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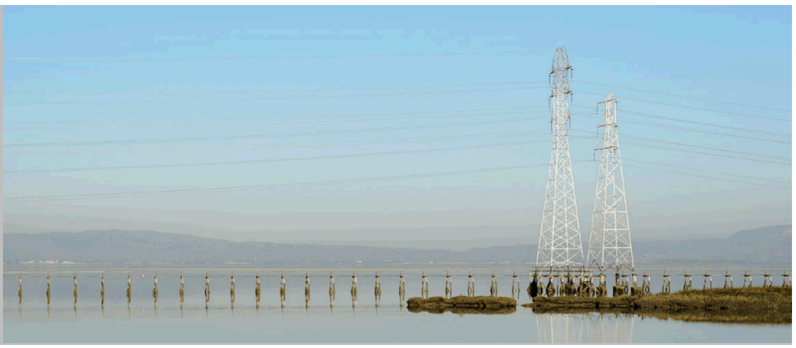

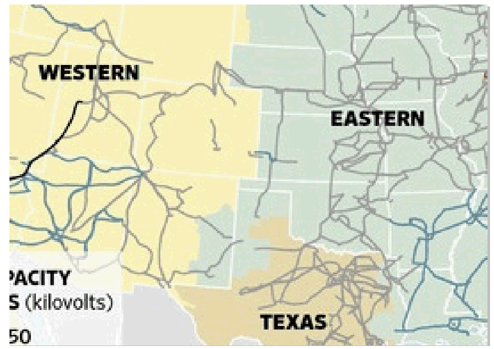

Complex Systems and the Electric Grid

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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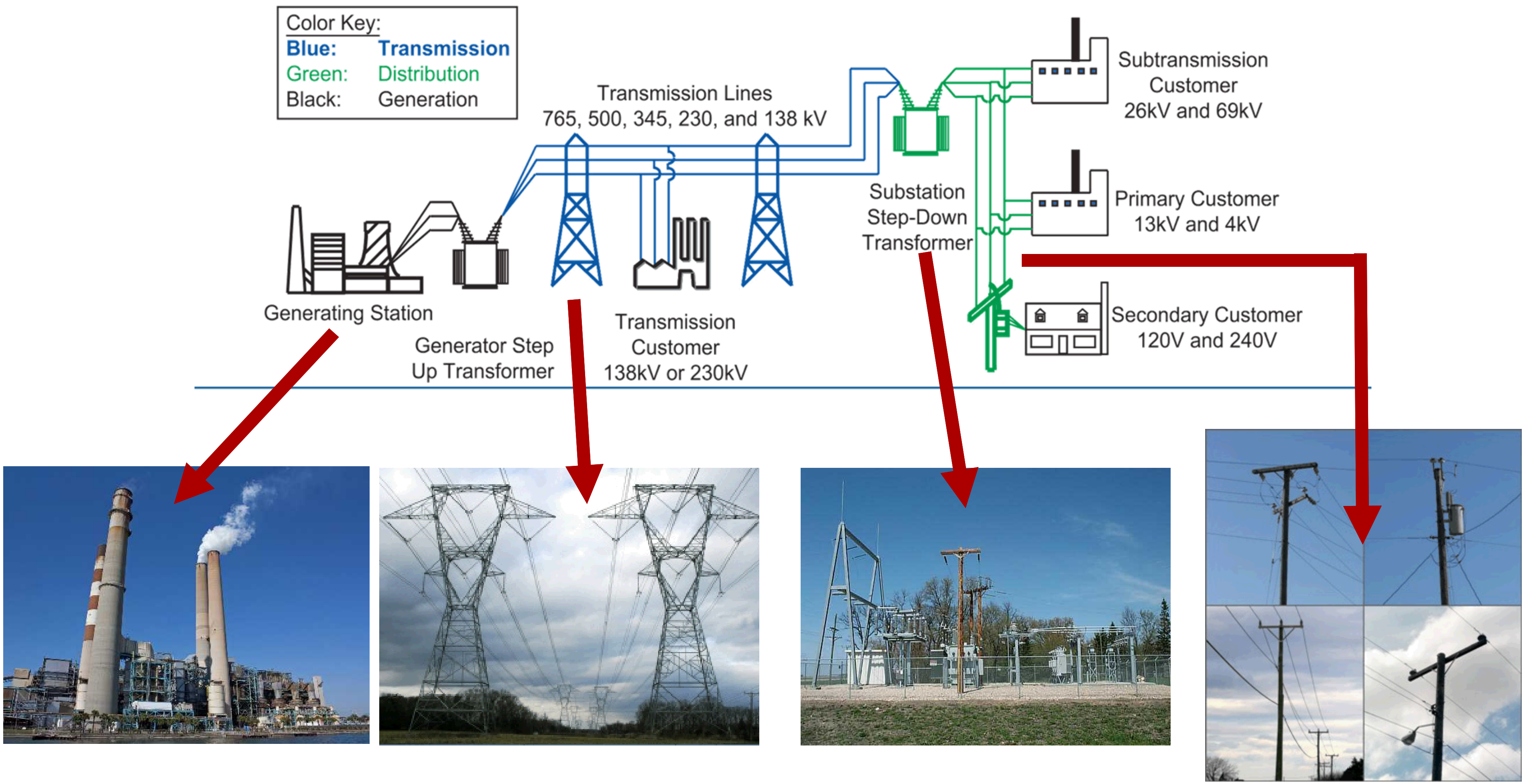
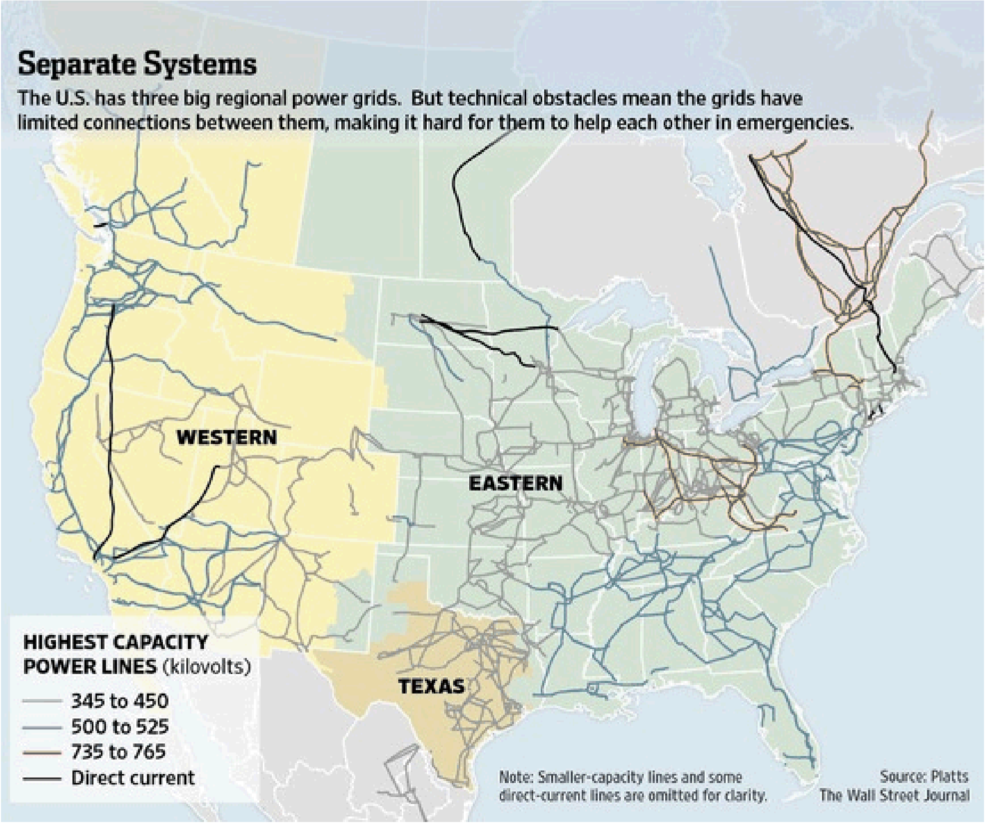
Components of the Electric Grid



