

Enhancing Power System Innovation Through the Use of Highly Detailed Synthetic Grids

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October 15, 2019

Acknowledgements

- The work presented here has been a collaborative effort involving many! A large number of these folks are PSERC researchers or with PSERC industrial members
 - **ARPA-E:** Tim Heidel, David Guarrera, Pat McGrath, Kory Hedman, Ashley Arigoni, Ray Duthu
 - **NSF:** Anil Pahwa, Kishan Baheti
 - **TAMU:** Adam Birchfield, Ti Xu, Hanyue Li, Jess Wert, Diana Wallison, Komal Shetye, Kate Davis, Ashly Bornsheuer, Juhee Yeo, Yijing Liu, Won Jang, Zeyu Mao, Maryam Kazerooni
 - **UIUC:** Pete Sauer, Kathleen Gegner



Acknowledgements, cont.

- **Cornell:** Ray Zimmerman, Bob Thomas
- **ASU:** Anna Scaglione, Eran Schweitzer
- **UT-Austin:** Hao Zhu; **PowerWorld:** Jamie Weber
- **Virginia Commonwealth:** Zhifang Wang, Hadi Athari
- **UW-Madison:** Bernie Lesieutre, Scott Greene, Chris DeMarco, Line Roald, Jonathan Snodgrass
- **NREL:** Tarek Elgindy, Bryan Palmintier, Venkat Krishnan
- **MIT:** Pablo Dueñas; **Comillas-IIT:** Carlos Mateo, Tomás Gómez Fernando Postigo, Fernando de Cuarda
- **LANL:** Carleton Coffrin
- **PNNL:** Renke Huang, Ahmad Krishnan, Steve Elbert, Jesse Holzer



A Common Request From Industry

- We're gathering all this data. Can you help us figure out what to do with it?
- However, often, after a lot of talks with lawyers to develop nondisclosure agreements (NDAs), at most a subset of the desired data and/or models is available
 - The data and models usually cannot be shared, and often a lot of associated metadata is removed
 - There is a high cost to industry to provide this data
 - It isn't just the amount of data (e.g., who has the most terabytes!) but rather the breadth of the data and whether the data is coupled to models



Changing the Question

- Assume you have all the information possible about the electric grid (data, models, coupled infrastructures) and can share it.
- And it can be provided with low access cost.
- **What would you do with it?**
 - This allows for large amounts of data fusion!
- The focus of this talk is mostly on how to develop this seemingly impossible information set
 - And, of course, one can never know everything!



Talk Overview

- The talk covers the development and application of high quality, geographically-based synthetic electric grids
 - What are they?
 - How can they provide all possible information?
 - How can they help to drive innovation?
 - How are they created?
 - What is the current state-of-the-art?
 - How are they being applied?
 - What's next?



Synthetic Electric Grids

- Synthetic electric grids are models of electric grids that were not created to represent any actual electric grid
- The below image shows the five bus synthetic grid I used as an undergraduate

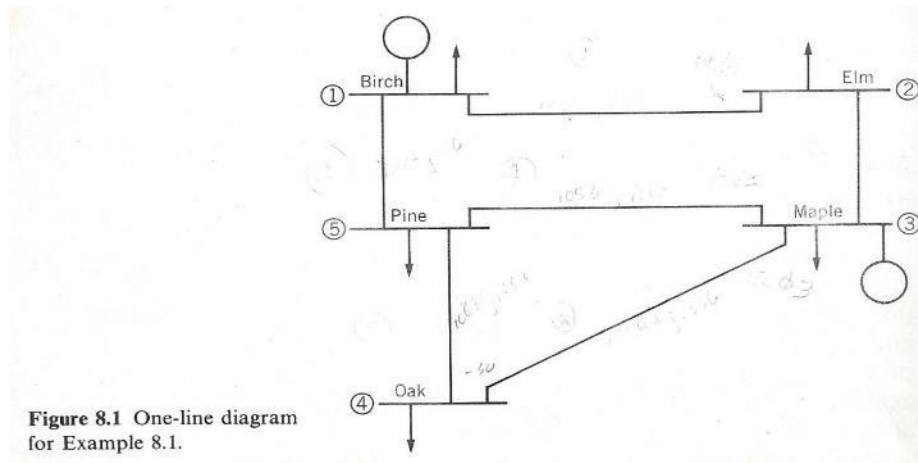


Figure 8.1 One-line diagram for Example 8.1.

