New Developments to Synthetic Grids

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GRID OPTIMIZATION (GO) COMPETITION
A Multi-Round Challenge to Revolutionize the American Grid

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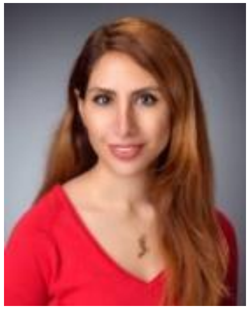



Acknowledgements

- Much of the initial work related to synthetic grids was originally funded through the ARPA-E Grid Data program in 2016-2018.
- Their support and the contributions of our collaborators on that project are gratefully acknowledged.
- Since then, additional support from ARPA-E, NSF, DOE, and others has helped to expand and improve this research.
- This work is a collaborative effort among researchers in the energy and power group at Texas A&M ECE.

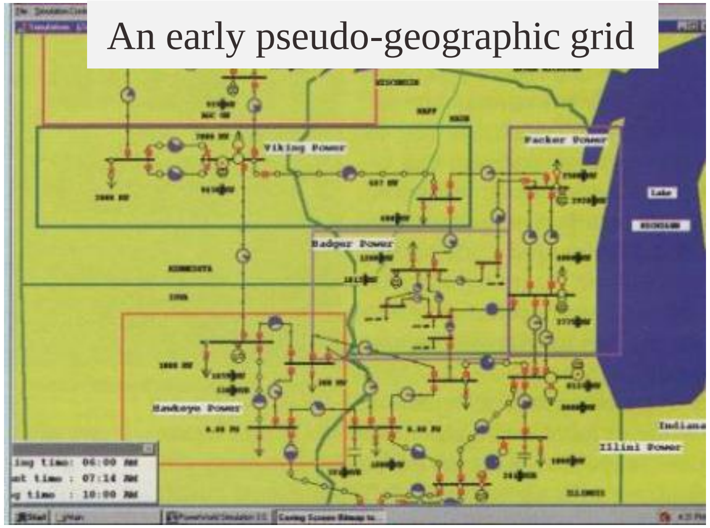
Overview of Synthetic Grids

- Access to actual power grid models is often restricted.
  - In the US detailed grid information is considered to be Critical Energy/Electricity Infrastructure Information (CEII)
- Lack of access can be a particular concern with data analysis and visualization since its purpose is to provide insight into the model, including weaknesses
  - Models cannot be freely shared and even presenting results can be difficult
- A solution is to create entirely synthetic (fictitious) models the mimic

characteristics of actual models

- ARPA-E has been supporting work in

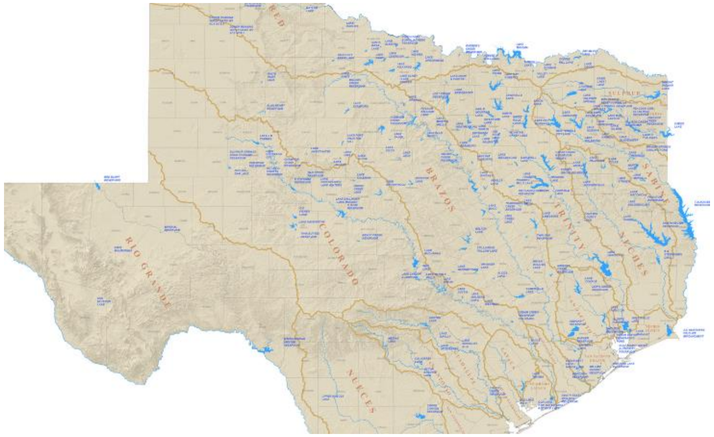
this area for about 8 years;



An early pseudo-geographic grid

Real-World Complex Networks

- A complex network is a large graph: collection of nodes (vertices) connected by links (edges) that represents some
  real-world interactions
- Examples: Interstate highways, movie co-stars, brain neurons, water drainage, Facebook, airline routes, the internet, the power grid
- Aspects of network structure provide insight for assessing system resilience and designing for greater robustness and efficiency
- For each type of network, what network characteristics or metrics do they have in common with other types, and what characteristics are unique? What sort of network is the power grid?



Sources: American Airlines, Texas Water Development Board

The U.S. Electric Grid Network

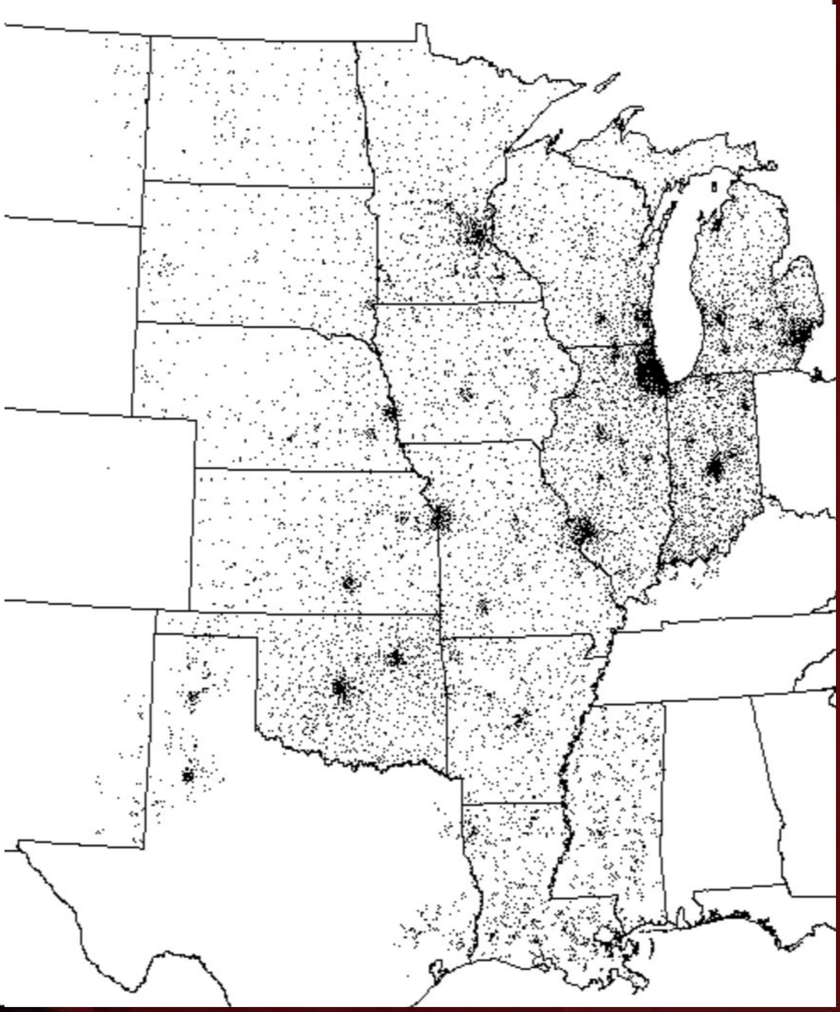
- Vertices: electric substations or circuit nodes/buses
- Edges: transmission lines, transformers
- Intuitive characteristics:
  - Carefully designed
  - Interconnected
  - Geographically constrained
  - Multi-level (MV, HV and EHV)
  - Robust to contingent outages

Source: EIA

Synthetic Grid Creation

The overall approach for building these networks

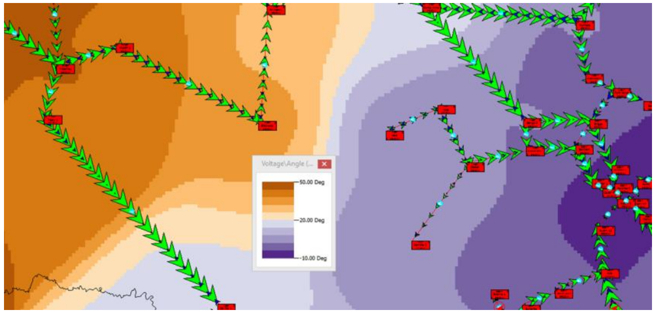
- Substation Planning
  - Start with public data for generation, load
  - Cluster substations, add buses, transformers
- Transmission Planning
  - Place lines and transformers
  - Iterative dc power flow algorithm
  - Match topological, geographic metrics
  - Contingency overload sensitivity
- Reactive Power Planning
  - Power flow solution (ac)
  - Voltage control devices
- Extensions