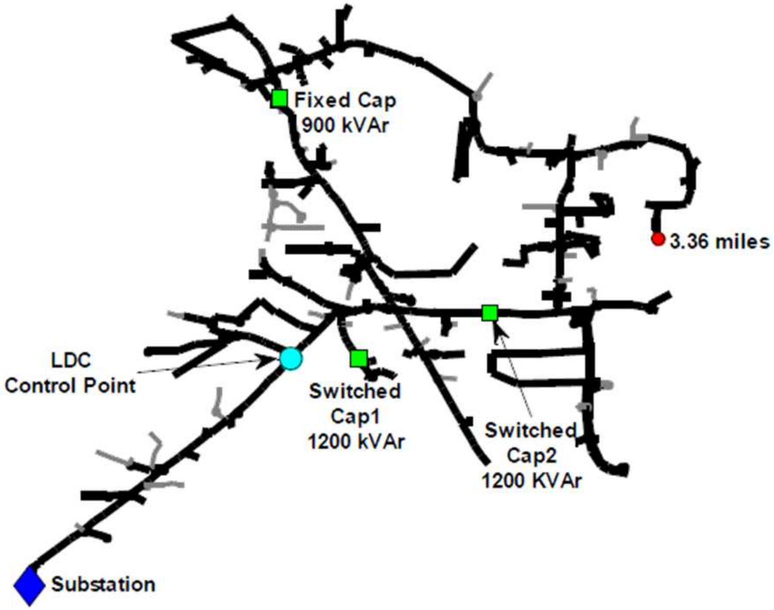
Transmission Grid

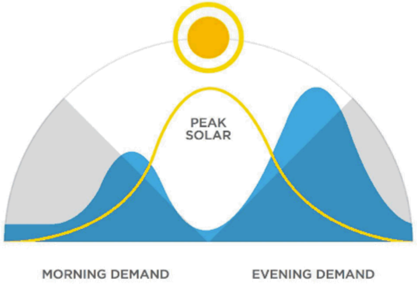


- Interconnected network with subsections overseen by different human operators
- Adaptive system: power flow magnitude and direction will change;
- Significant effort spent on outage (low-probability event) planning: “n-1” contingencies

http://www.energyandpolicy.org/value-of-solar-versus-fossil-fuels-part-three

Distribution Feeders





<u>Now</u>

- Little/no monitoring along feeder
- Photovoltaic (PV) installations inject variable power at locations along feeder
- Incomplete information about PV locations, performance

<u>Upcoming</u>

- Ubiquitous sensing (e.g., smart meters)
- Customer-owned storage
- Demand incentives: customer reactions
- Customer-owned PV inverters: grid support

Electric Grid Model/Decision Pairs

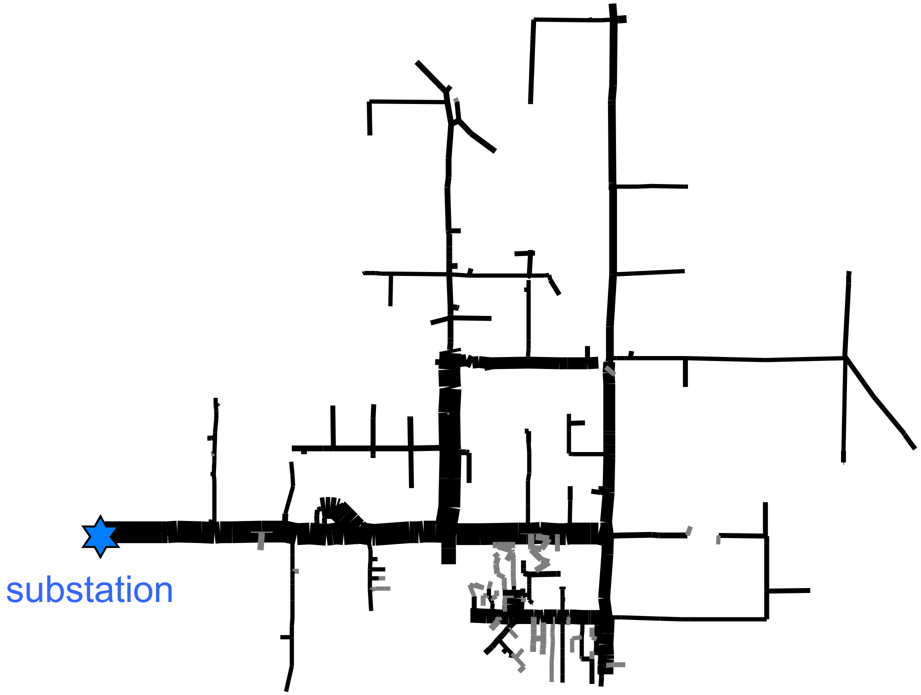
- **Traditional**
  - Rigorously derived from well-established physics and mathematics.
  - Example: Power flow with known loads and generation.
  - Decision: To accommodate a given load, what line rating do I need (how much current must it be able handle)?
- **Non-Traditional**
  - Typically involve layers of uncertainty and/or require large amounts of data to properly characterize.
  - Example: Stochastic Optimization
  - Decision: How to operate grid with uncertain solar power production (weather)?
- **Adaptively Complex**
  - Involving human activity and long timescales. Applications include determining likelihoods and consequences of rare events as well as subsequent contingency planning and recovery management.
  - Model: Coupled Simulations (weather, contingency analysis, cascading failures, agent-based models, sociological models, logistics, etc.).
  - Decision: How should the electric grid and associated infrastructure be designed and operated to maximize resilience?

