

# The Power Grid and Complexity Science

Single  
Engaged  
Divorced  
✓ **It's Complicated**  
Separated  
In a Relationship  
Married

Santa Fe Institute  
Complex Systems  
Summer School

*Seth Blumsack,  
Penn State*

*sab51@psu.edu*

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

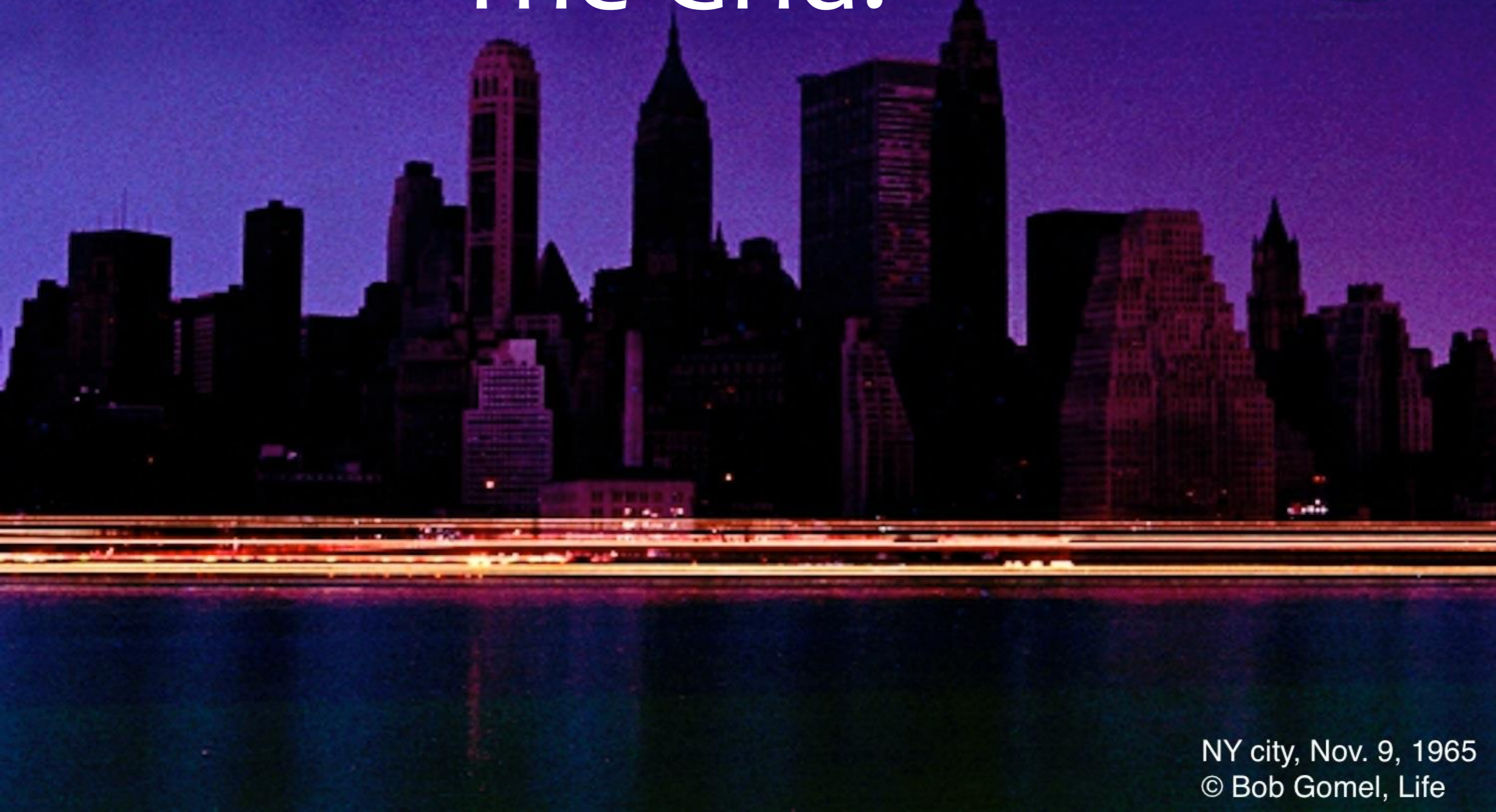
1. We can't agree on what the “structure” of the power grid looks like.

1a. This probably doesn't matter.

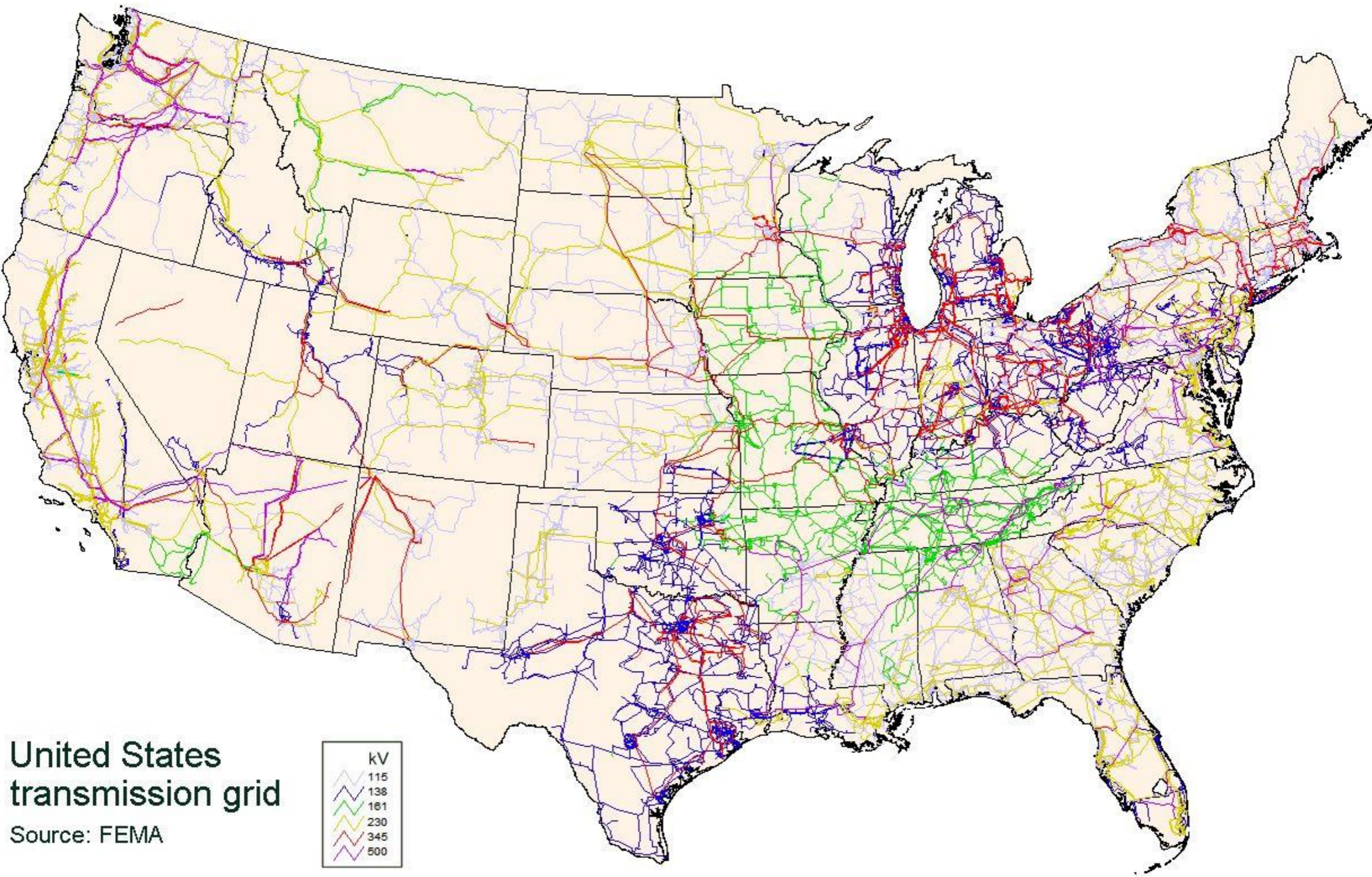
2. Why not? Propagation of disturbances in power grids is not like disease, or information, or...really anything.

3. Electrons are highly social creatures.

# The Grid!

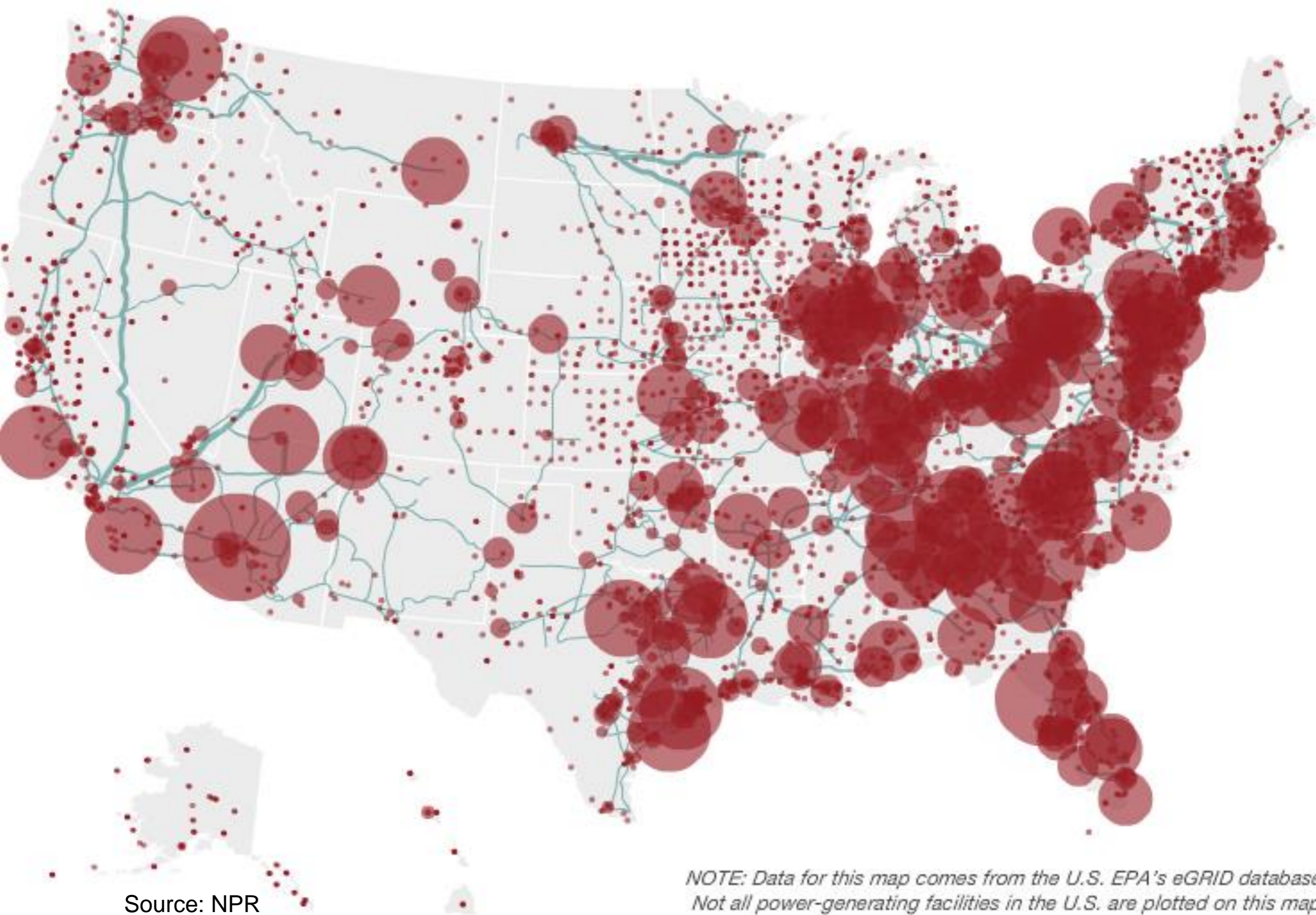


NY city, Nov. 9, 1965  
© Bob Gomel, Life



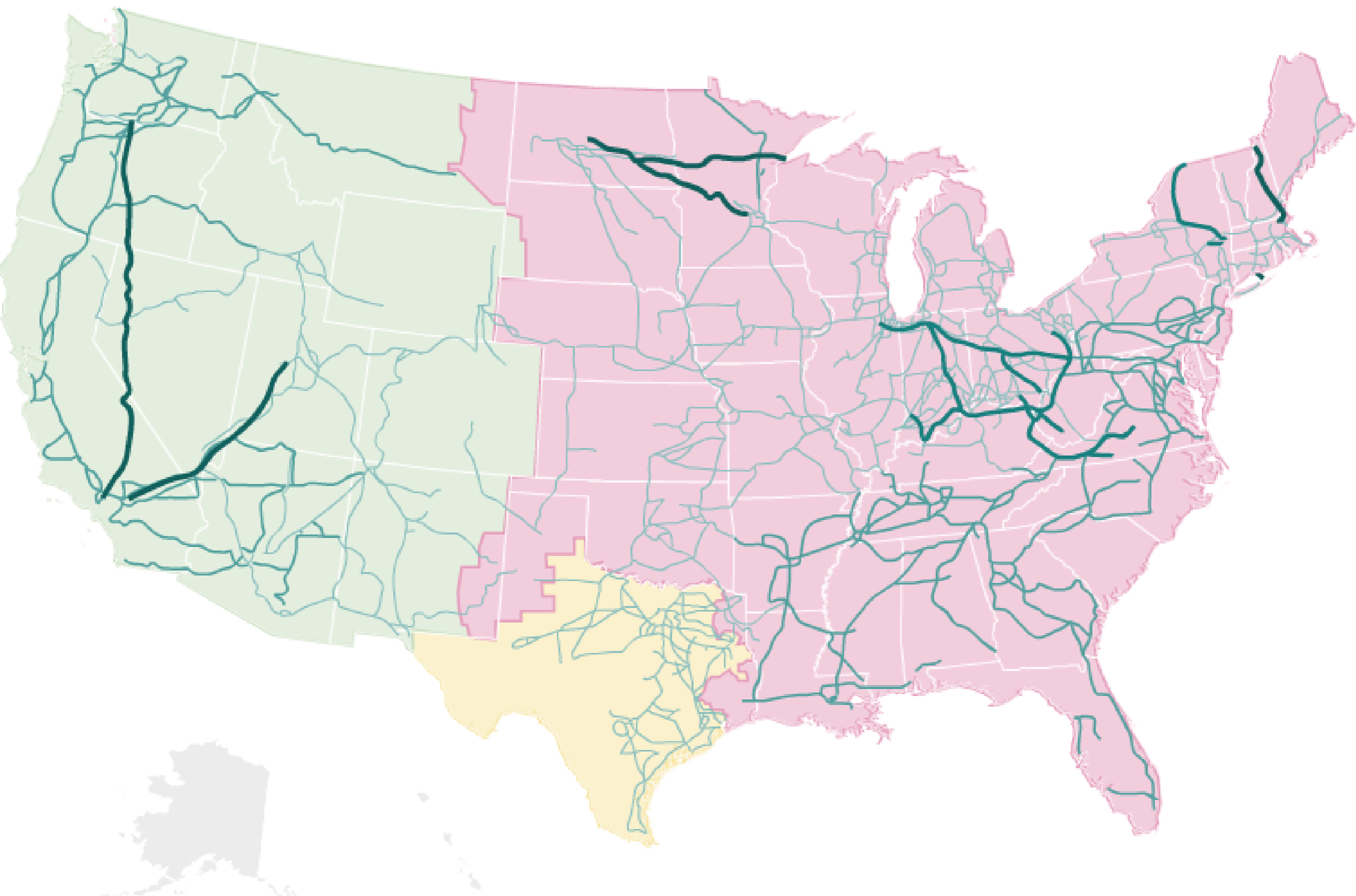
United States  
transmission grid

Source: FEMA



Source: NPR

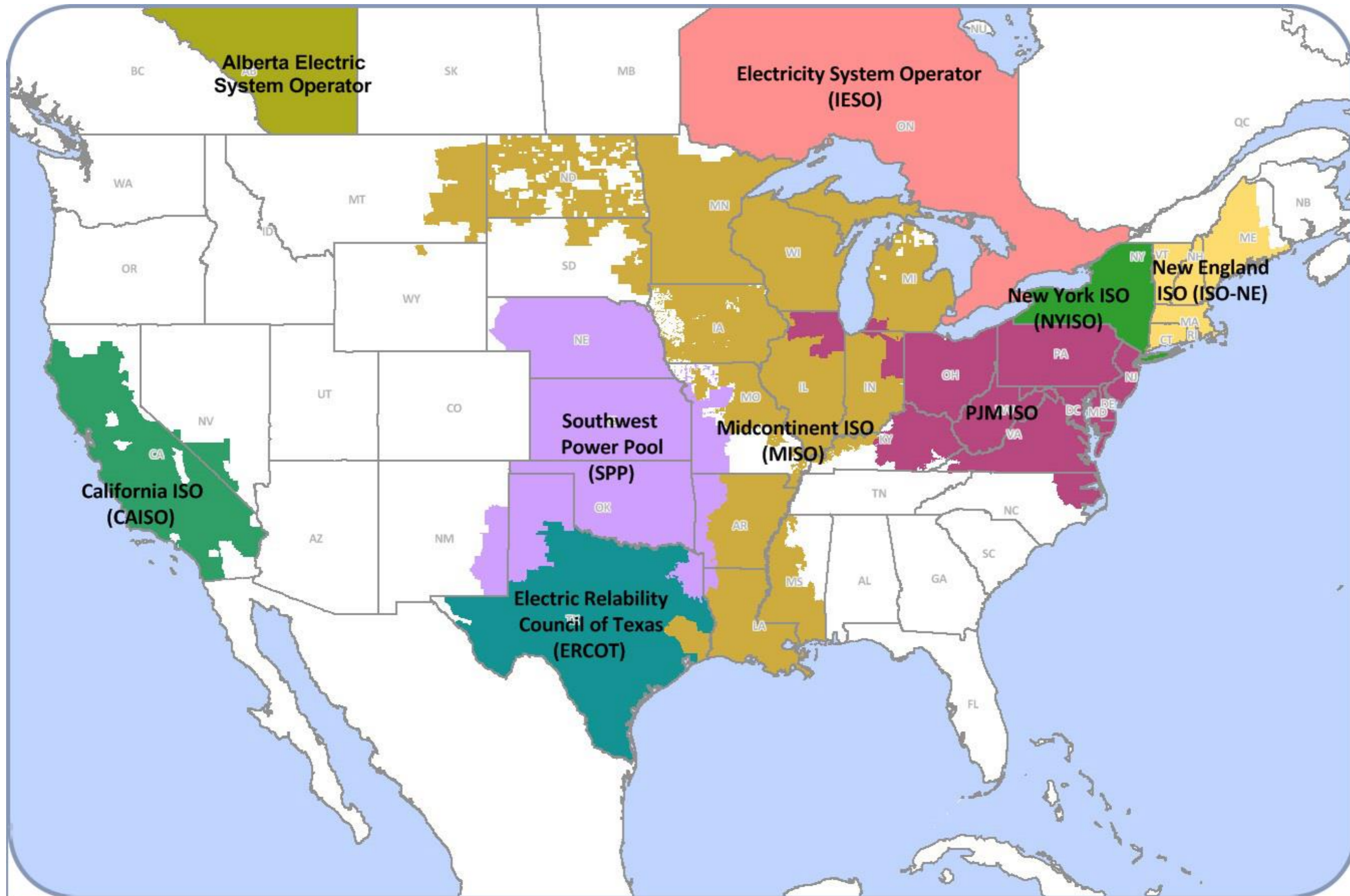
*NOTE: Data for this map comes from the U.S. EPA's eGRID database.  
Not all power-generating facilities in the U.S. are plotted on this map.*