Image Source: W.D. Stevenson, *Elements of Power Systems*, Fourth Edition, McGraw-Hill Book Company New York, 1982 (the first edition was in 1955)

Geographically-Based Synthetic Electric Grids

- Synthetic electric grids can be created with or without reference to actual geography
- The image shows an early geographically-based synthetic electric grid
- This grid was designed to show concepts to regulators

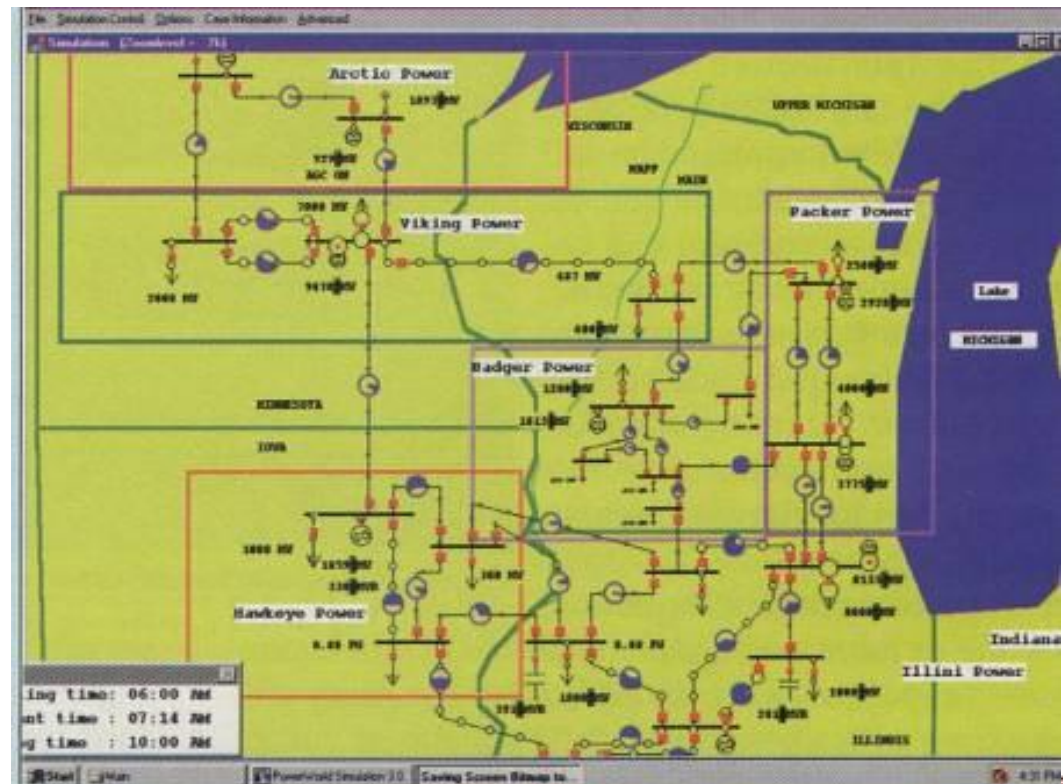


Image Source: PowerWorld Corporation, 1995

High-Quality, Geographically-Based Synthetic Electric Grids

- High-quality synthetic electric grids are designed to have a wide range of characteristics that are similar to those found in actual electric grids
 - “Realistic but not real” to quote Wisconsin colleagues
 - Fictional, but hopefully good fiction
 - **Developed techniques can be applied to real grids**
- However, importantly these grids are not designed to try to duplicate any actual grid
- Over the last three years tremendous progress has been made through ARPA-E at both the transmission and distribution levels