Distribution and Transmission Models

- Distribution grid models
  - Often traditional
    - Straightforward decisions e.g. on line ratings
  - Becoming non-traditional
    - Addition of solar PV as generation: no longer radial flow from substation
  - Later, adaptively complex
    - PV inverters provide grid services – incentives
    - Additional devices such as programmable thermostats and home battery walls change consumption behaviors.
- Transmission grid models
  - Already non-traditional to adaptively complex
    - Stochastic analysis
    - Many human operators
    - Contingency n-1 and n-k analysis

Distribution Grid: Traditional

- Planning line ratings
  - Based expected effective resistance (load)
  - Essentially V = IR
- Adjust voltage settings at substation
  - Use basic electric equations to estimate voltage at end of line based on substation voltage and simple assumptions



An example distribution grid. Thicker lines mean higher line ratings (can handle higher current).

Distribution Grid: Non-Traditional

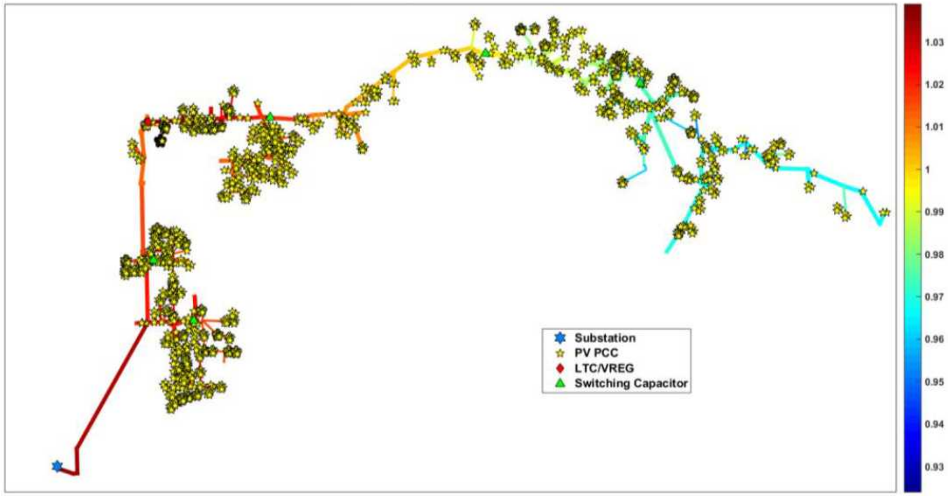
Keep safe voltage levels with PV

- Solar PV injects power and raises voltage along a distribution feeder
- May lead to voltage violations on the feeder
  - Fines, blackouts
- Uncertainty in PV production due to weather

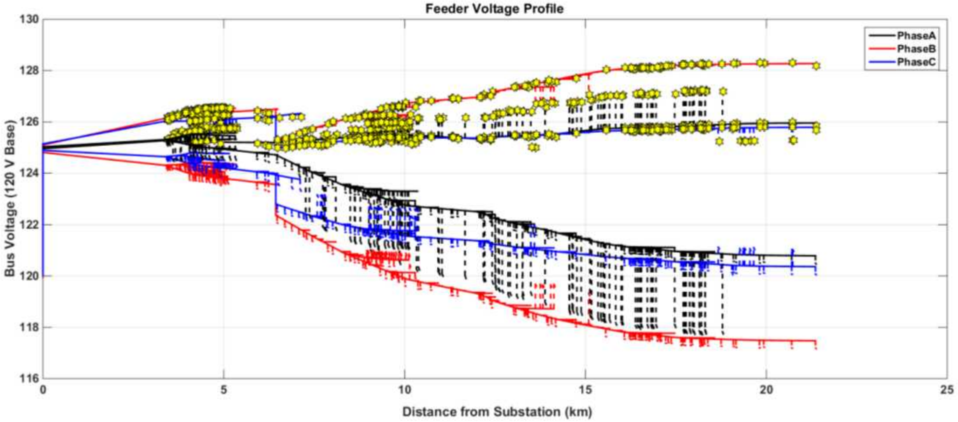
Non-traditional because:

- Uncertainty in PV production due to weather
- PV system locations, sizes, performance are often unknown, can change
- Utility may have no local monitoring, or may on "see" net load: load minus PV generation

Feeder layout and PV locations



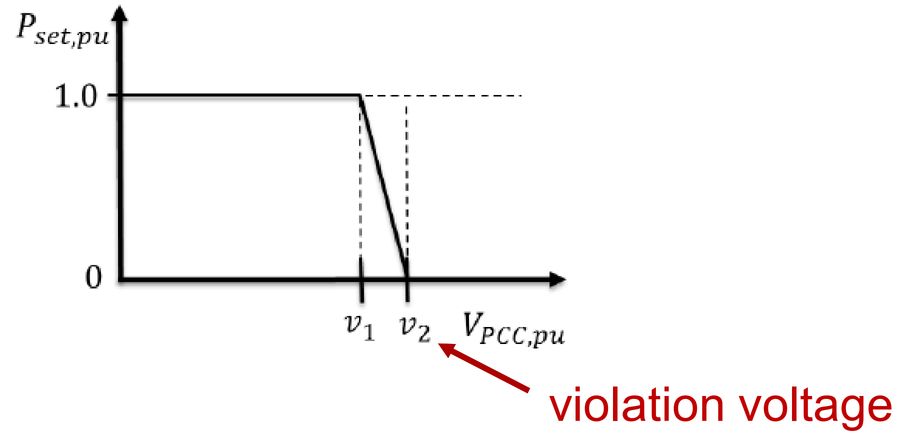
Feeder voltage profile (w/ and w/out PV)



Distribution Grid: Non-Traditional

PV controls can help mitigate voltage violations.

