The Power Grid and Complexity Science

Santa Fe Institute Complex Systems Summer School

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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.
United States transmission grid

Source: FEMA
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
Things started decentralized:
Pearl-street station (1882)
And then we learned how to move power over distances
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

information & communication
automatic controls, sensors, smart grid
human operators

electricity markets

other infrastructures
electrical infrastructure

public policy, sentiment
cost, reliability
climate change
extreme weather
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

\[ P_m = P_g + D\omega + M\omega \]

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

![Graph showing the probability of electric load unserved versus loss of load](image)

- **Carreras, et al. (2004)**: Customers unserved
- **Zhao (2015)**: Electric load (MW) unserved
Extreme Events

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

Hines, et al. (2008)
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

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

Barabasi and Albert (1999)

Chassin and Posse (2004)
## Any Evidence for Any Structure?

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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?

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
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

Wang and Rong (2009)

The Value of Topological Models

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.
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

Hines, Dobson, Rezai (2017)
Challenge #3: Sustainability and the Social Side of Electrons
So, You Want Renewable Power?
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!
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.

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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