TEXAS A&M UNIVERSITY Engineering

Creating Realistic Synthetic Electric Grids to Promote Open Science in Power Engineering

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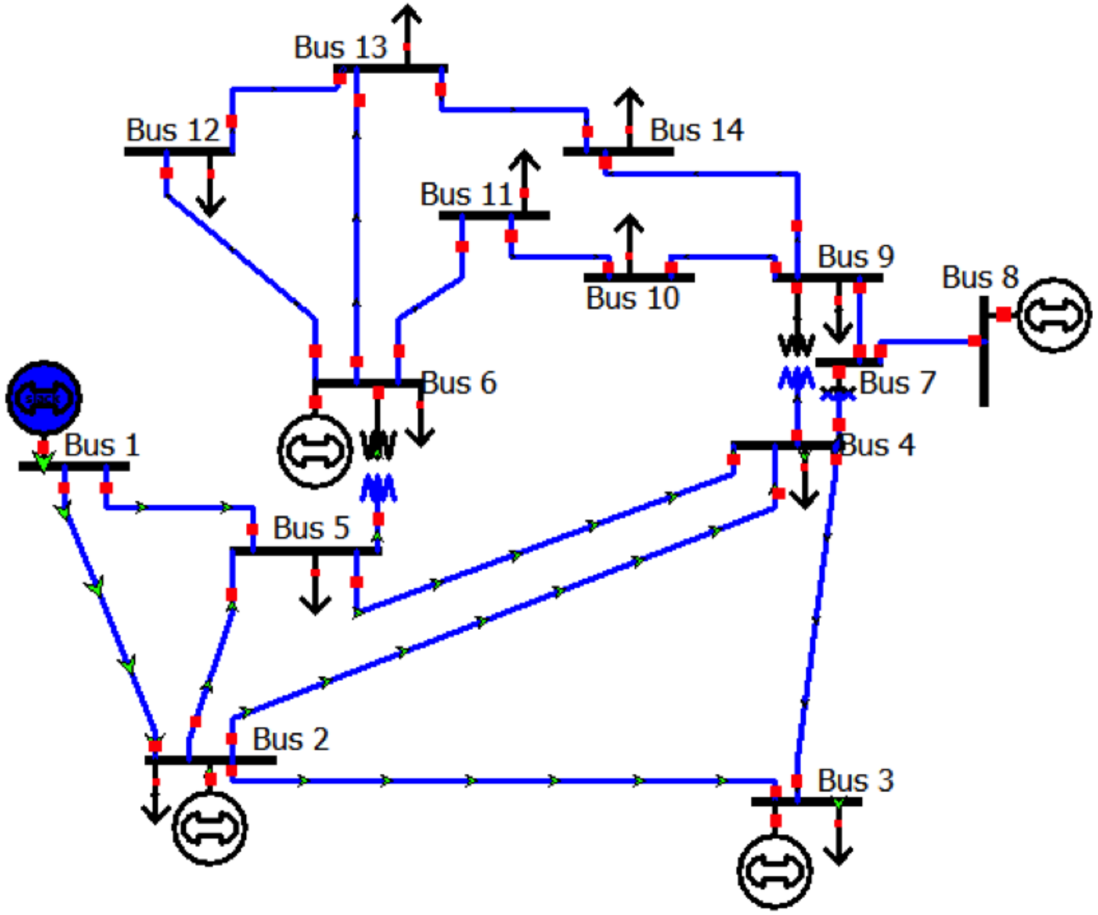
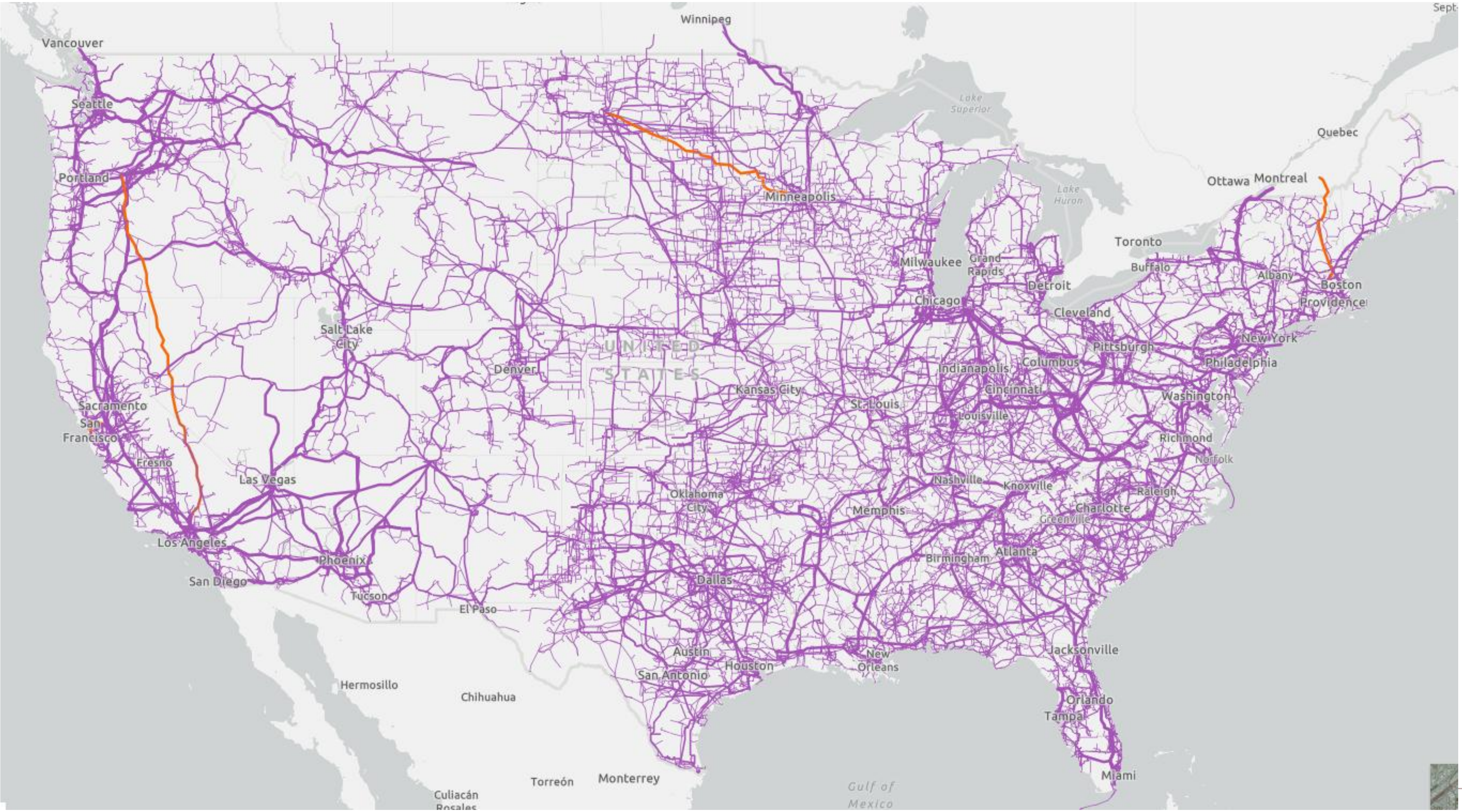
Test Cases for Power Systems Research

- Power grid data is critical energy infrastructure information (CEII)
- Existing test cases—prior to synthetic grids—are small, simple, and outdated
- Goal of building synthetic power grids is to drive innovation by providing test cases that are large, complex, realistic, and fully public.
- Applications include research, innovation, education, cross-validation and demonstration



Some existing test cases, such as the IEEE 14-bus (pictured) and 118-bus case, despite their popularity, are known to vary significantly from actual grids.