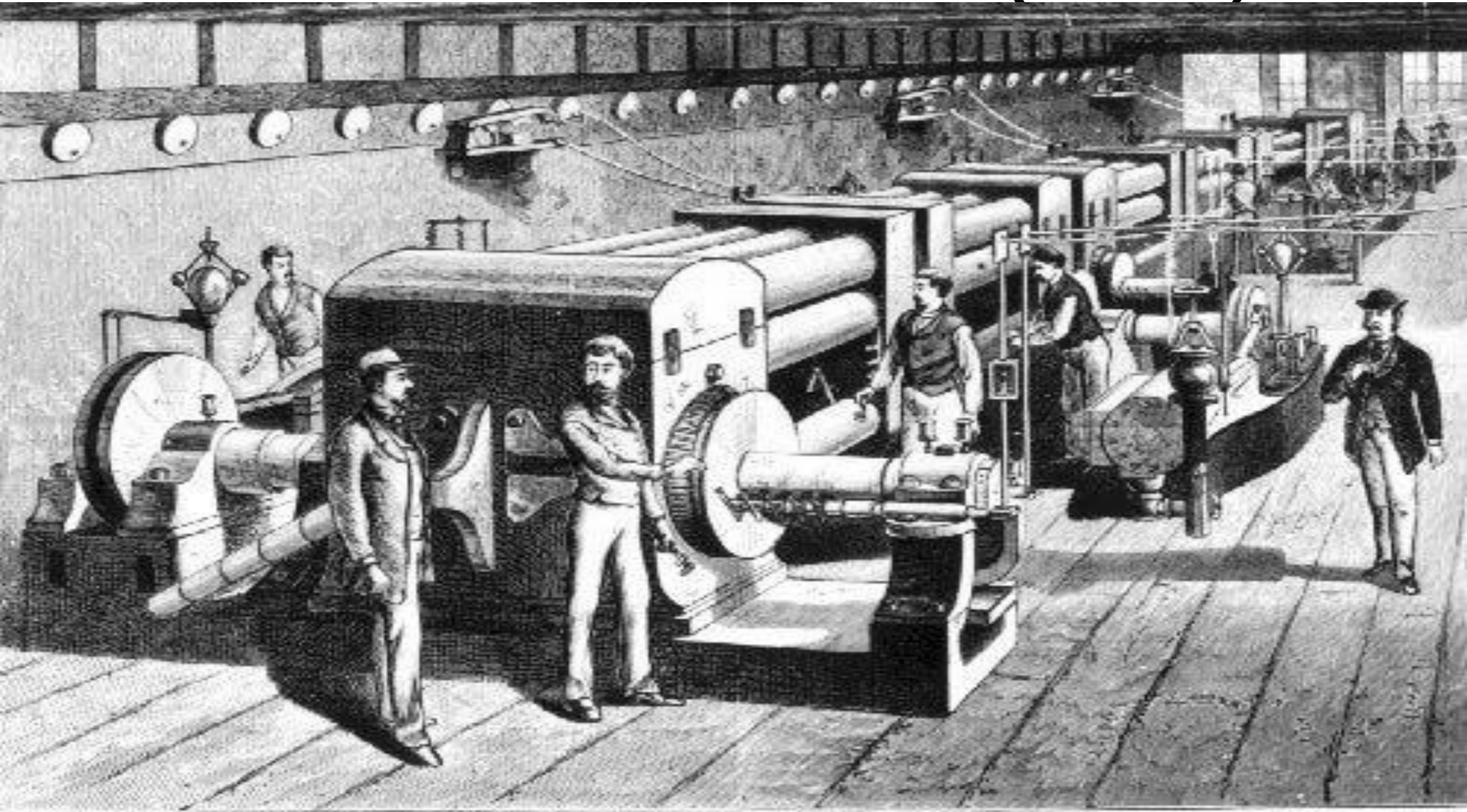
Source: NPR



# North American Regional Transmission Organizations

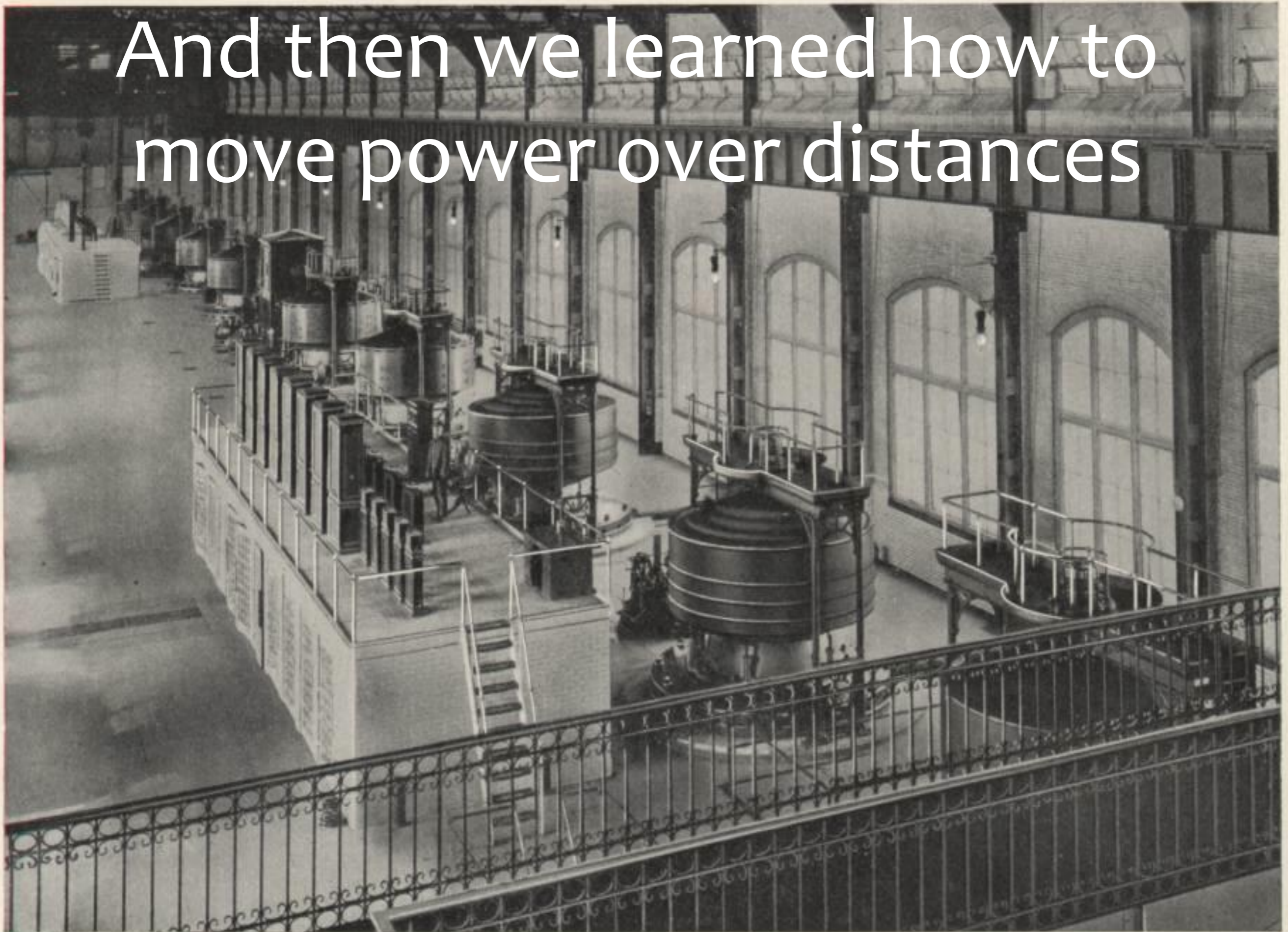


# Things started decentralized: Pearl-street station (1882)

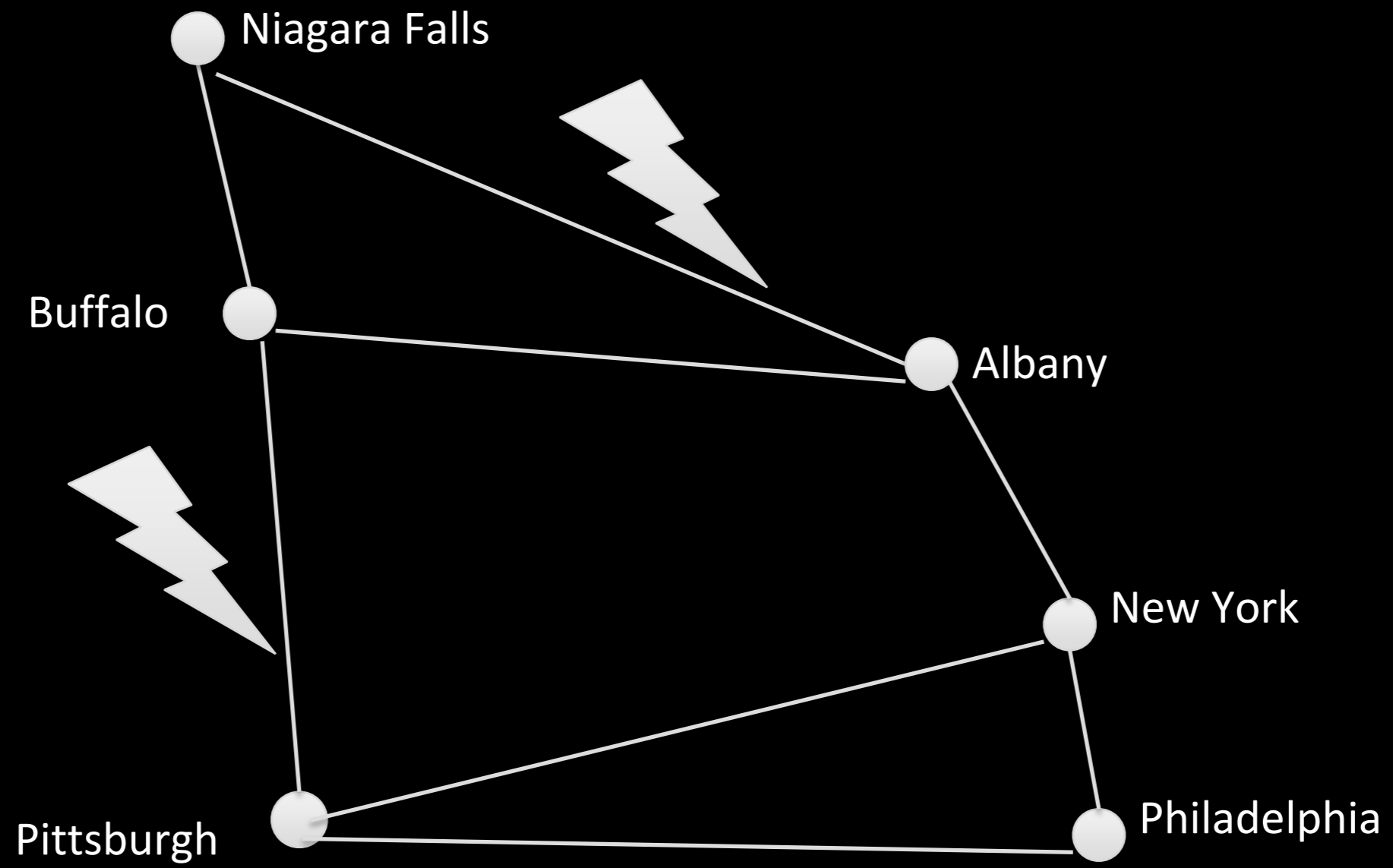


THE DYNAMO ROOM.  
FIRST EDISON ELECTRIC LIGHTING STATION IN NEW YORK.

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



# Things we know about power grids



The physics  
of generation

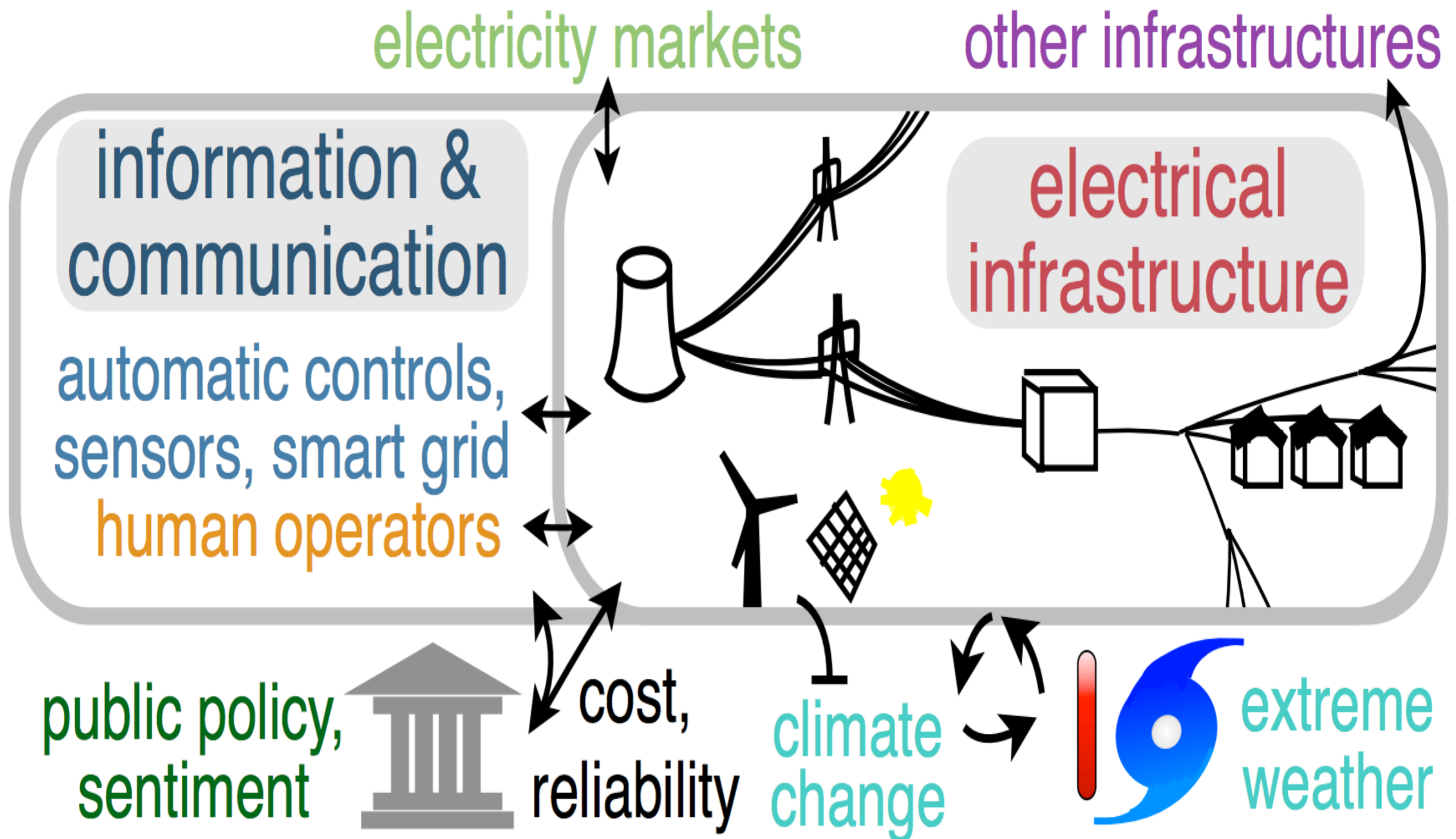


The physics of  
transmission

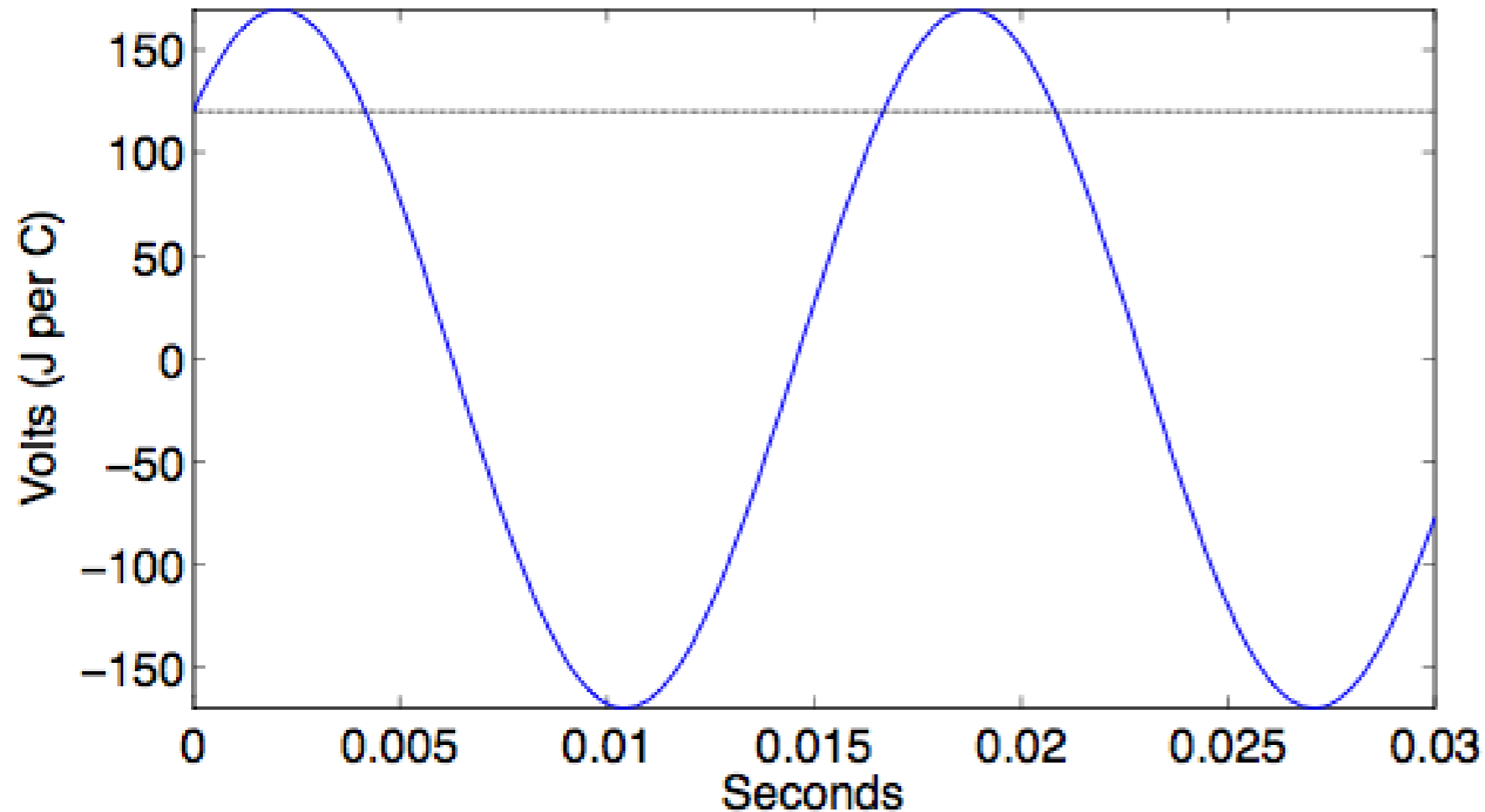


That they  
mostly work  
(note the simple  
interface)

# Things we don't know



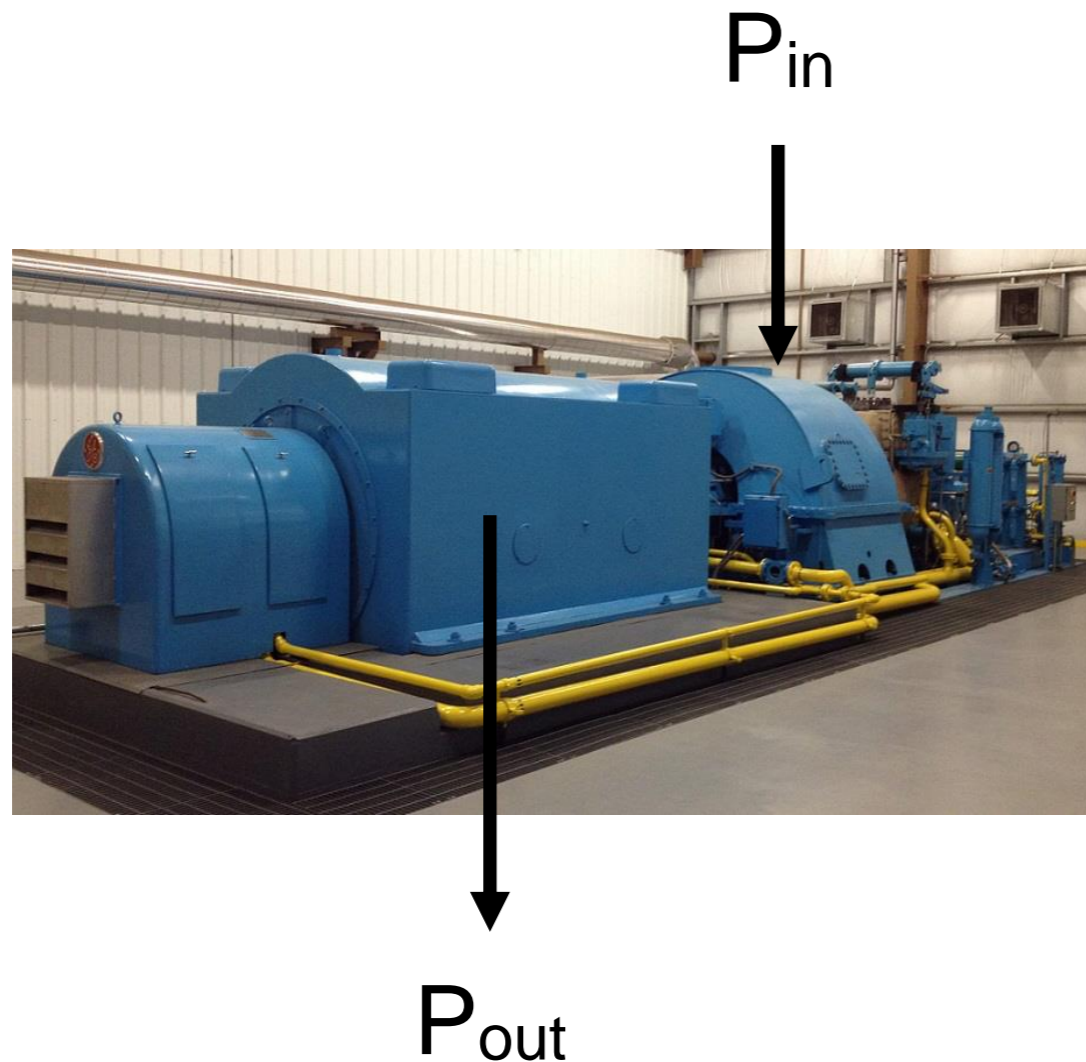
# Key principle #1



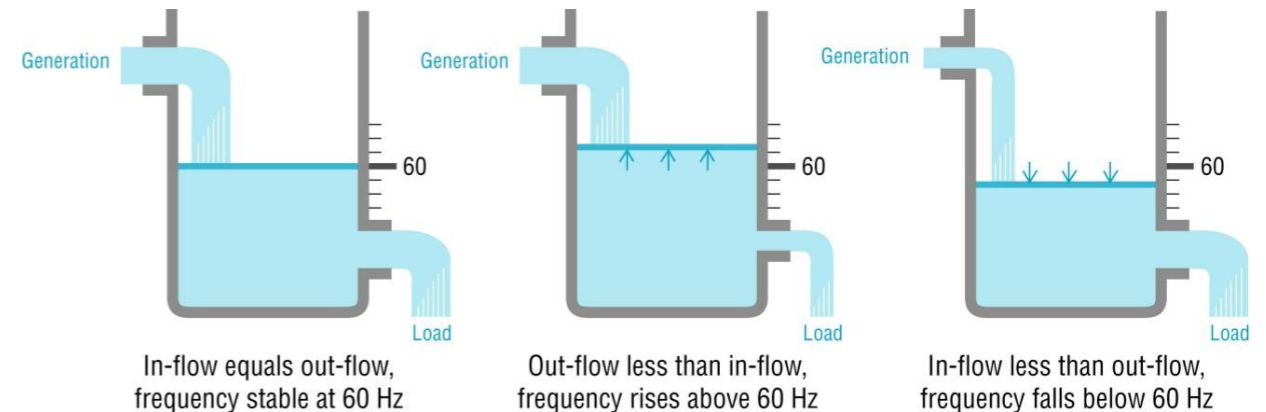
What goes in,  
must come out  
(there is no  
storage)