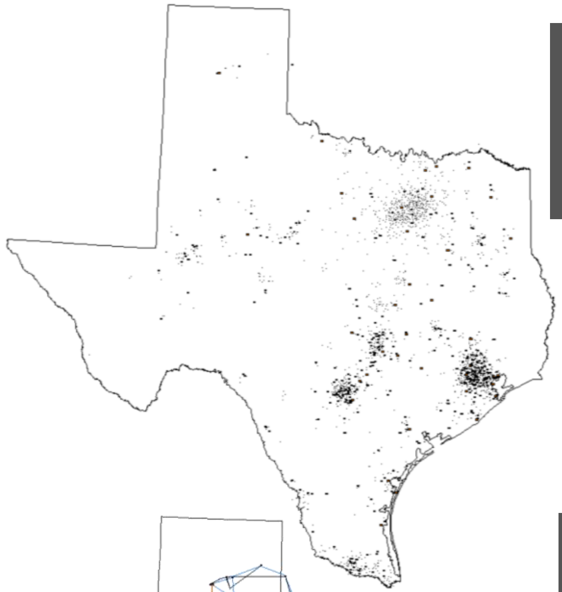
Transmission Planning Approach

- Key Considerations
  - Geography drives transmission planning
  - Network topology parameters
  - Power flow feasibility in base and N-1 contingency conditions
  - Intractability: 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

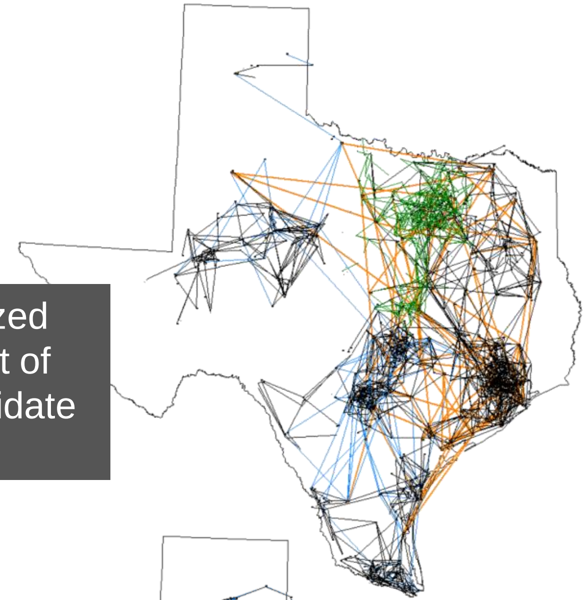
- Outline of Approach
  - Reduce search space from n^2 to $21n$ with Delaunay triangulation (up to 3rd neighbors = 99% of lines)
  - Geographic constraints by voltage level
  - Depth first search to check connectivity
  - Dc Power flow base case and N-1 contingency analysis, determine sensitivity of candidate lines to contingency overloads
  - Iterative process of random removal, analysis, targeted addition for each same-voltage subnet



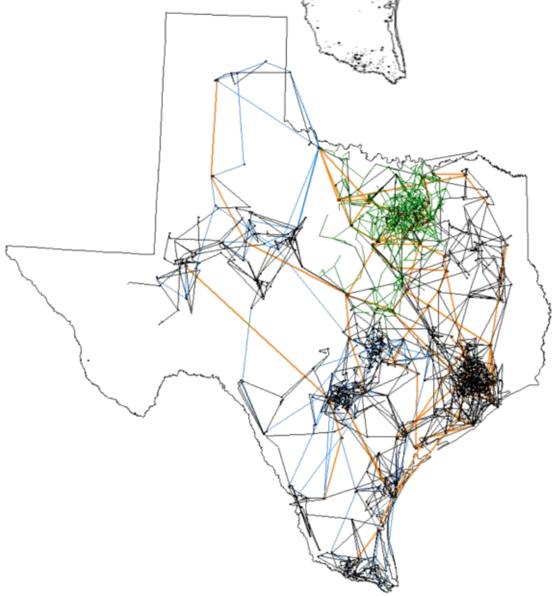
Stages of Transmission Planning Process



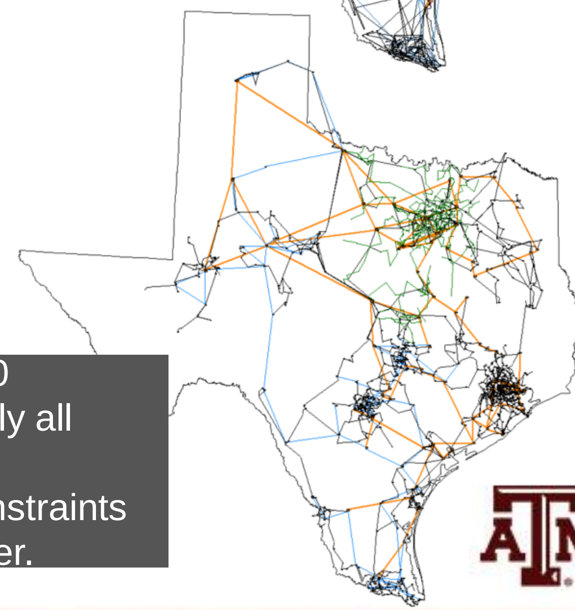
(1) The starting point is the geographic placement of substations



(2) The grid is initialized with a random subset of 1.2n of the 21n candidate transmission lines



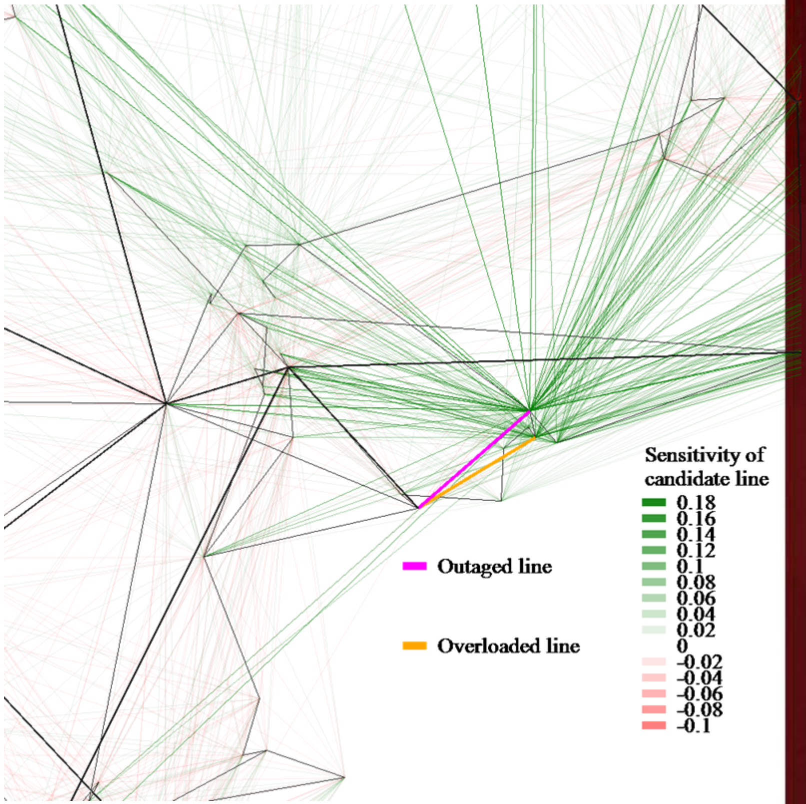
(3) After 100 iterations of random removal followed by targeted addition, the grid begins to match more geographic and reliability constraints



(4) After 10,000 iterations, nearly all reliability and geographic constraints are met together.