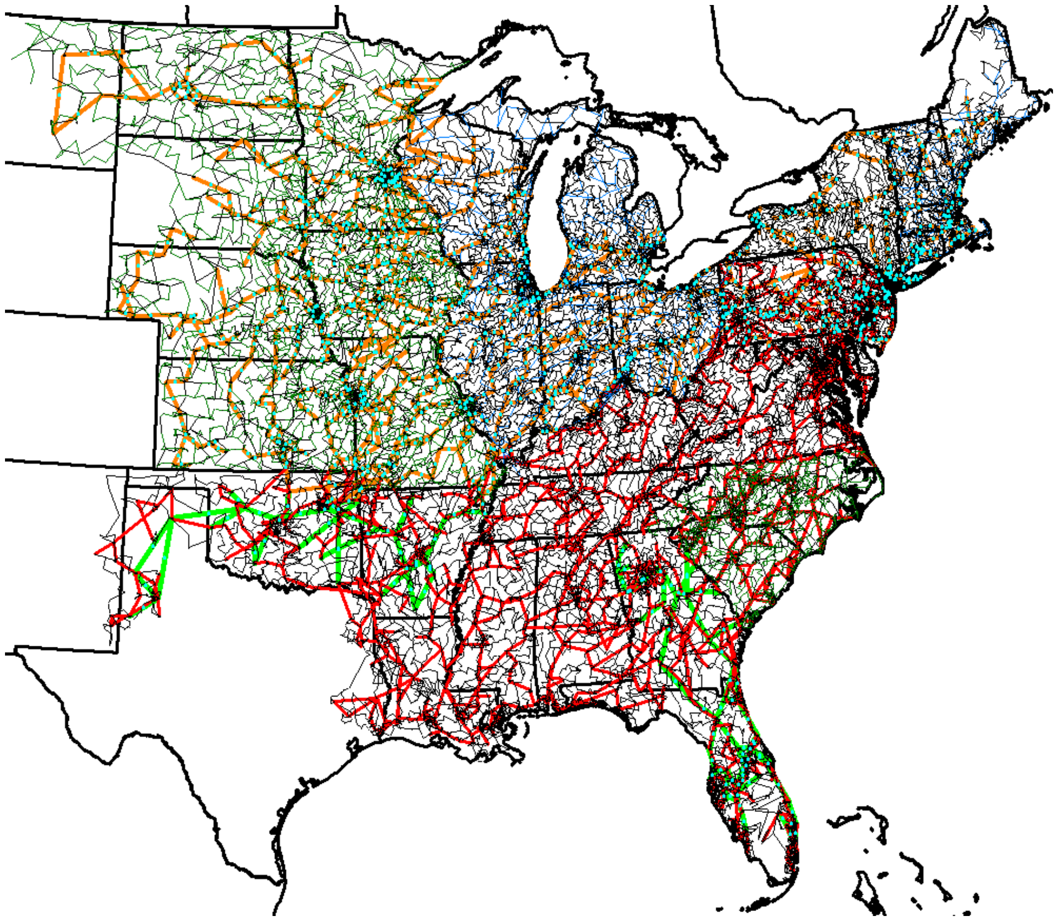
The U.S. Electric Grid Network



Source: US EIA Energy Atlas

Synthetic Power Grids

- **Large**: This case is 70,000 buses, similar to the actual Eastern Interconnect
- **Complex**: Multiple interacting voltage levels, remote regulation, capacitors, taps
- **Realistic**: Matching a large suite of validation metrics against actual systems
- **Fully public**: It does not correspond to any actual grid or contain any confidential information



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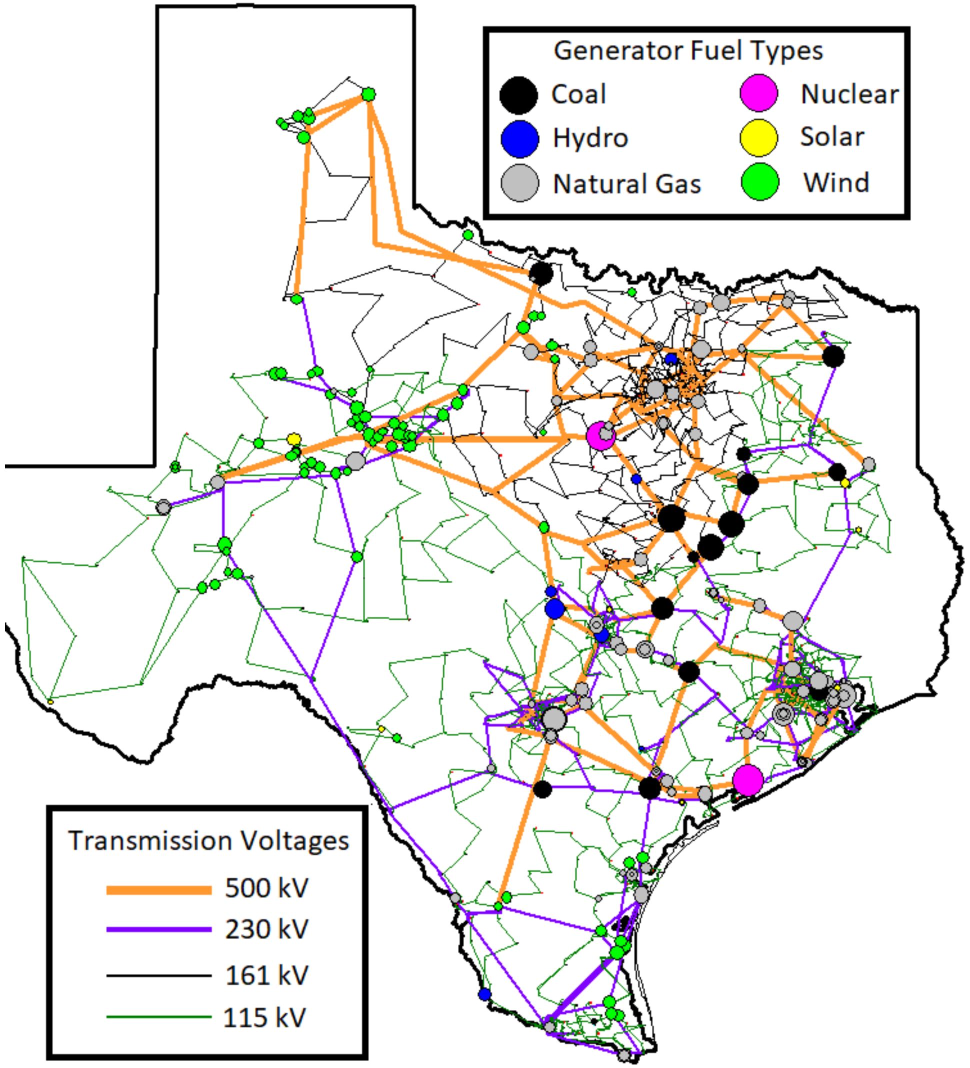
How Do We Build Synthetic Grids?

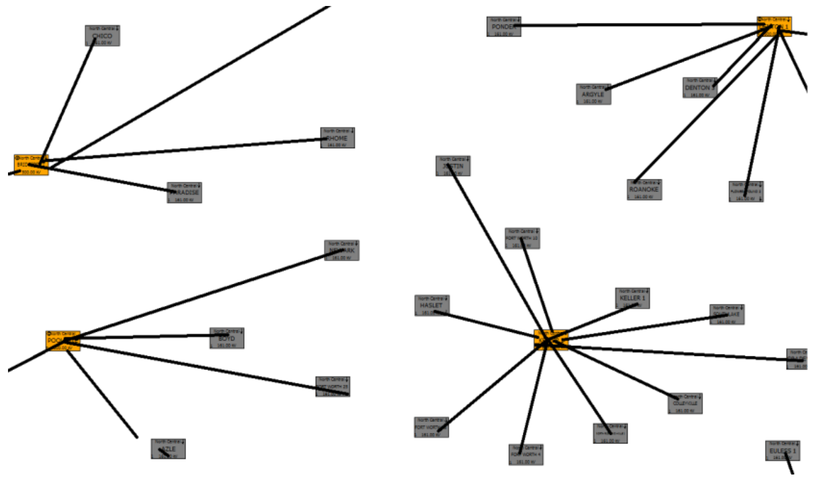
- Substation Planning
  - Start with public data for generation and load
  - Cluster substations, add buses, transformers
- Transmission Planning
  - Place lines and transformers
  - Iterative dc power flow algorithm
  - Match topological, geographic metrics
  - Contingency overload sensitivity
- Reactive Power Planning: Power flow solution (ac), Voltage control devices
- Extensions: Transient stability, geomagnetic disturbances, single-line diagrams, optimal power flow (OPF), time series scenarios, interactive simulations, …



2000-bus synthetic grid on the Texas footprint

Synthetic Substation Planning

- Substation planning is seeded by public Energy and Census data
- For large systems, decouple by area
- Modified hierarchical clustering technique combines zip code fragments and generators into substations
  - Use the same technique to assign higher voltage to about 20% of substations
  - Higher load/generation more likely to have higher voltage buses
  - Need cross-area connections for neighboring areas that do not share kV levels
- Economic generation dispatch assuming peak planning load