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

# Key principle #2



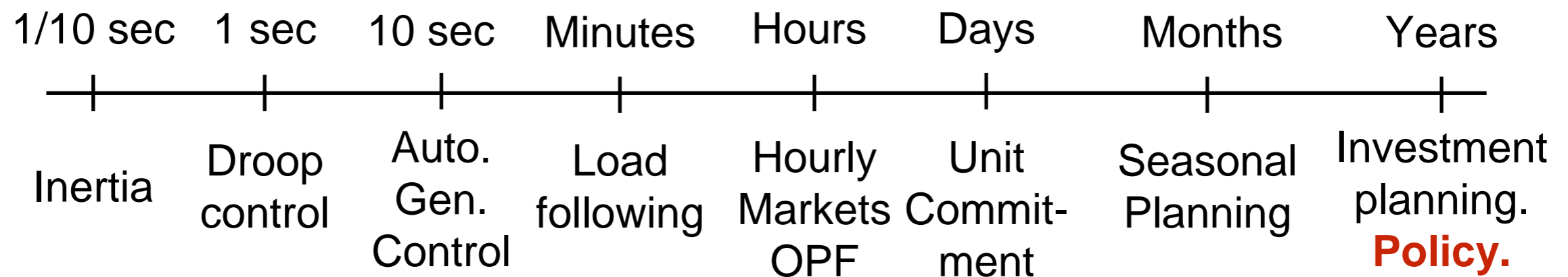
$$P_m = P_g + D\omega + M\dot{\omega}$$



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

# We have learned some things about managing this system

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



US Northeast and Canada  
August 14, 2003  
50 million people





California, Arizona, Mexico  
September 8, 2011  
5 million people



Northern India

July 30, 2012: 350 million people

July 31, 2012: 700 million people



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

# Bangladesh. 1 November 2014



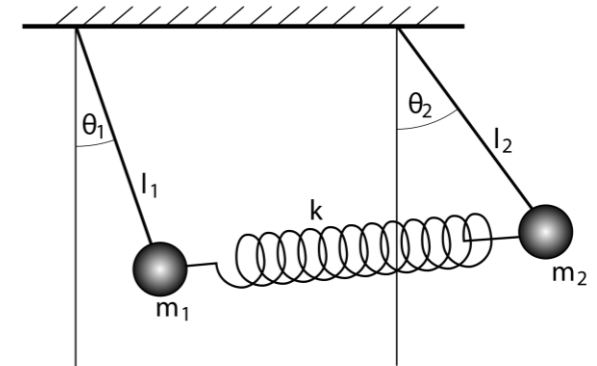
**Officials said it would take at least 12 hours to repair the system and restore power to the capital Dhaka [AP]**

Washington DC, April 7, 2015



# 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.

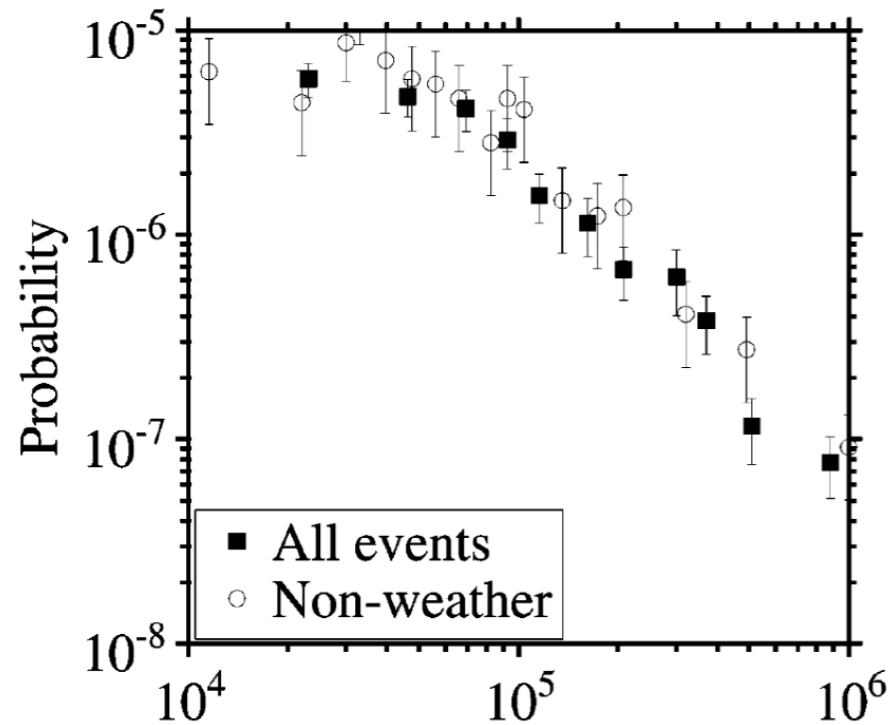


# Challenge #1: Hints of Complexity and the Struggle for Structure



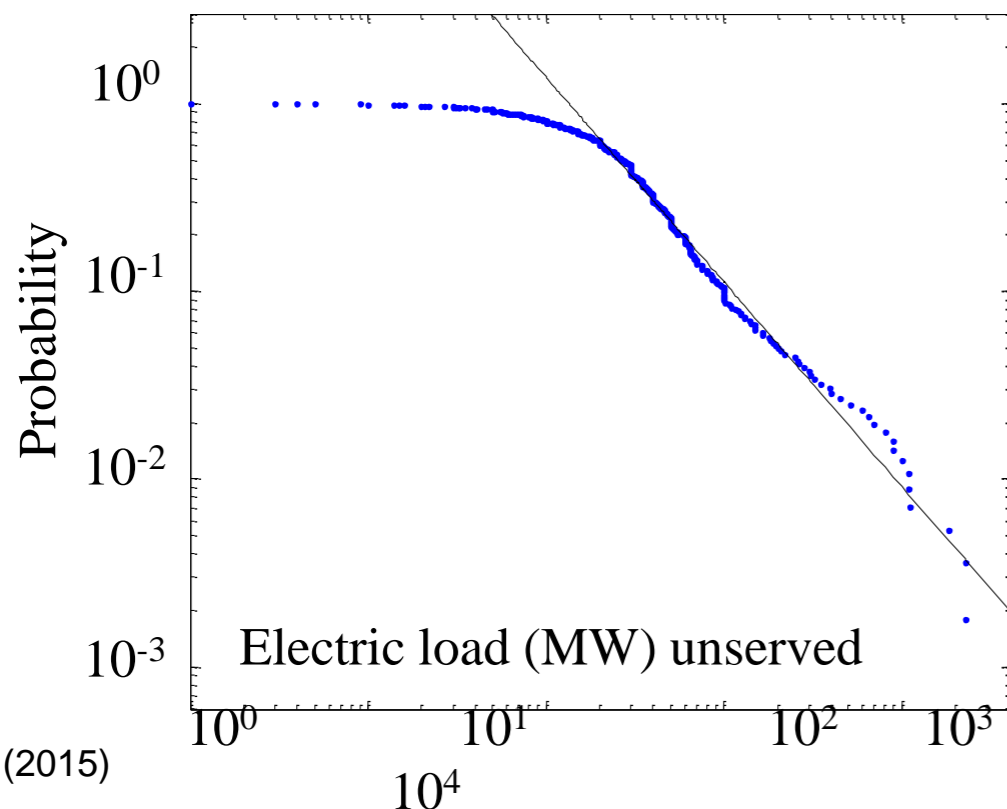
NY city, Nov. 9, 1965  
© Bob Gomel, Life

# Extreme Events



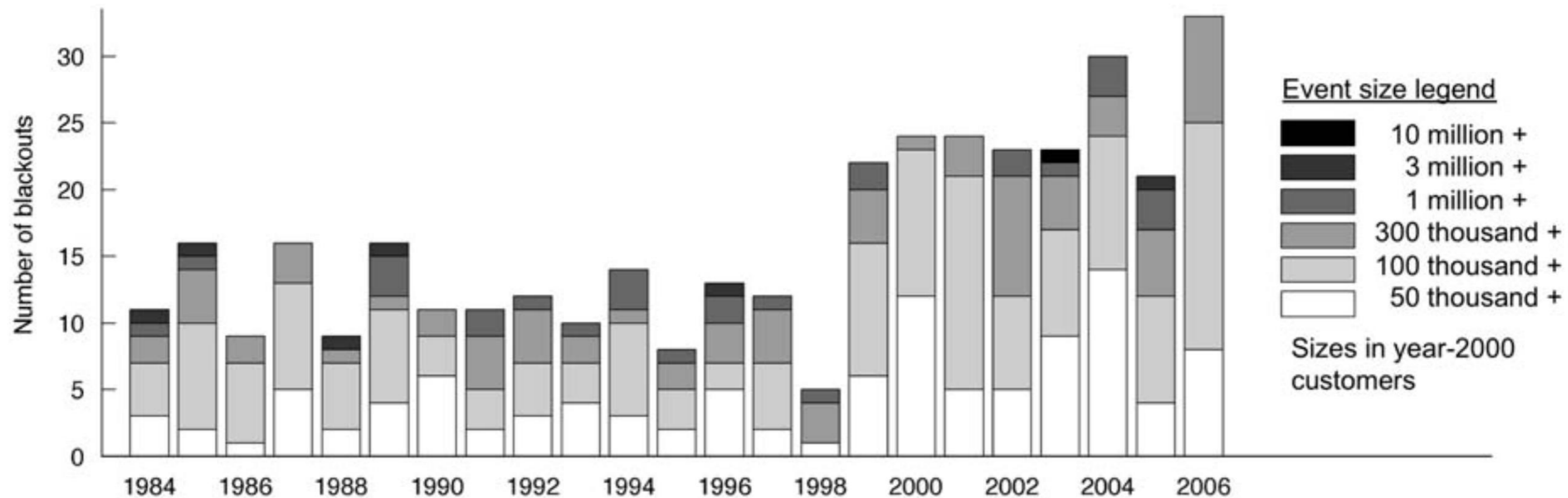
Carreras, et al. (2004) Customers unserved

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



Zhao (2015)

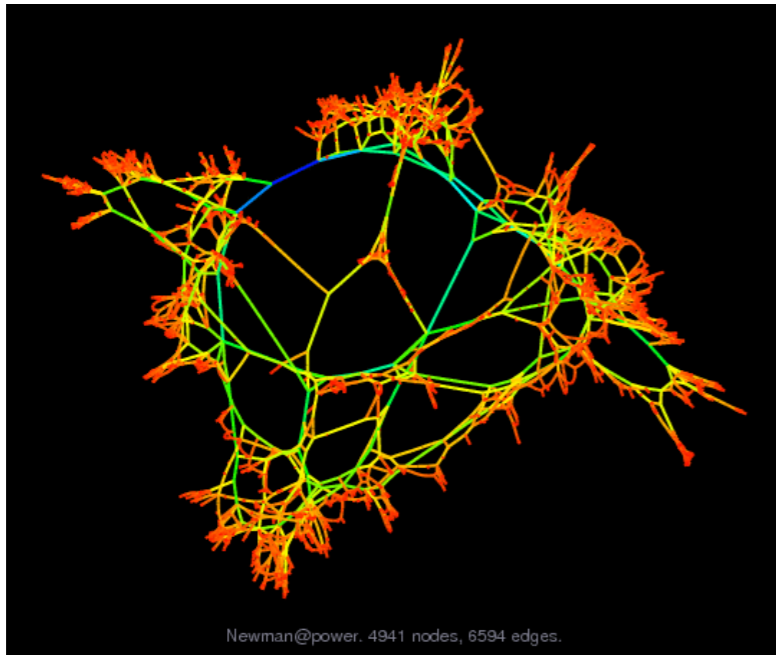
# Extreme Events



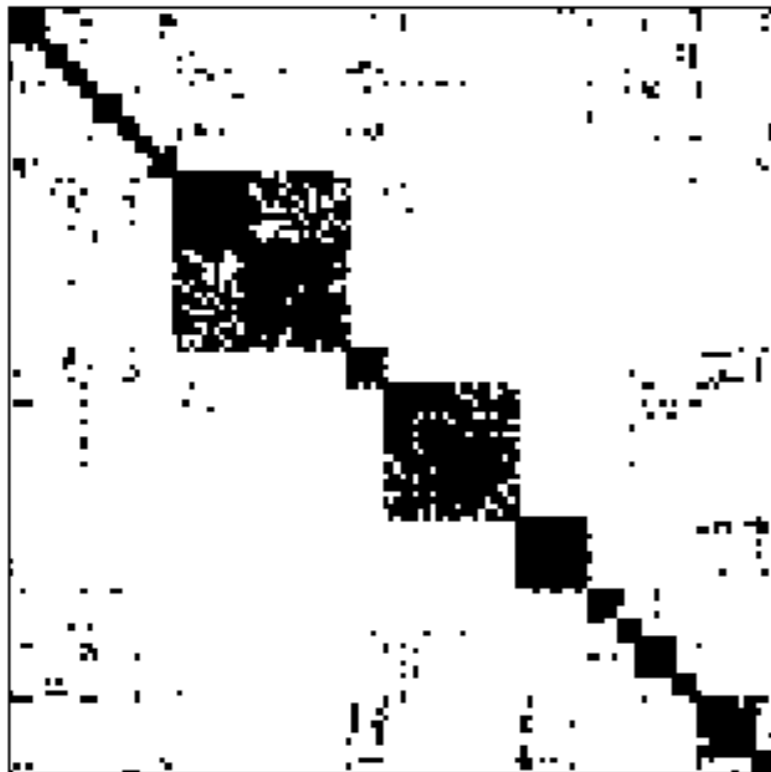
Hines, et al. (2008)

...And the frequency of large blackouts is not decreasing.

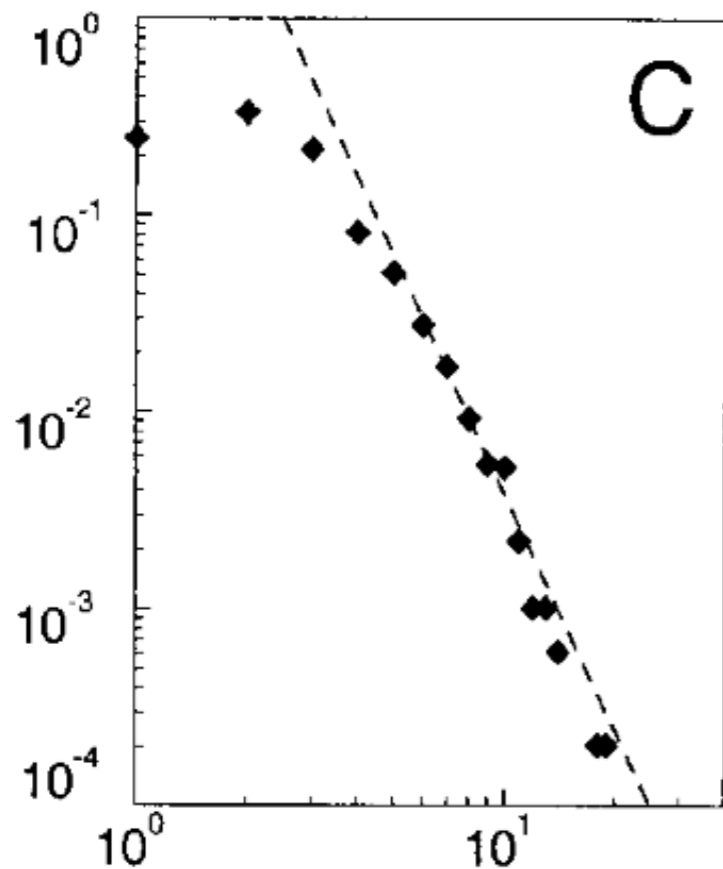
# Evidence for Small-World Structure



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

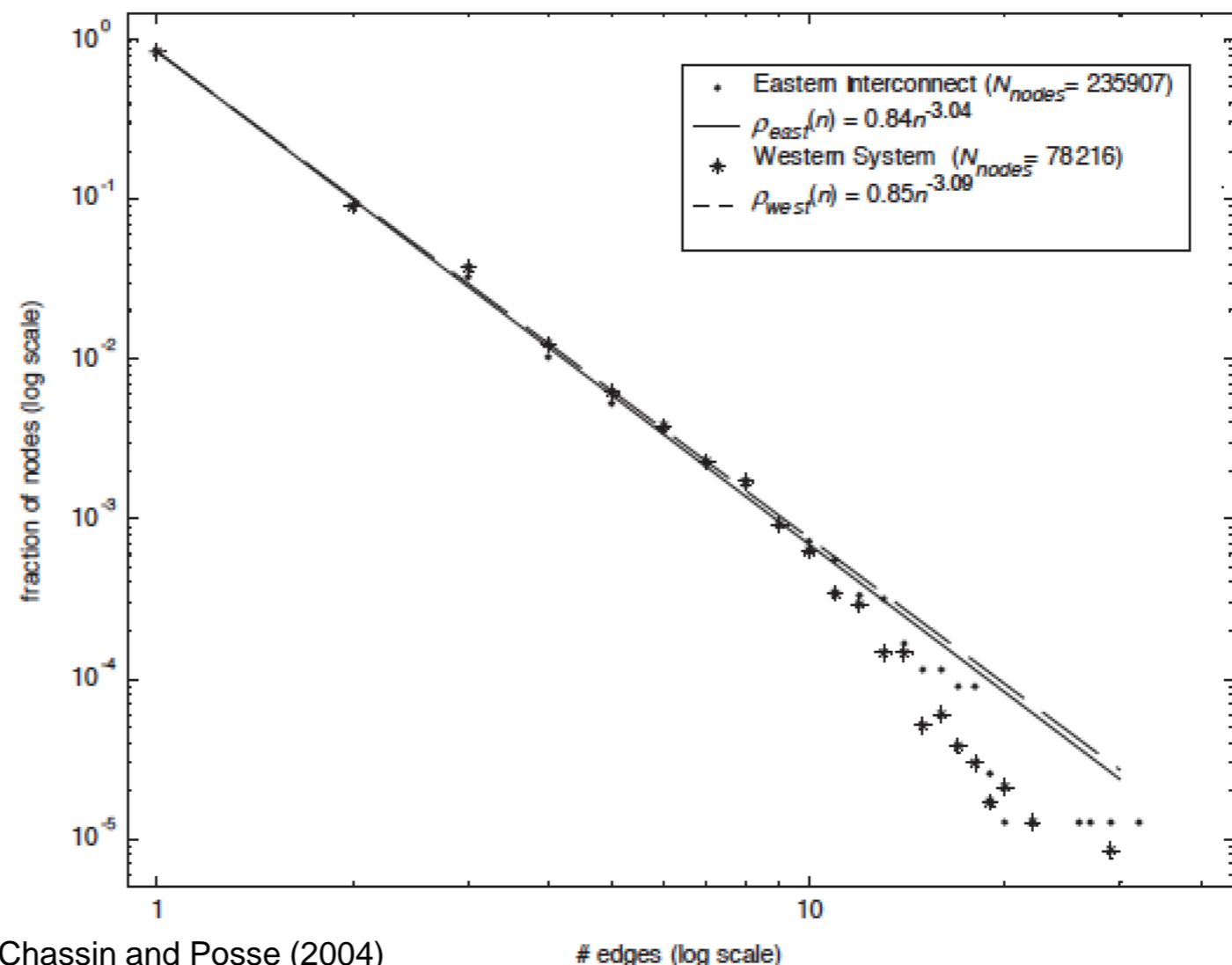


# Evidence for Scale-Free Structure



Barabasi and Albert (1999)