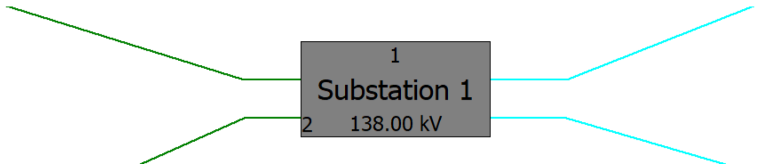
Line Sensitivity Results

- This is part-way through the transmission grid creation process
- Black lines are currently in the network
- We're focusing on a contingency of the magenta line causing an overload in the orange line
- Possible candidates are shown in red, gray, and green
- The darkest green lines are the most helpful to improving this contingency outage
- This metric is balanced against other considerations, such as line length

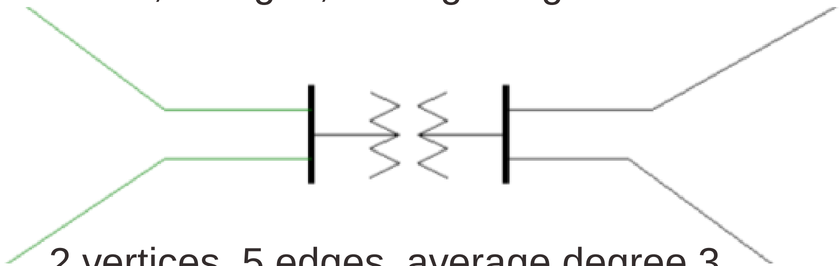


Modeling Considerations

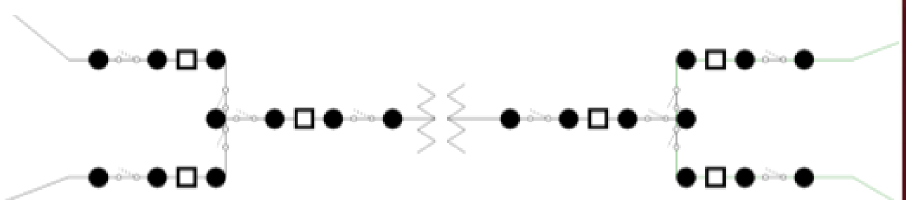
- Power grid statistics can be contradictory in the complex network literature
- Some explanations for this:
  - Different data sources and the fact that electric grids in different places have different design practices—not all electric grids are alike
  - Modeling decisions: substation-line, bus-branch, node-breaker
- To avoid these issues, in this presentation we look primarily at substation-line topologies



1 vertex, 4 edges, average degree 4



2 vertices, 5 edges, average degree 3

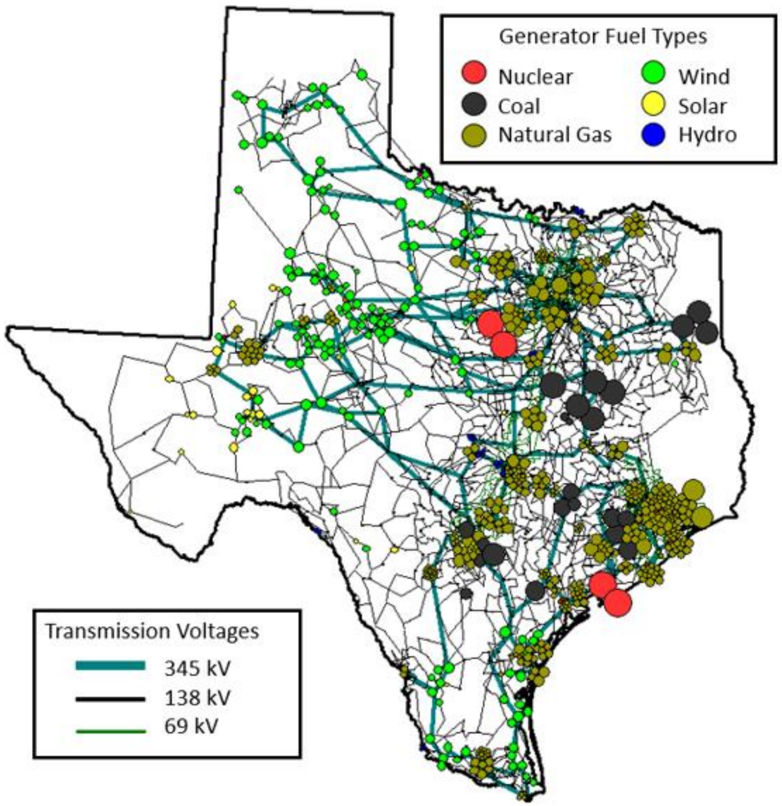


20 vertices, 23 edges, average degree 2.1

A. B. Birchfield and T. J. Overbye, "Planning sensitivities for building contingency robustness and graph properties into large synthetic grids," *HICSS*, Jan. 2020.

Synthetic Grids Examples

24k buses in the
MISO and SPP footprint



7000 buses in the
ERCOT footprint

Validation: Ensuring High Quality

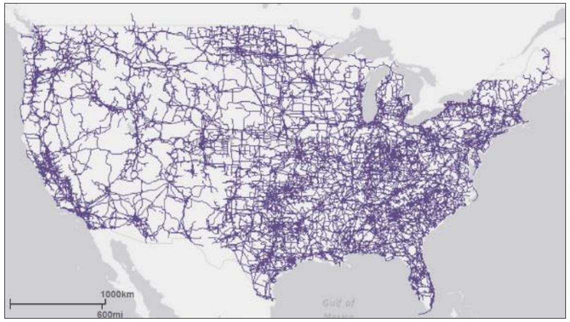
- Based upon data from actual grids we've developed a large and ever-growing number of metrics that cover many aspects of primarily transmission grids
- For example:
  - Buses/substation, Voltage levels, Load at each bus
  - Generator commitment, dispatch
  - Transformer reactance, MVA limit, X/R ratio
  - Percent of lines on minimum spanning tree and various neighbors of the Delaunay triangulation
  - Bus phase angle differences, flow distribution

Some Complex Network Metrics

Symbol	Description	EI Value	WECC Value	ERCOT Value	Scaling Pattern
n	Number of nodes	36,187	9398	3827	
$\bar{d}$	Average node degree (how many edges on each node)	2.61	2.58	2.61	Independent of system size
$\bar{c}$	Average clustering coefficient (how likely are neighbors to be mutually interconnected)	0.044	0.058	0.032	Independent of system size
$\bar{\ell}$	Average shortest path length between any two points	29.2	18.9	14.2	Approximately quadratic
$\bar{b}$	Average betweenness centrality (what fraction of shortest paths pass through a node)	0.083	0.21	0.4	Approximately inverse quadratic

Geometric Properties – Crossings

- Location-aware metrics can give additional insight
- One of these is graph crossings, which measures the number of times two edges cross without intersecting.
  - For some networks (waterways) this never occurs (planar)
  - For others (airplane routes) it is extremely common.
  - Electric grids are somewhere in-between
- The crossings analysis given on the next slide utilizes data from the U.S. Energy Information Administration (EIA) which gives right-of-way paths for each high-voltage transmission line in the U.S., plus information such as the nominal voltage class.
- This analysis focuses on each voltage class independently.