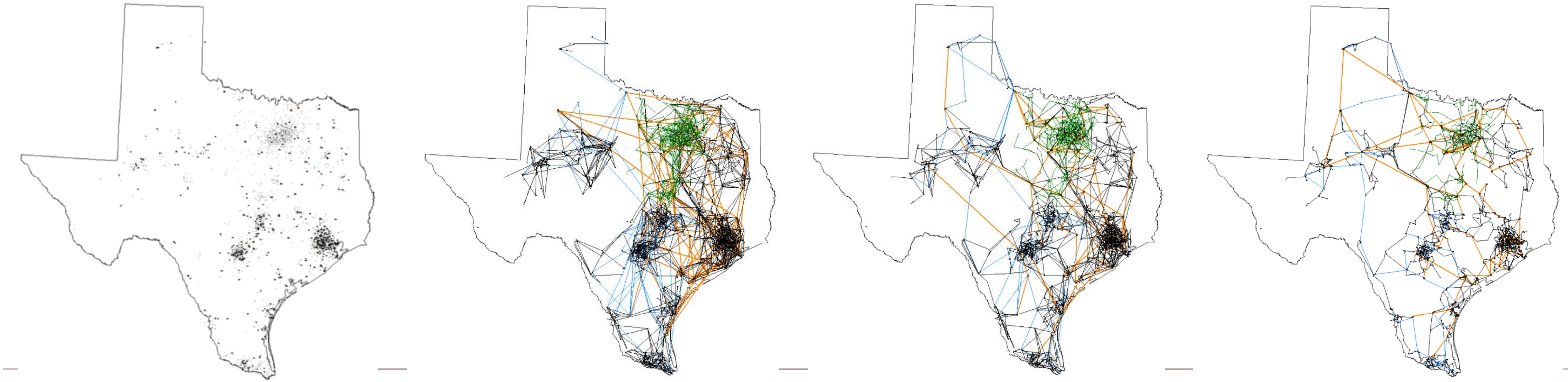


Synthetic Transmission Planning

- Geography drives transmission planning, and is central to the approach
- Network topology parameters: Graph metrics considering both individual voltage level networks and combined bus-branch topology
- Power flow feasibility: Avoid line limit violations in base and N-1 contingency conditions
- Difficulties for large grids
  - Possible branches is n^2, possible combinations of branches is intractable
  - Many competing metrics to meet
  - Large grids have many overlapping voltage networks that connect at substations
  - Consideration of contingency conditions increases computation even more
  - Manual adjustments grow with system size

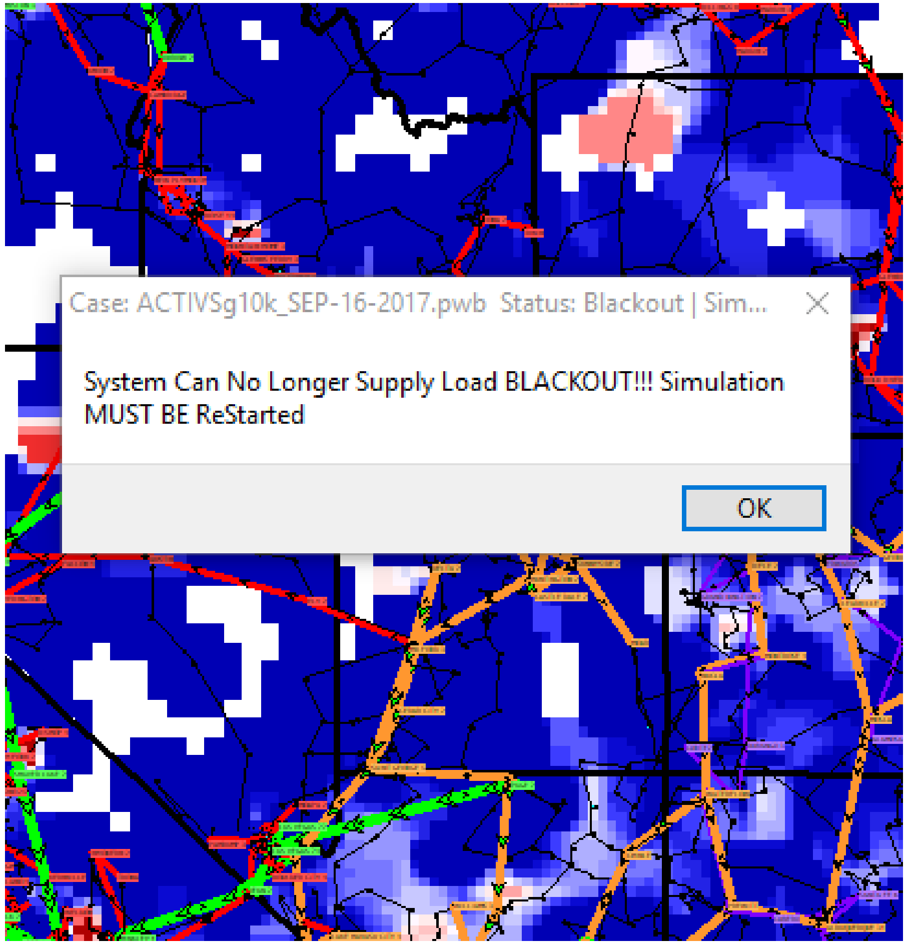
Synthetic Transmission Planning, Cont.

- Our solution
  - Reduce search space from n^2 to $21n$ with Delaunay triangulation (99% of lines < 3 dist.)
  - Begin with randomized graph and iterate toward high-quality network
  - Consider N-1 contingency analysis with DC power flow and overloading sensitivity metric
    - Line "innage" sensitivities rapid to calculate for 100k+ candidate lines
  - Parameterize to get the right balance of fixed cost and network/simulation performance
  - Validate metrics against metrics collected from actual grids



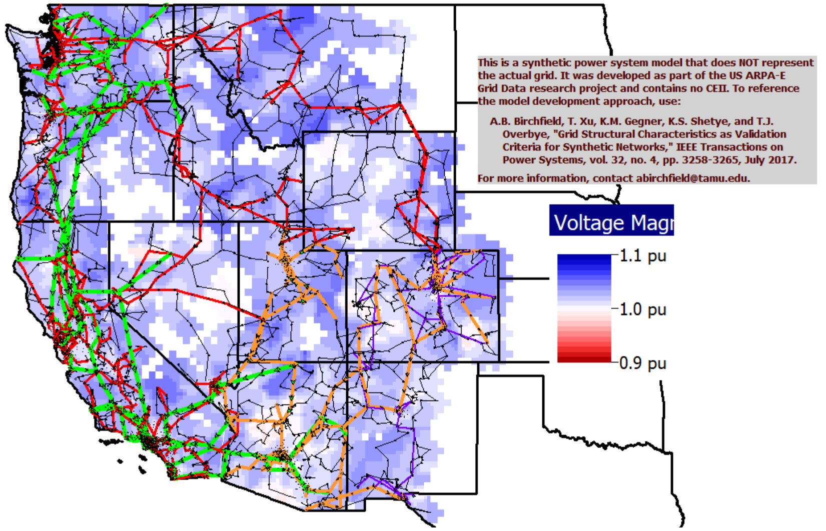
Synthetic Reactive Power Planning

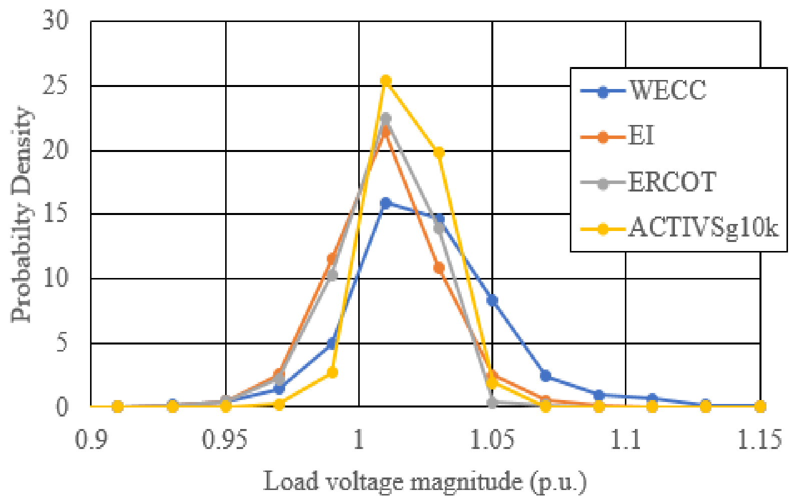
- Flat start often does not converge!
- For real interconnects, start with a prior solution
  - Doesn't work for new synthetic grids
  - Also synthetic grids, without reactive compensation, might not even have a solution
- So what do we do?
  - Since we have a good dc solution, iteratively move from that to a realistic ac solution
  - Add a temporary generator to the highest voltage bus of every substation with 0 MW, controlling the bus voltage
  - Solve the ac power flow solution with this large number of PV buses
  - Iterate over 100 groups, removing most temporary generators and adjusting the others, until the remaining ones become shunt capacitors and reactors.