- E.g., volt-watt control



Decision: What are best settings for PV controls to maximize PV energy?

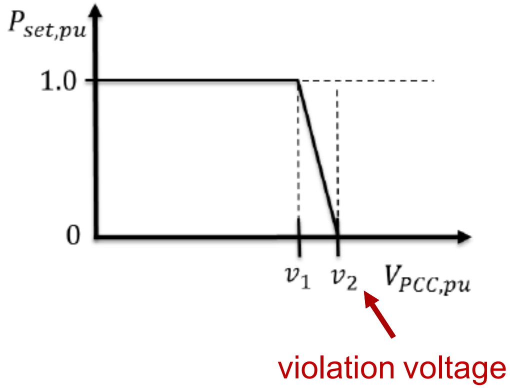
- Due to interplay between different PV systems, difficult/impossible to "traditionally"* define v1 and v2.
- Instead, determined experimentally through model optimization.

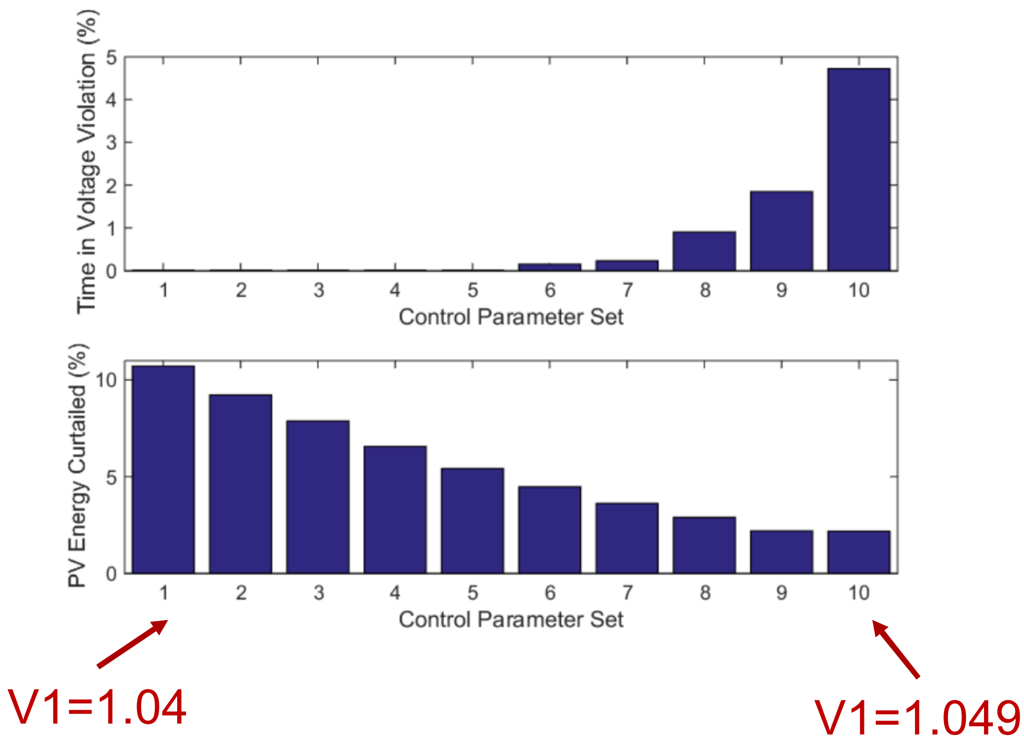
* "traditionally" as in: v1 = fn(location, PV size)

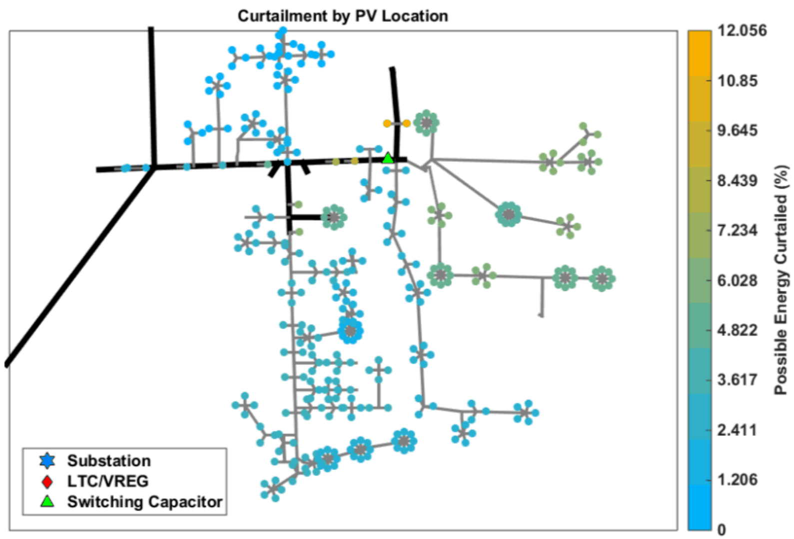
Distribution Grid: Non-Traditional

PV controls can help mitigate voltage violations.

- Tradeoff between curtailment of PV energy and voltage violations.
- Different results at each PV location.





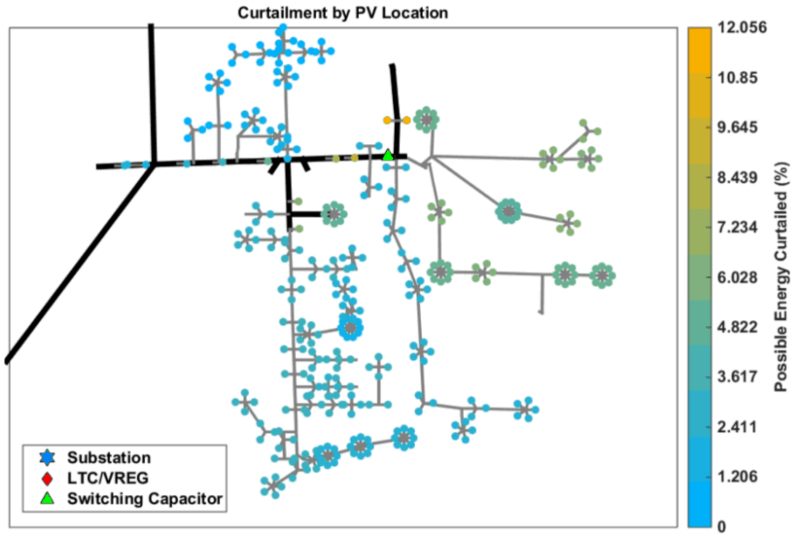


Distribution Grid: Adaptively Complex

Determine the impact of incentives/what are best policies

- How will customers react to price signals, incentives, etc.?