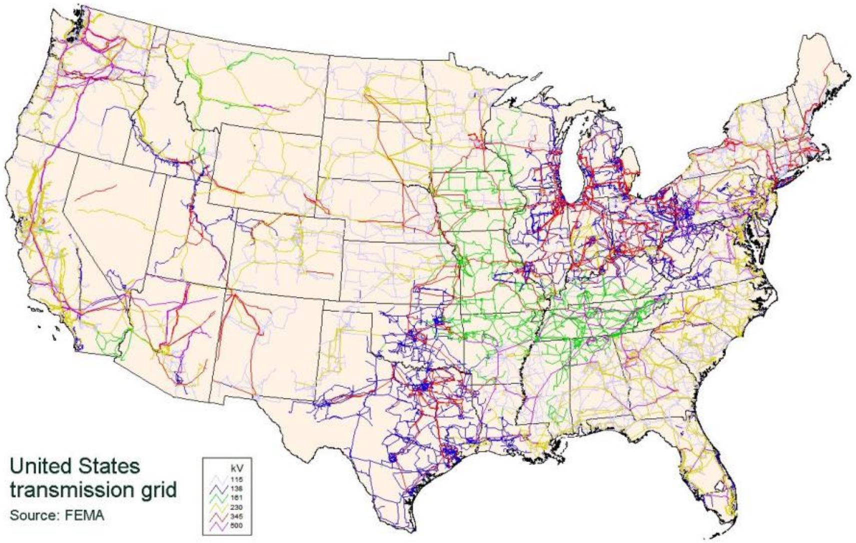


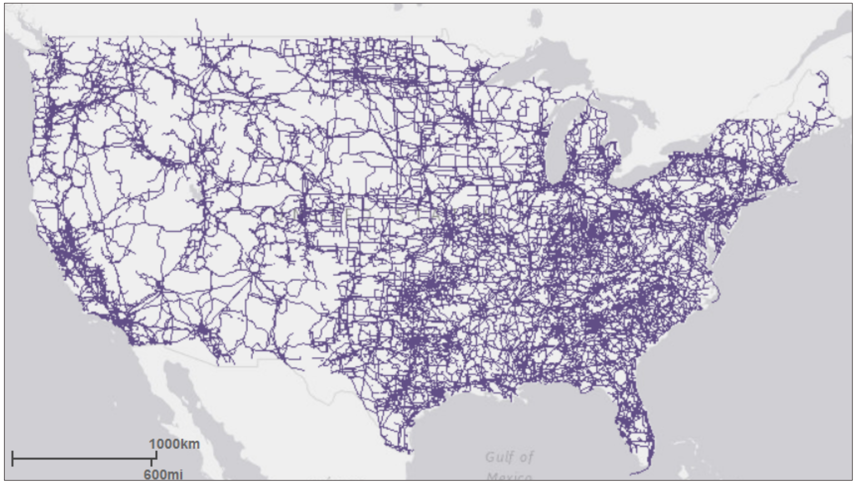
Two 765 kV lines crossing

Graph Crossing Metrics

Most high-voltage networks have crossing numbers around 30% of the number of lines. The very highest and lowest voltage levels tend to be lower. When only considering the straight-line path between the substations (as opposed to the reported actual right-of-way) the crossing numbers reduce to 10-15%.

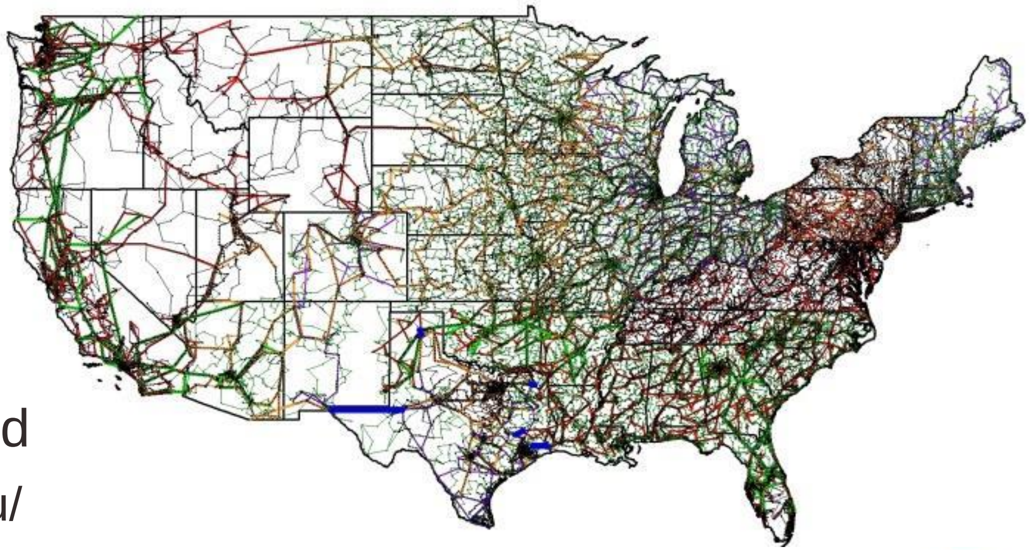
Voltage class	Number of substations	Number of lines	Number of lines, no parallel	Crossings, straight-line		Crossings, right-of-way		Crossings, no parallel	
				Number	% of lines	Number	% of lines	Number	% of lines
765 kV	40	42	42	1	2.4	1	2.4	1	2.4
500 kV	529	732	596	67	9.2	219	29.9	162	27.2
345 kV	1526	2171	1778	297	13.7	628	28.9	563	31.7
230 kV	4648	6233	5109	935	15.1	2266	36.4	1977	38.7
161 kV	2633	3172	2858	405	13.0	952	30.0	845	29.6
138 kV	8611	10684	9129	1617	15.3	2951	27.6	2658	29.1
115 kV	12826	15031	13161	1485	10.2	3137	20.9	2734	20.8
100 kV	894	1595	1002	118	7.5	282	17.7	215	21.5
69 kV	8022	8022	7271	289	3.7	618	7.7	582	8.0