Synthetic Reactive Power Planning, Example

- 10,000 bus case representing WECC
- Initial power flow solution diverges!
- Algorithm previously described was applied
- 387 shunt capacitors remained for 4762 substations
  - This is 8%, actual grid has 10-20% (good)
- Voltage profile matches actual interconnect observations



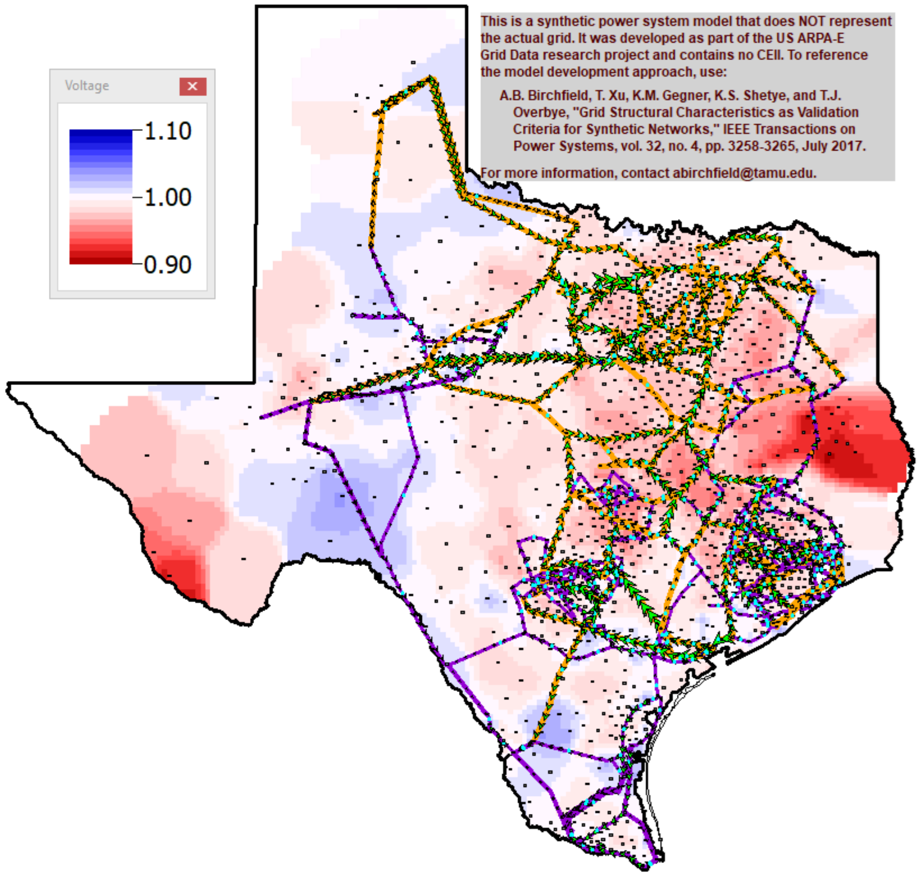


Results and Validation

- The results are large, solved power flow cases that do not contain CEII! They are also highly realistic…
- …how can we show they are highly realistic?
- Complex problem: our validation metrics collected from many actual US electric grid cases help to provide a check on case quality. Because of the variety in engineering design and practice, actual grids are quite diverse. Some metrics:
  - Overall size and structure (ratios of loads/generators/shunts/buses, dispatch, capacity)
  - Device parameters (XFMR reactance, X/R ratio, t-line limits and per-distance Z and B)
  - Network topology (degree distribution, cycle basis, SIL, clustering coefficient, average shortest path length)
  - Technical performance (static N-1 contingencies, voltage profile, loss levels, reactive power balance)

Impact of Synthetic Grids – R&D

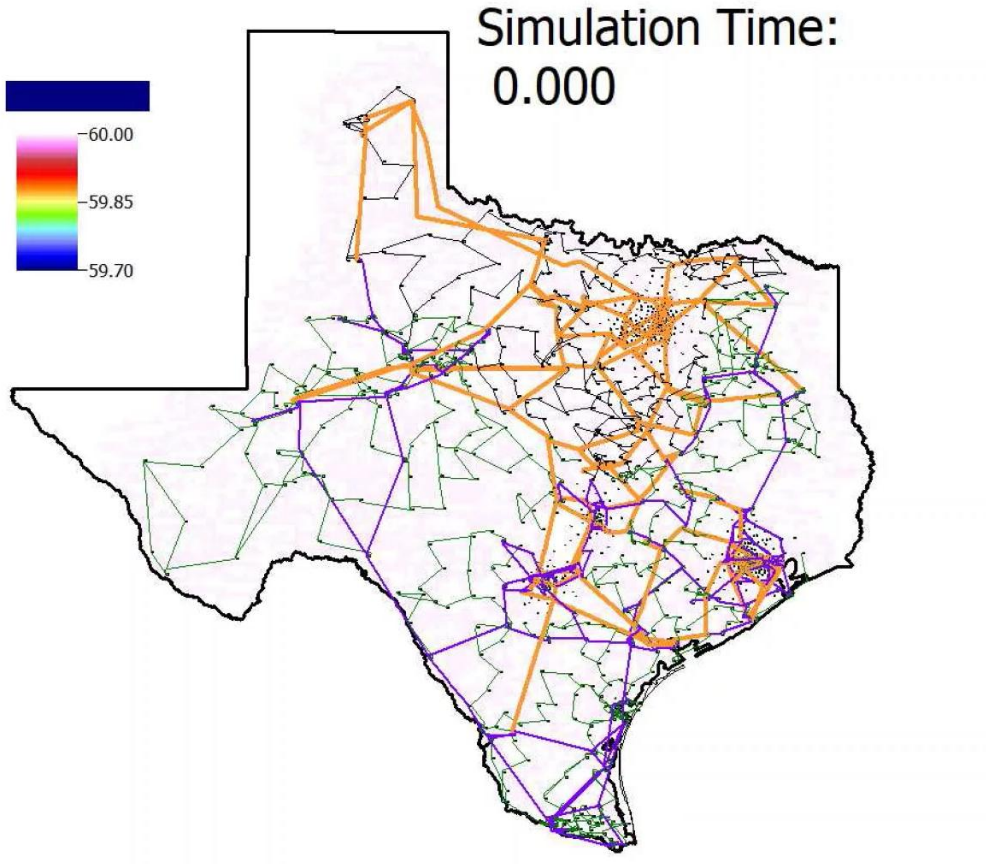
- Higher quality, larger, more complex, and more realistic than existing test cases
- Improved ability to cross-validate published research results in power systems literature
- For industry, ability to demonstrate new capabilities for analysis without compromising sensitive data
- Geographic embedding allows connection with other geographically-oriented datasets
- Our more recent work has developed higher quality dynamic models for transient stability and EMT analysis