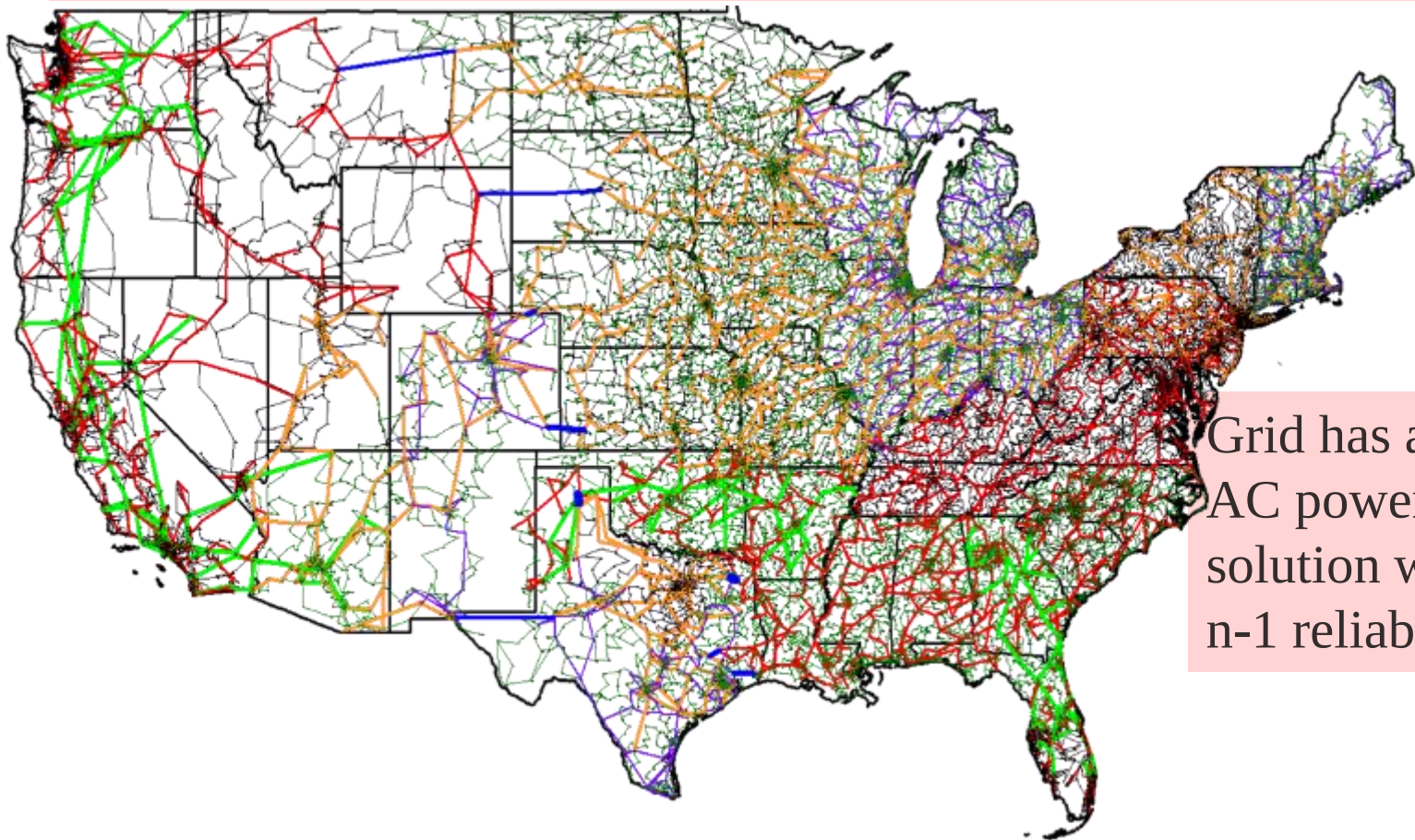
A Guiding Thought

- All models are wrong but some are useful," George Box, *Empirical Model-Building and Response Surfaces*, (1987, p. 424)
 - Models are an approximation to reality, not reality, so they always have some degree of approximation
 - Data might be “right”, but usually engineers want to use it to predict or control the future, requiring models
- Synthetic grids can’t really be “wrong” but they can be unrealistic, so I welcome your feedback on where we have been unrealistic.



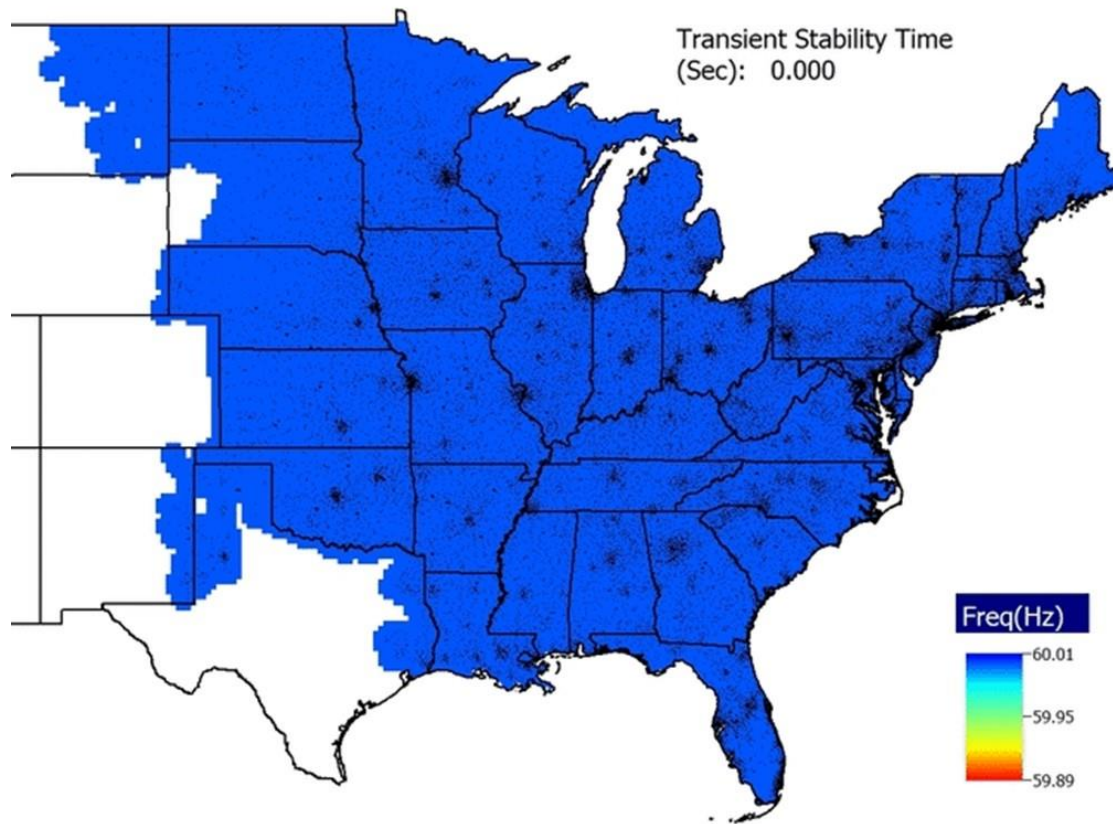
Current Status: Large-Scale Grids are Now Available