Federal Emergency Management Agency

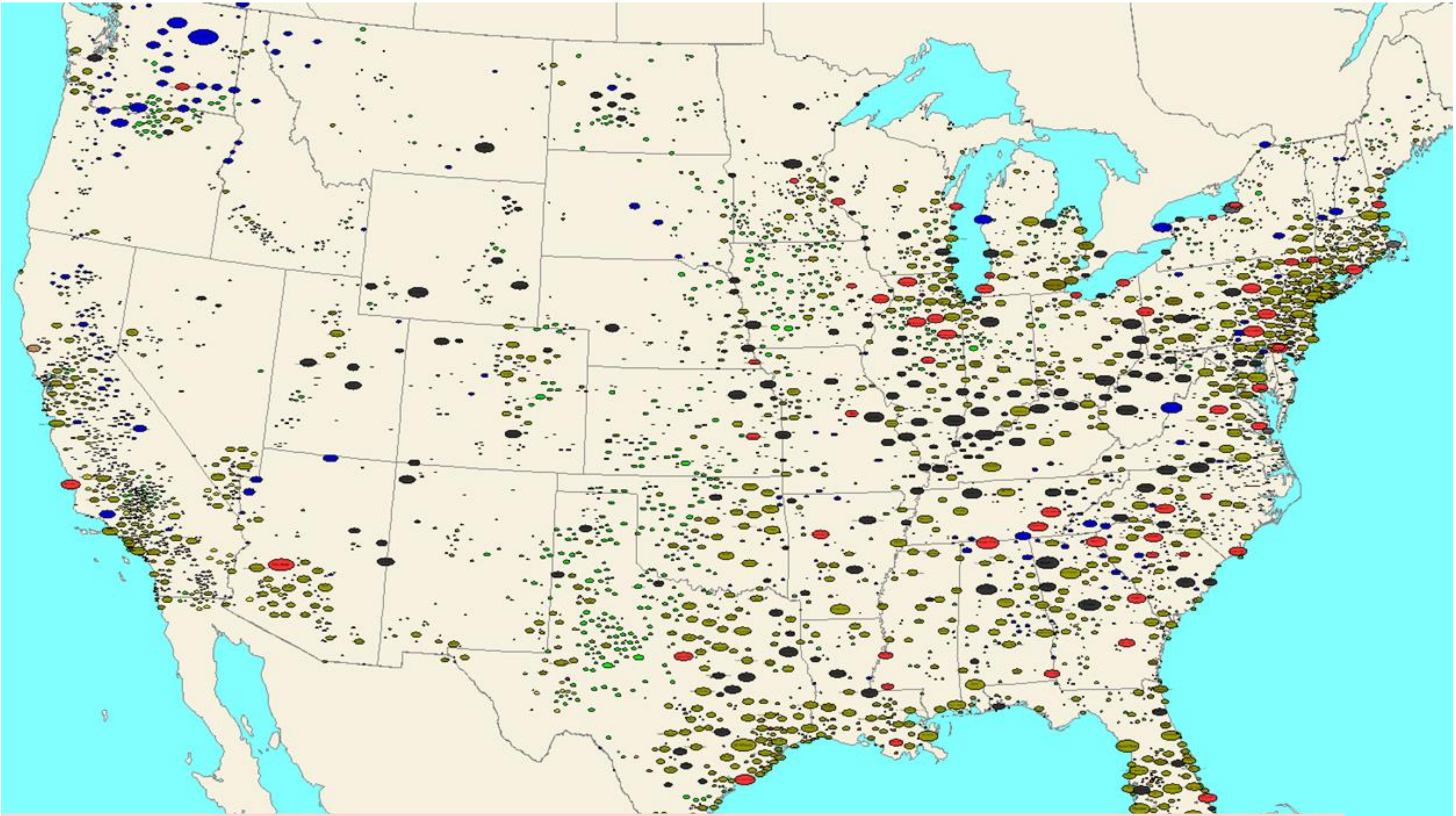
FEMA



The US 82K Bus Synthetic Grid

https://electricgrids.engr.tamu.edu/

Visualizing the EIA-860 Data



Oval size is proportional to the substation generation capacity, and color indicates primary fuel type (red nuclear, black coal, brown natural gas, blue hydro, green wind, yellow solar). Image shows public data from EIA Form 860; image created using PowerWorld Simulator.

Augmentations, Extensions and Adjustments

- Generator Parameters
- Shunt Type Conversion
- Price Responsive Demand
- Transmission & Distribution Co-Simulation
- Electric Grid & Other Infrastructures Co-Simulation, including Natural Gas and Transportation.
- Coupling with Actual Weather
- Reserve zones and requirements
- Dynamics and Stability – This is a Key Need for Future Research!

Generator Cost/ Load Benefit Data

- Actual Gen. Fuel and Unit Types from EIA 860
- Gen Costs based on Fuel Types, Unit Types, and Heat Rates from EIA-923 and the EIA Annual Energy Outlook
- Variable O&M Costs, Fixed Start-up Costs
- Cost Curve Co-efficients
- Cubic Cost Model and Piecewise Linear using 4 Break Points for both
- Controllable load with high prices which may be shed

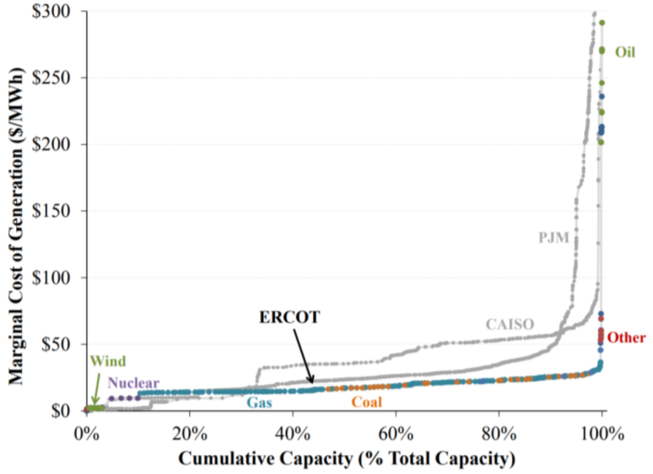
Temporal Generator Parameters

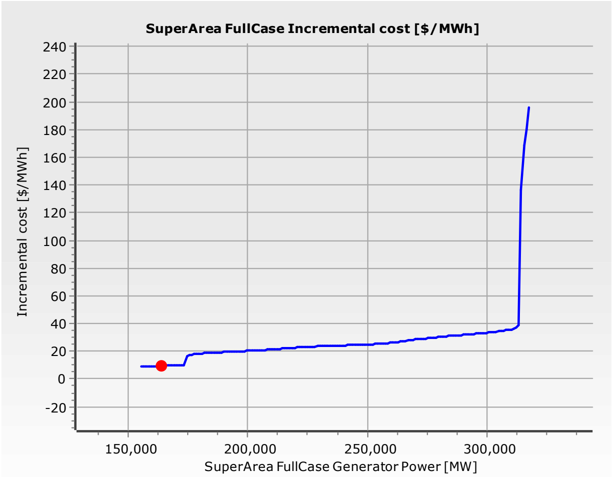
Field	Description	Units	Primary Source	Sec. Source
Ramp Rate Up, Down	% of Pmax	%/min	JBG	ERCOT RTC Tool Input Files (MW/min)
Minimum Up Time		hours	Vaid, IRENA for IC units	JBG
Minimum Down Time		hours	JBG Table 3.10, IRENA	
Variable O&M cost		$/MWh	Vaid	JBG
Fuel Cost		$/MMBtu	EIA 923 Sched. 2: Fuel Receipts and Costs	
Generator Cost Midwest	Heat-rate curve parameters		CEMS Heat Rates (2016-2017)	ERCOT 60-Day SCED Disclosure Reports
Generator Cost ERCOT	Bid Curves	(MW, $)	ERCOT 60-Day SCED Disclosure Reports	ERCOT RTC Tool Input Files

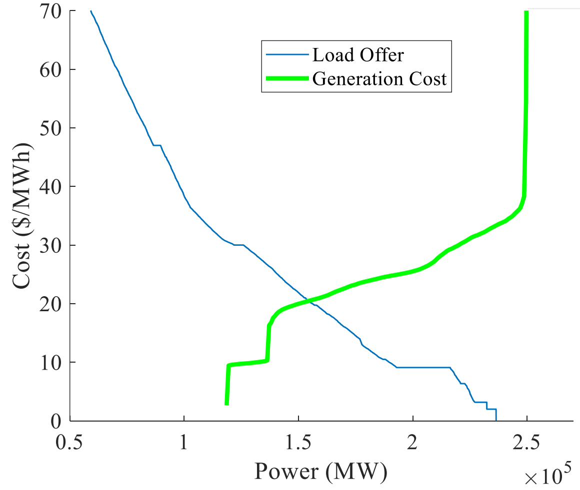
References for Unit Commitment Parameters and Cost Curves

- CEMS: Continuous Emissions Monitoring System; RTC: Real Time Co-optimization
- Vaid: P. Vaid, Analyses and Tabulation of Heat Rates, Unit Commitment Generator Constraint Parameter Values and Emissions Estimates of the Electricity Generators of Power Plants in Texas, MS Thesis, UT Austin, 2019
- JBG: Garrison, J. B. (2014). A grid-level unit commitment assessment of high wind penetration and utilization of compressed air energy storage in ERCOT (Doctoral dissertation).
- IRENA: IRENA (2019), Innovation landscape brief: Flexibility in conventional power plants, International Renewable Energy Agency
- CEMS Heat Rates: Rossol, Michael; Brinkman, Gregory; Buster, Grant; Denholm, Paul; Novacheck, Joshua; Stephen, Gordon (2018): A National Thermal Generator Performance Database. National Renewable Energy Laboratory. https://data.nrel.gov/submissions/100
- ERCOT RTC Tool Input Files: https://www.dropbox.com/sh/7wg5yz35ycred1f/AABgX_tGebTYcp8pym0k5crca/2017publicdata.zip?dl=0
- ERCOT 60-Day SCED Disclosure Reports: https://sa.ercot.com/misapp/GetReports.do?reportTypeId=13052&reportTitle=60-Day%20SCED%20Disclosure%20Reports&showHTMLView=&mimicKey

