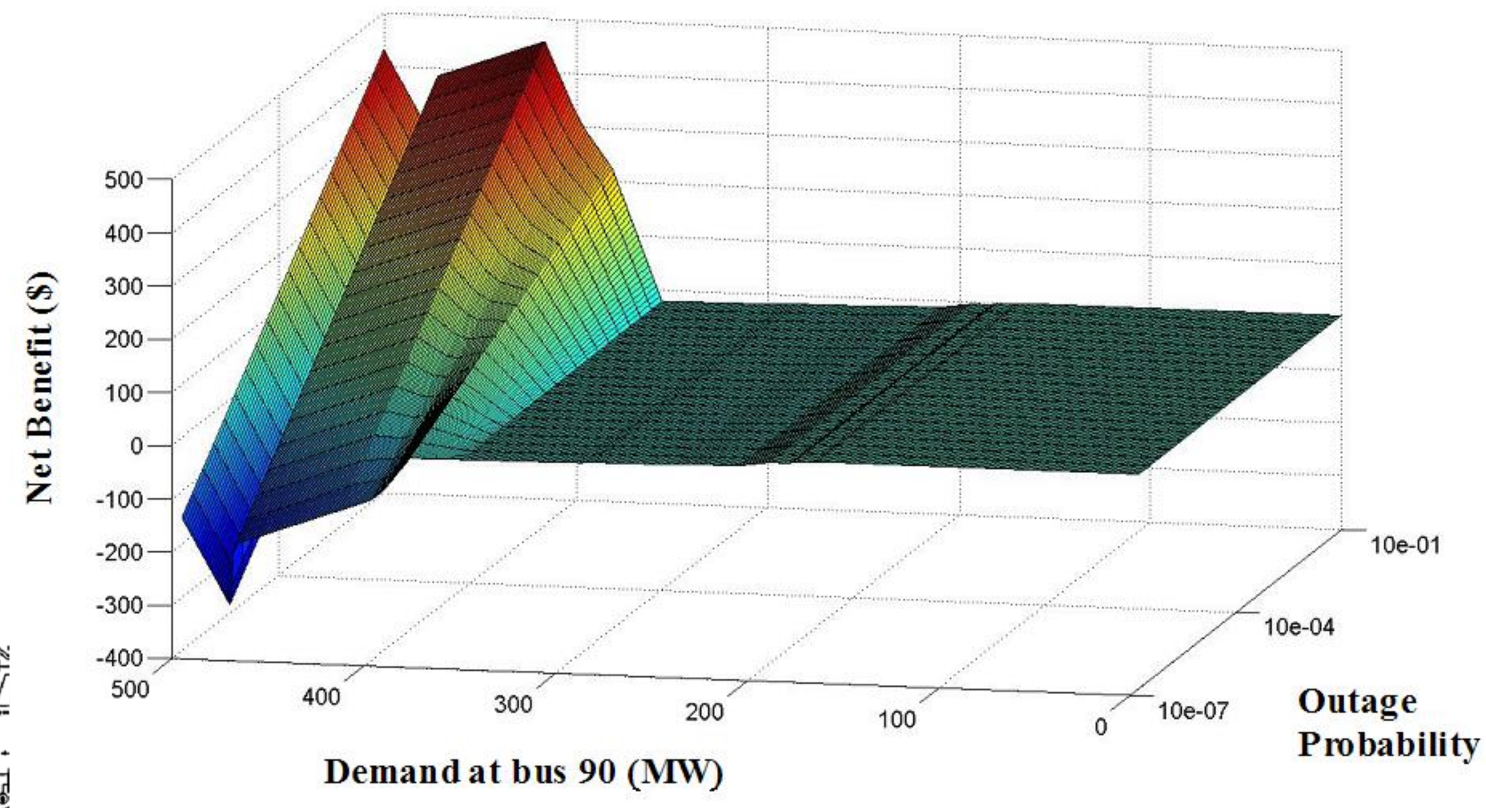


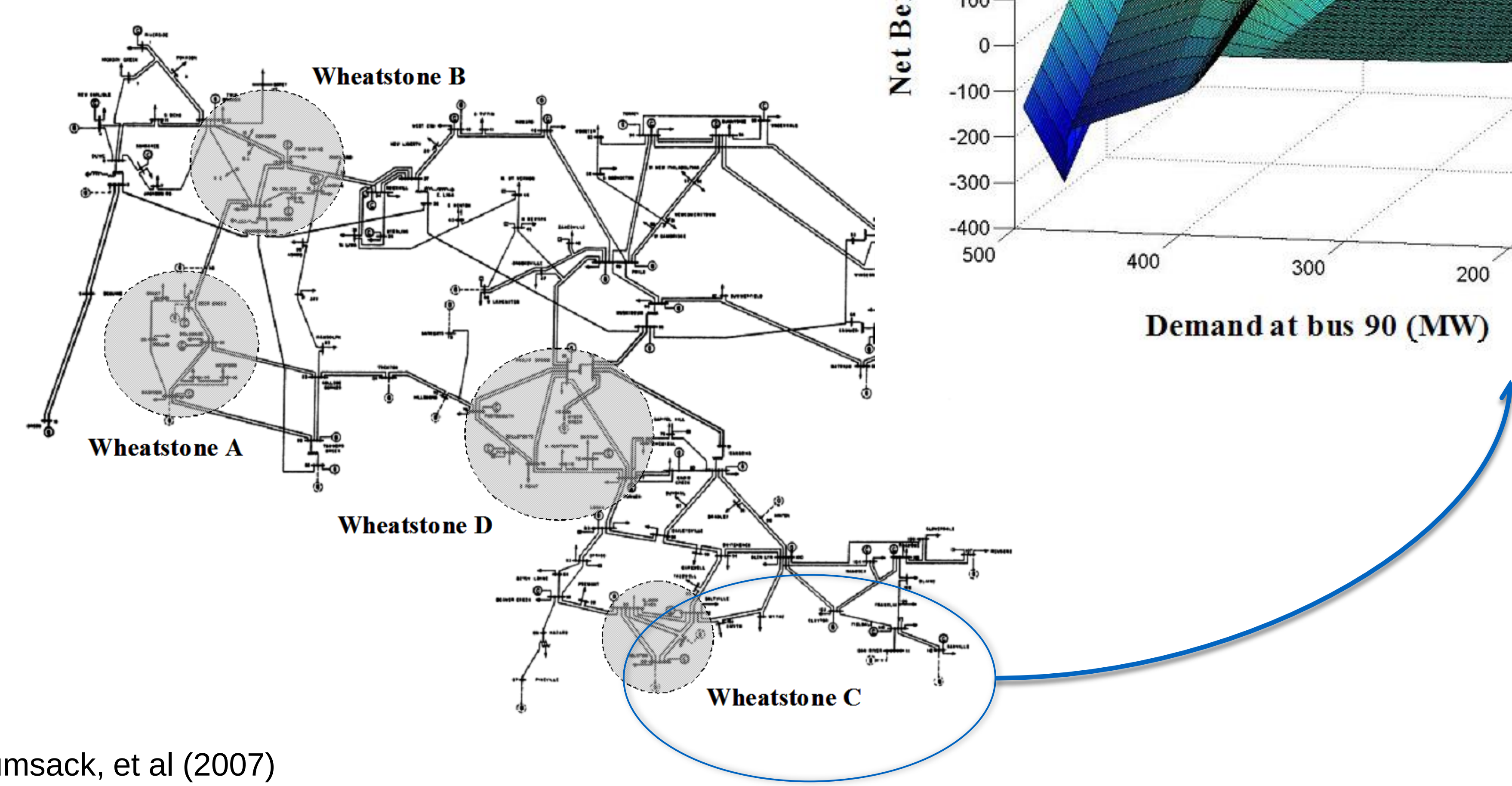
Or maybe the transition should look like this