This is an 82,000 bus synthetic model that we publicly released in summer 2018 at electricgrids.engr.tamu.edu



Grid has an AC power flow solution with n-1 reliability

The Grids Have Dynamics Models



The models and all the data associated with this image are public

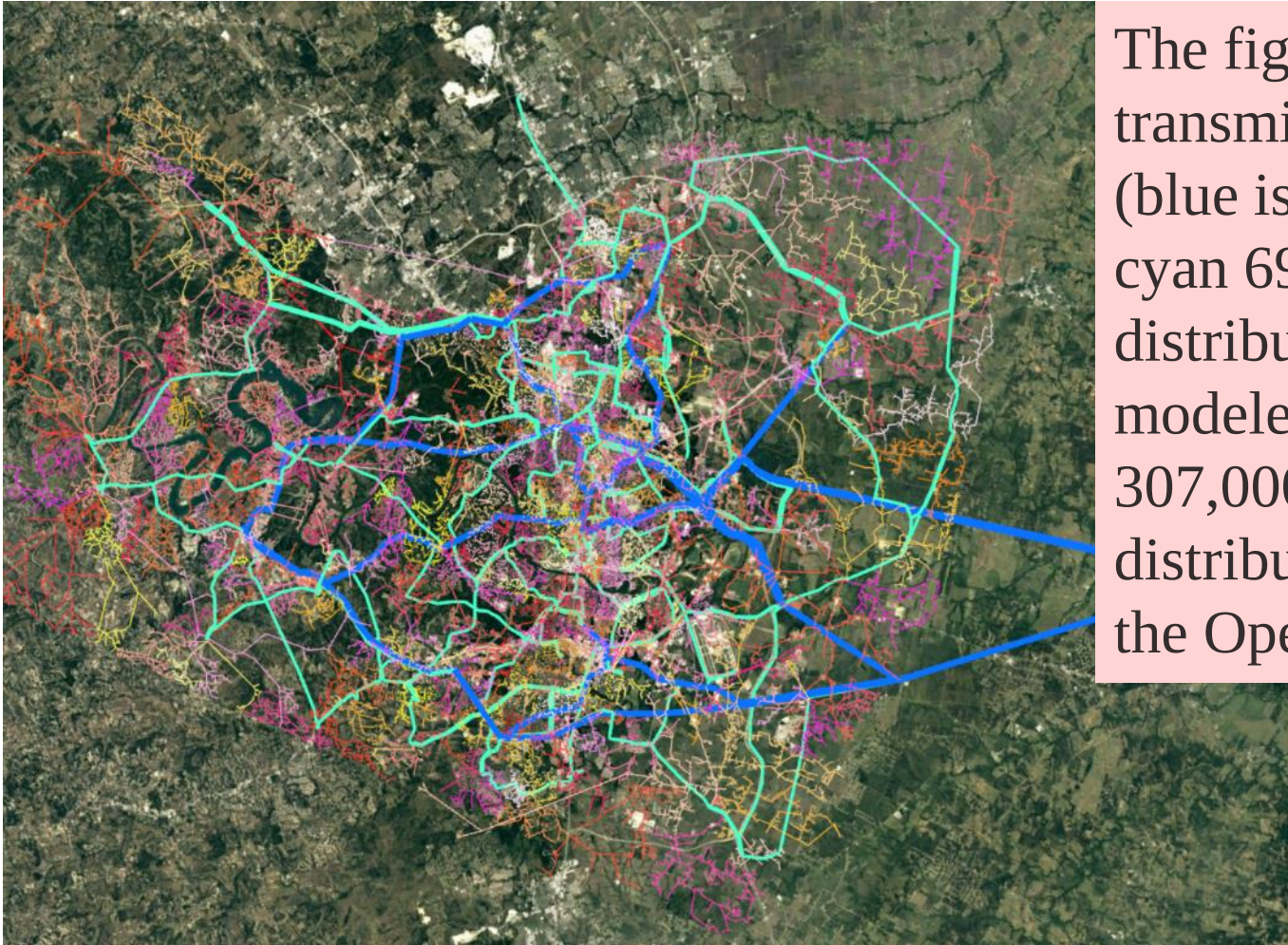
Ongoing research is focused on developing more detailed dynamic models, including the protection systems