Supply Cost and Demand Benefit Offer

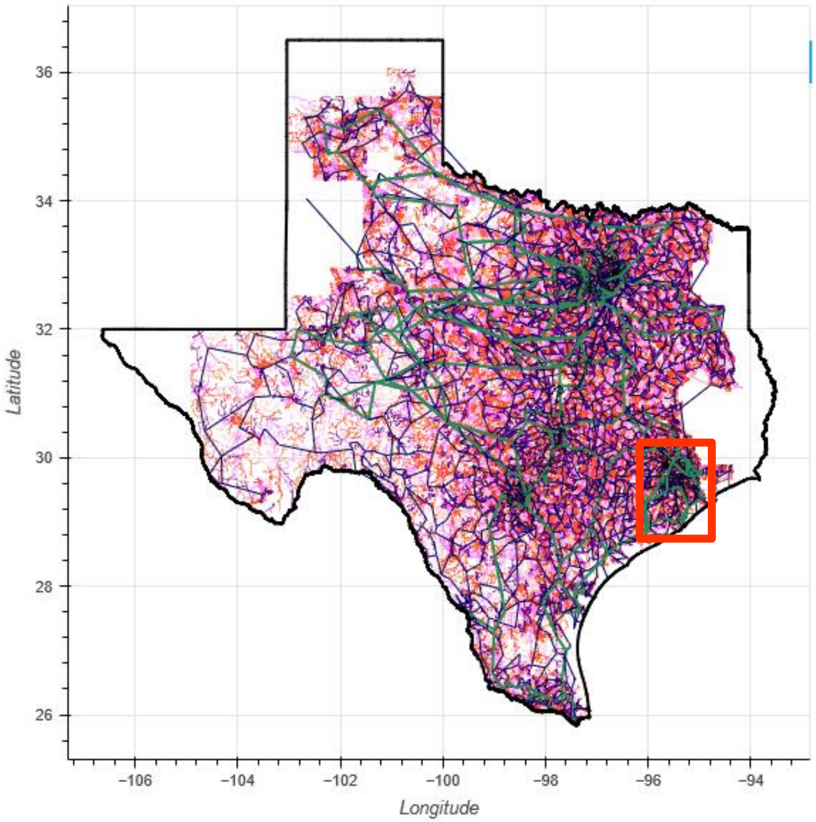


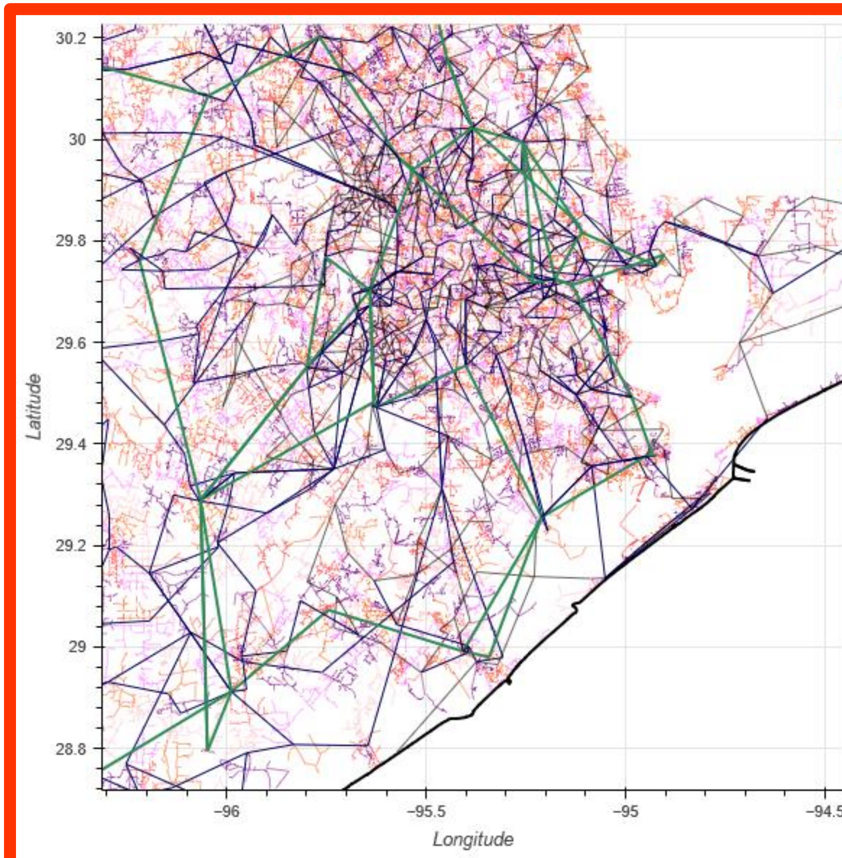




Source: http://www.ercot.com/content/gridinfo/resource/2015/mktanalysis/Brattle_ERCOT_Resource_Adequacy_Review_2012-06-01.pdf

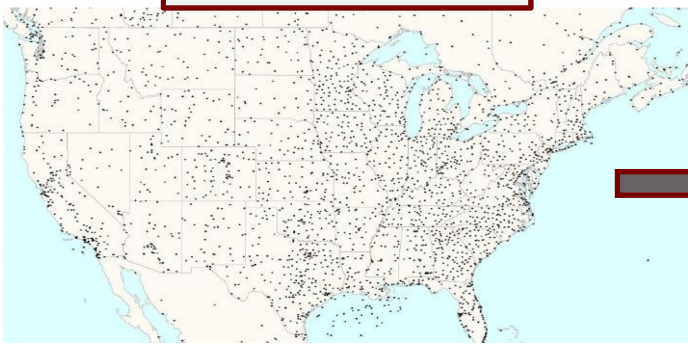
We Now Have All of Texas Modeled – Several Million Nodes!





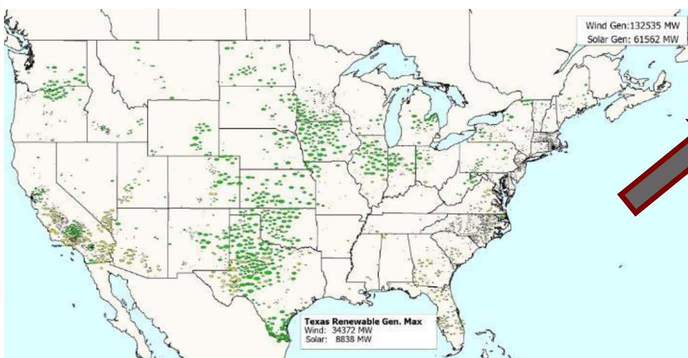
Example: Inclusion of Actual Weather

Weather Data



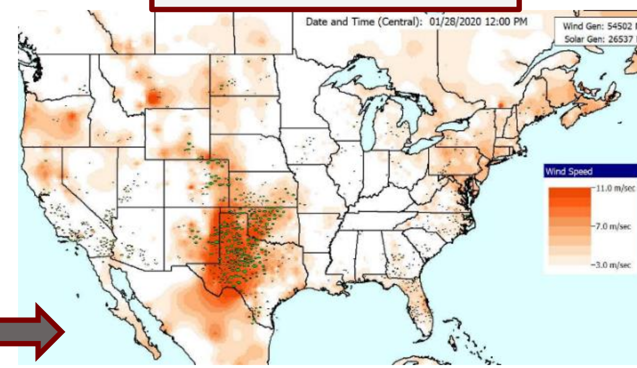
Map weather stations to generators

Apply generator weather models



Generator Data (2021)