- Previous slide results:
  - Based on load from one historical year
  - Based on weather from one historical year
  - Based on static, hypothetical PV scenario

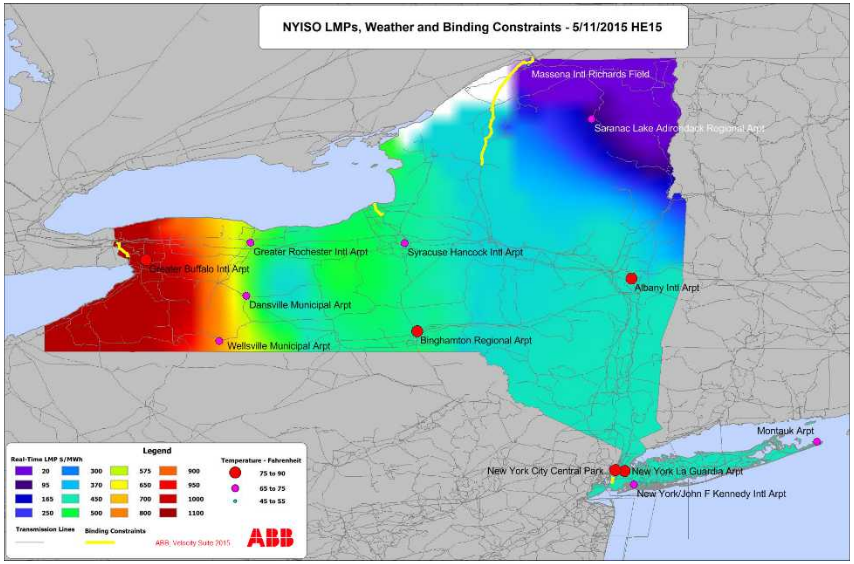


- But really,
  - All of these change (adapt) due to incentives, social acceptance, technology, etc.

Transmission Grid Complexity

Transmission grid models used for:

- Load/generation balancing
  - Import/export
- Locational marginal pricing
  - Incentivize generation at certain nodes
- “n-1” contingency analysis
  - Plan for loss of generator or line
- “n-k” contingency analysis
  - Threat and vulnerability analysis



Locational marginal pricing showing high prices in Western New York due to unexpectedly high temperatures and hence high AC loads.

Image from: http://energymarketintel.com/wp-content/uploads/2015/05/NYISO-LMP-and-Weather-Heat-Map-5.11.15-HE15_v2-copy.png

Transmission Grid Complexity

Many different human operators, each with their own overlapping but not fully aligned incentives

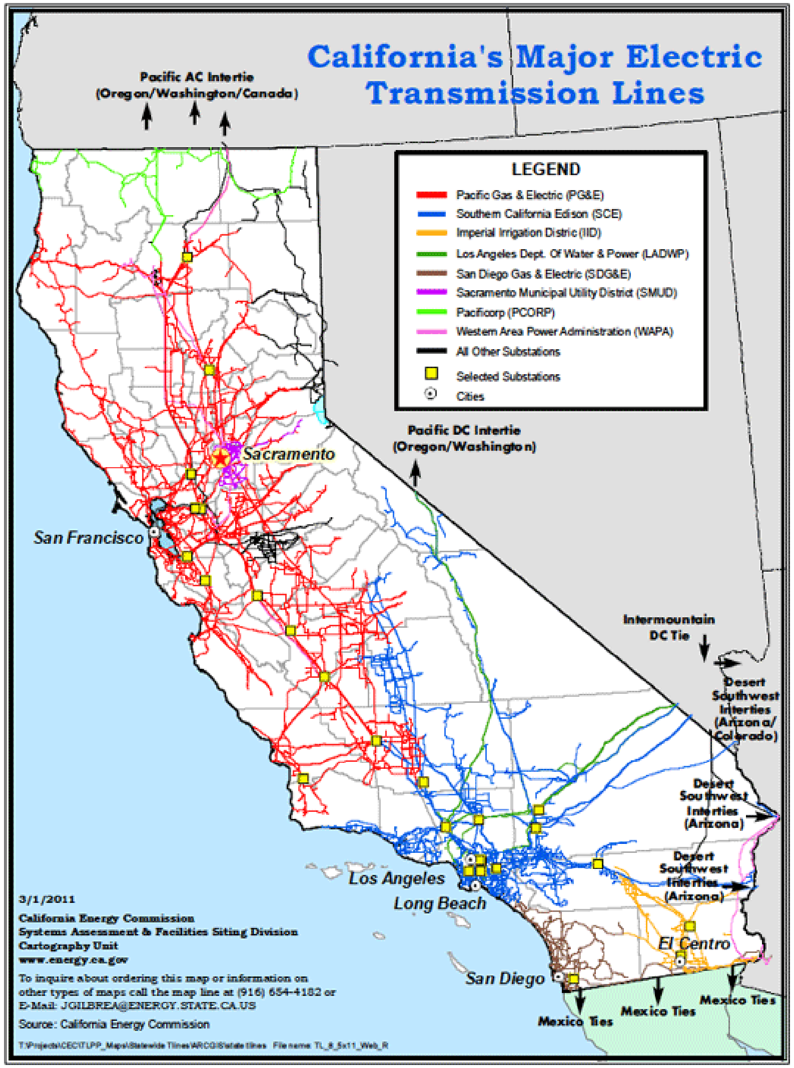
- Avoid blackouts in own territory
- Manage generation you can control
- Communicate with neighbors for assets you don’t have control over

NY Times: *On the Front Lines of the Power Grid, Oct. 25, 2011:*

“QUICK! You are on duty in a secret control room in a nondescript, windowless building. …your task is crucial: you are matching the ever-changing power needs of tens of millions of electricity customers with supply coming from hundreds of electricity generators, deciding which units will run and which ones will be idle, and making quick adjustments for the generators you can’t schedule, like the wind machines and solar panels.