Highly Detailed Combined Transmission and Distribution Grids

- Previous transmission grids were geographic to the zip code level
- On current ARPA-E project we (with NREL, MIT and Comillas-IIT University) are developing “down to the meter” synthetic grids
- Actual parcel data is used to determine location of the electric meters. The parcels are connected by a distribution system, and the distribution system by a transmission grid
- Currently we have about 20% of the load in Texas done (Travis and Harris Counties)



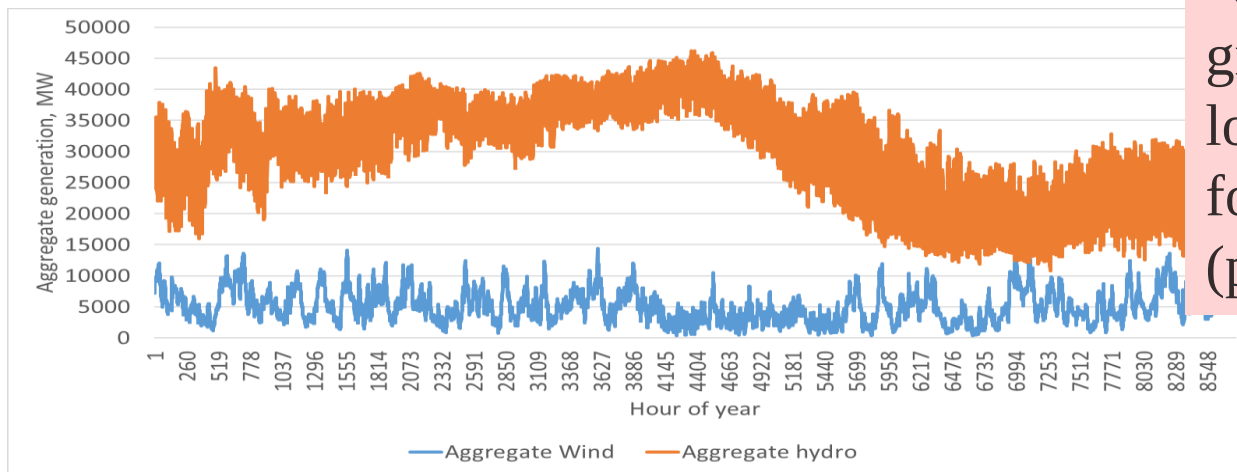
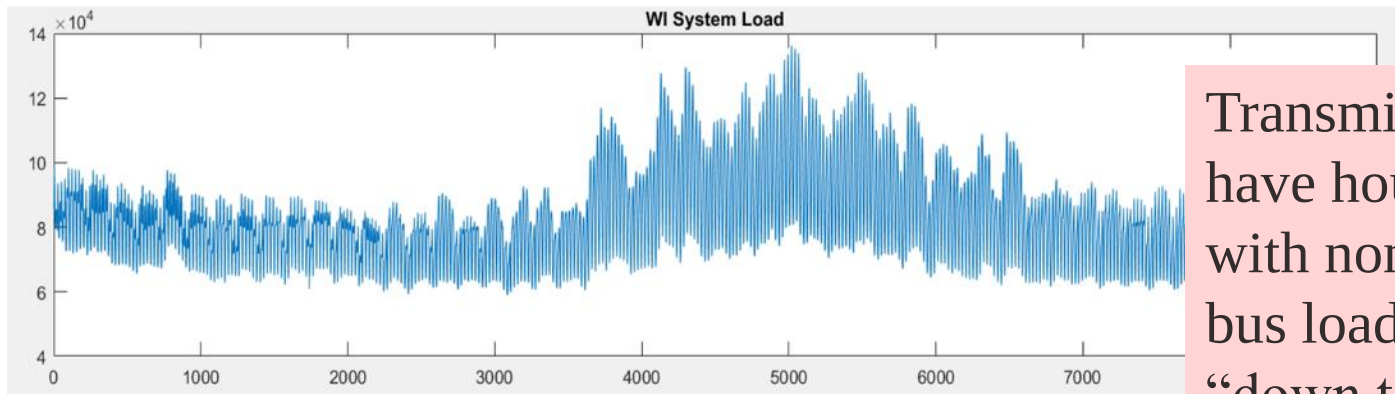
Travis County, Texas (location of Austin, TX)



The figure shows the transmission system (blue is 230 kV and cyan 69 kV) and the distribution system modeled down to 307,000 meters. The distribution data is in the OpenDSS format.

Synthetic Electric Grid Scenarios

- We have developed detailed, yearly scenarios with variation of both bus level load and gen.