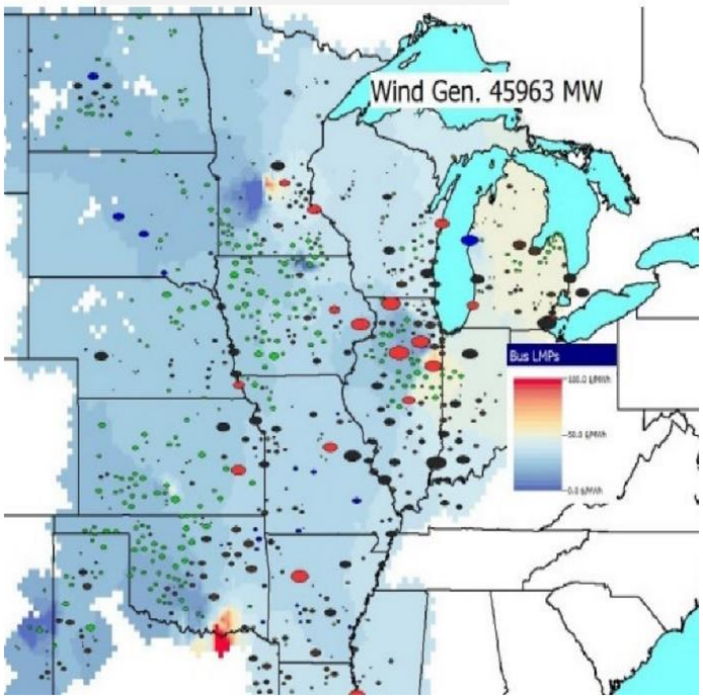
Renewable Generator Capacity



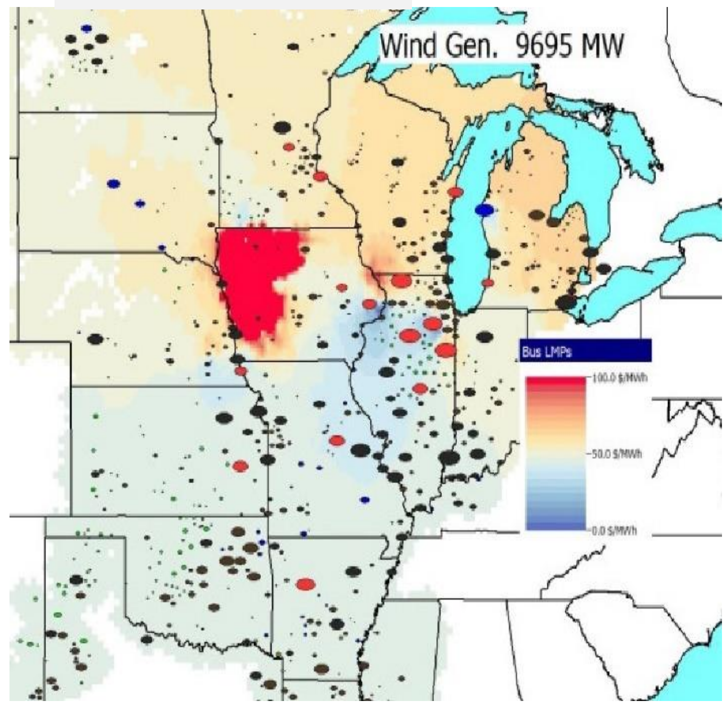
Example: Coupled with Weather

- Example shows impact of wind capacity on LMPs in 24K Grid

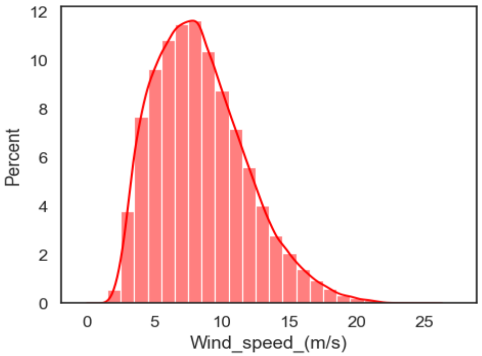
High-wind day

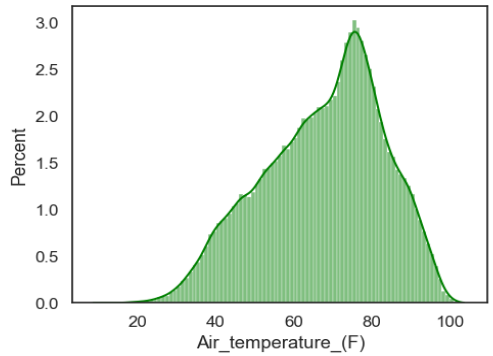


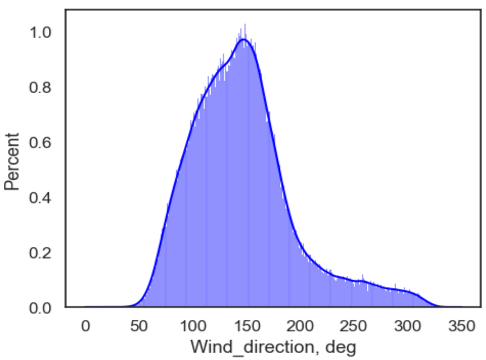
Low-wind day

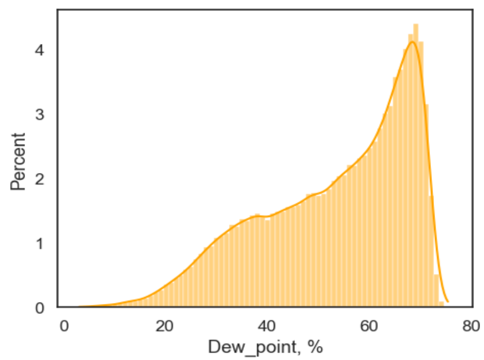


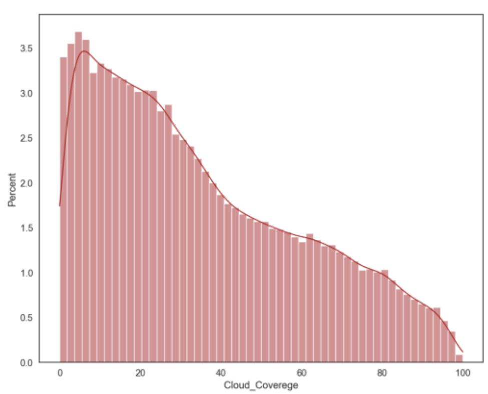
Texas Weather Data Distribution

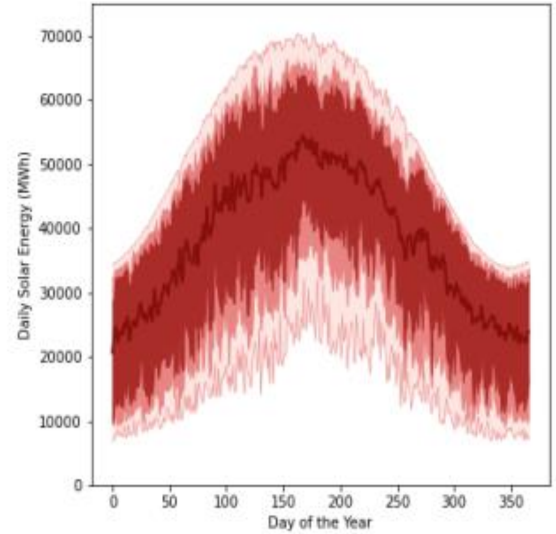


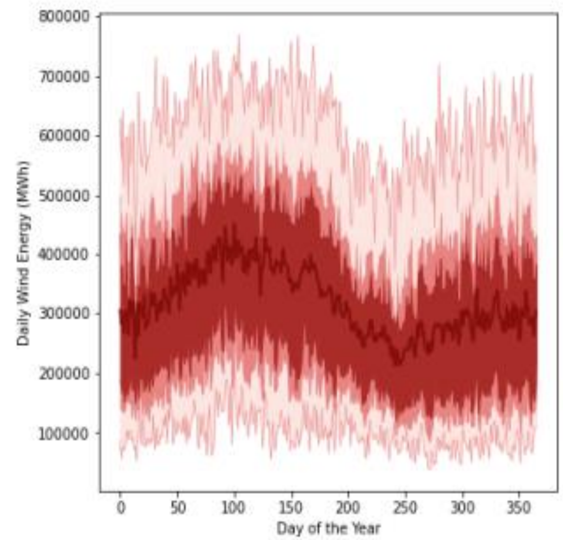






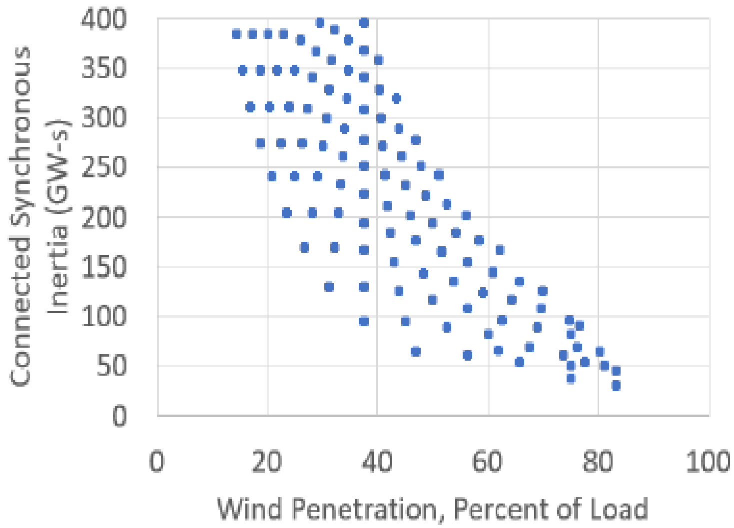


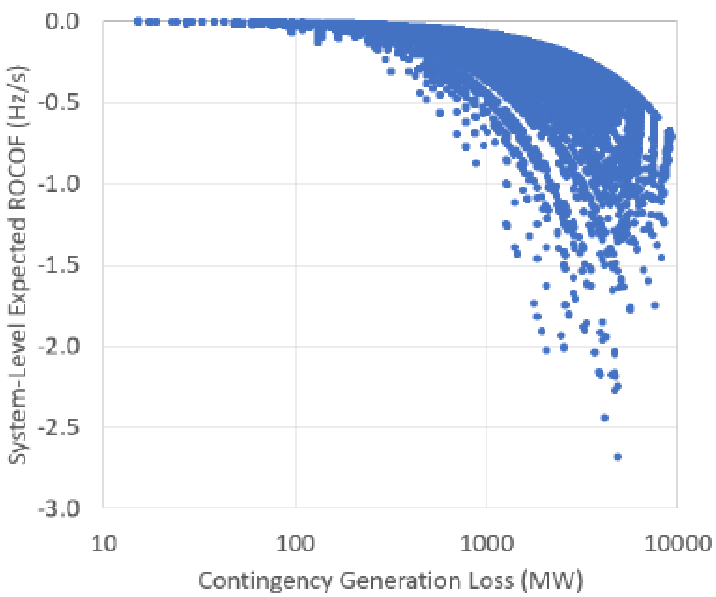




Developed Thousands of Test Cases

- 7000 bus synthetic case, 125 base loading cases, 163 contingencies
- Base cases cover realistic plus extreme loading (15-75 GW) and wind (10-30 GW)
- Contingencies cover loss of generation, up to benchmark event (2750 MW) and beyond, up to about 5000 MW
- Lots of variety in geographic distribution of inertia and outage





Methodology – Required Reserves

- For Qres, in each zone a pilot node is selected – highest SC MVA rating.
- For N-1 contingencies, scenarios with highest voltage violations are identified.

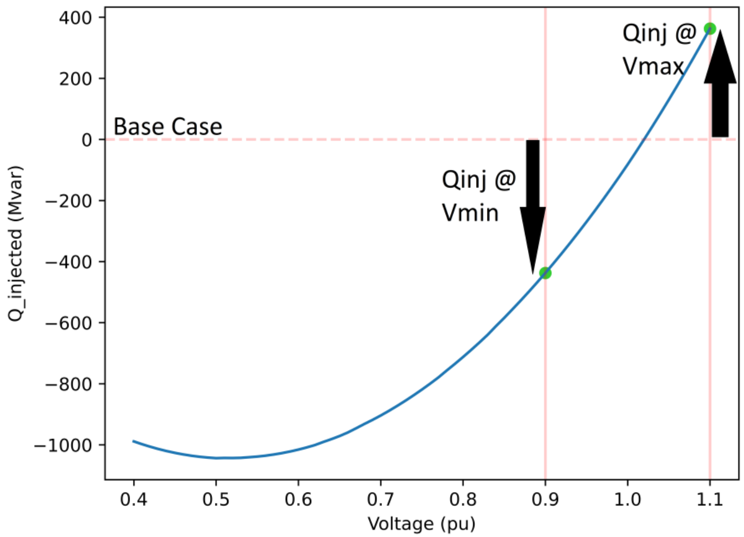