What We (Kind of) Understand: The Risk-Cost Nature of Connectivity

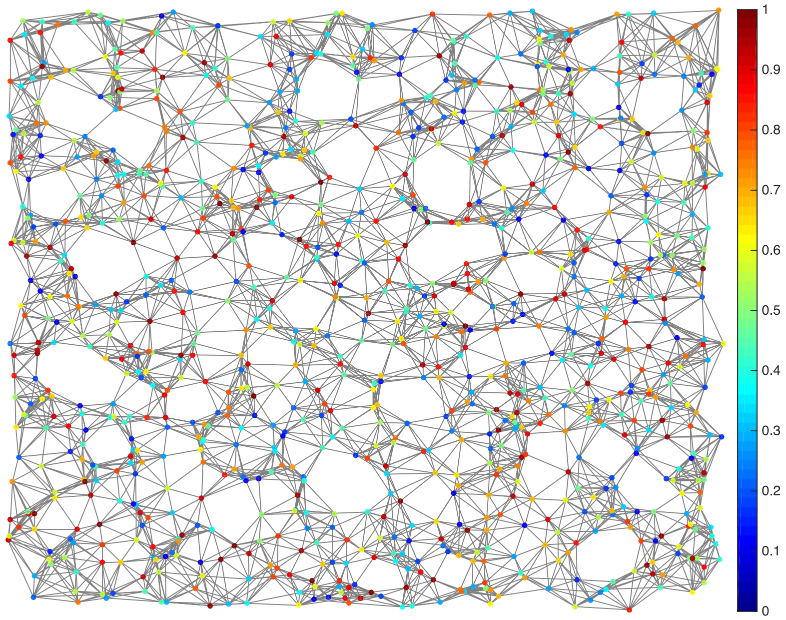
Power grids are particularly susceptible to the ‘Braess Paradox’ – connections built for redundancy can degrade operational efficiency.