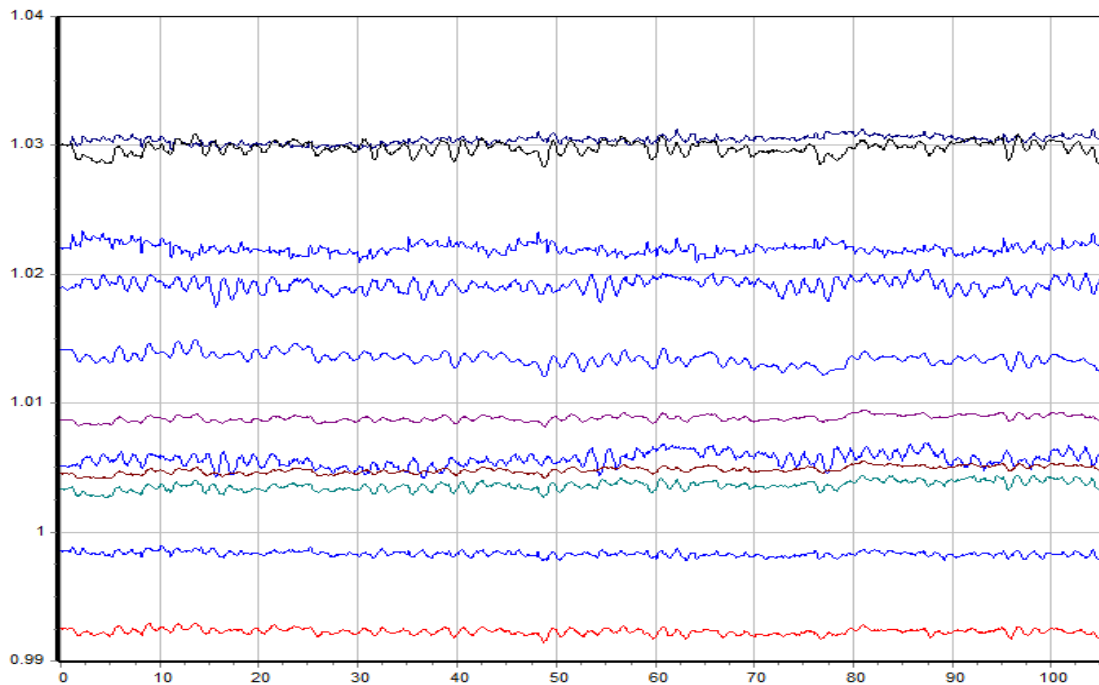


Transmission models have hourly snapshots, with nonconforming bus loads modeled. The “down to the meter” grids have synthetic loads every 15 minutes for each meter (provided by NREL).



Synthetic PMU Data

- To create synthetic PMU data we use dynamic simulations with realistic variation in the load and generation, and appropriate PMU errors.



On our 2000 bus Texas synthetic grid we can provide more than 10,000 signals at PMU data rates (30 times per second) in real-time. This is data creation at about 4GB per hour.

The Need for Synthetic Grids

- Prior to 9/11/01, a lot of grid information was publically available
- Now access to data and models about the actual power grid in the US is quite restricted (e.g., critical energy/electricity infrastructure [CEII])
 - What is available is often partial, and can't be shared
- To do effective research, and to drive innovation, researchers need access to common, realistic grid models and data sets
 - Scientific principle of reproducibility of results



The Need for Synthetic Grids, cont.

- Synthetic grids and datasets are, of course, designed to augment, not replace actual grids
- But the synthetic grids offer some significant advantages, both to industry and researchers
 - Since there are no CEM or privacy concerns, full models and their associated datasets can be freely shared; this is particularly helpful for interdisciplinary research
 - Synthetic grids can allow future grid scenarios to be considered in-depth (i.e., high renewables or high impact, low frequency events) yet still be potentially public



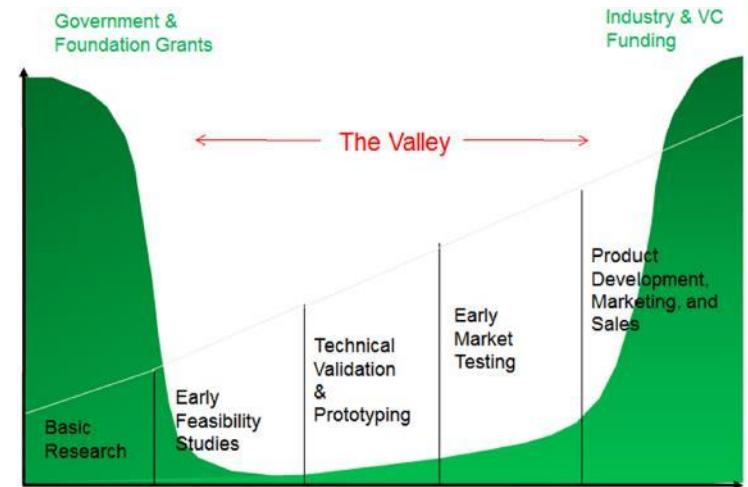
The Need for Synthetic Grids, cont.