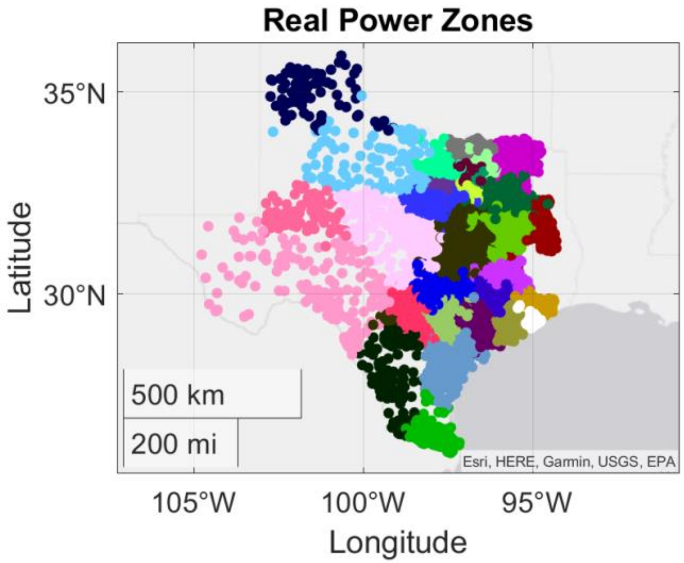


TABLE I
RESERVE REQUIREMENTS (% OF PEAK DEMAND/MW) DEFINED IN [12]

Type of Reserve	ERCOT	SPP	MISO
Regulating Up	0.48%	0.92%	0.35%
Regulating Down	0.42%	0.63%	0.35%
Spinning	3.76%	1.14%	0.61%
Non Spinning	2.21%	1.43%	0.92%

[12] P. L. Denholm, Y. Sun, and T. T. Mai, “An introduction to grid services: Concepts, technical requirements, and provision from wind,” National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2019.

Required Reserves Results – 7k Grid



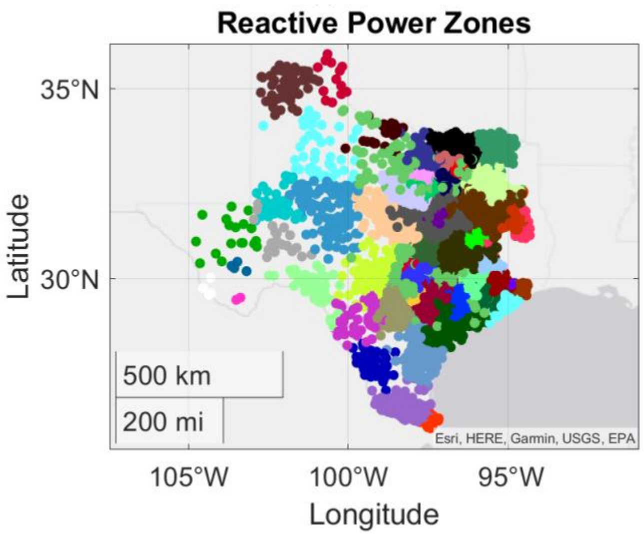


TABLE V
REQUIRED REAL POWER RESERVE FOR THE FIRST 3 ZONES OF THE 7K CASE

Zone No.	Annual peak demand (MW)	Reg. Up (MW)	Reg. Down	Spin. (MW)	Non Spin. (MW)	Ramping (MW)
1	10347	50	43	389	229	207
2	10750	52	45	404	238	215
3	2666	13	11	100	59	53

TABLE VI
REQUIRED REACTIVE POWER RESERVE FOR THE FIRST 3 ZONES OF THE 7K CASE

Zone No.	Pilot Node	Nom kV	Vmax (pu)	Qinj at Vmax (Mvar)	Vmin (pu)	Qinj at Vmin (Mvar)
1	240317	13.80	1.1	197.89	0.9	-460.26
2	110128	138.00	1.1	345.17	0.9	-728.01
3	200204	18.00	1.1	97.64	0.9	-263.01

Thank You! Questions?

The papers associated with these projects are available at www.overbye.engr.tamu.edu/publications
The models themselves are at www.electricgrids.engr.tamu.edu