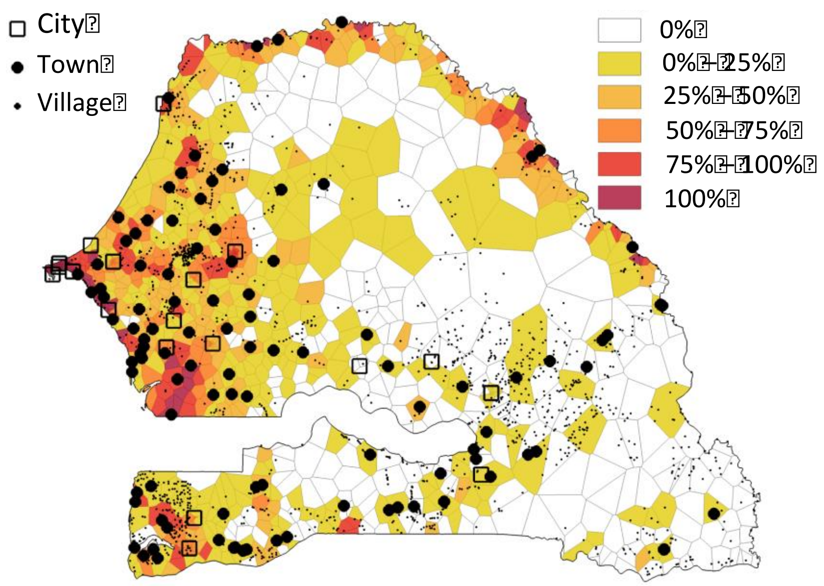


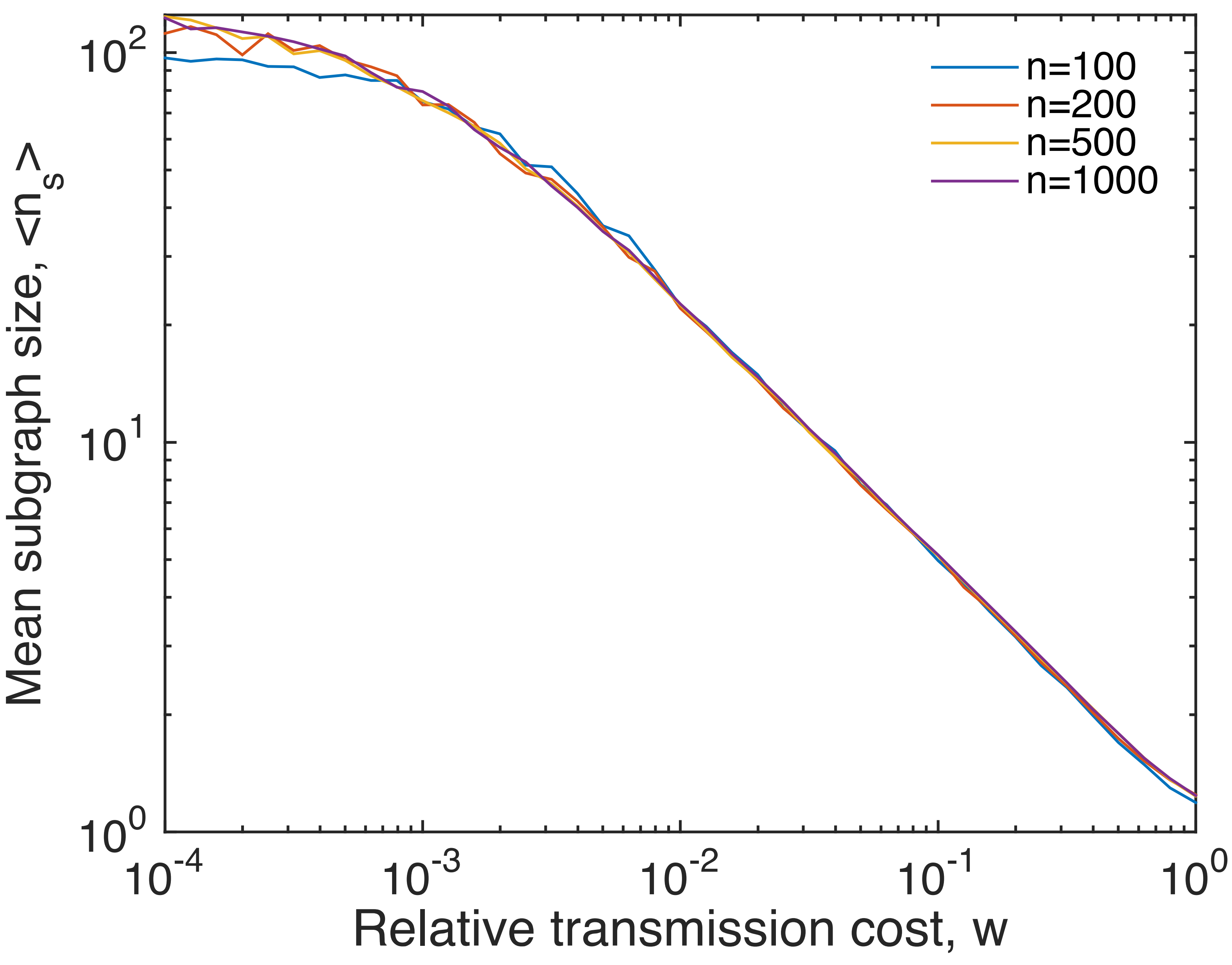


Blumsack, et al (2007)

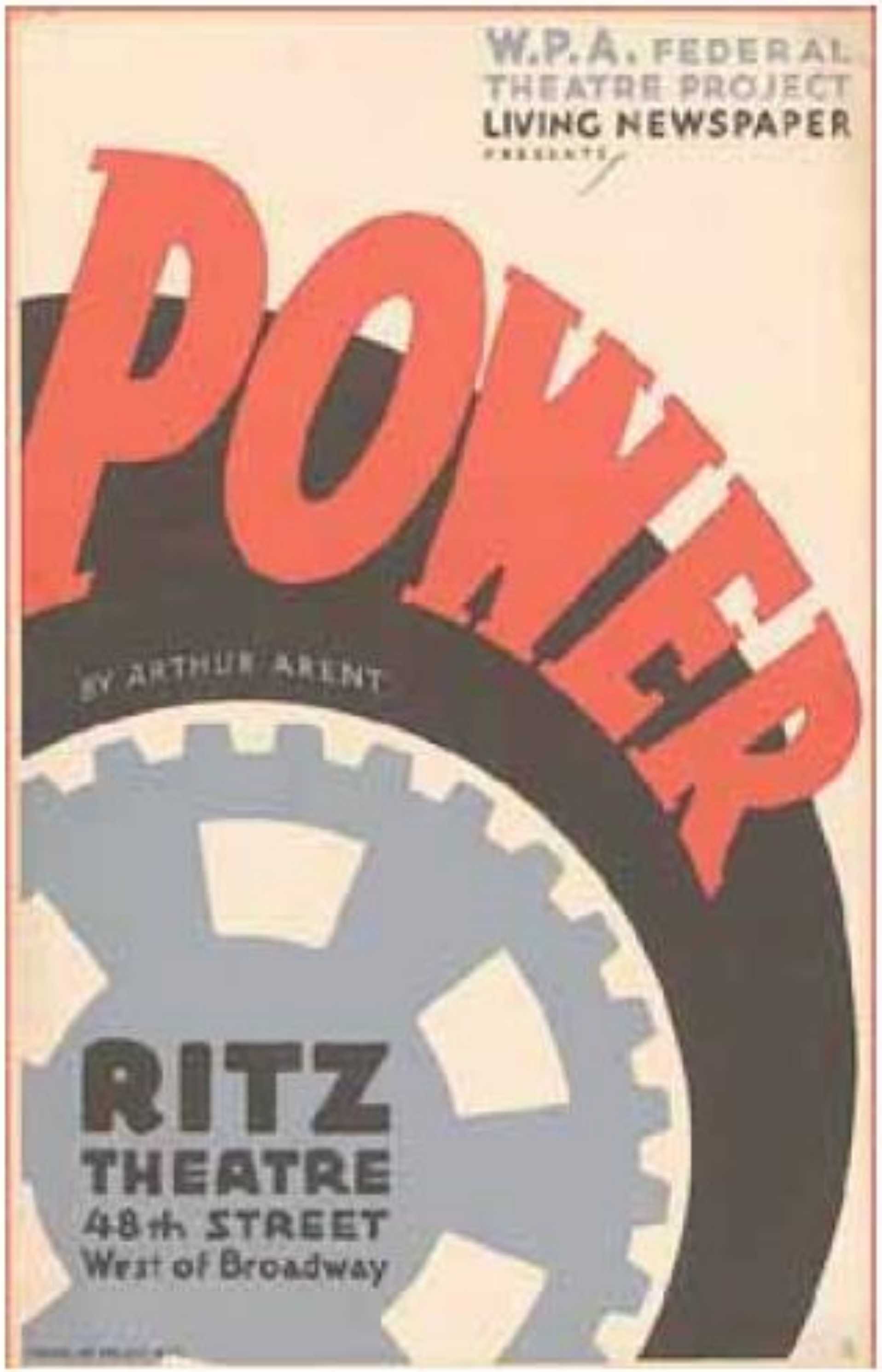
"Centralized" vs "Decentralized" is Never Optimal