GMD-induced voltage sag

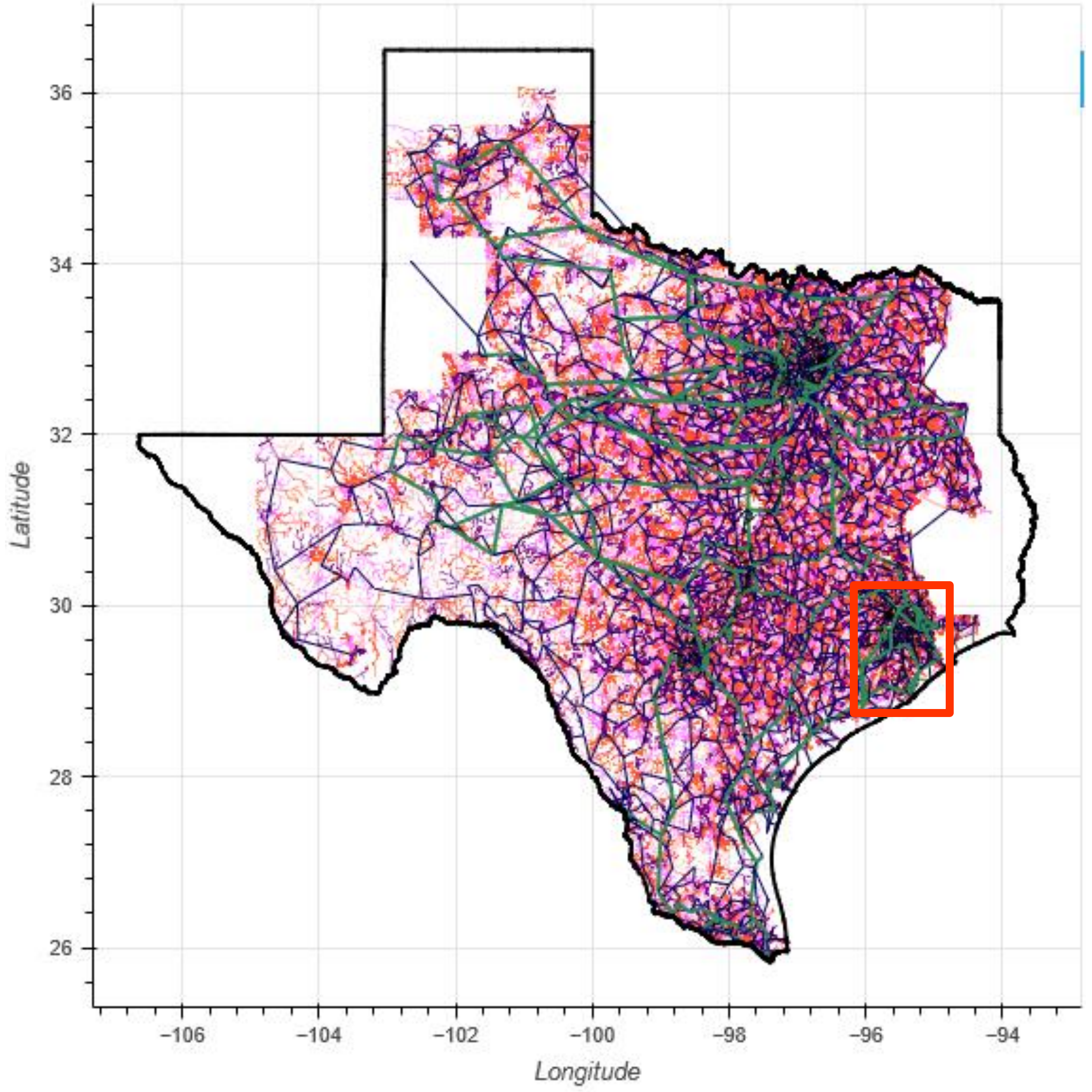
Synthetic Grid Dynamics

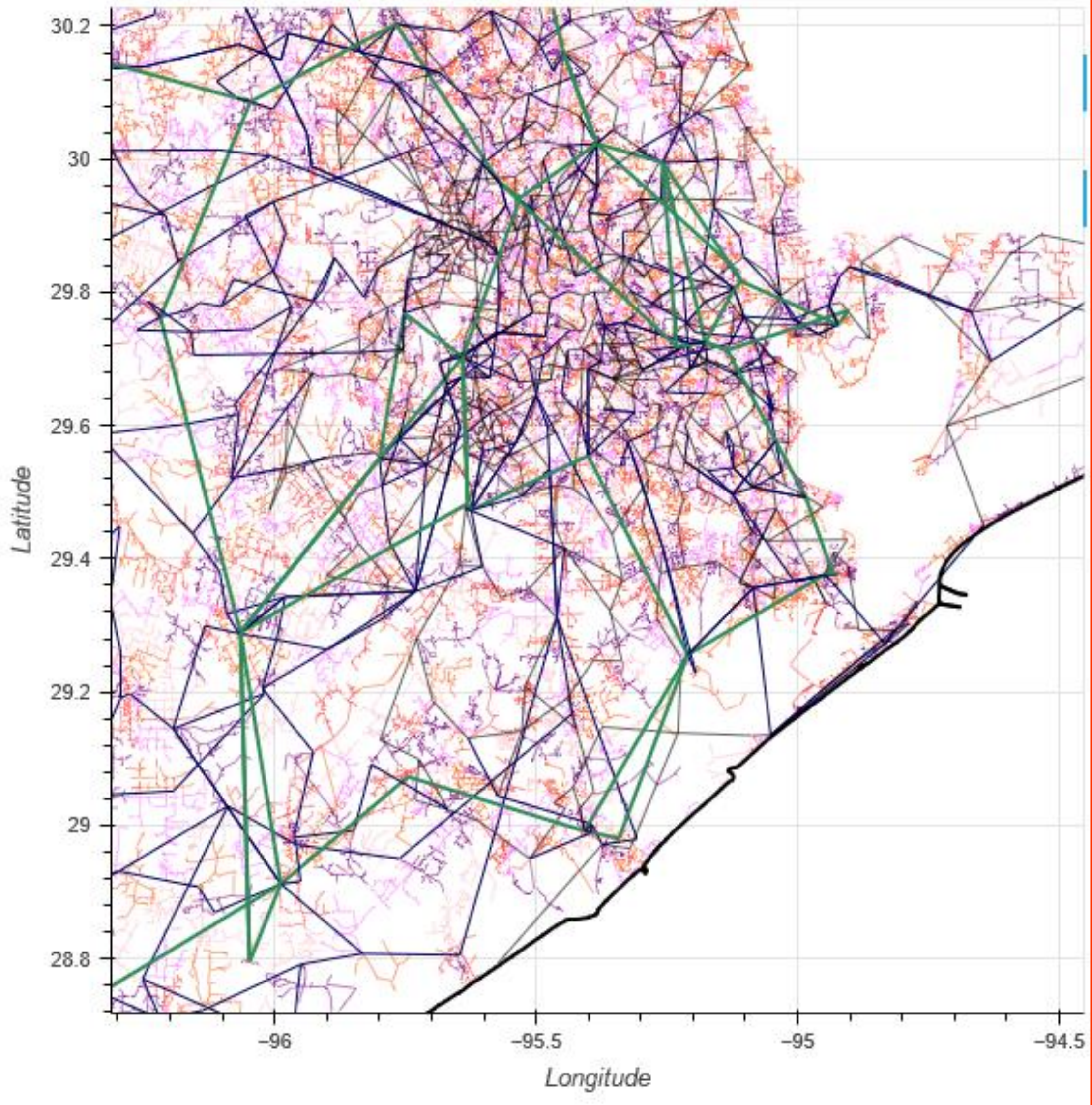
- Augmenting a power flow case with dynamics models is a major undertaking
- There are large numbers of models with many parameters that need to be tuned
- Idea is to match statistical characteristics of actual grids in model parameters
- Match system frequency response characteristics by tuning system-wide governor model and associated inverter controls
- Match voltage control performance by tuning exciter dynamic response



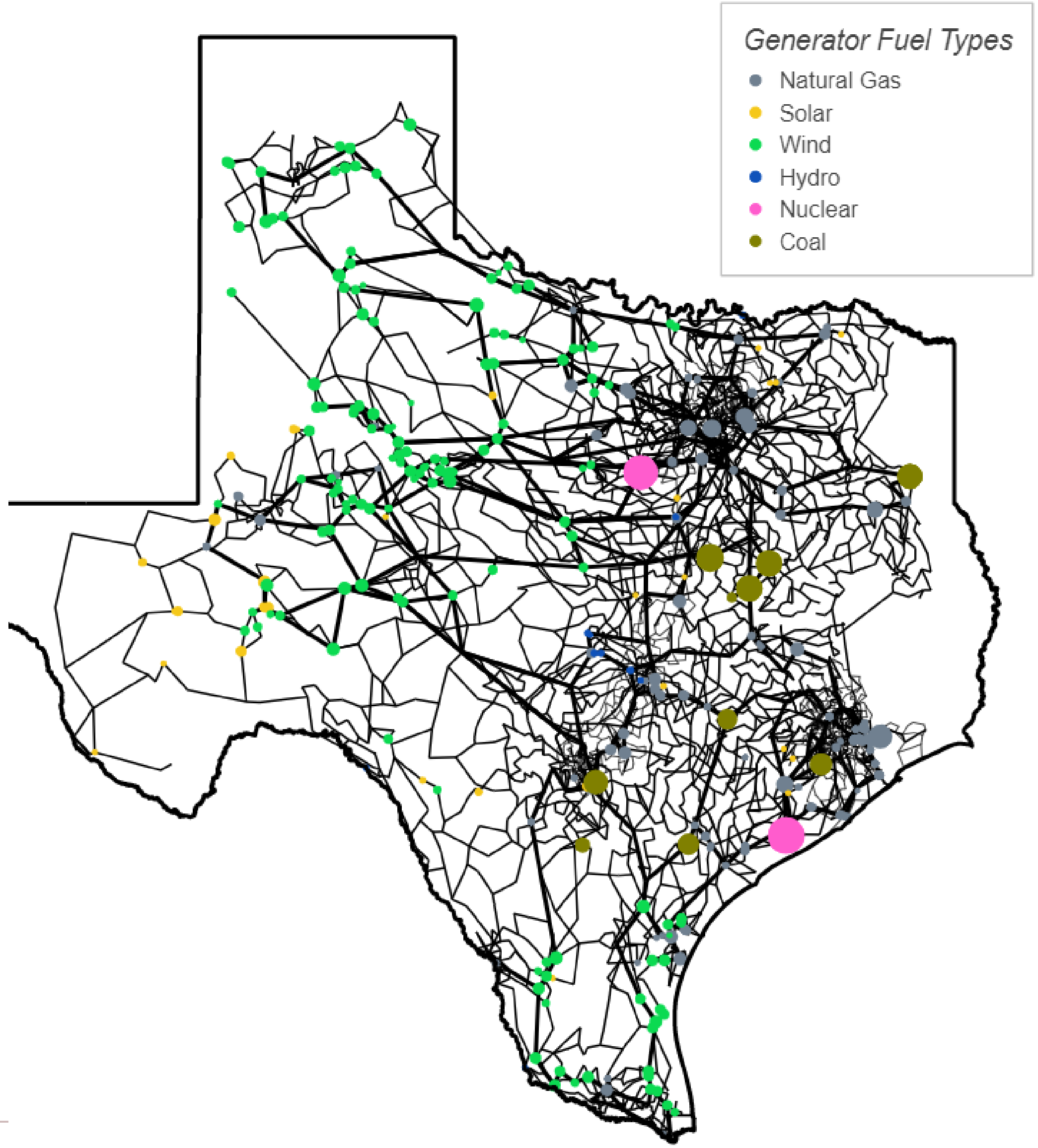
J. Baek and A. B. Birchfield, "A tuning method for exciters and governors in realistic synthetic grids with dynamics," *2023 North American Power Symposium (NAPS)*, Asheville, NC, USA, Oct. 2023, pp. 1-6.