Hardly anybody will ever know you are here, unless you mess up.
All is going smoothly until you get a message from a neighboring electrical entity requesting emergency assistance. A quick glance at your computer screen tells you that you have sufficient spare capacity to help.”

What do you do?



Transmission Grid Complexity Example: San Diego, September 8th, 2011

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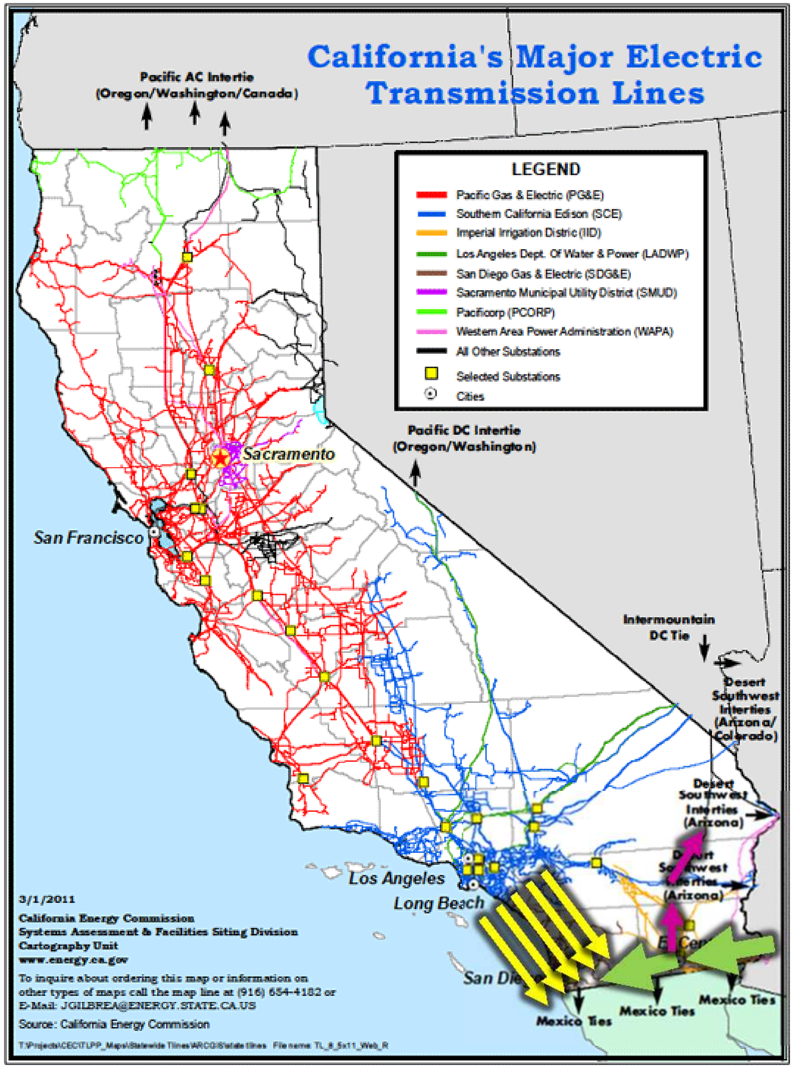
Hot day in San Diego

- Demand greater than local supply
  - September considered shoulder season: fewer generators online than summer
  - But, this alone is not a cause for concern

- generation being imported from the north (Los Angeles) and from the east (Arizona through El Centro)

- power flowing north from El Centro to Imperial Valley



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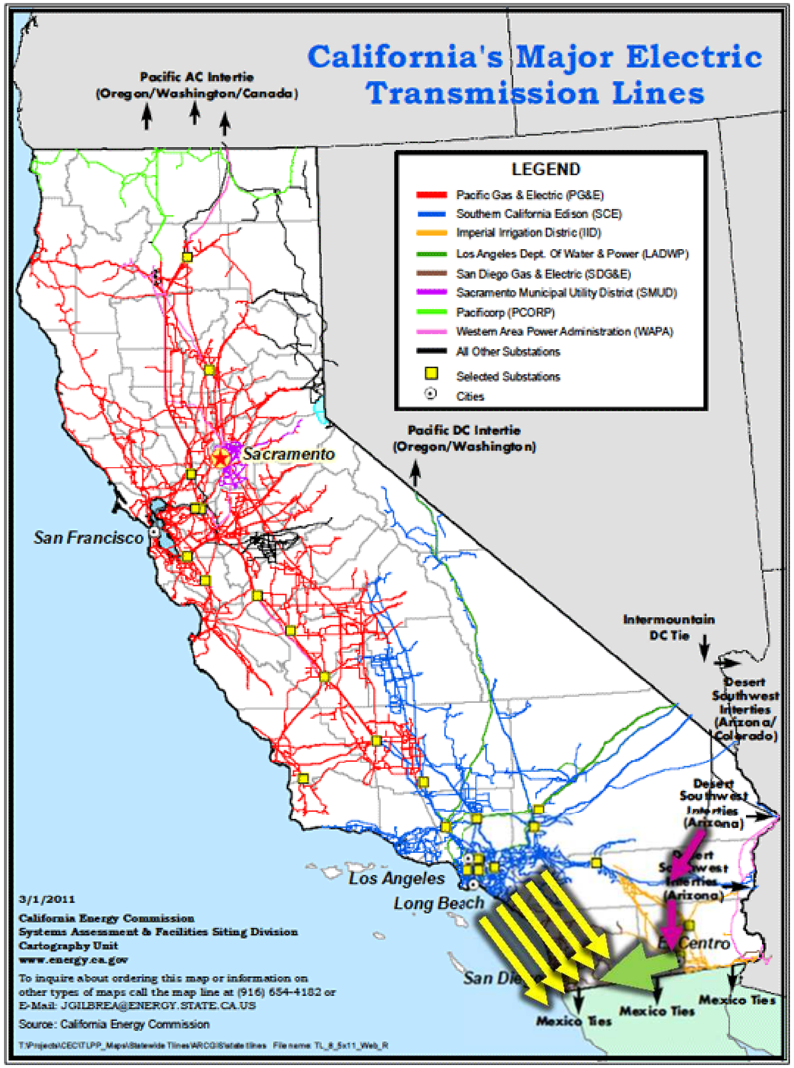
Three human events lead to blackout

1) Worker in western Arizona accidentally misses a step in maintenance on a capacitor: Southwest Powerlink crossing AZ/CA border trips off. Increased power flow from Los Angeles, and reversal of flow to be in from Imperial Valley.