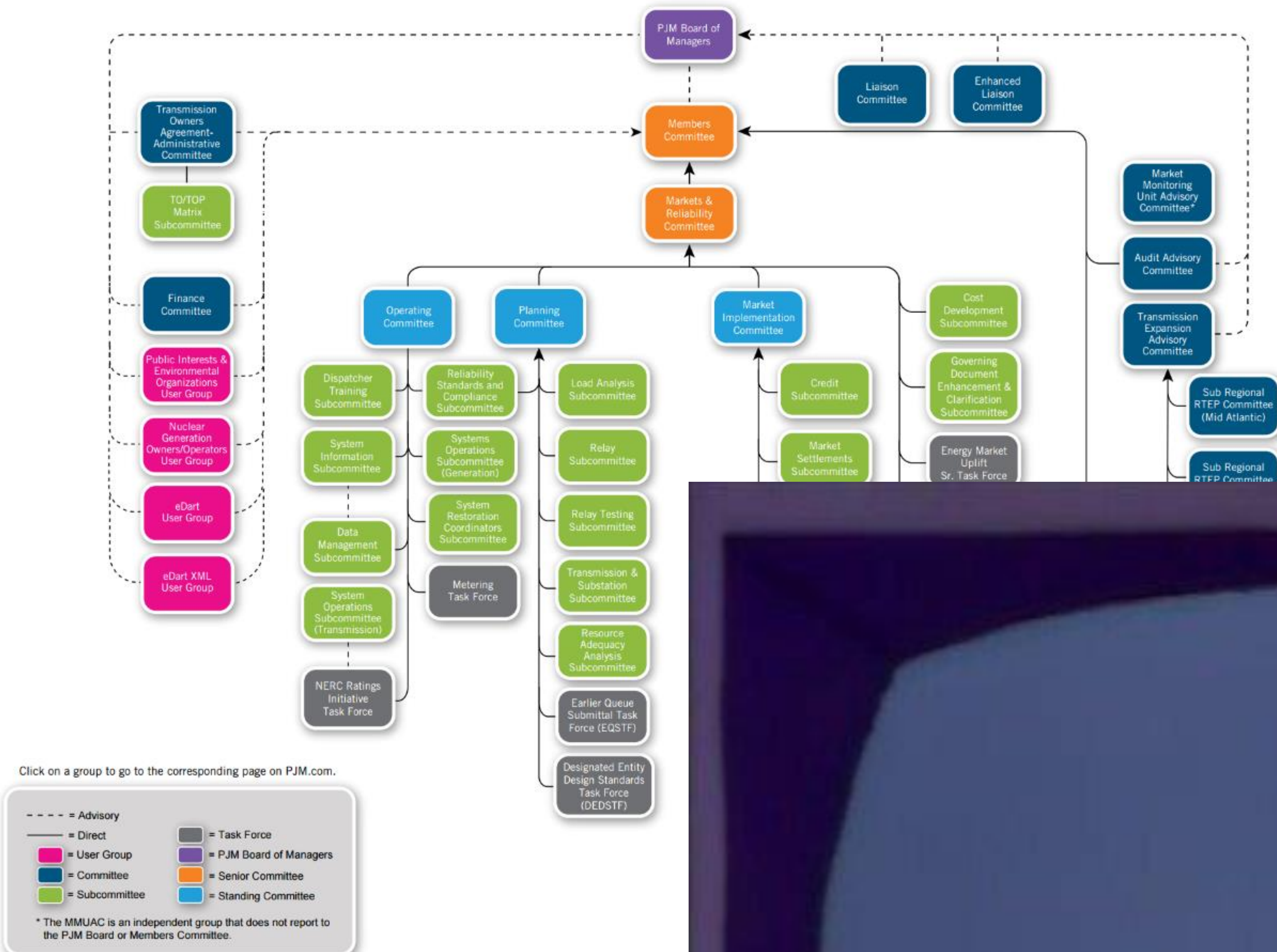






Electrons Have a Social Side!