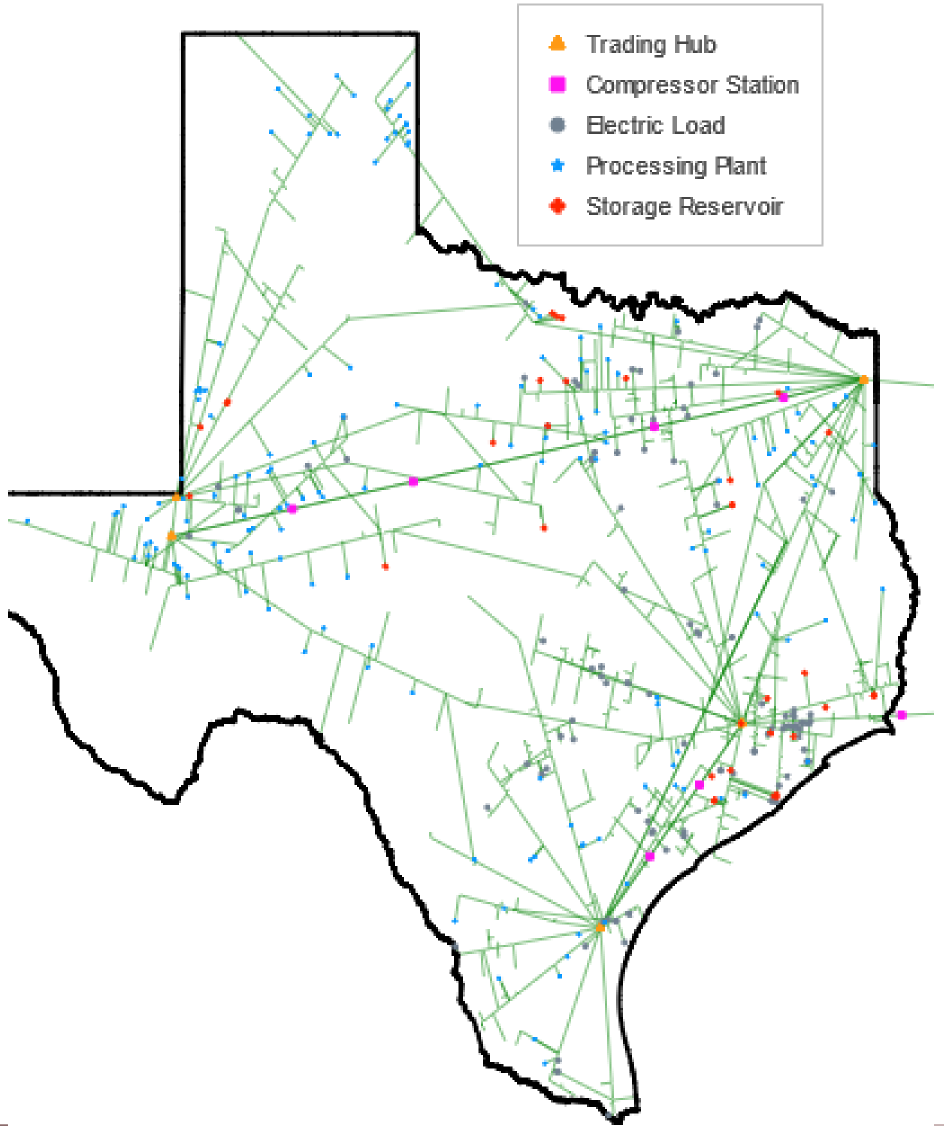
Combined T&D Synthetic Grids



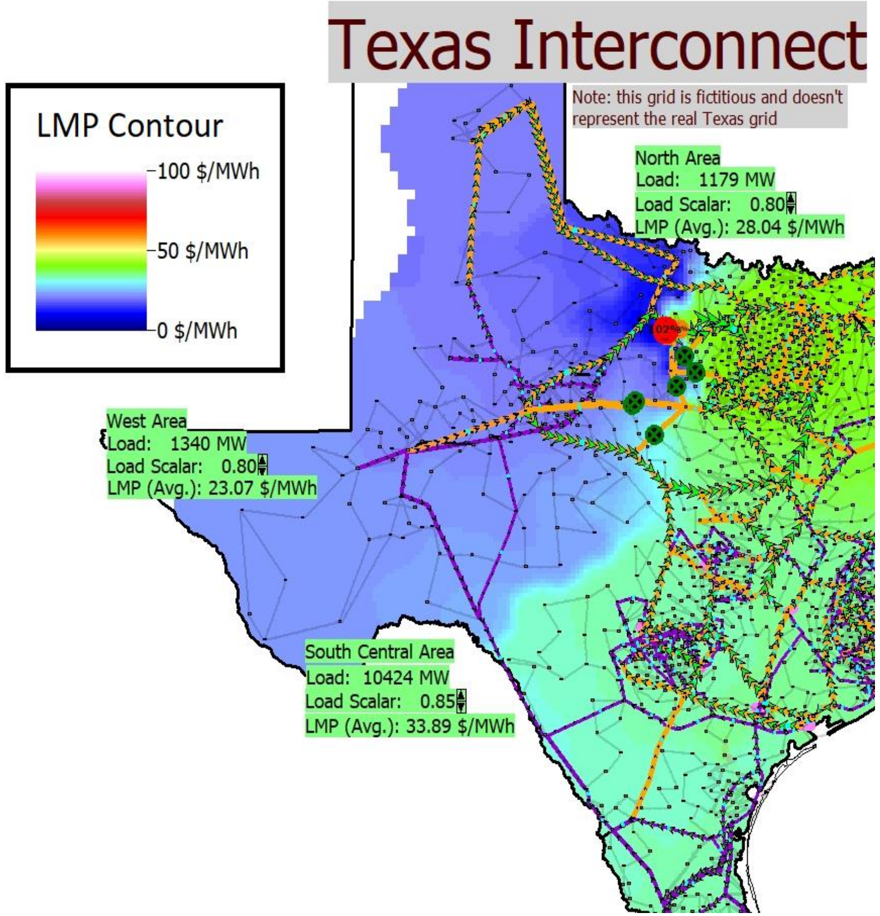


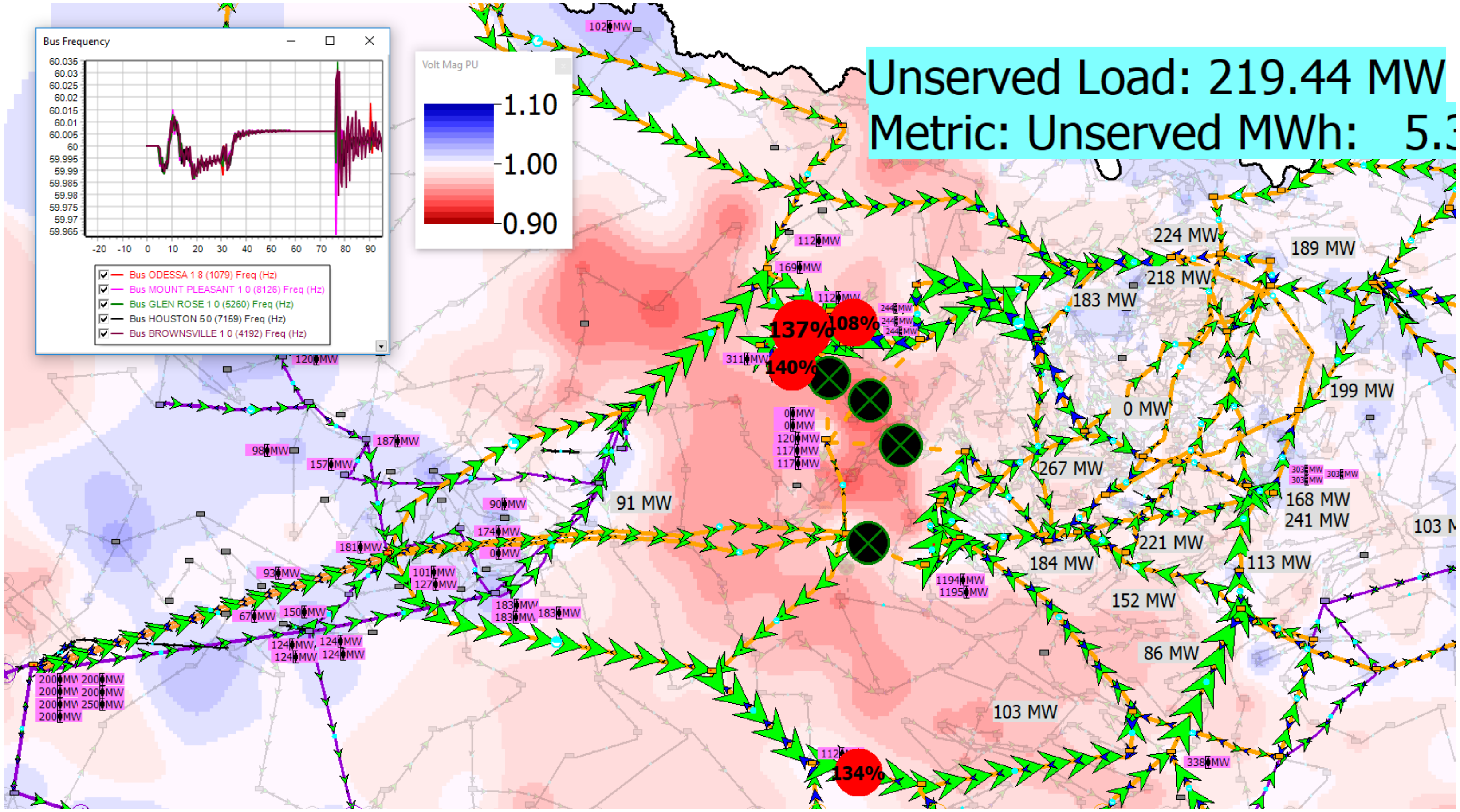
Combined Electric & Gas Grids





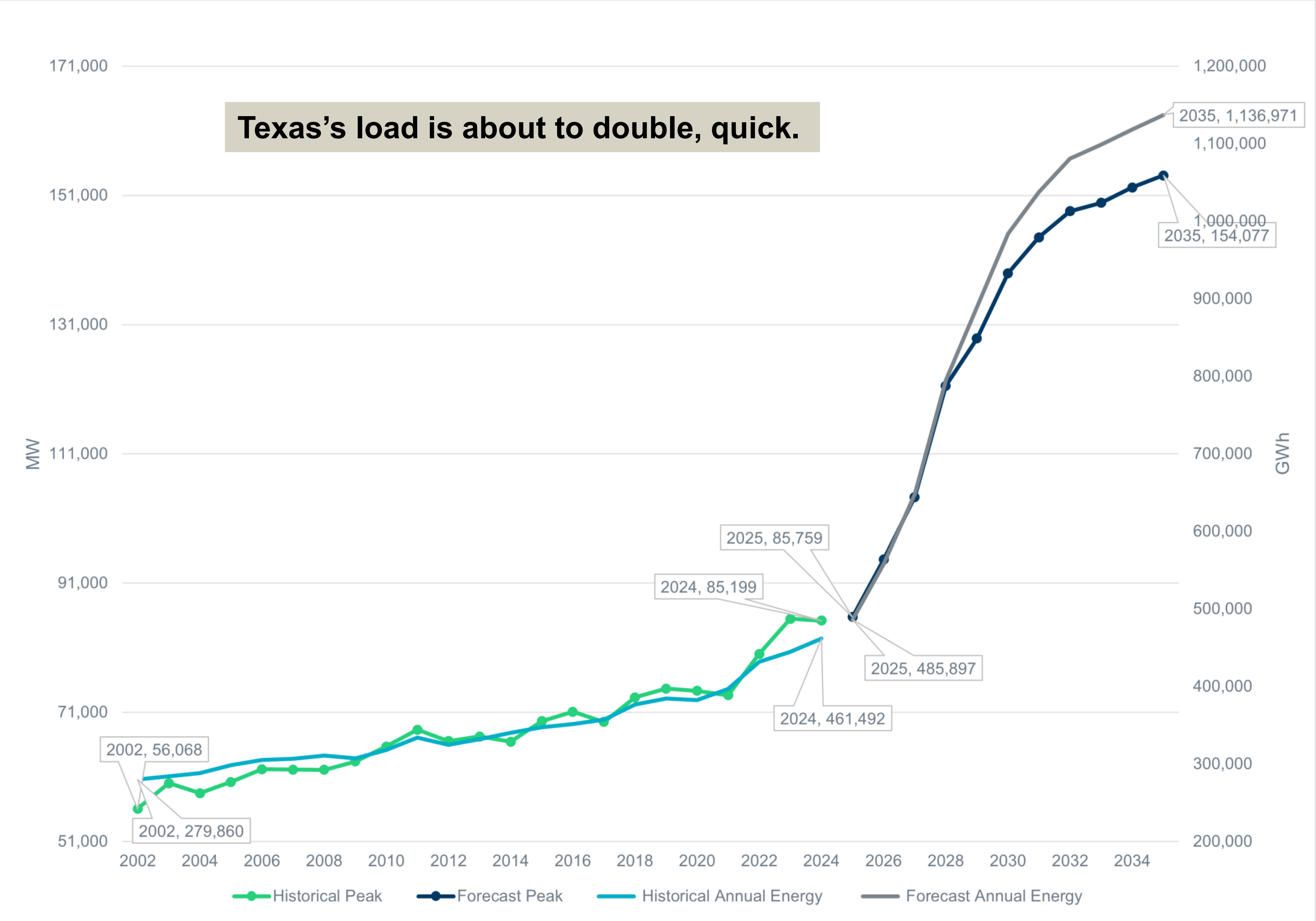
Transforming Education and Training





ARPA-E GO Competition

- Our cases were used in the ARPA-E Grid Optimization (GO) Competition
- Goal was for participants to develop scalable, high-quality SCOPF solvers.
- Our work involved creating difficult, realistic problem scenarios to enable evaluation of competitors
- Much of the data is available on our website


Texas's load is about to double, quick.
171,000
151,000
131,000
111,000
91,000
71,000
51,000
MW
1,200,000
1,100,000