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

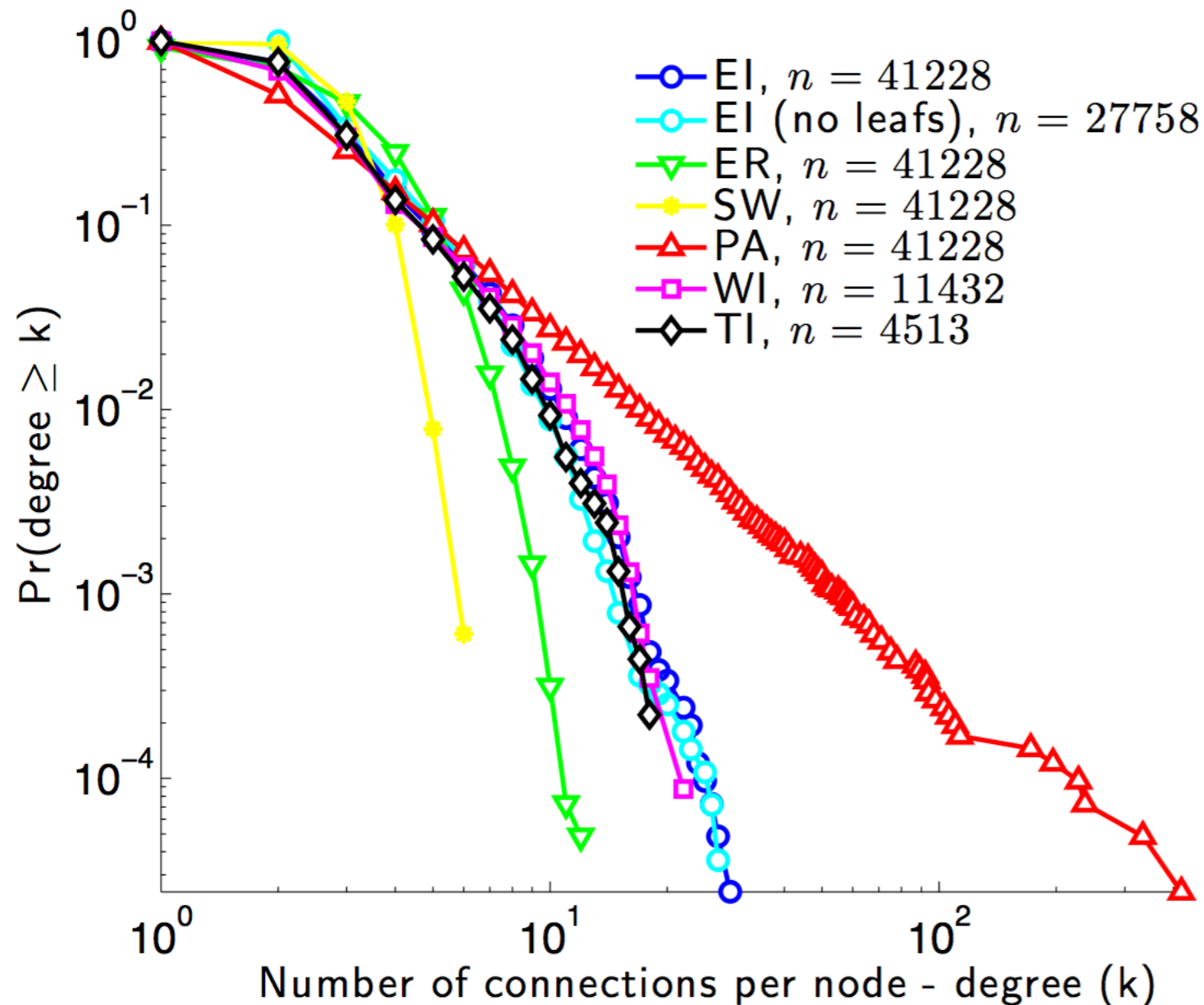


Chassin and Posse (2004)

# Any Evidence for Any Structure?

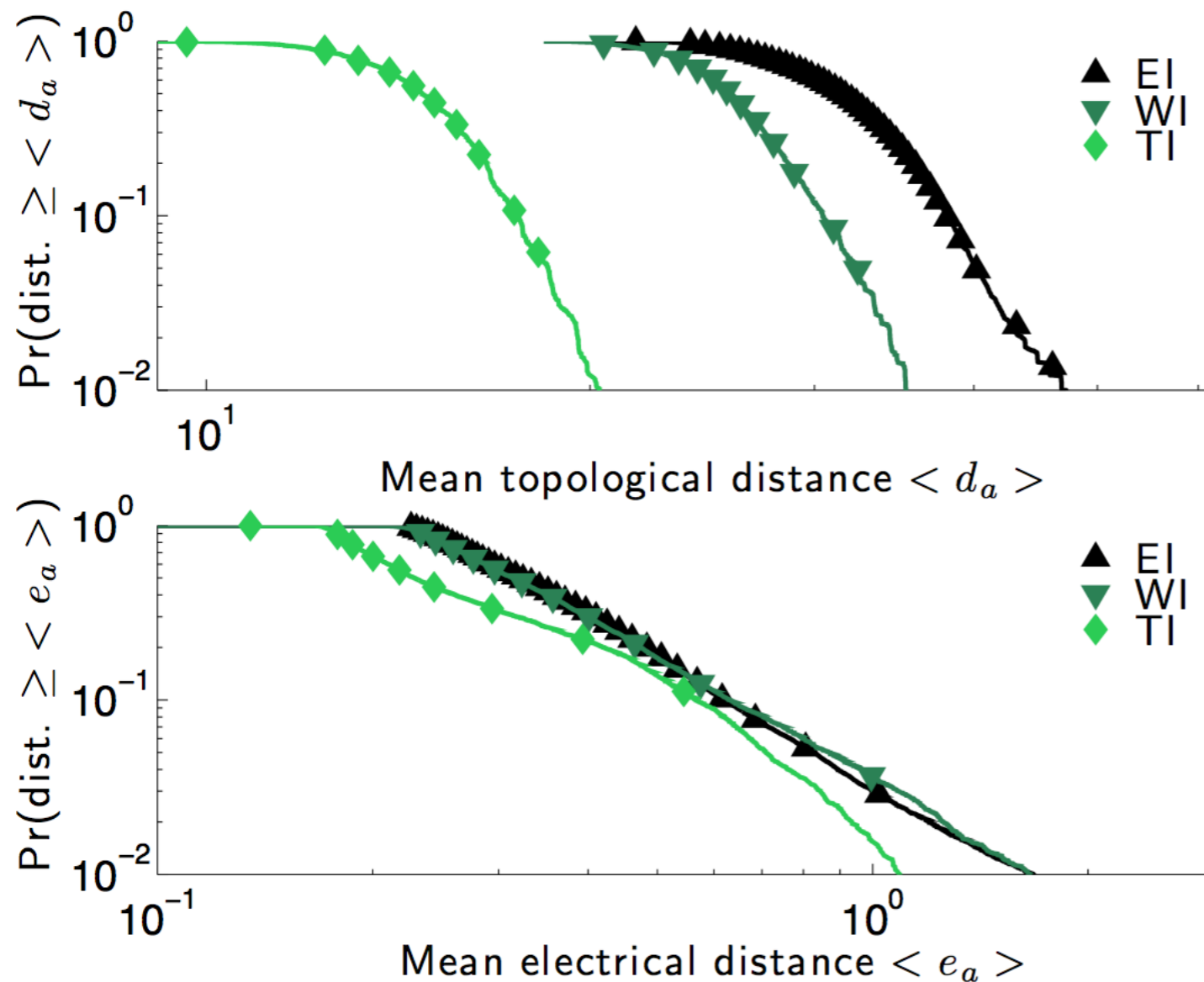
Authors	Power grid data	Findings
Watts and Strogatz (1998)	Western US	Power grids are small-world
Amaral et al. (2000)	Southern California	Exponential degree
Albert et al. (2004)	North America	Exponential degree, scale-free behavior
Crucitti et al. (2004)	Italy	Power-law degree
Chassin and Possee (2005)	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



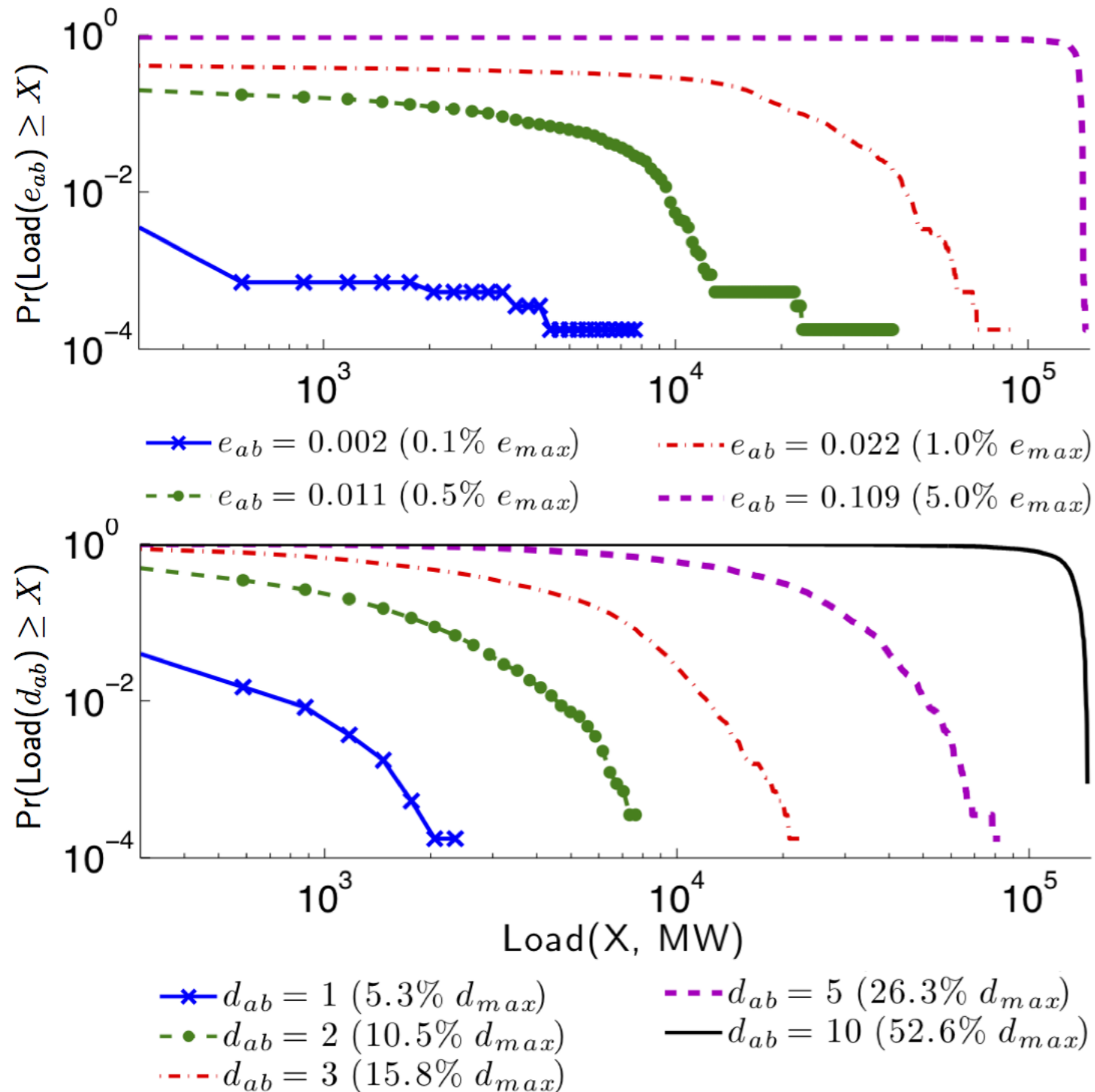
The three North American grid interconnections share topological similarities with one another...but not with canonical graph models.

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



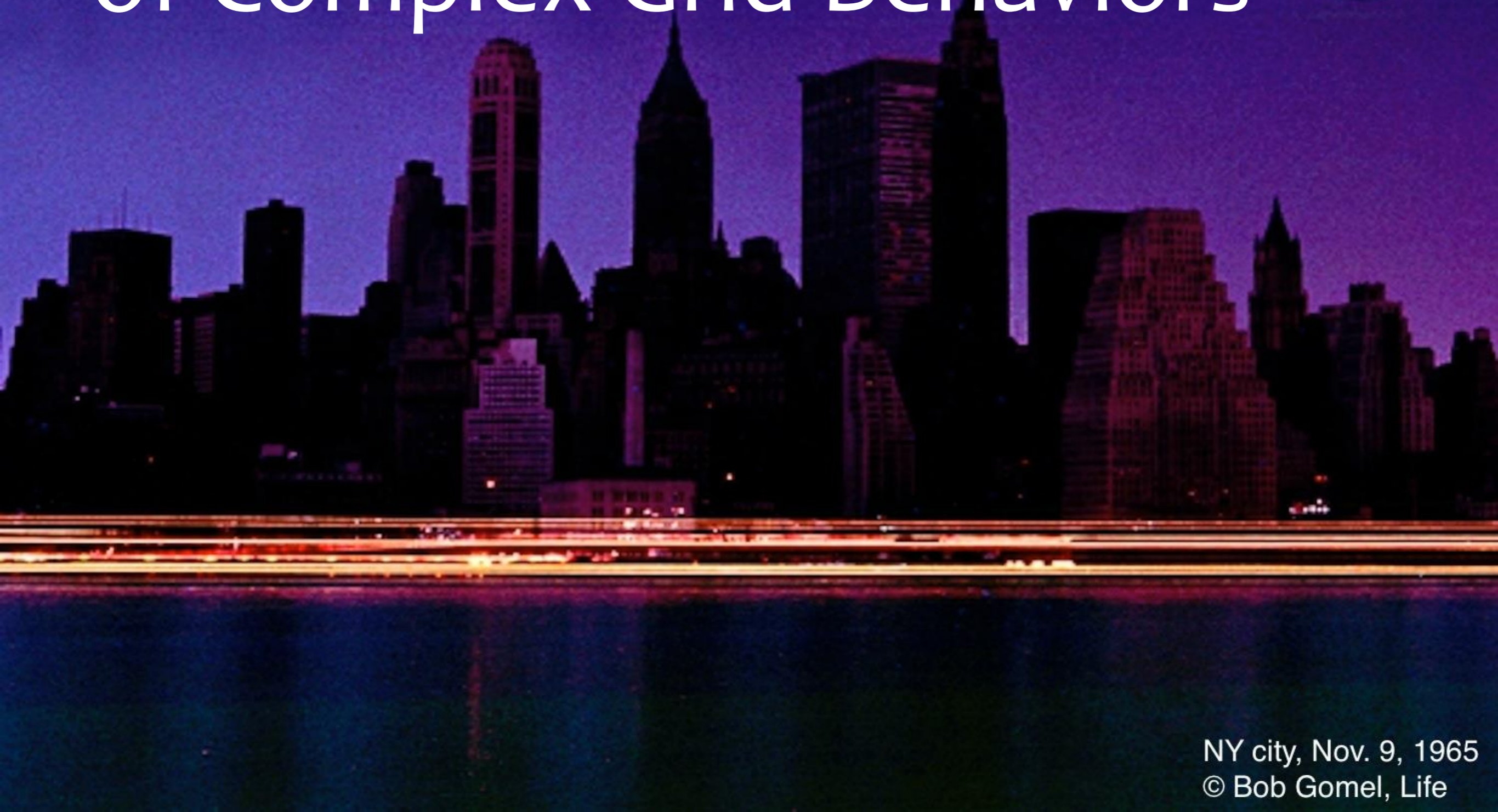
What does 'distance' even mean for the power grid?  
A topological or electrical concept?

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



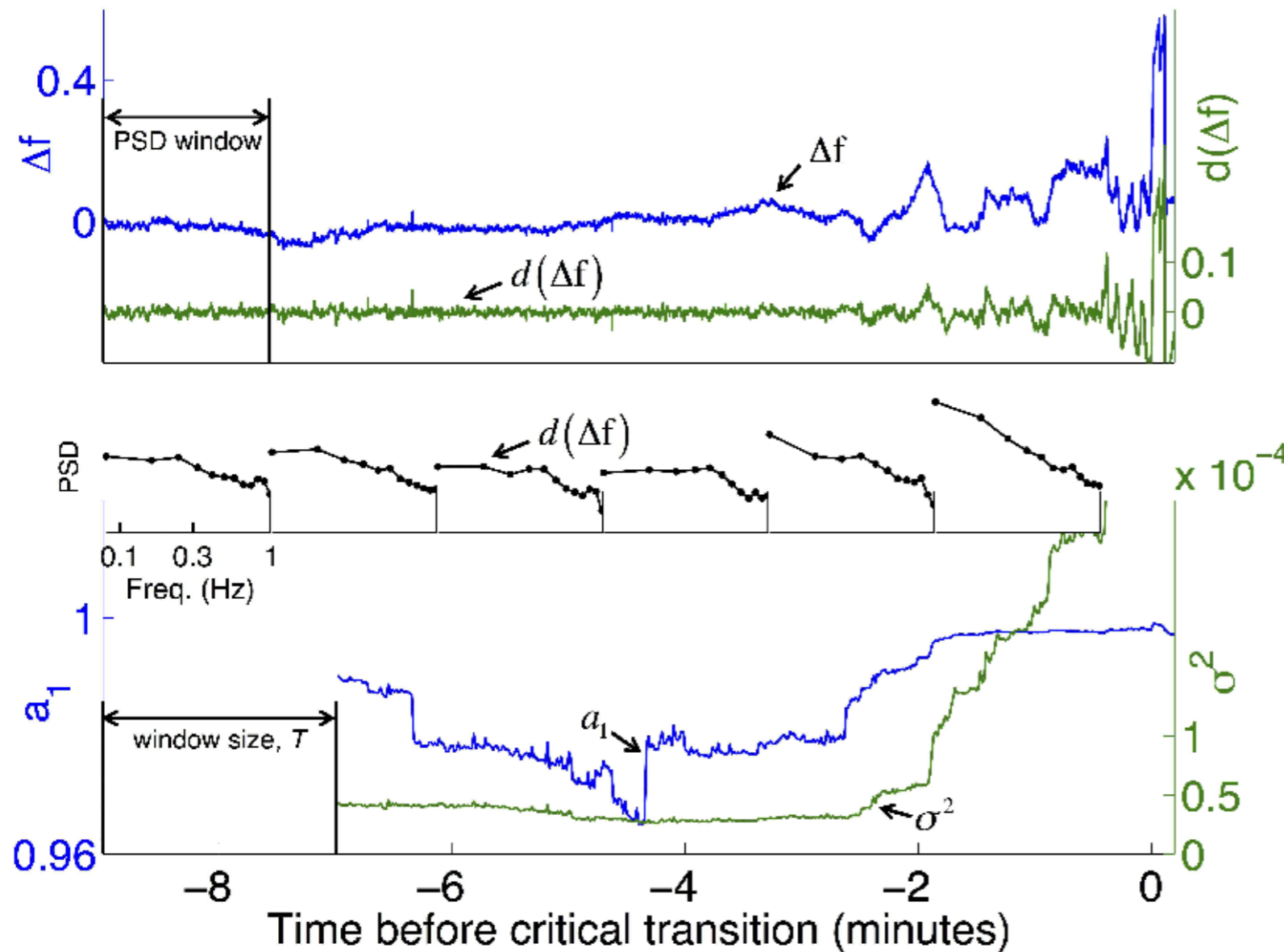
Electrical (top) and topological (bottom) connectivity to demand centers in the Mid-Atlantic US power grid

# Challenge #2: The Nature of Complex Grid Behaviors



NY city, Nov. 9, 1965  
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# What We (Kind of) Understand: Oscillations and Instability



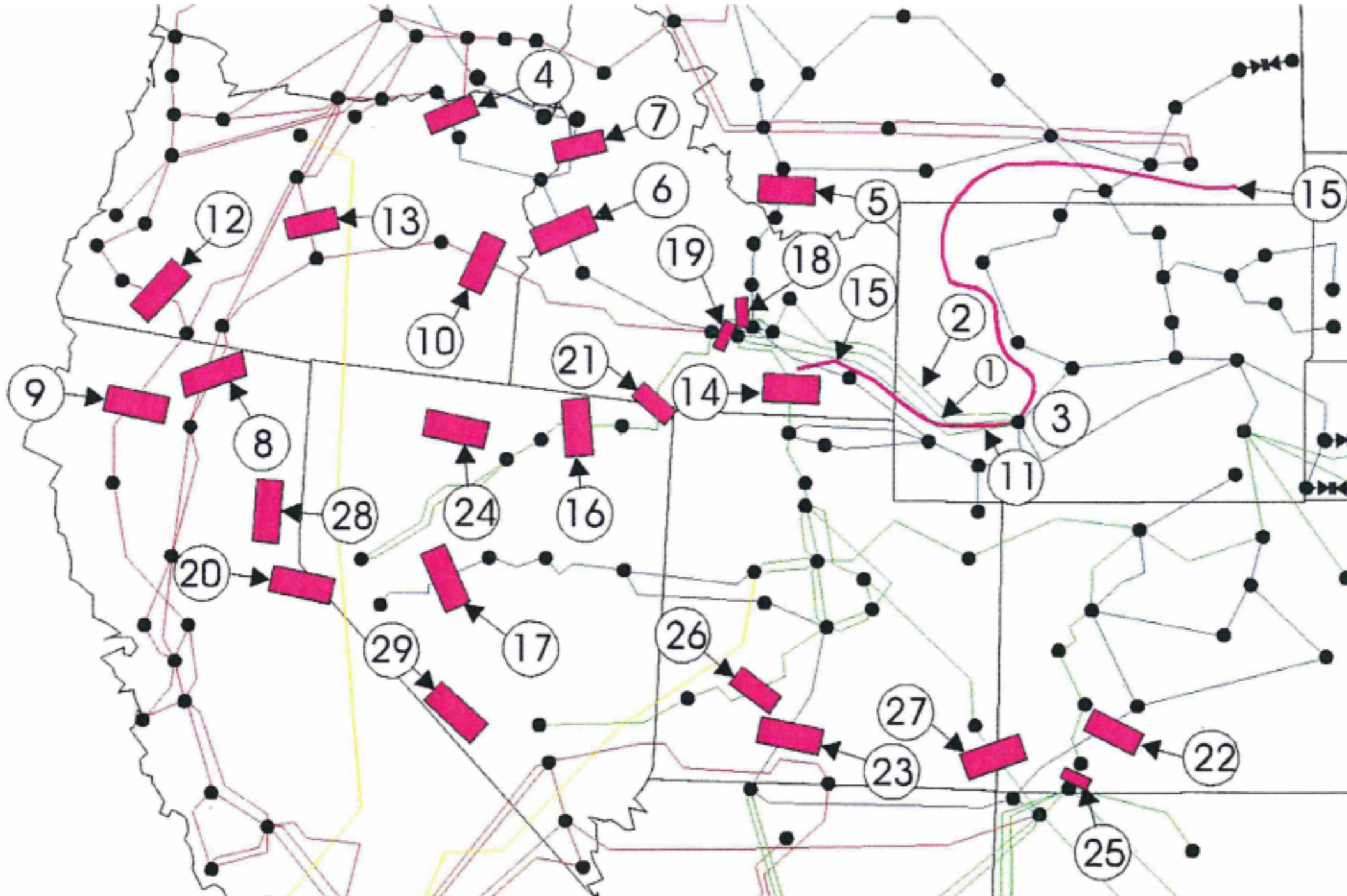
Time series signatures in the rotational frequency of the grid can serve as early-warning precursors for instability and blackouts.