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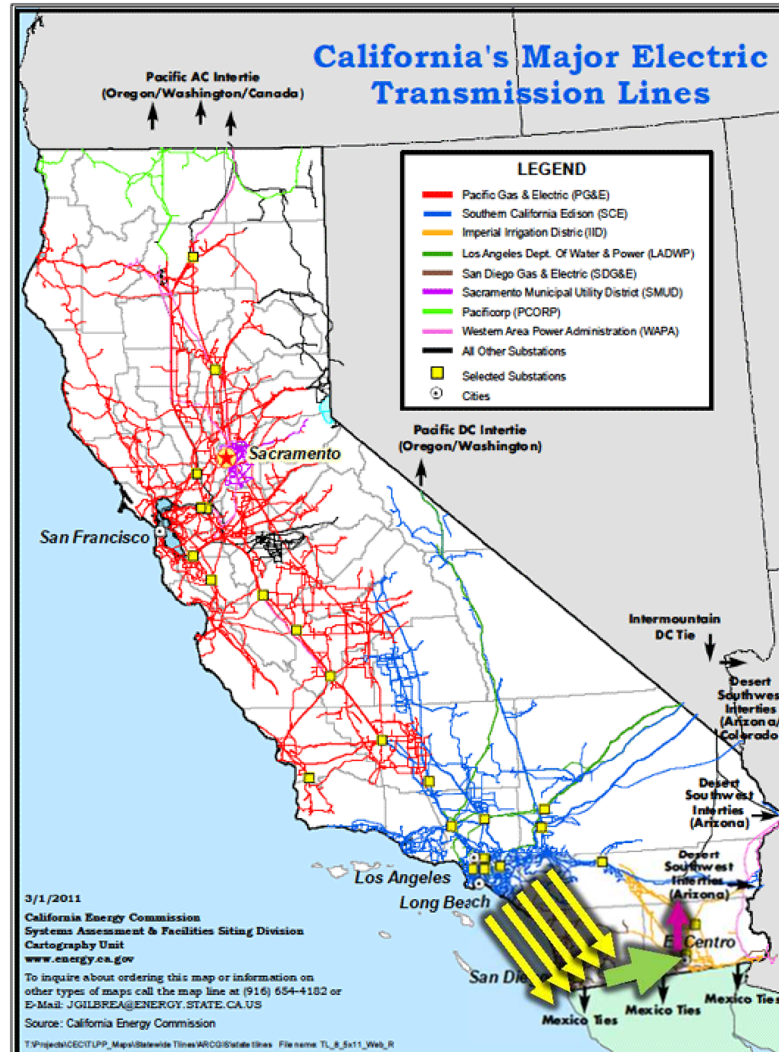

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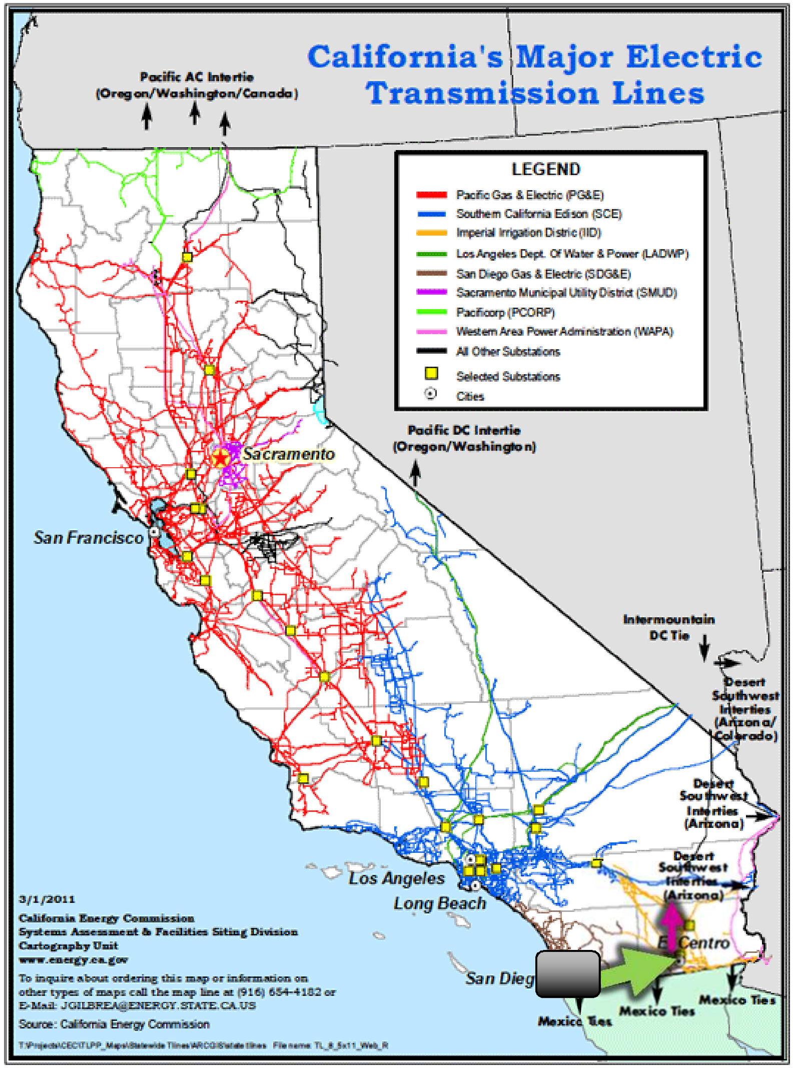
3) Human operators unaware of 8000 amp limit on line from Los Angeles, line exceeds that (operators know and think it is ok) and disconnects. This San Diego island does not have enough local generation to meet demand. **Blackout!**