- Advantages, cont.
 - Synthetic grids can be customized to represent particular grid idiosyncrasies; utilities can provide this to researchers or potential vendors
 - We've deliberately designed ours using different voltage levels than those used in the actual grid (e.g., 500/230 versus 345/138 in Texas) to emphasis they are synthetic
 - The highly detailed (down to the meter grid) allow coupling with real infrastructures
 - We're working with the Texas Transportation Institute to study electric grid/transportation couplings
 - Synthetic grids can be used for education, including vendor training and short courses



Crossing the Valley of Death

- One of the greatest perils to university research commercialization is to cross what is known in as “the valley of death.”
- On the one side is “well-funded” university research, pursued mostly by graduate students and postdocs, while on the other is a successful commercial product
 - Synthetic grids and datasets can help bridge this gap!

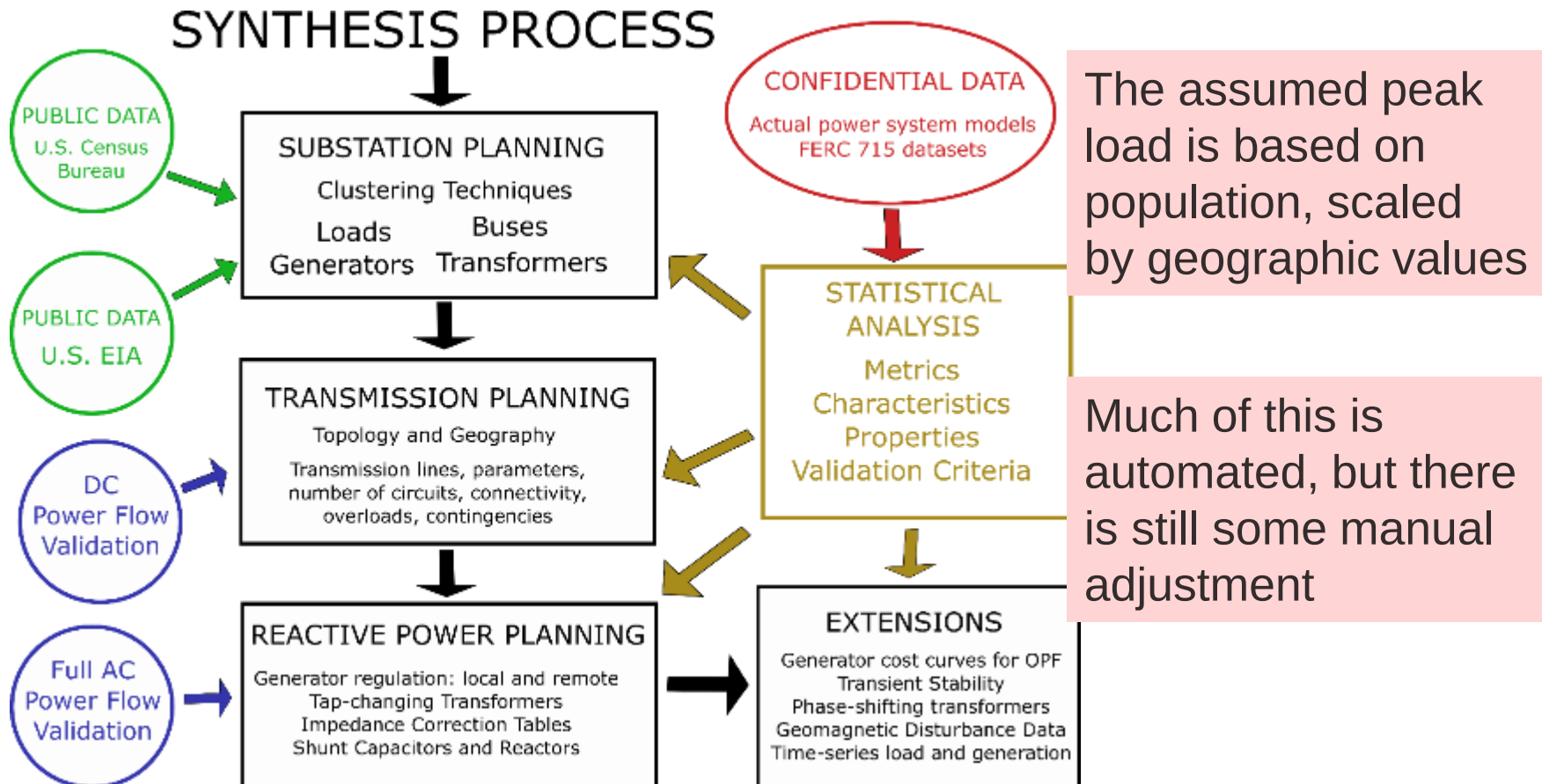


Our Synthetic Grid Approach

- Make grids that look real and familiar by siting them geographically (North America for us) and serving a population density the mimics actual
- Goal is to leverage widely available public data
 - Geography
 - Population density (easily available by post office)
 - Load by utility (US FERC 714), state-wide averages
 - Existing and planned generation (Form US EIA-860, which contains lots of generator information)
- Substation locations and transmission system is entirely fictional (but hopefully good fiction!)



