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!
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
Key principle #1

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

\[ v(t) = 120\sqrt{2}\cos(2\pi60t - \pi/4) \]
Key principle #2

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

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

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

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?

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

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)
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)

The Value of Topological Models


![Graph showing the value of topological models](image-url)

Random Failure Statistics:
- \( \mu = 14.04 \)
- \( \sigma = 19.45 \)

- Blue: Degree-Based
- Red: Max-Traffic
- Orange: Min-Traffic
- Green: Betweenness

Blackout size (deviation from random, %)

Number of bus failures ➔

1 2 10
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 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

Hines, Dobson, Rezai (2017)
Lesson 2: “Centralized” vs “Decentralized” is a False Dichotomy
Questions?

Seth Blumsack: blumsack@psu.edu
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?”

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

- 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 summertime.

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

Average Hourly KW Difference During Event Hours (Treatment - No-Notification Control)

- CPR: 5.3%
- CPR+IHD: 7.4%
- CPP: 7.3%
- CPP+IHD: 6.5%
- Flat Rate w/ notification: 14.1%
Do People Know What is Good for Them?
What do People Value?

- Monetary Savings: 41%
- Improvement in Service: 40%
- Like Conservning Energy: 14%
- Like the IHD Technology: 5%

“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

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

1/10 sec 1 sec 10 sec Minutes Hours Days Months Years
Inertia Droop control Auto. Gen. Control Load following Hourly Markets OPF Unit Commitment Seasonal Planning Investment planning. Policy.
Stakeholder Processes
A “Demand Curve” for Power Plants

![Graph showing a demand curve for power plants with various packages and their respective VRR prices as a function of percentage points above target IRM.]
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
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

Institutional and Physical Architecture
Measurement (Direct and Latent)
Innovation and Implementation
Questions?

Seth Blumsack: blumsack@psu.edu