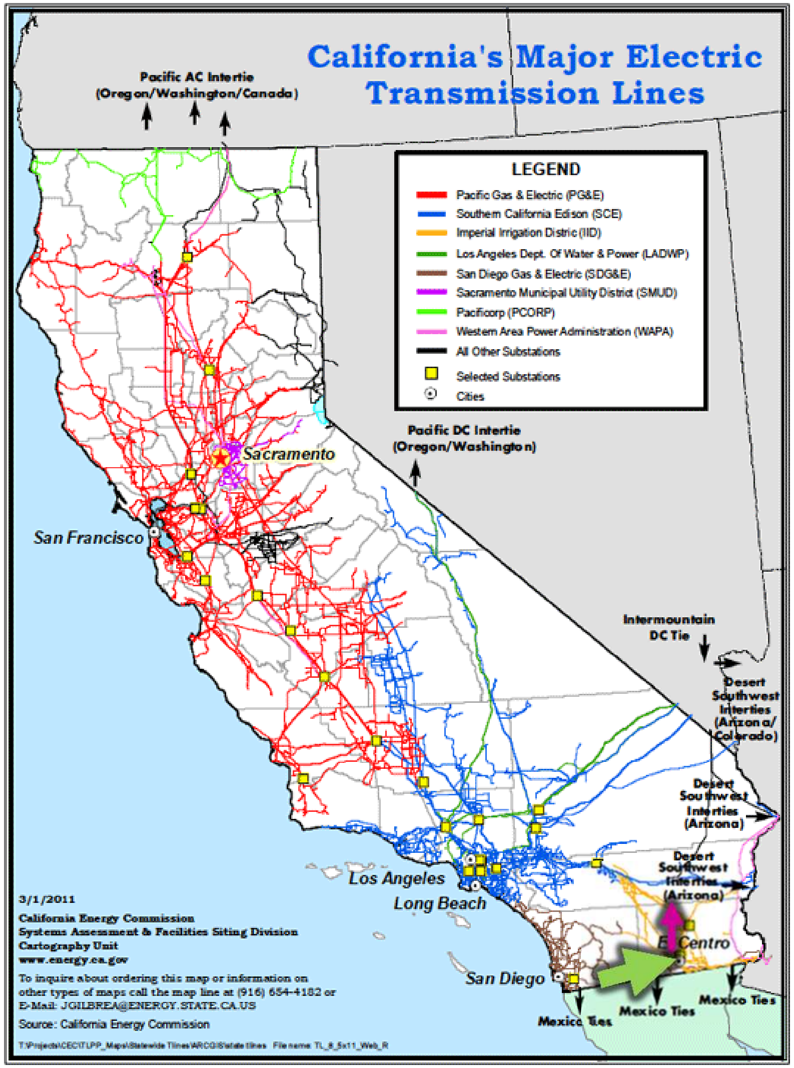
Transmission Grid Complexity Example: San Diego, September 8th, 2011

Blackout caused by accident, poor planning, and unknown grid limit.

- All very low probability events.
- No blackout if any of the 3 events didn't happen.

"Traditional" works have looked at vulnerable nodes/lines: what happens if this line fails. Limited stochastic analysis.

Challenge is to model (and validate!) human cognition and decisions coupled with low probability events.



Challenges in Electric Grid Modeling

Grid operator actions

- Many individual operators, incentives not always aligned
- Competition/interaction with other grid operators
- Shift to renewable, variable generation (wind/solar) introduces generation uncertainty

- Customer actions
  - Influenced by policy, but how do customers respond?
  - Customers acting different from expected, trying to game the system
  - Shifts in consumption behavior (electric vehicles, power walls, etc.)
- Low probability events
  - Blackouts
  - Operator errors/Incorrect information
  - Attacks (physical and cyber)
  - Extreme weather (Hurricane Sandy)
- Complex interactions
  - As distributed PV increases, power may flow from distribution grids to transmission during some times

Validation and UQ

Need to validate electric grid models:

- Quantitative
  - Accurately represent PV production/customer loads
  - Accurately determine voltage/current violations
- Qualitative:
  - **Convince grid operators that models are useful**
  - Ensure policies are working

Need to understand uncertainty:

- Penalties to utility for exceeding voltage/current limits; may lead to unsafe conditions, blackout, etc….how big is the risk?
- Suggested optimized state plus confidence: operator may choose to go against suggestion if confidence is low
- Threat analysis

Quantities/Questions of Interest

Quantity of Interest	Reason	Challenges
Electrical quantities: voltage, current, power	Ensure operation of electric grid is within allowable limits	Limited validation data, extreme events (e.g., power outages), evolving grid layout (upgrades, new PV)
Customer behavior: typical electric use, response to price incentives	Optimize operation of electric grid	Complicated human decisions, evolving behaviors
Resiliency of electric grid	Understand impact of threats	Resiliency difficult to quantify, extreme events (never happened previously), modeling recovery of the grid
Impact of renewable energy generation	Maximize amount of energy from renewable generation while maintain a safe, reliable, resilient grid.	Renewable generation is variable (weather), coupled human adoption/electrical impact, grid support from renewables (control and $)

Questions of Interest
What is the value of increased sensors/data on electric grids? – e.g., Does additional data reduce uncertainty and hence enable more renewable energy installations?
How does customer generation and storage (plus control schemes) impact electric grid resiliency and reliability?
What are best policies to safely increase renewable generation on the electric grid (incentivize installations, grid support, etc.)?

Electric Grid and Cybersecurity

Ukraine, December 23rd, 2015

From *Wired*, "Inside the cunning, unprecedented hack of Ukraine's power grid"

- "Inside the Prykarpattyaoblenergo control center,…as one worker was organizing papers at his desk that day, the cursor on his computer suddenly skirted across the screen of its own accord…He watched as it navigated purposefully towards buttons controlling the circuit breakers at a substation in the region then clicked on a box to open the breakers and take the substation offline."
- "Somewhere in a region outside the city he knew that thousands of residents had just lost their lights and heaters…All he could do was stare helplessly at his screen while the ghosts in the machine clicked open one breaker after another, eventually taking about 30 substations offline."
- "Ukrainian and US computer security experts involved in the investigation say the attackers overwrote firmware on critical devices at 16 of the substations, leaving them unresponsive to any remote commands from operators. The power is on, but workers still have to control the breakers manually."
- "That's actually a better outcome than what might occur in the US, experts say, since many power grid control systems here don't have manual backup functionality…"

https://www.wired.com/2016/03/inside-cunning-unprecedented-hack-ukraines-power-grid/