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
GWh
2035, 1,136,971
2035, 154,077
2025, 85,759
2024, 85,199
2025, 485,897
2024, 461,492
2002, 56,068
2002, 279,860
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2032
2034
Historical Peak
Forecast Peak
Historical Annual Energy
Forecast Annual Energy

Transmission Expansion Planning (TEP)

- Given today's grid
  - And tomorrow's new load and generation
- Objective is to find what new transmission lines we need to build to
  - Minimize investment cost, and
  - Have sufficient network reliability and efficiency
- This problem goes back many decades, and has many notorious challenges

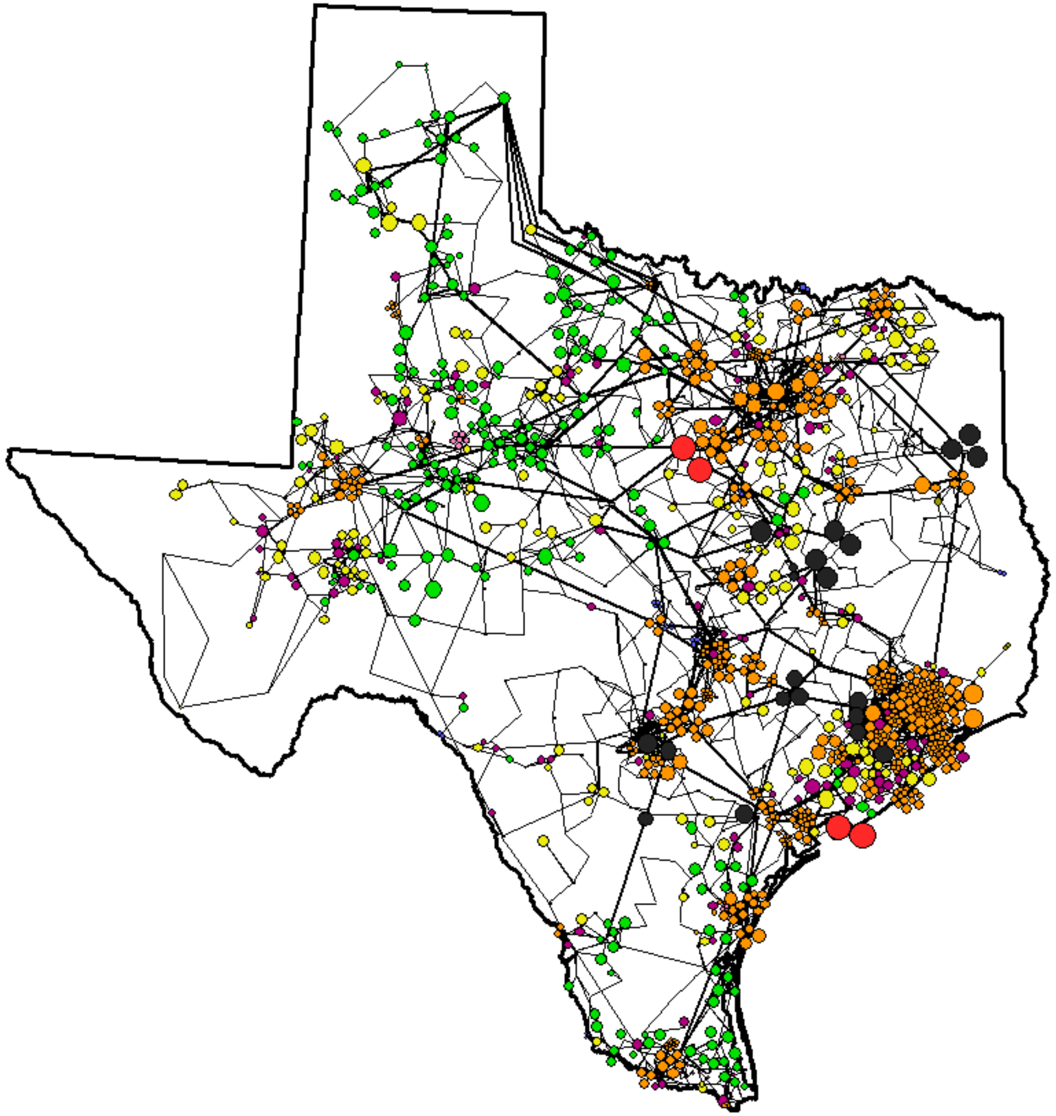
What makes TEP hard?