PJM Board of Managers
Liaison Committee
Enhanced Liaison Committee
Transmission Owners Agreement-Administrative Committee
Members Committee
TO/TOP Matrix Subcommittee
Markets & Reliability Committee
Market Monitoring Unit Advisory Committee*
Finance Committee
Audit Advisory Committee
Transmission Expansion Advisory Committee
Operating Committee
Planning Committee
Market Implementation Committee
Cost Development Subcommittee
Public Interests & Environmental Organizations User Group
Dispatcher Training Subcommittee
Reliability Standards and Compliance Subcommittee
Load Analysis Subcommittee
Credit Subcommittee
Governing Document Enhancement & Clarification Subcommittee
Sub Regional RTEP Committee (Mid Atlantic)
Nuclear Generation Owners/Operators User Group
System Information Subcommittee
Systems Operations Subcommittee (Generation)
Relay Subcommittee
Market Settlements Subcommittee
Energy Market Uplift Sr. Task Force
Sub Regional RTEP Committee
eDart User Group
Data Management Subcommittee
System Restoration Coordinators Subcommittee
Relay Testing Subcommittee
eDart XML User Group
System Operations Subcommittee (Transmission)
Metering Task Force
Transmission & Substation Subcommittee
Resource Adequacy Analysis Subcommittee
NERC Ratings Initiative Task Force
Earlier Queue Submittal Task Force (EQSTF)
Designated Entity Design Standards Task Force (DEDSTF)
Click on a group to go to the corresponding page on PJM.com.
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= Direct
= User Group
= Committee
= Subcommittee
= Task Force
= PJM Board of Managers
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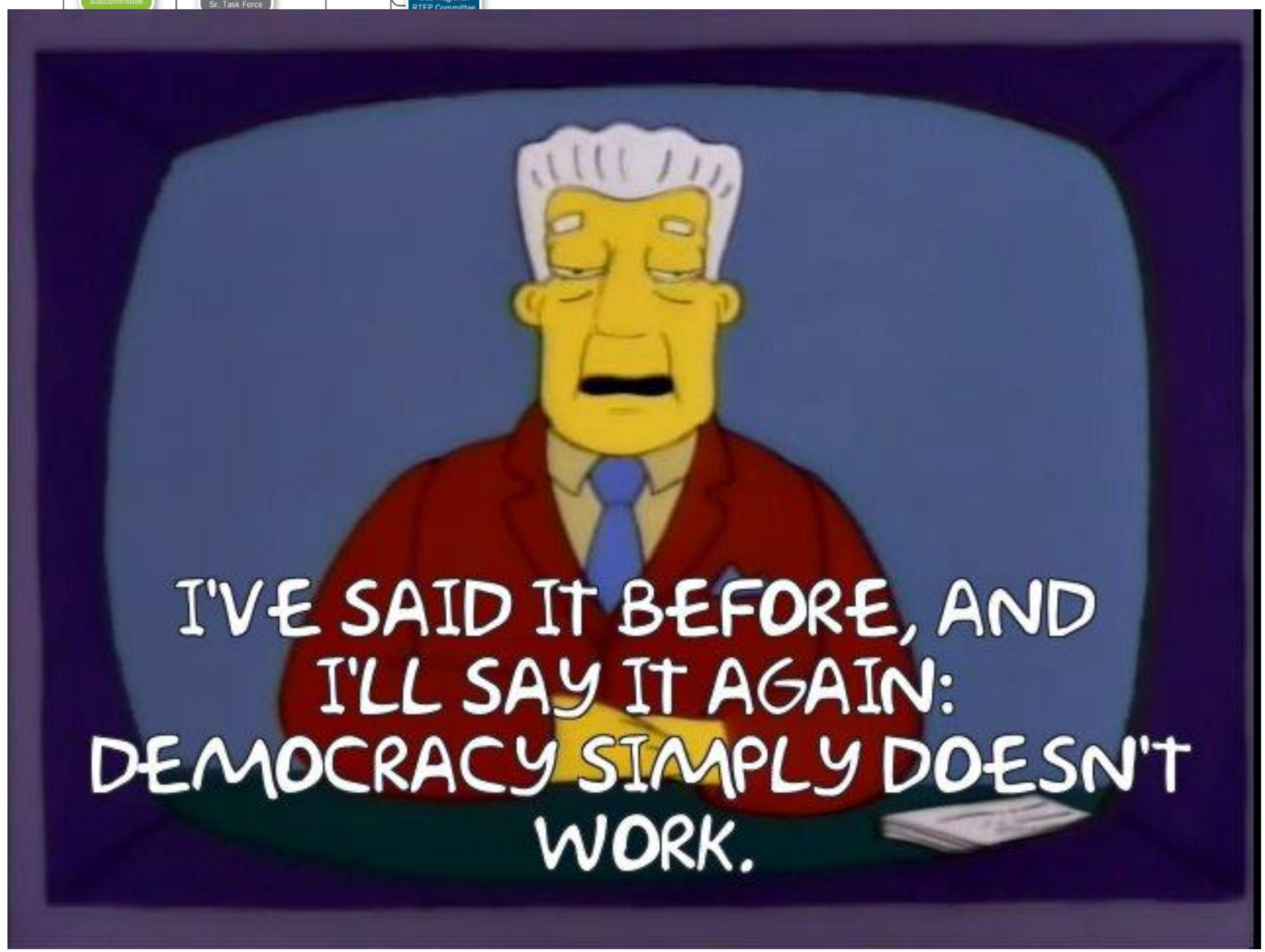
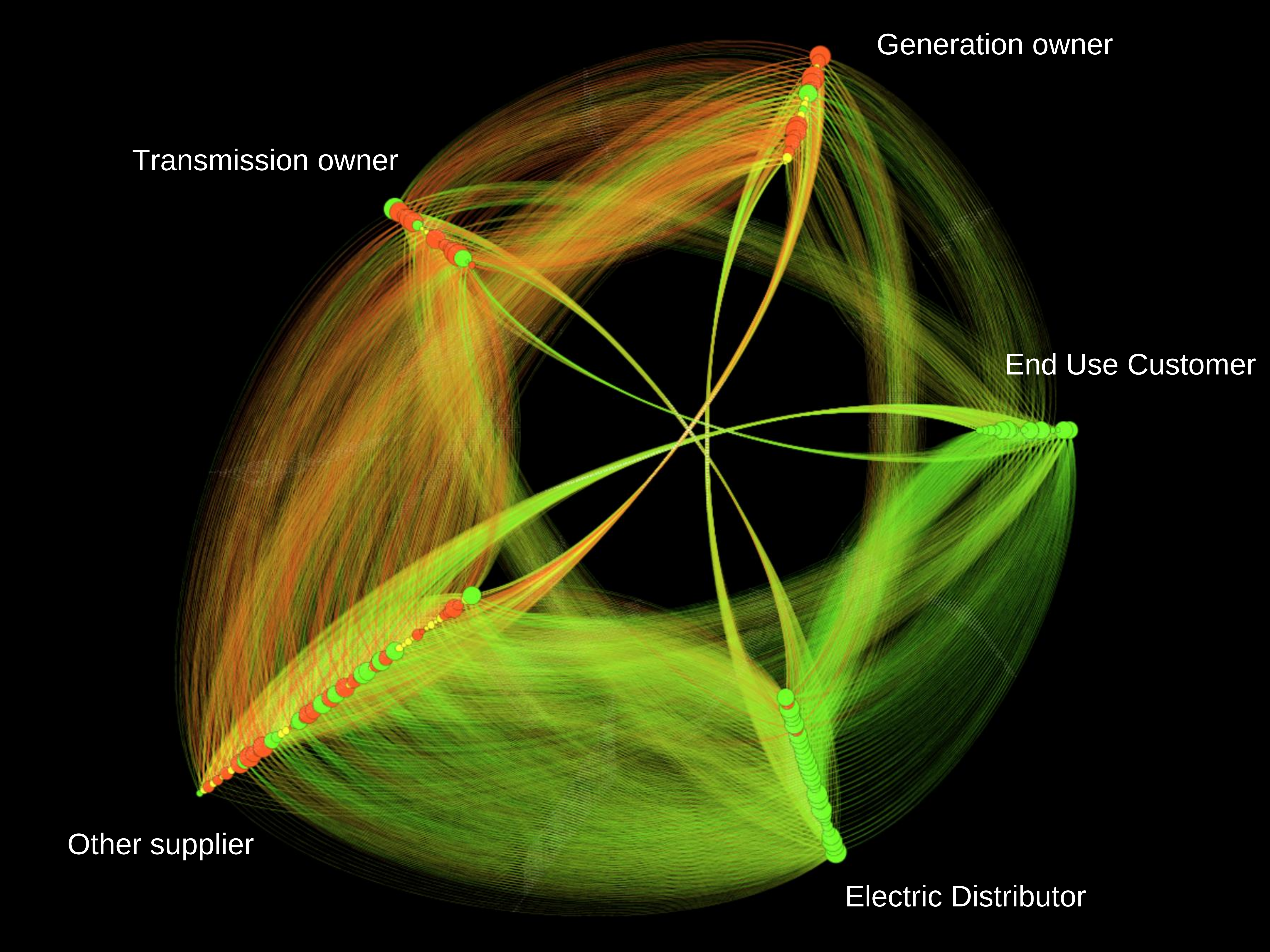
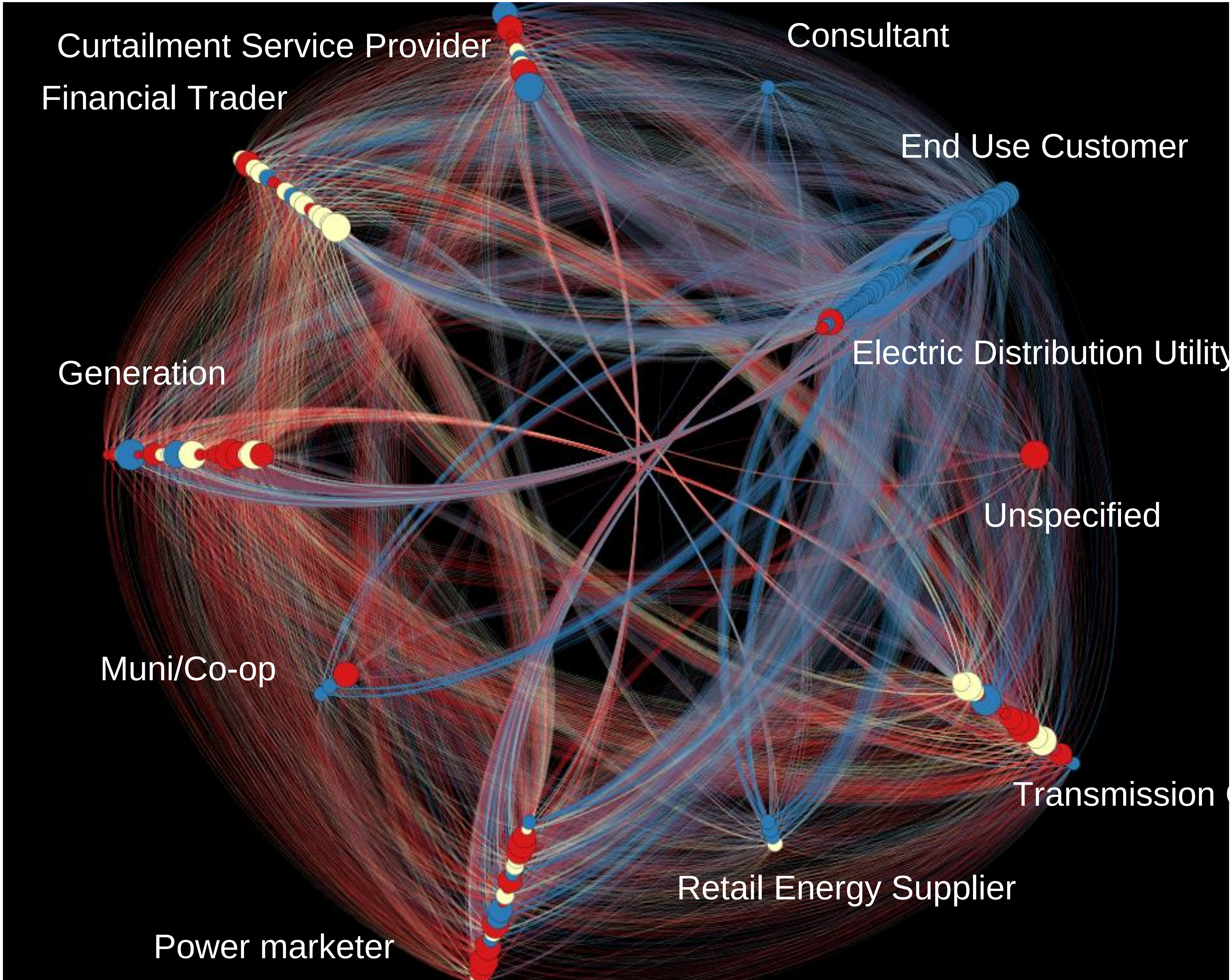
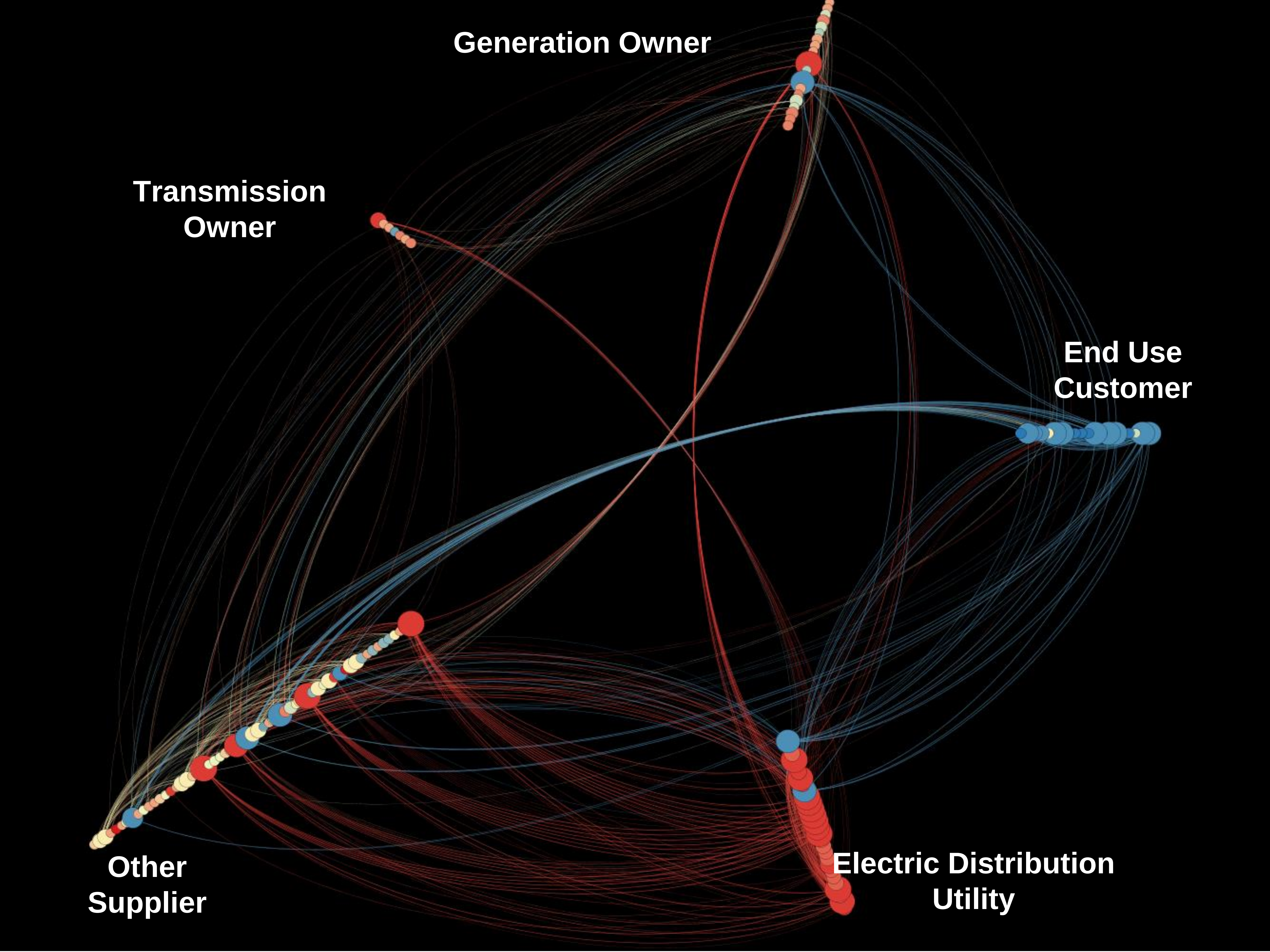
= Standing Committee
* The MMUAC is an independent group that does not report to the PJM Board or Members Committee.