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

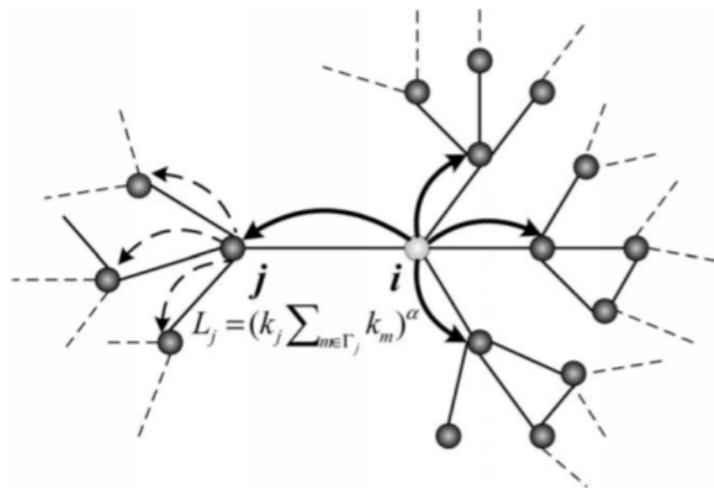


One of the worst power grid failures in the Western US started right here. Based on what you have learned about networks, how do you think it propagated through the system?

# 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 a 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)

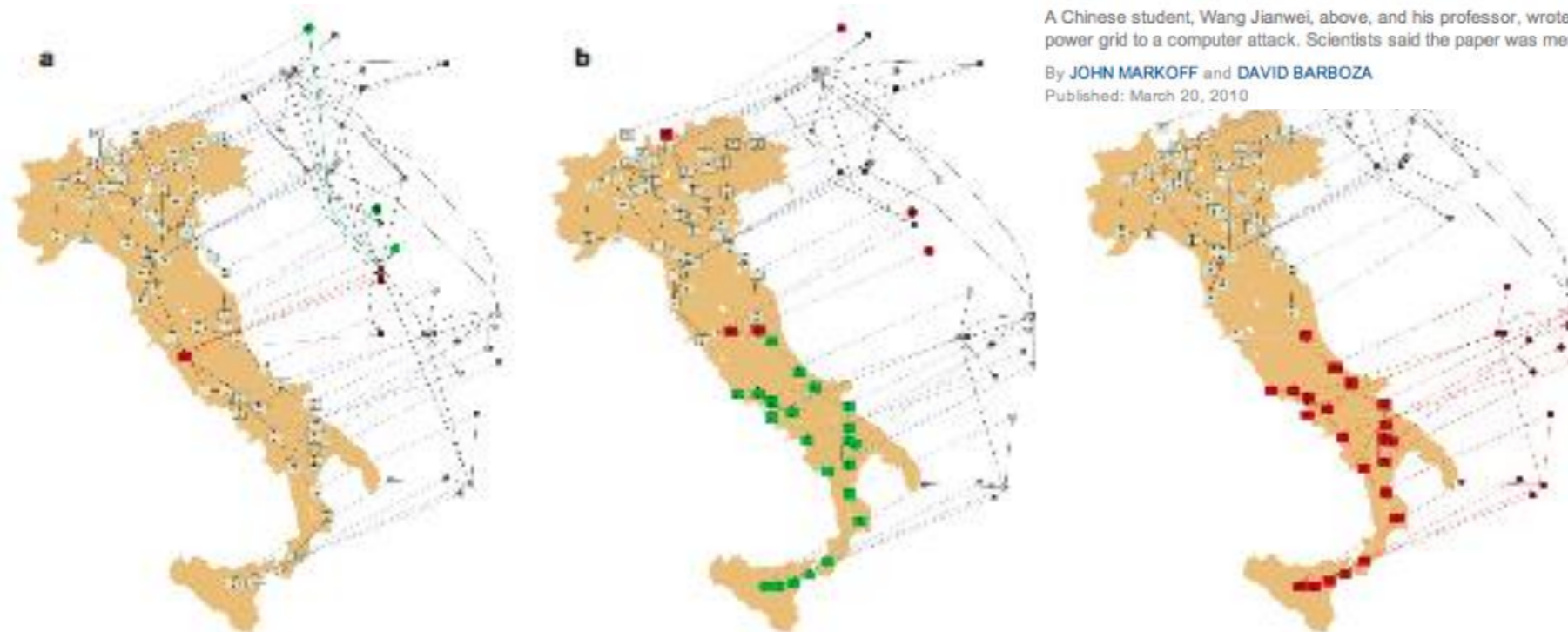
## Academic Paper in China Sets Off Alarms in U.S.



Du Bin for The New York Times

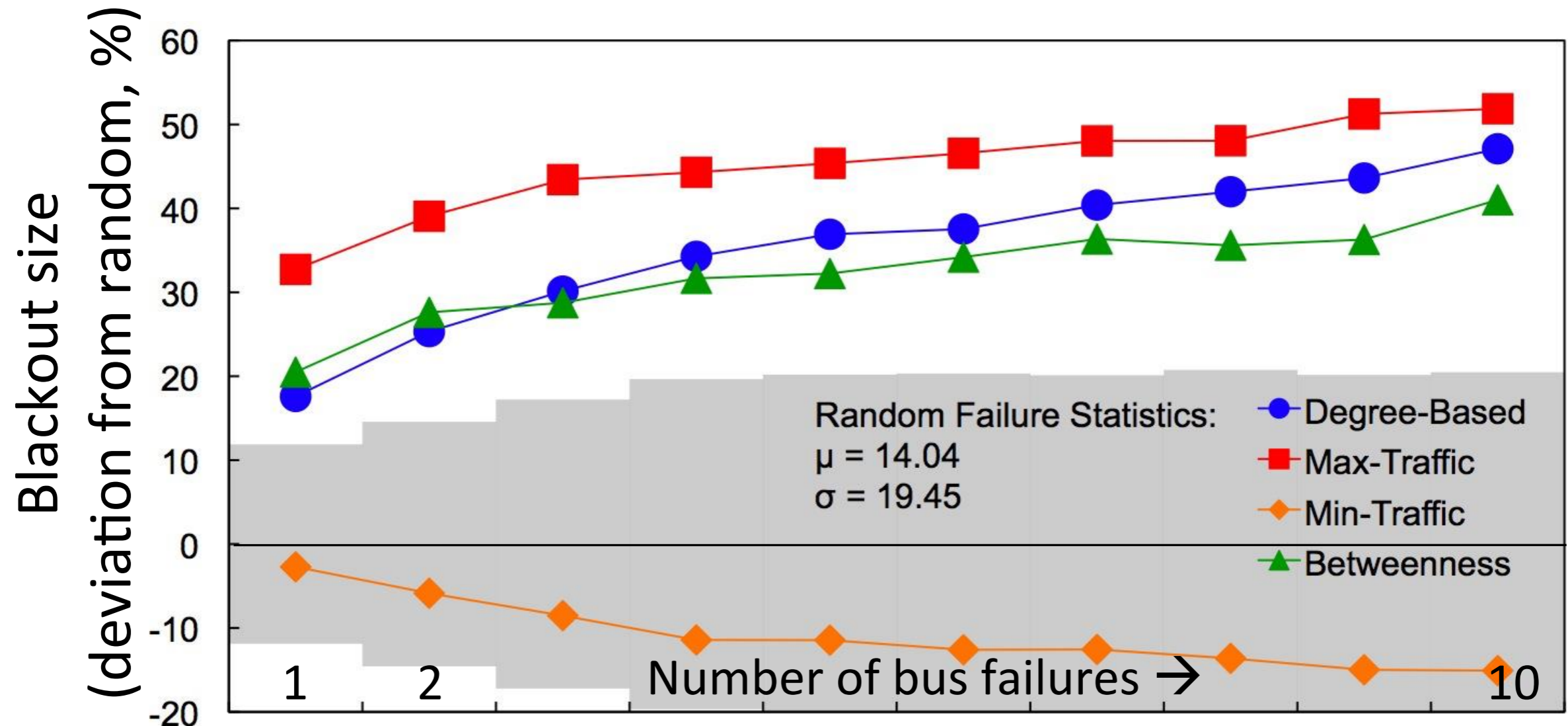
A Chinese student, Wang Jianwei, above, and his professor, wrote an academic paper on the vulnerability of the American power grid to a computer attack. Scientists said the paper was merely a technical exercise.

By JOHN MARKOFF and DAVID BARBOZA  
Published: March 20, 2010

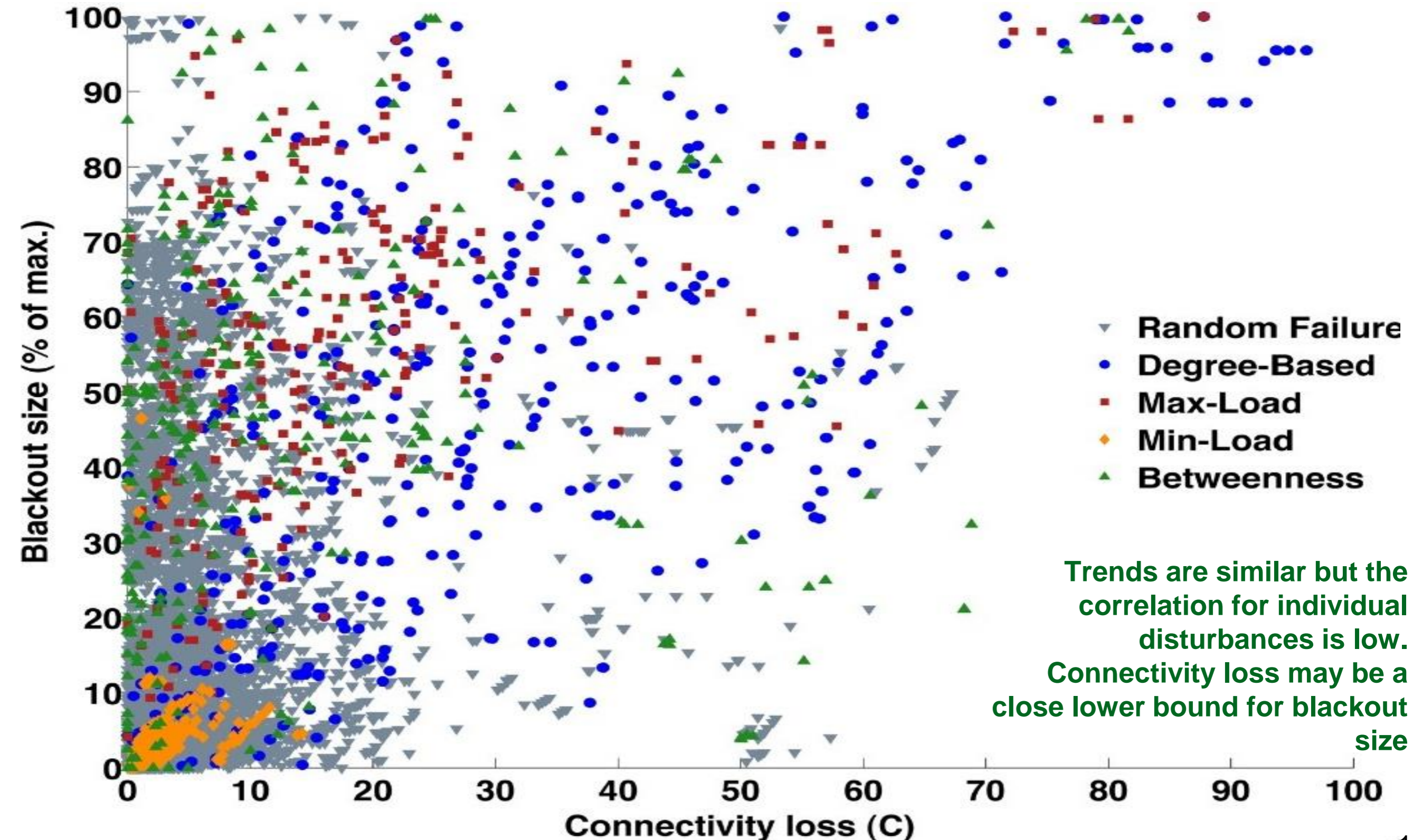


Buldyrev, et al (2010)