1. Possibilities are (nearly) endless
   - For n buses, there are n^2 possible lines that could be built, and the number of possible grids starts to grow factorially
   - For larger cases, the search space is enormous
   - Integer programming problem
2. Multi-faceted evaluation criteria
   - To adequately evaluate even *one* potential solution, need very complex and detailed modeling and analysis
   - Check power flow, contingency analysis, stability, voltage control, etc…

- So what do we do?
  - In industry practice, very little application of integer programming
  - Pick 3-10 possible solutions based on engineering judgement and run detailed economic and engineering analysis for each one
    - May miss better options we hadn't thought of

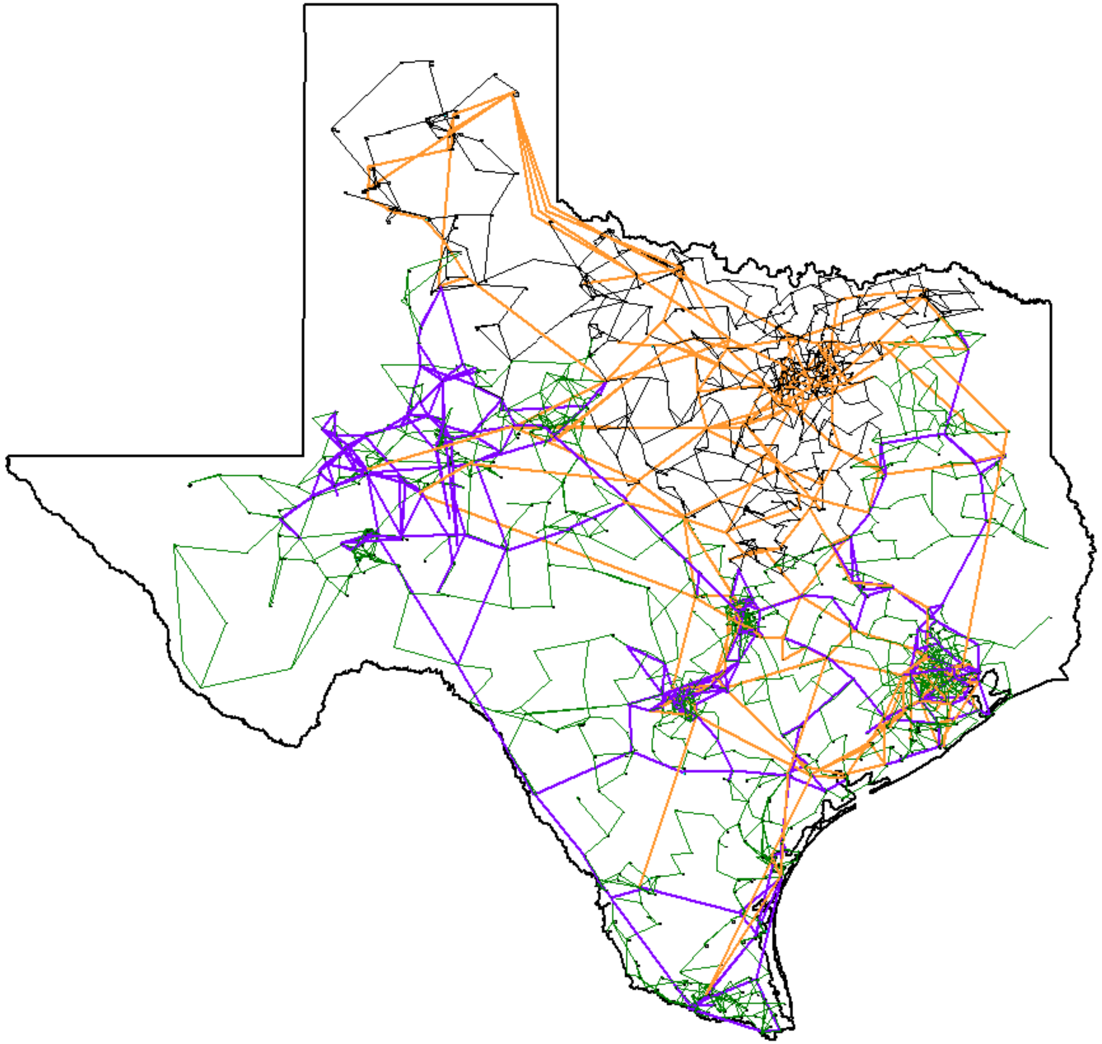
Example TEP Application: New Generation/Load

- Base cases is the 2016 prior synthetic grid
- Increased load area-by-area according to ERCOT data from 2016 to 2025
- Used 2025 existing and planned generation from US EIA reporting
- Right figure shows generation
  - Green wind
  - Yellow solar
  - Purple is batteries



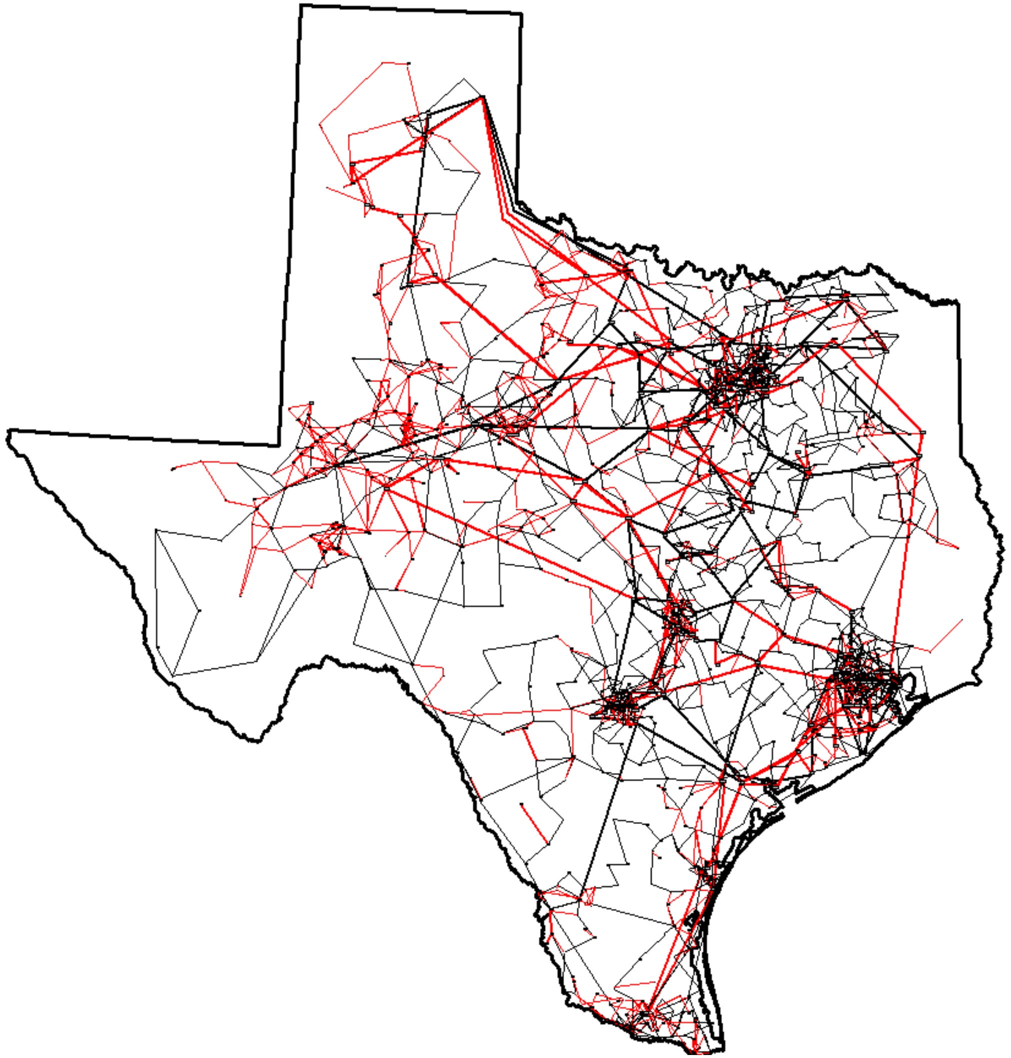
Transmission Planning Process

- Began with prior transmission network – constraint to keep these lines
- Iterative addition/removal in the same style as network synthesis
- Candidates come from Delaunay analysis, with costs based on geographic assumptions
- N-1 contingency sensitivities applied
- Computation time was about 24 hours on desktop workstation



Study Results

- Figure shows lines added by transmission planning in red
- New transmission, as expected, organized around the western part of the system where most new generation and load was added
- Additional transmission added as backbone to the overall system and along the gulf coast where new solar was added



Summary Thoughts

- There is no substitute for running studies on the actual grid!
- Synthetic grids are designed to complement real-grid studies and spur innovation with modern, public, high-quality, scalable test cases for power systems R&D and education
- Our synthetic grids are available for your research—and we are always looking for feedback to improve them

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