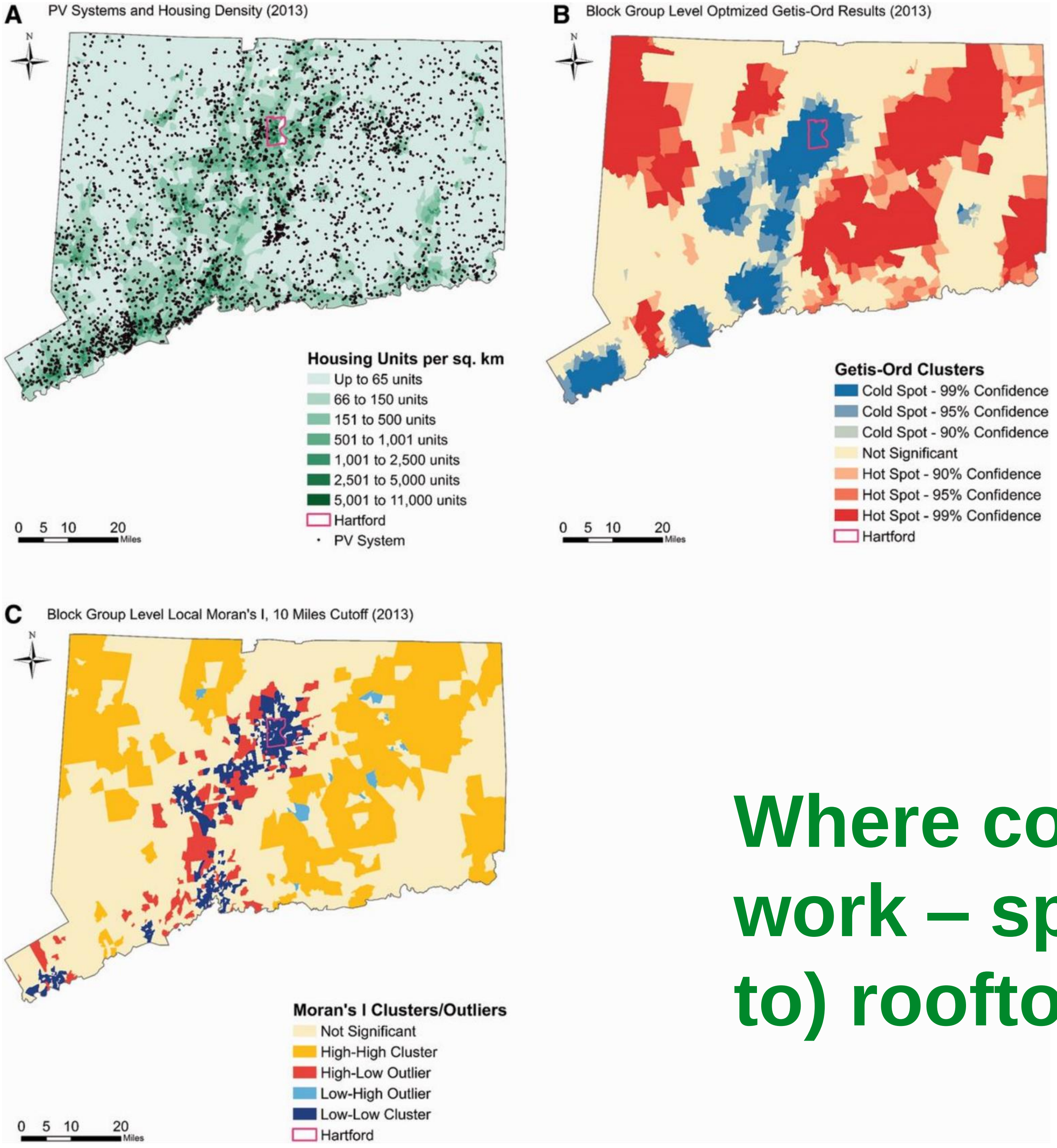

I'VE SAID IT BEFORE, AND I'LL SAY IT AGAIN: DEMOCRACY SIMPLY DOESN'T WORK.