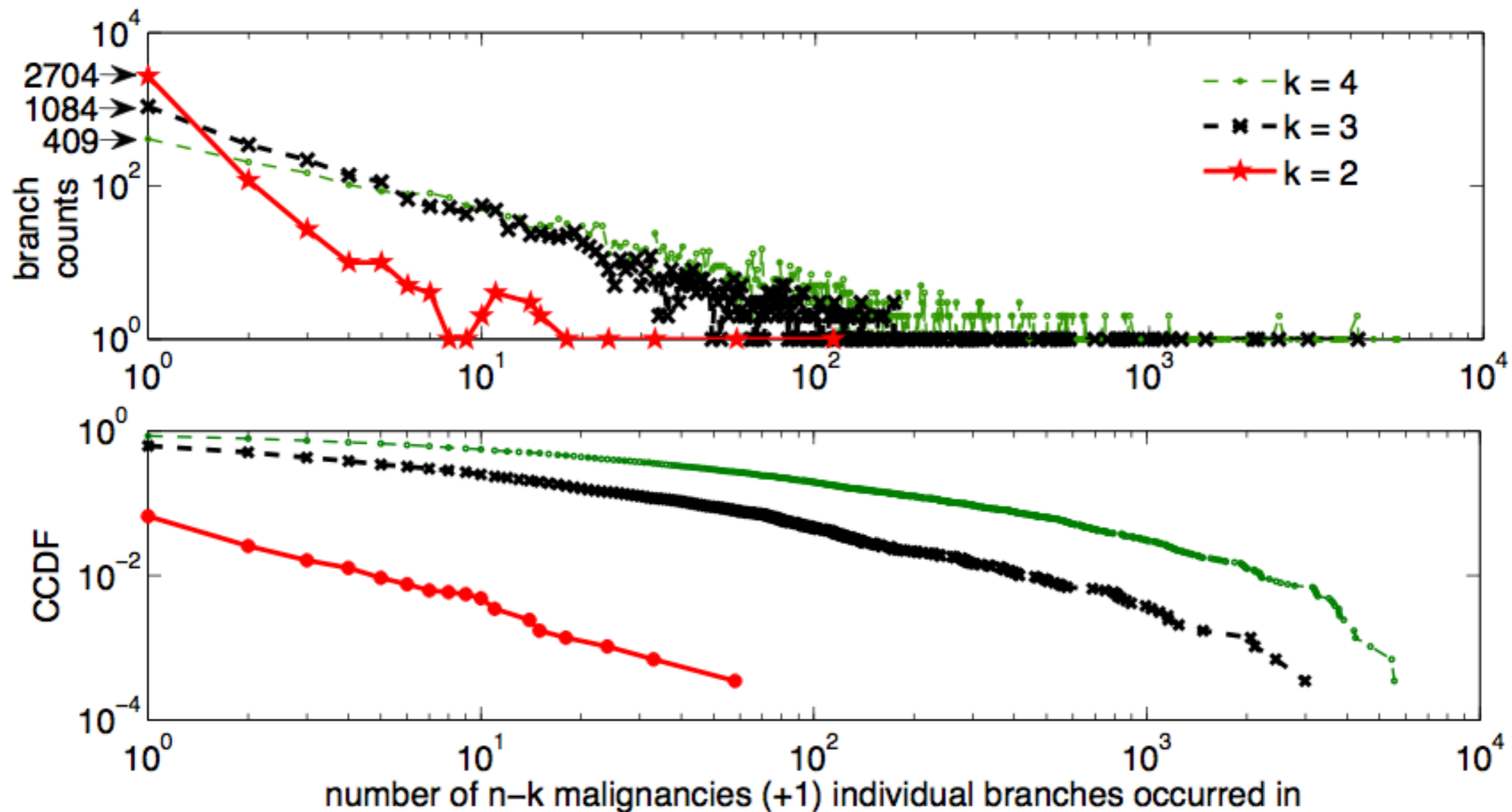
# The Value of Topological Models



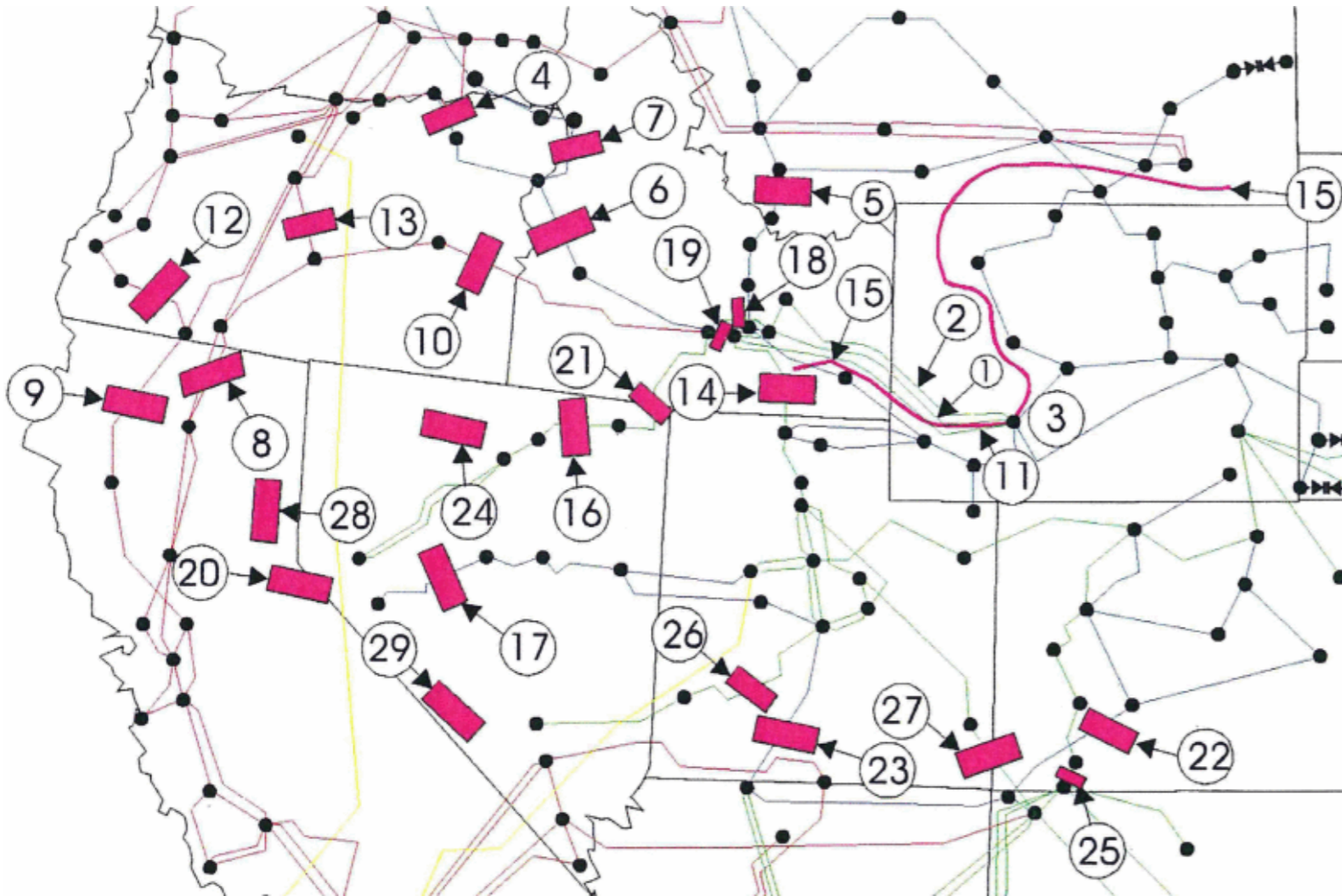
# The Value of Topological Models



# Yet, Power Grids do have Critical Elements

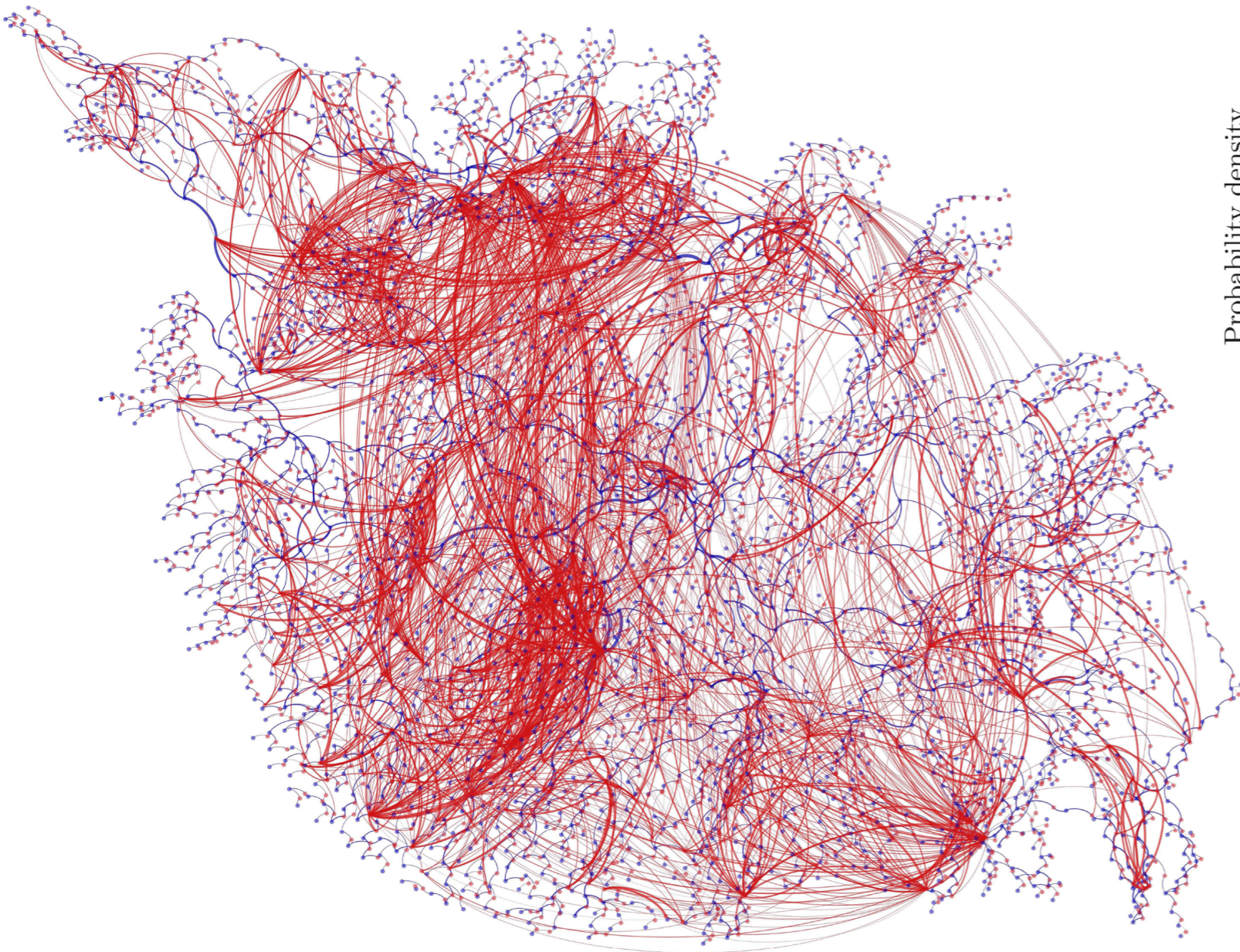


# Challenge 1: Rethinking Propagation

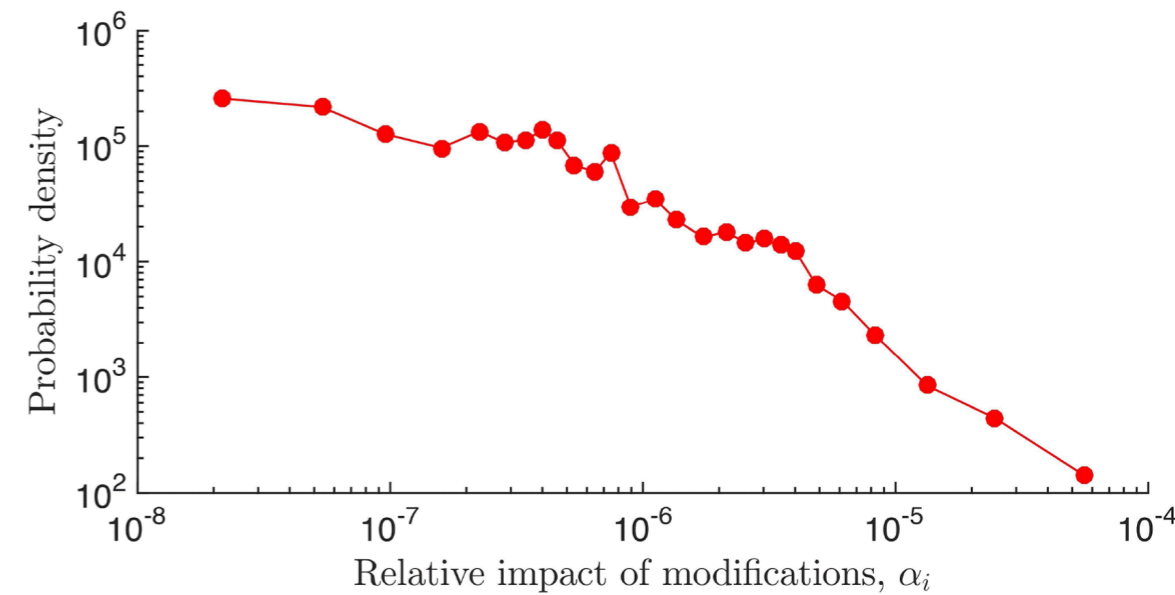


Let's forget about network structure, or even topology. Reverse the question: Suppose that there were a network structure under which disturbances would propagate in a way that we think we understand. What would such a network look like?

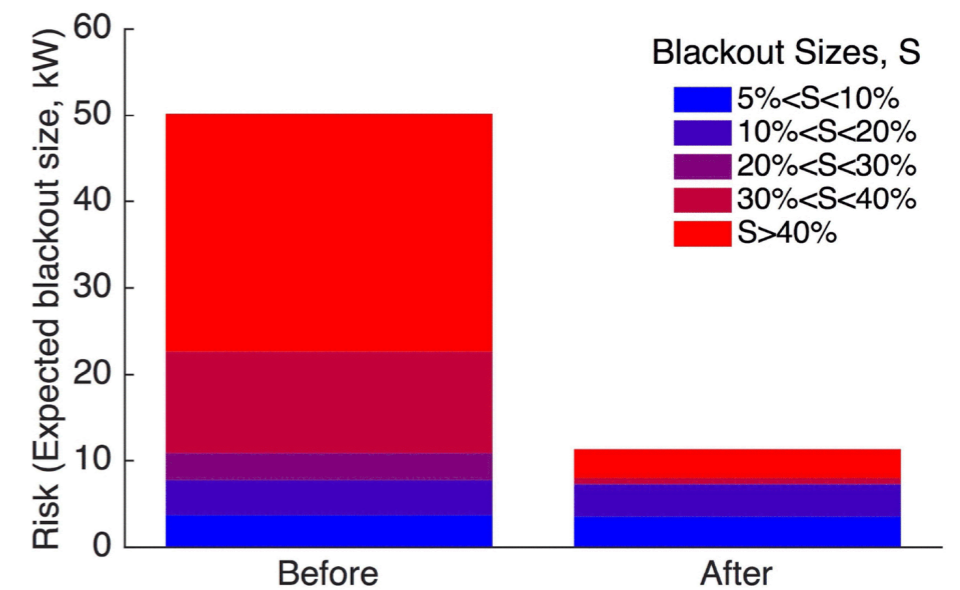
# Lesson 1: Rethinking Propagation



(a)



(b)



(c)

# 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

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



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

Mark Z. Jacobson<sup>a,1</sup>, Mark A. Delucchi<sup>b</sup>, Mary A. Cameron<sup>a</sup>, and Bethany A. Frew<sup>a</sup>

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

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

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

<sup>a</sup>Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80505; <sup>b</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80505; <sup>c</sup>Department of Physics and Astronomy, Uppsala University, 752 37 Uppsala, Sweden; <sup>d</sup>Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213; <sup>e</sup>Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213; <sup>f</sup>Center for Global Energy Policy, Columbia University, New York, NY 10027; <sup>g</sup>Department of Energy Resources Engineering, Stanford University, Stanford, CA 94305; <sup>h</sup>Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305; <sup>i</sup>Department of Earth System Science, University of California, Irvine, CA 92697; <sup>j</sup>Omni Optimum, Evergreen, CO 80437; <sup>k</sup>Enduring Energy, LLC, Boulder, CO 80503; <sup>l</sup>Electrical Engineering and Complex Systems Center, University of Vermont, Burlington, VT 05405; <sup>m</sup>Energy and Resources Group, University of California, Berkeley, CA 94720; <sup>n</sup>Goldman School of Public Policy, University of California, Berkeley, CA 94720; <sup>o</sup>Renewable and Appropriate Energy Laboratory, University of California, Berkeley, CA 94720-3050; <sup>p</sup>Lawrence Livermore National Laboratory, Livermore, CA 94550; <sup>q</sup>Renewable and Sustainable Energy Institute, University of Colorado, Boulder, CO 80505; <sup>r</sup>Council on Foreign Relations, New York, NY 10005; <sup>s</sup>Prescott Energy Efficiency Center, Stanford University, Stanford, CA 94305-4206; <sup>t</sup>Management Science and Engineering Department, Huang Engineering Center, Stanford University, Stanford, CA 94305; <sup>u</sup>Department of Mechanical and Aerospace Engineering, Jacobs School of Engineering, University of California, San Diego, La Jolla, CA 92093; <sup>v</sup>School of Global Policy and Strategy, University of California, San Diego, La Jolla, CA 92093; and <sup>w</sup>Brookings Institution, Washington, DC 20036

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 WW S [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). The high level of decarbonization is facilitated by an optimally configured continental high-voltage transmission network. There seems to be some consensus that substantial amounts of greenhouse gas (GHG) emissions could be avoided with widespread deployment of solar and wind electric generation technologies along with supporting infrastructure.

Furthermore, it is not in question that it would be theoretically possible to build a reliable energy system excluding all bioenergy, nuclear energy, and fossil fuel sources. Given unlimited resources to build variable energy production facilities, while expanding the transmission grid and accompanying energy storage capacity enormously, one would eventually be able to meet any conceivable load. However, in developing a strategy to effectively mitigate global energy-related CO<sub>2</sub> emissions, it is critical that the scope of the challenge to achieve this in the real world is accurately defined and clearly communicated.

Wind and solar are variable energy sources, and some way must be found to address the issue of how to provide energy if their immediate output cannot continuously meet instantaneous demand. The main options are to (i) curtail load (i.e., modify or fail to satisfy demand) at times when energy is not available, (ii) deploy very large amounts of energy storage, or (iii) provide supplemental energy sources that can be dispatched when needed. It is not yet clear how much it is possible to curtail loads, especially over long durations, without incurring large economic costs. There are no electric storage systems available today that can

Author contributions: C.T.M.C. and J.F.W. designed research; C.T.M.C. and S.A.Q. performed research; C.T.M.C., S.A.Q., and J.F.W. analyzed data and C.T.M.C., S.A.Q., J.A., M.B., A.R.B., K.C., S.J.D., V.D., M.A.H., P.D.H., P.J., D.M.K., J.C.S.L., M.G.M., A.R., V.S., J.S., G.R.T., D.G.V., J.P.W., and J.F.W. wrote the paper.

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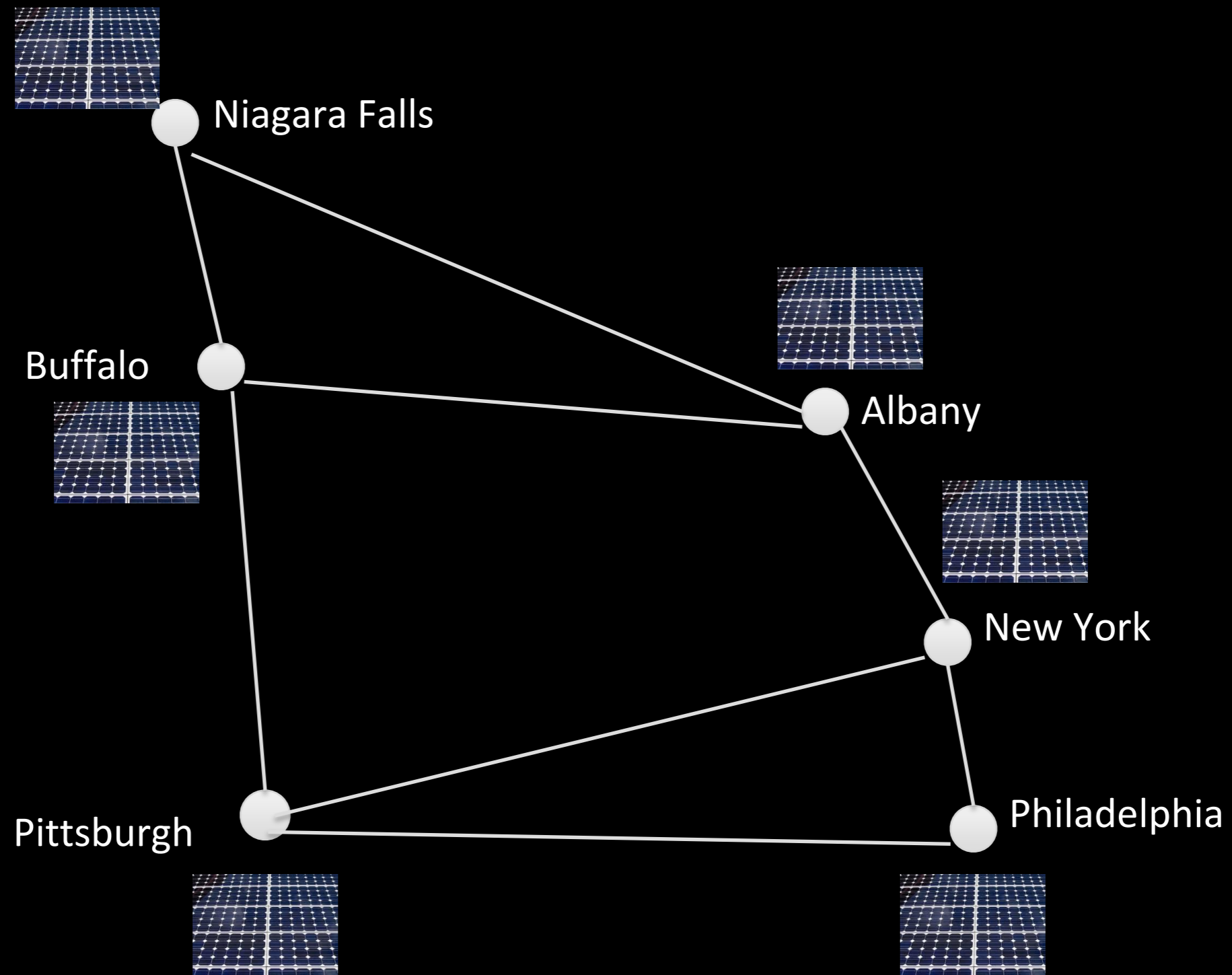
<sup>1</sup>To whom correspondence should be addressed. Email: christopher@brancik.com.

<sup>2</sup>Present address: Vibrant Clean Energy, LLC, Erie, CO 80516.

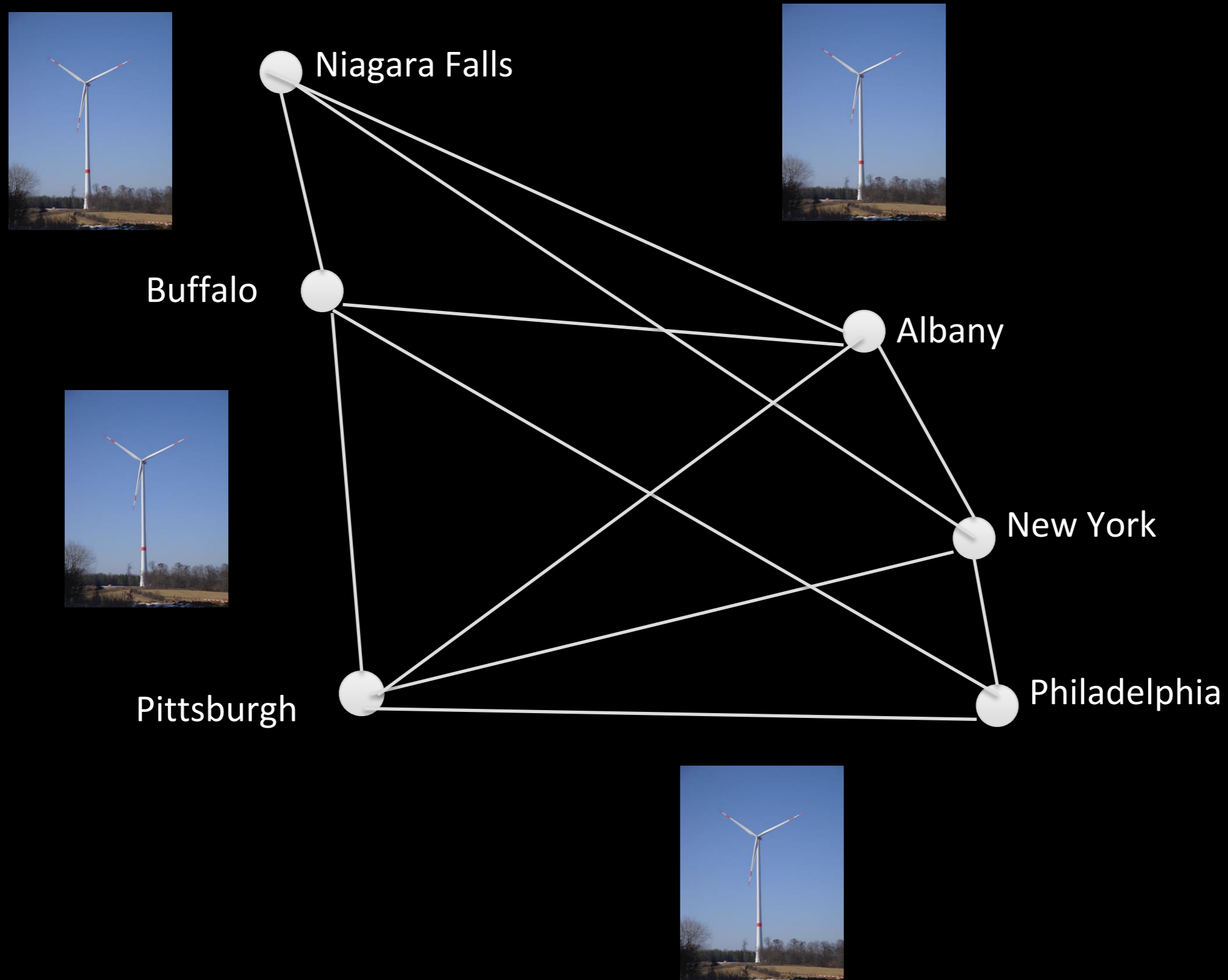
<sup>3</sup>Retired.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1610081114/-DCSupplemental.