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

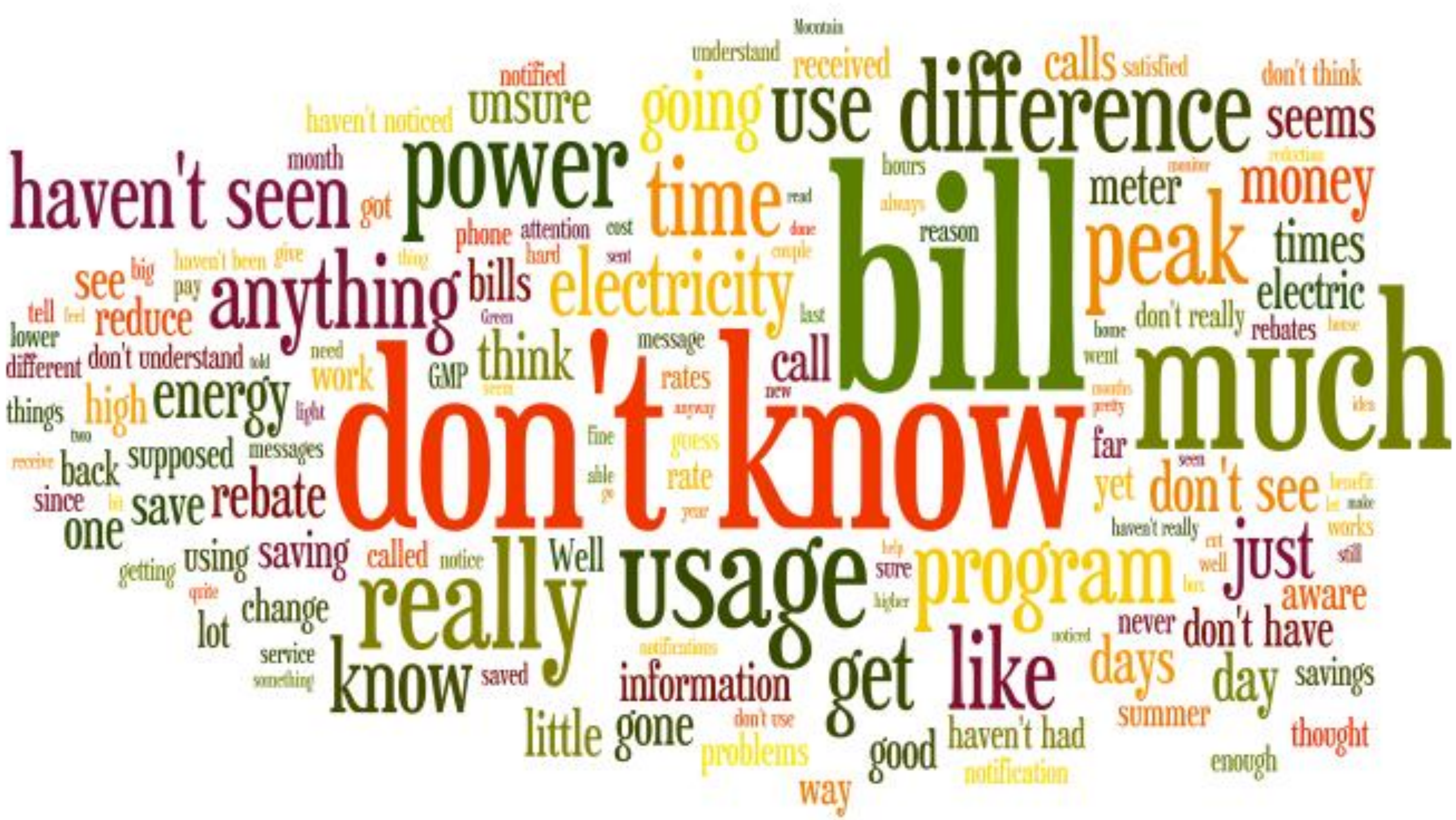

Generation Owner
Transmission Owner
End Use Customer
Other Supplier
Electric Distribution Utility



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

Source: Graziano and Gillingham

Engaging (but not confusing, exacerbating) the consumer



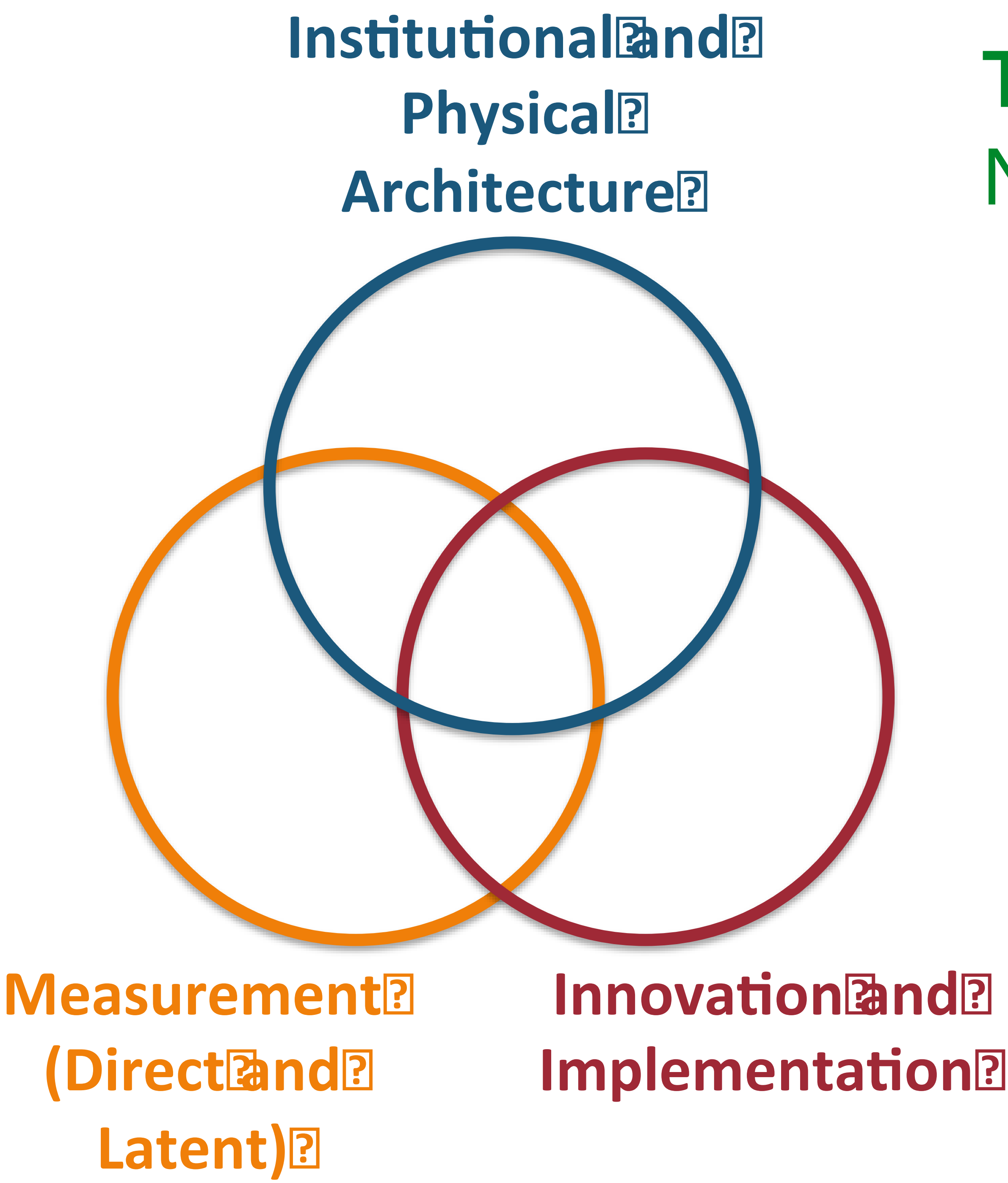
Making the Rules = Blood Sport

"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!

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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