Maybe the transition should look like this

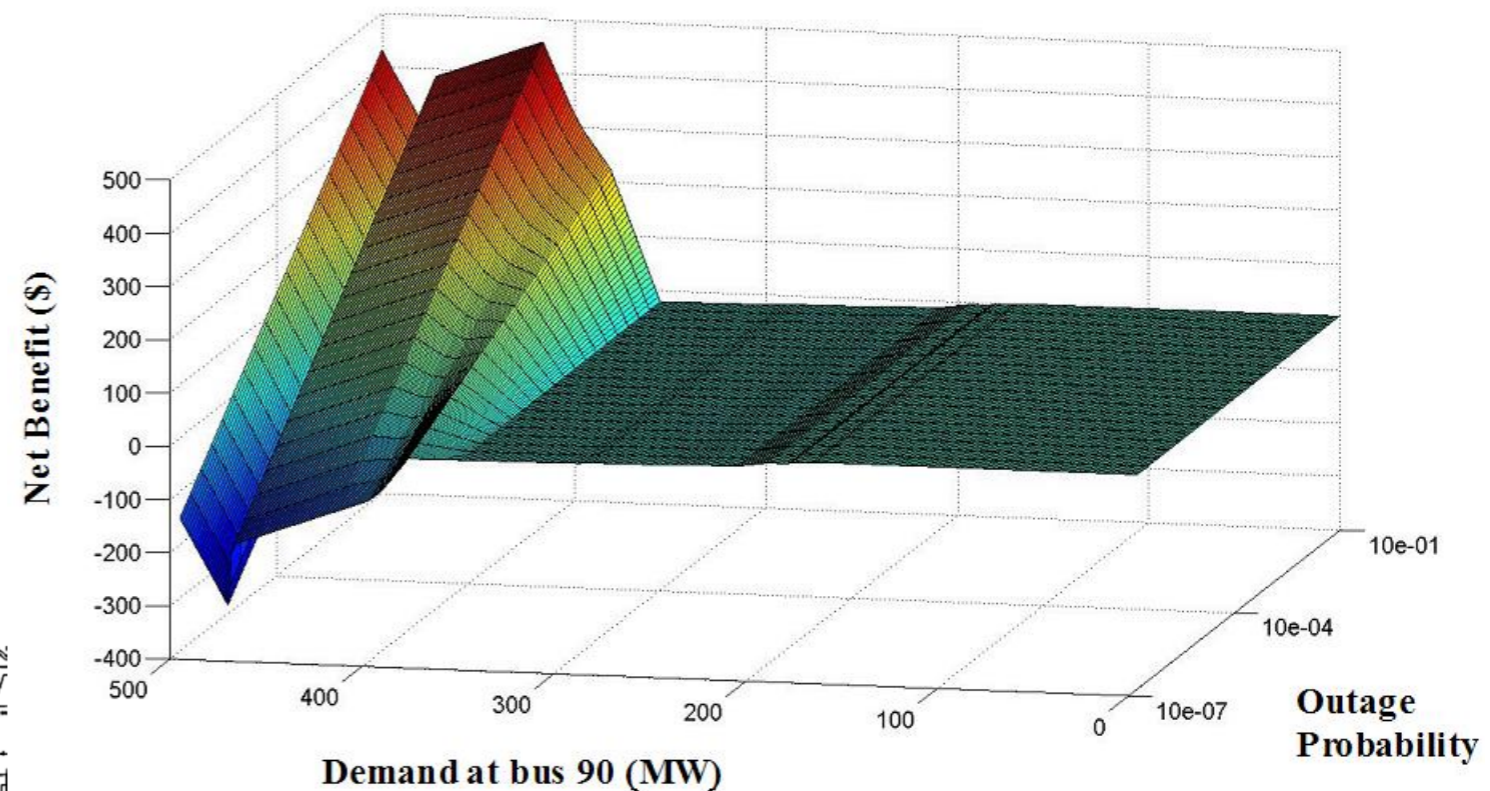
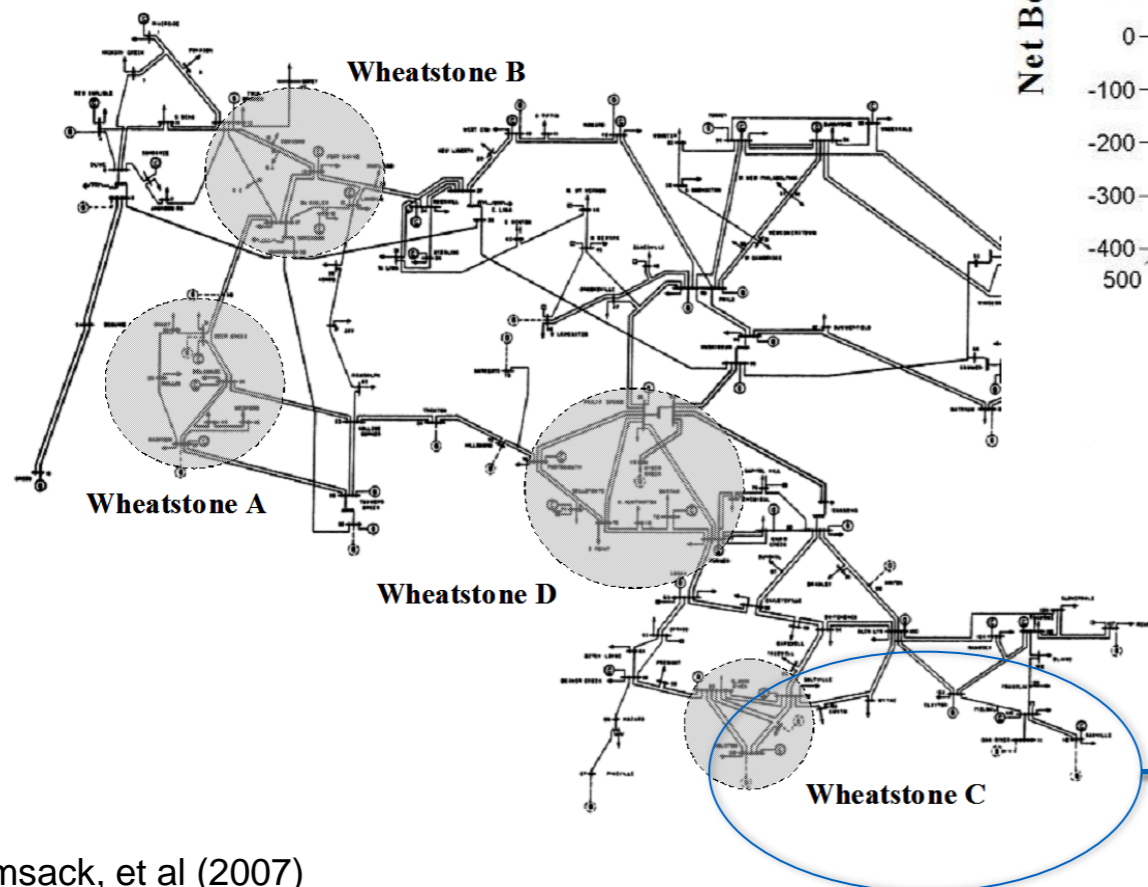


Or maybe the transition should look like this

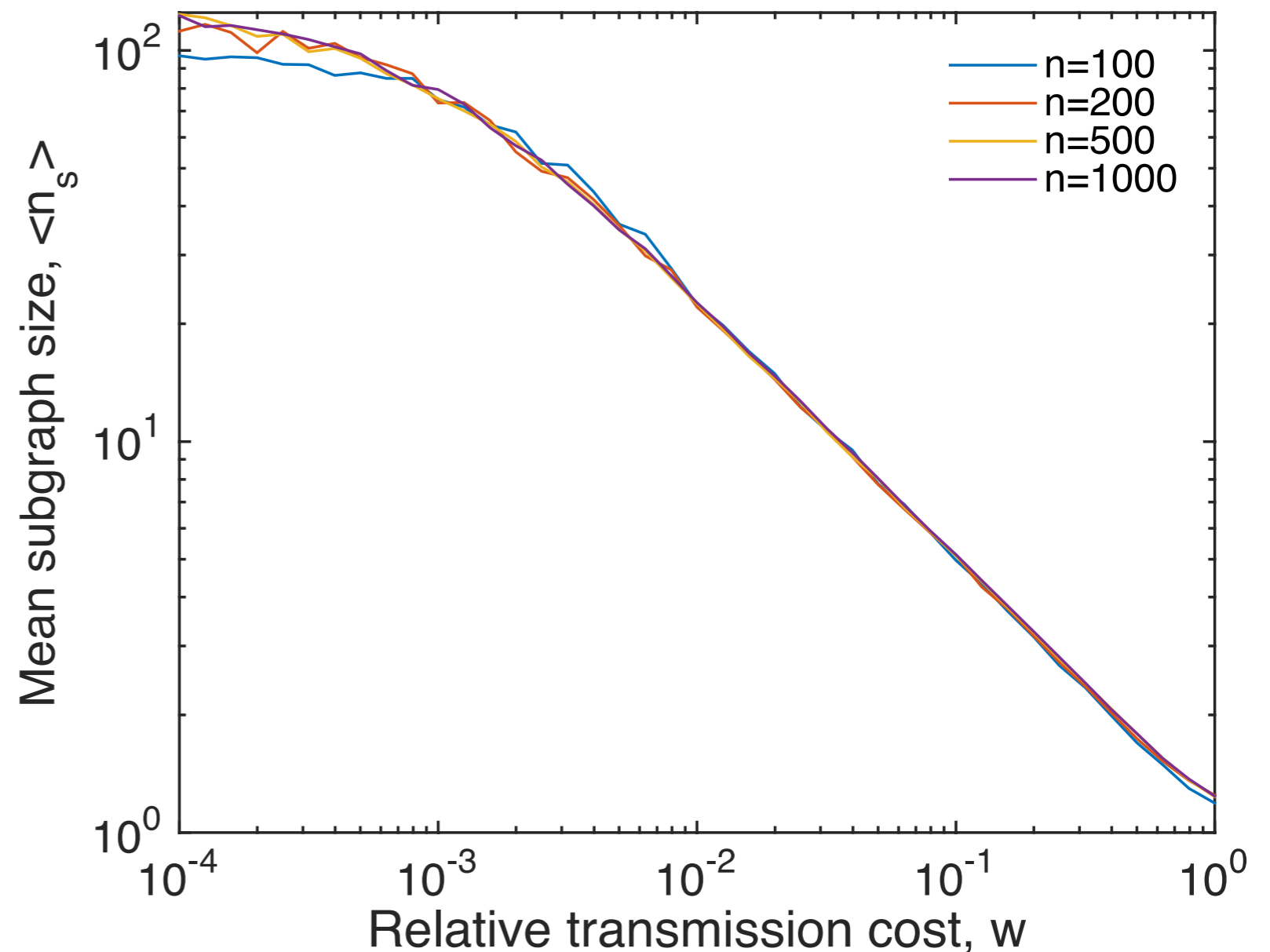
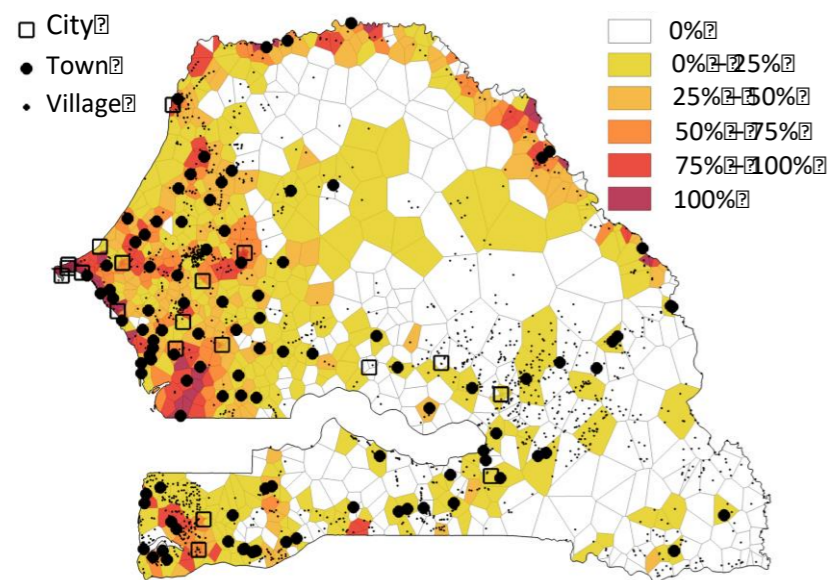
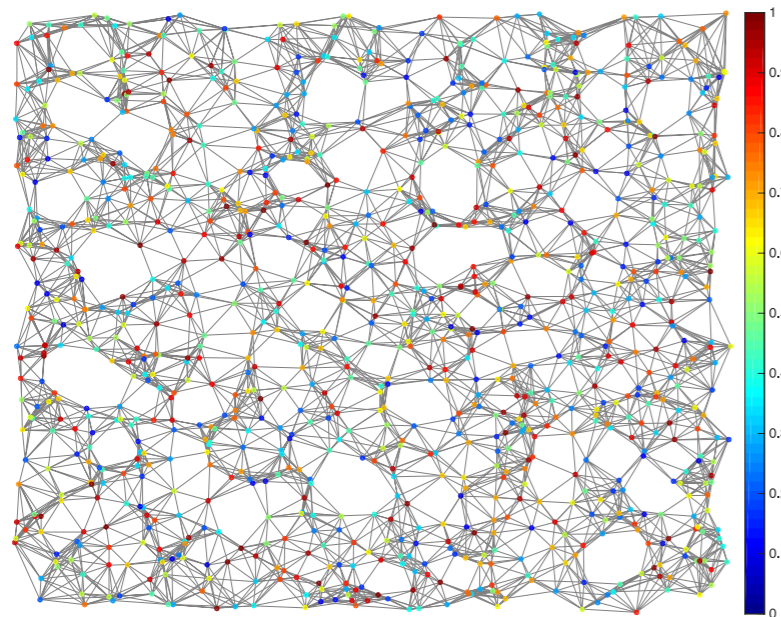


# What We (Kind of) Understand: The Risk-Cost Nature of Connectivity

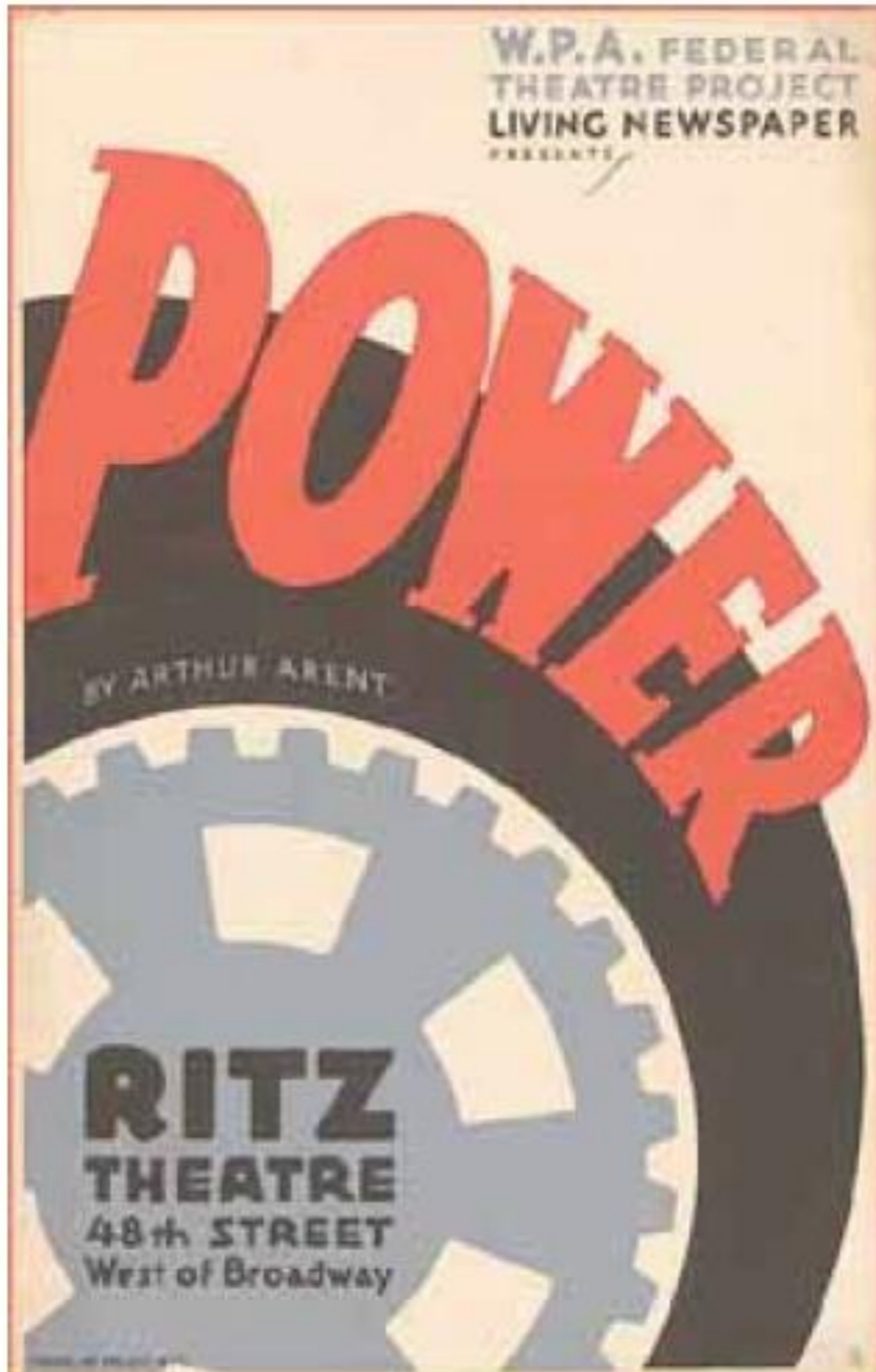
Power grids are particularly susceptible to the 'Braess Paradox' – connections built for redundancy can degrade operational efficiency.

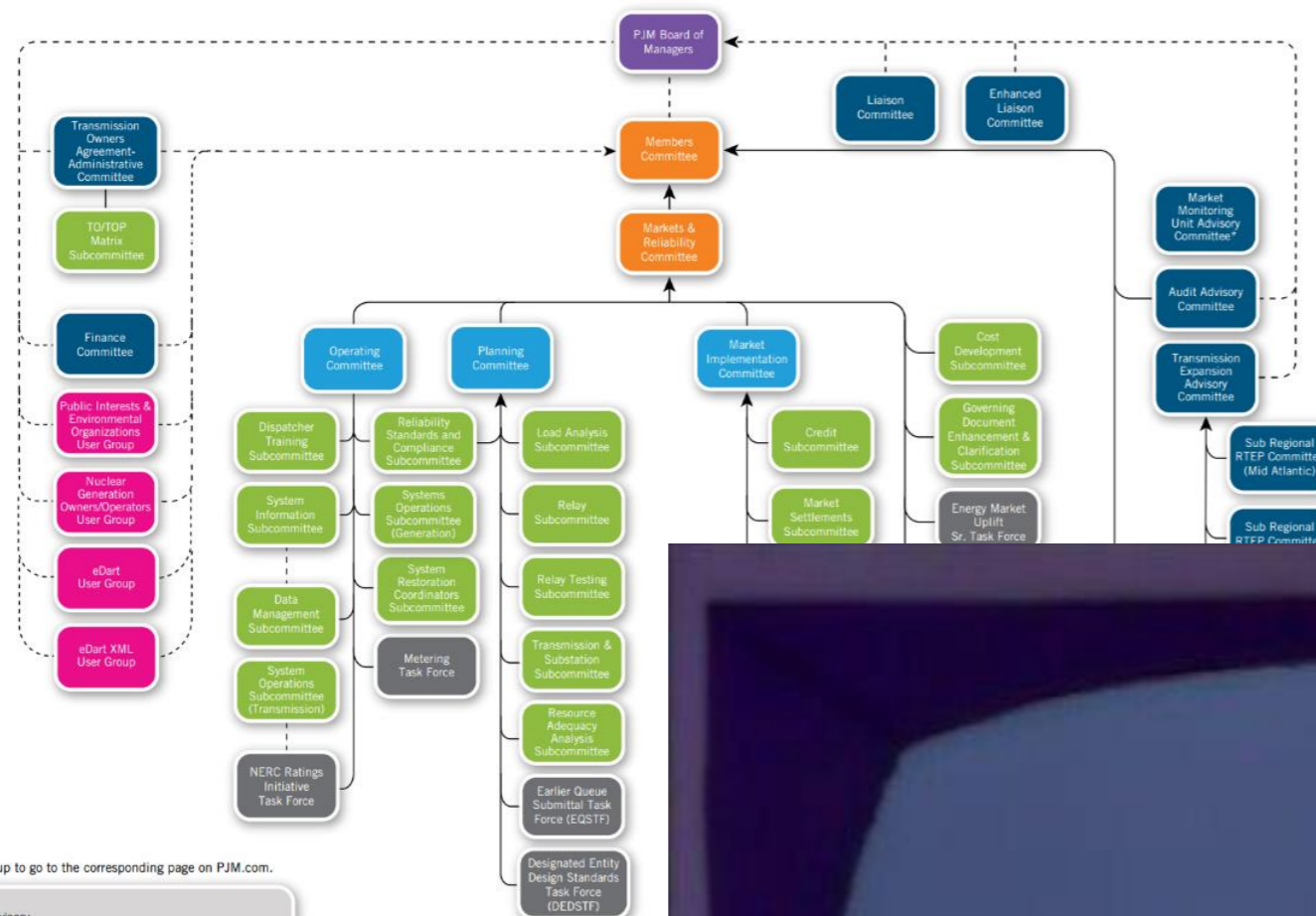


# “Centralized” vs “Decentralized” is Never Optimal



# Electrons Have a Social Side!



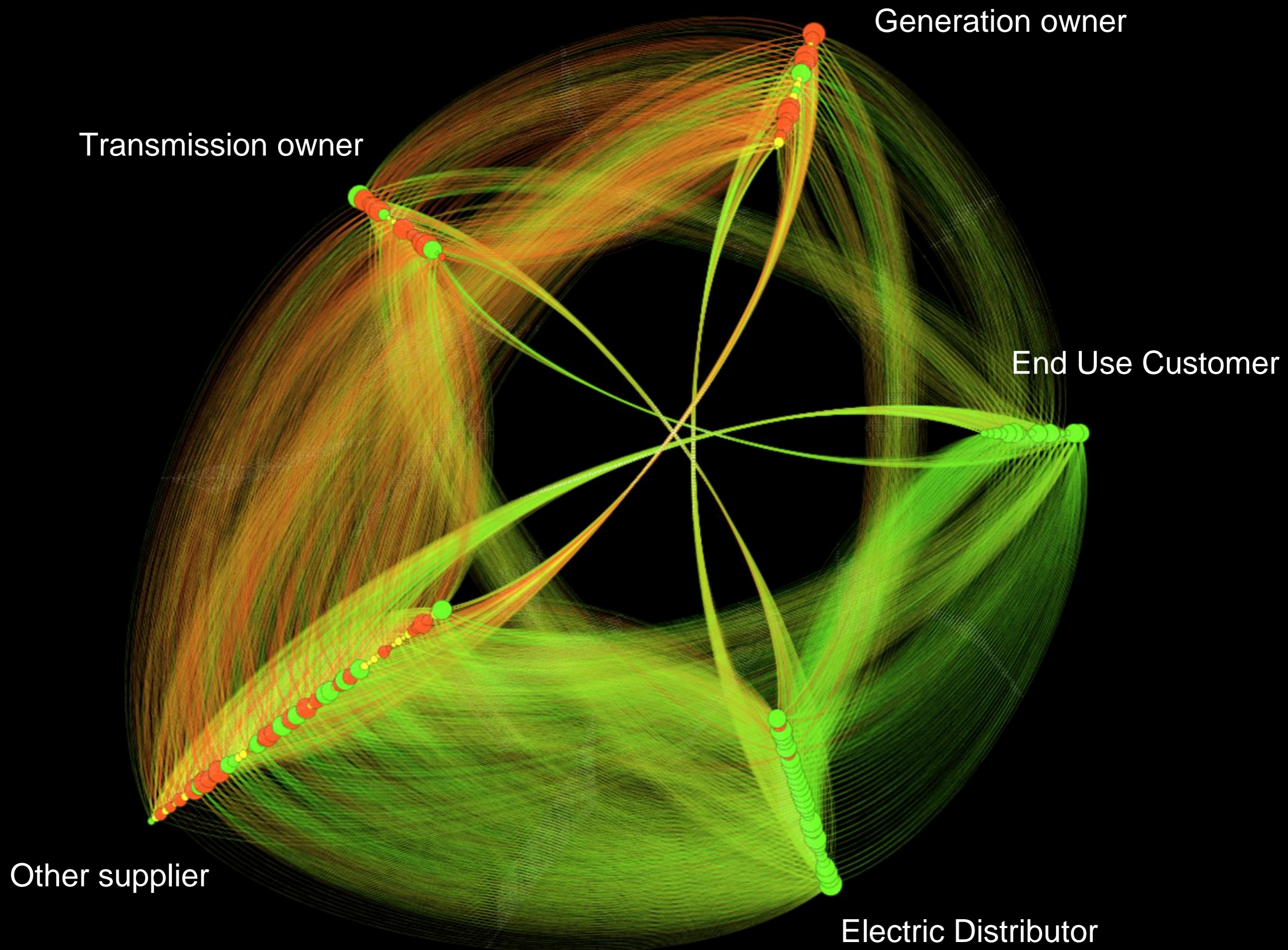


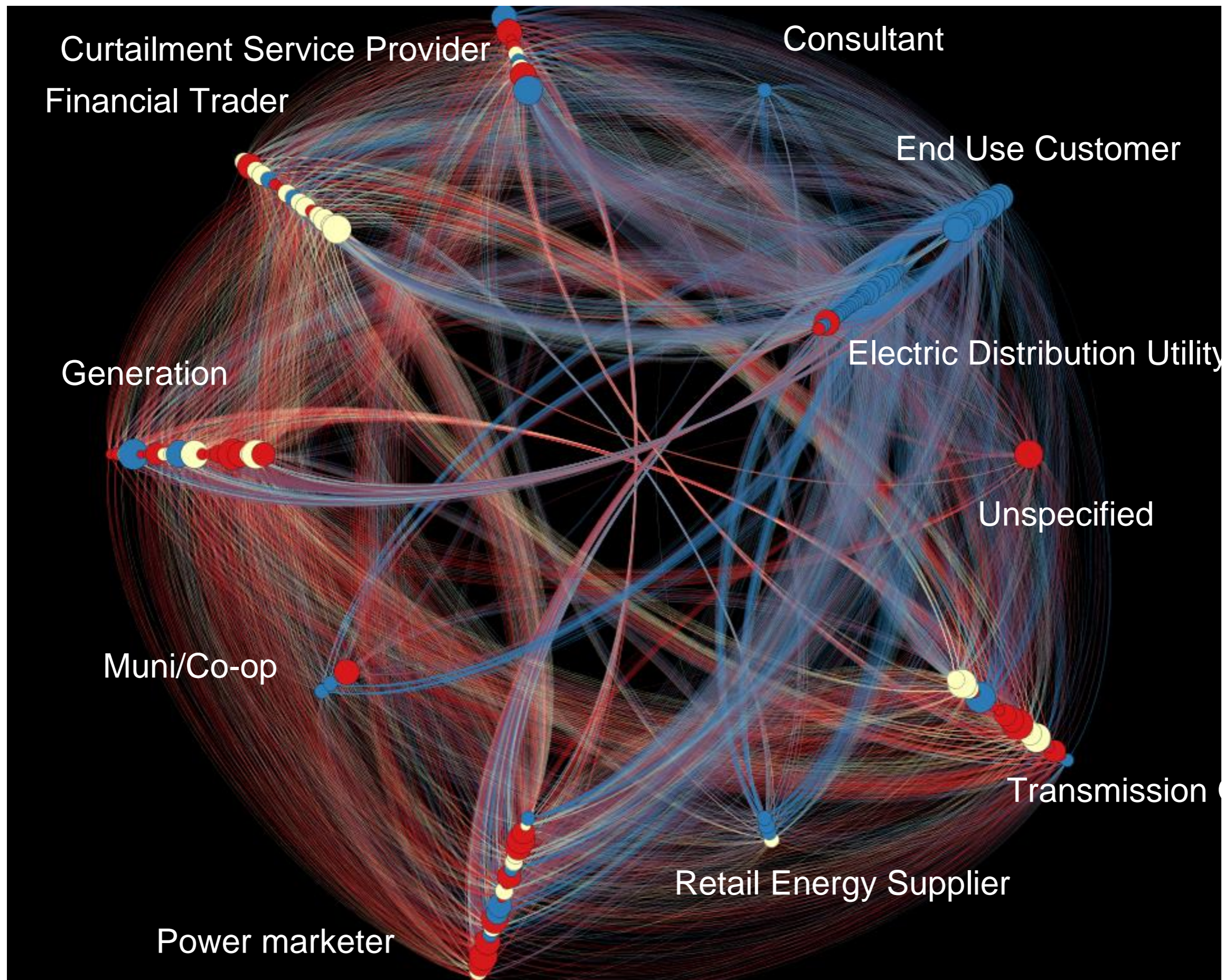
Click on a group to go to the corresponding page on PJM.com.

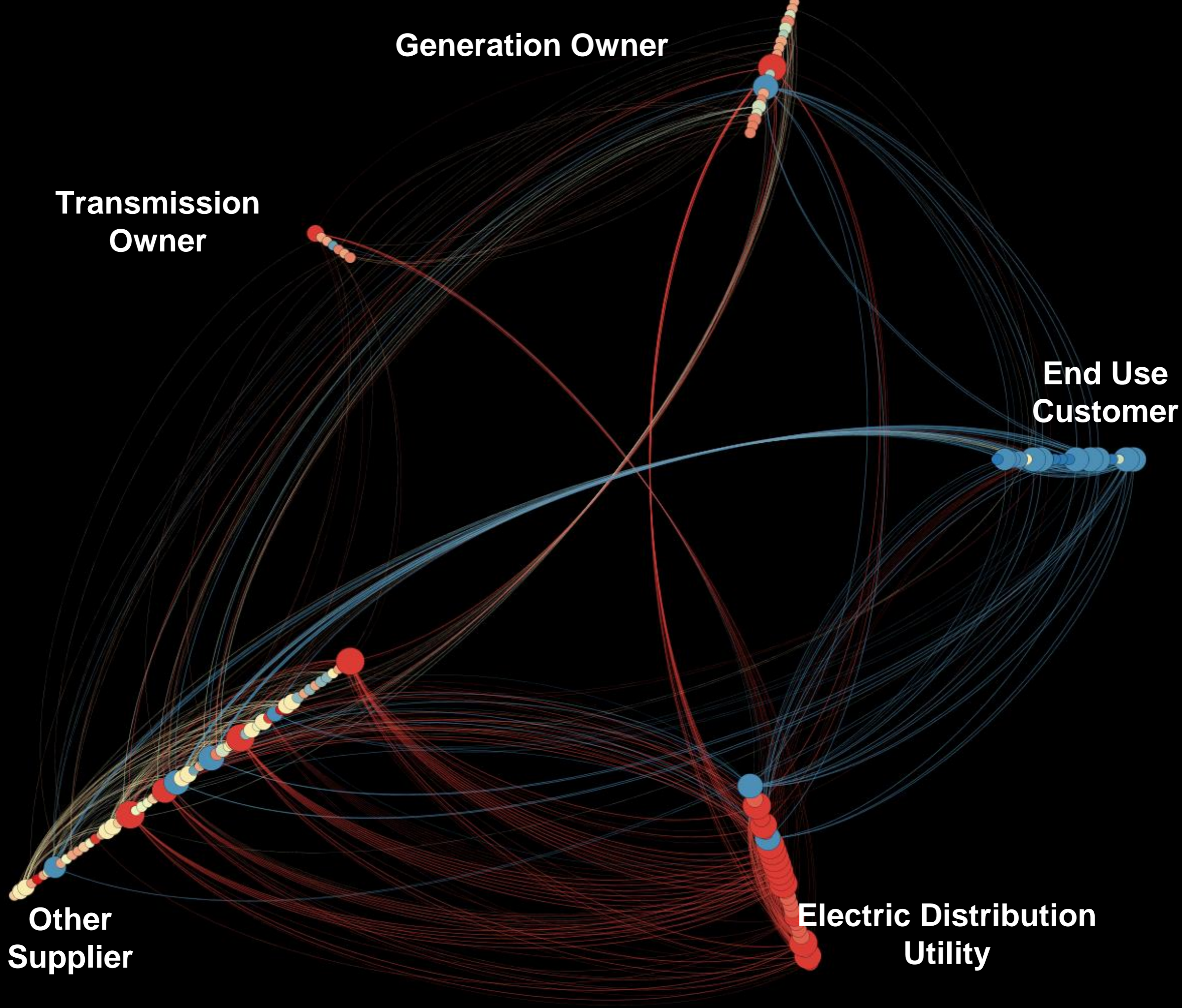
- - - - = Advisory  
 — = Direct  
 [Pink Box] = User Group  
 [Blue Box] = Committee  
 [Green Box] = Subcommittee  
 [Grey Box] = Task Force  
 [Purple Box] = PJM Board of Managers  
 [Orange Box] = Senior Committee  
 [Light Blue Box] = Standing Committee

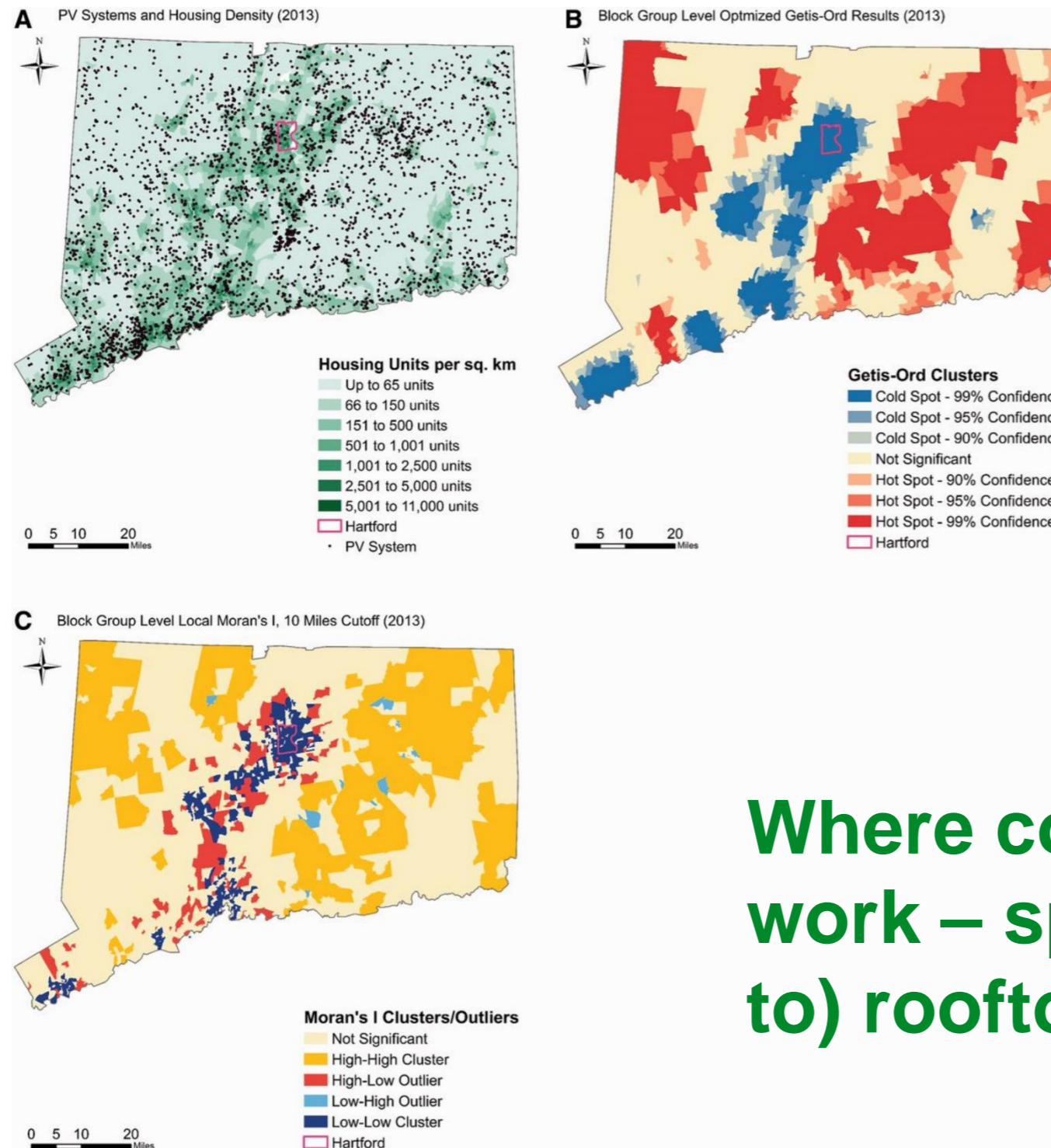
\* The MMUAC is an independent group that does not report to the PJM Board or Members Committee.

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



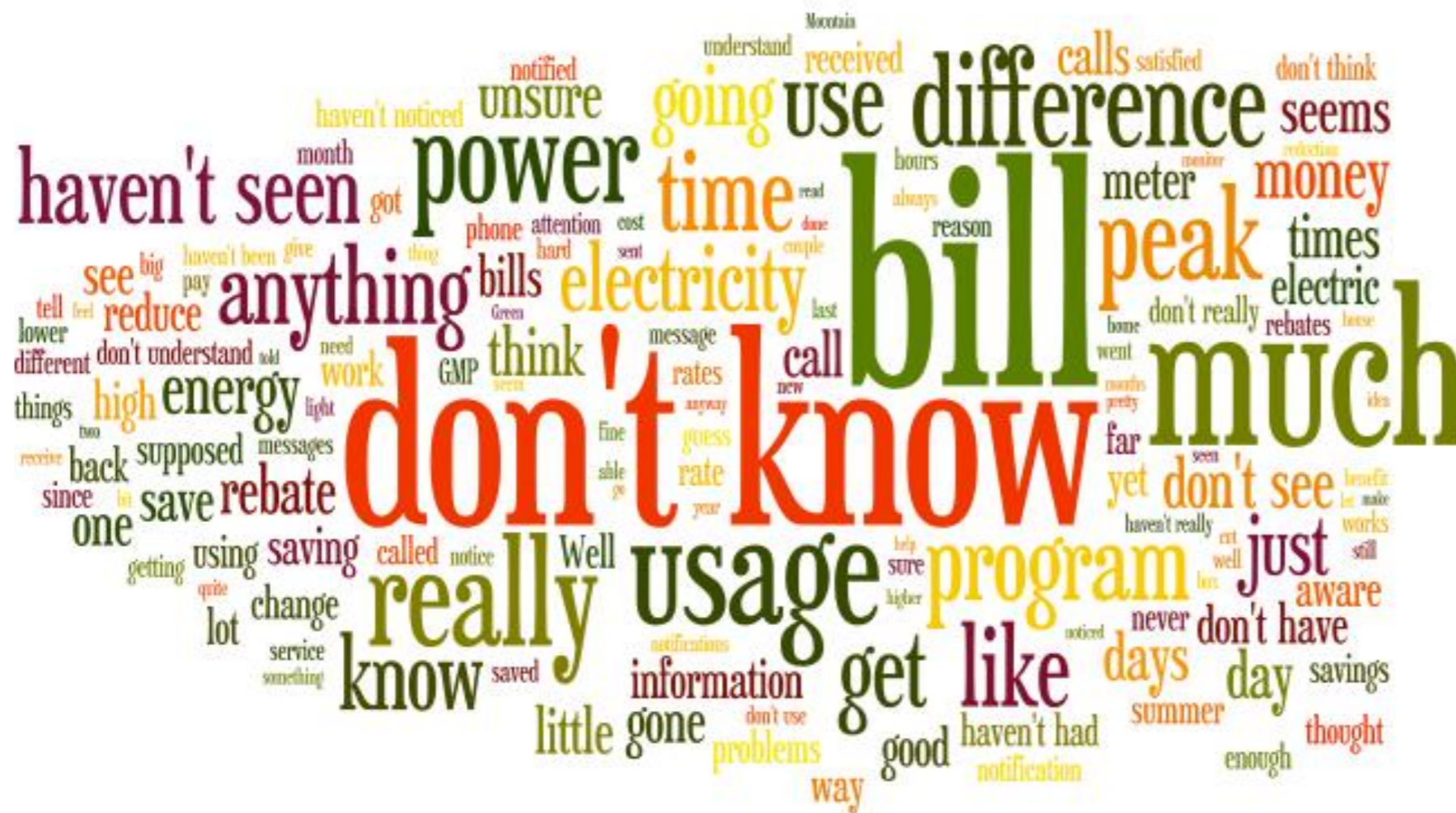






**Where contagion models DO work – spread of (or resistance to) rooftop solar power.**

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

Institutional and  
Physical  
Architecture

**Transdisciplinary Needs**  
Not just an engineering problem

**Creative Thinking**

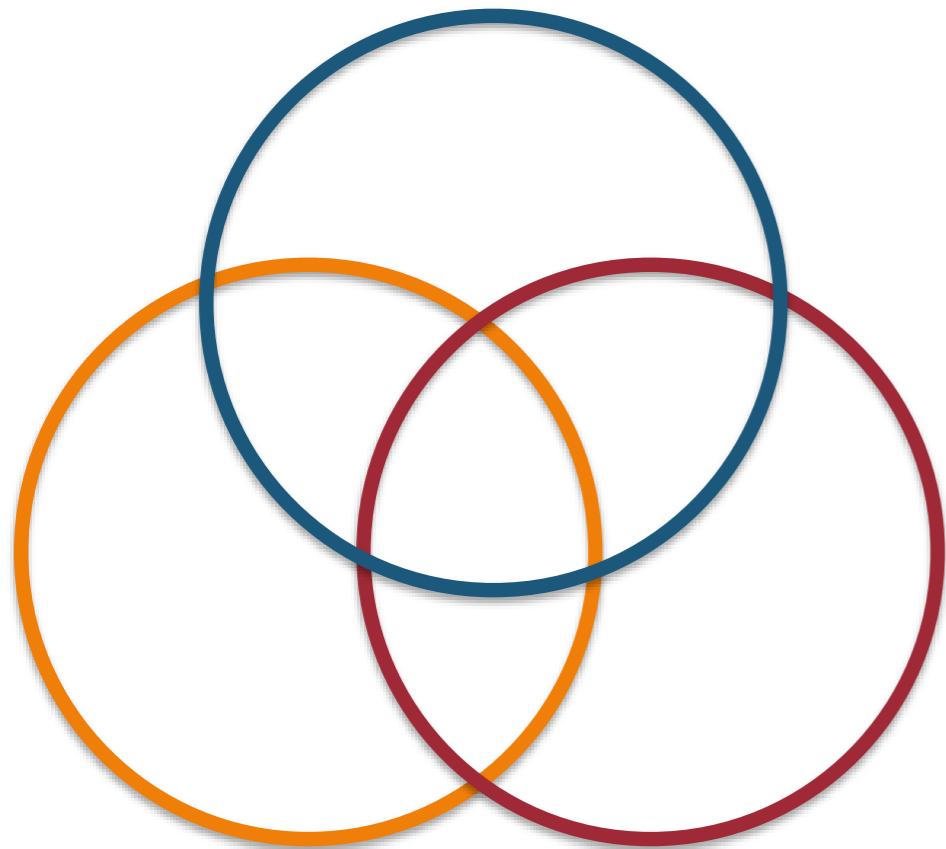
Bring the spirit of complexity science...but many of the models can stay at home

**Not Just the Grid**

Couplings with other physical, natural and social infrastructure

Measurement  
(Direct and  
Latent)

Innovation and  
Implementation



# Questions?

Seth Blumsack: [blumsack@psu.edu](mailto:blumsack@psu.edu)

Paul Hines: [paul.hines@uvm.edu](mailto:paul.hines@uvm.edu)