Synthetic Model Design Process



This process can be augmented to couple with detailed distribution grids

More Details on Design Process

- Substation planning: cluster actual population and energy data into correctly-sized substations and assign load, generation, bus voltage levels, and internal branches, along with parameters.
- Transmission planning: use iterative penalty-based dc power flow algorithm to place transmission lines, with the Delaunay triangulation and neighborhood as base
- Reactive power planning: iterative ac power flow starting from known solution to place capacitors and adjust generator set points.

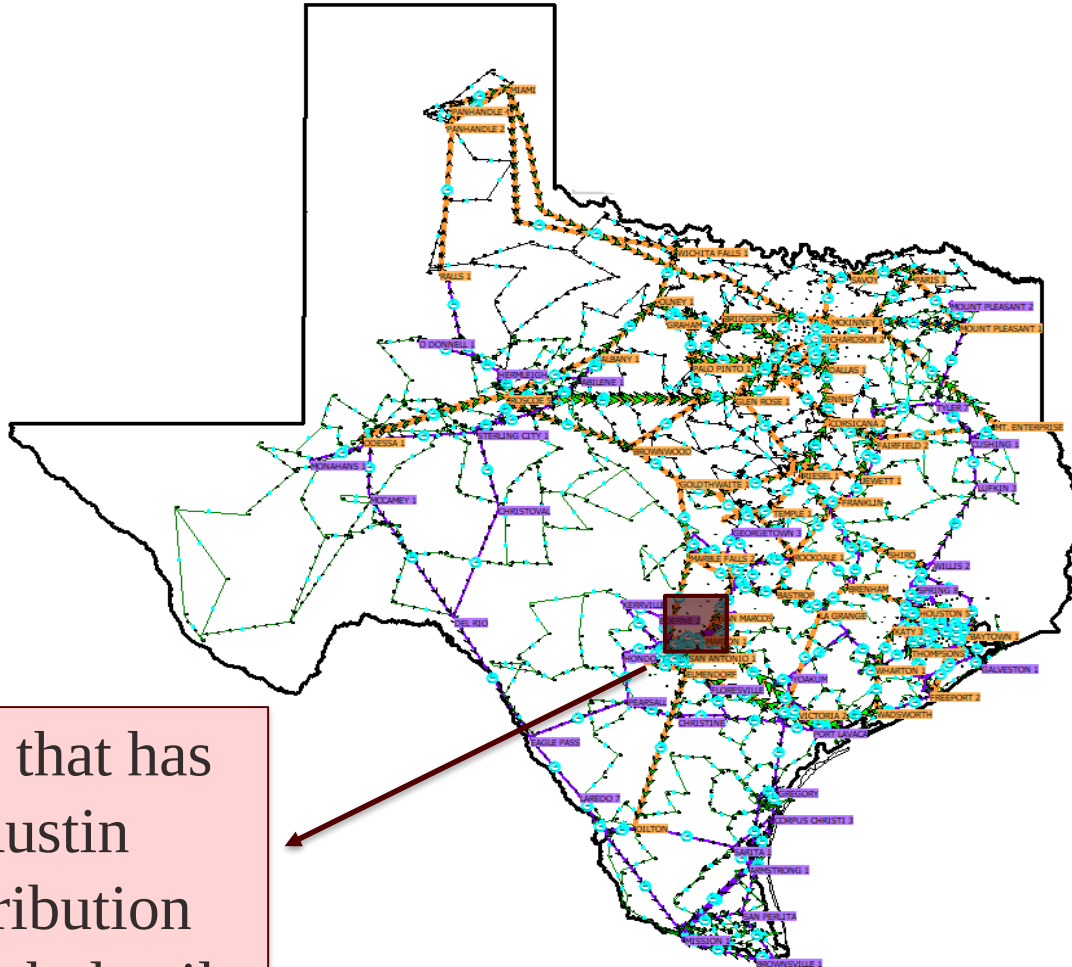


Coupled Transmission-Distribution System Design

- Our first approach to developing the highly detailed grids was to design the distribution first, then design the transmission
 - Earlier Travis County case was an example
- Now we design the overall transmission system first, and update it as more distribution systems become available
 - We're currently doing Texas on a county-by-county basis (Texas has 254 counties!)
 - Updating the transmission grid is a mostly automated process



The Expanding Texas 2000 Bus Transmission Model



Area that has
Austin
distribution
network details

NREL is providing load data for each of the meters at 15 minute resolution for a year. This is driven by historical weather data. Eventually we will have about 10 million meters.

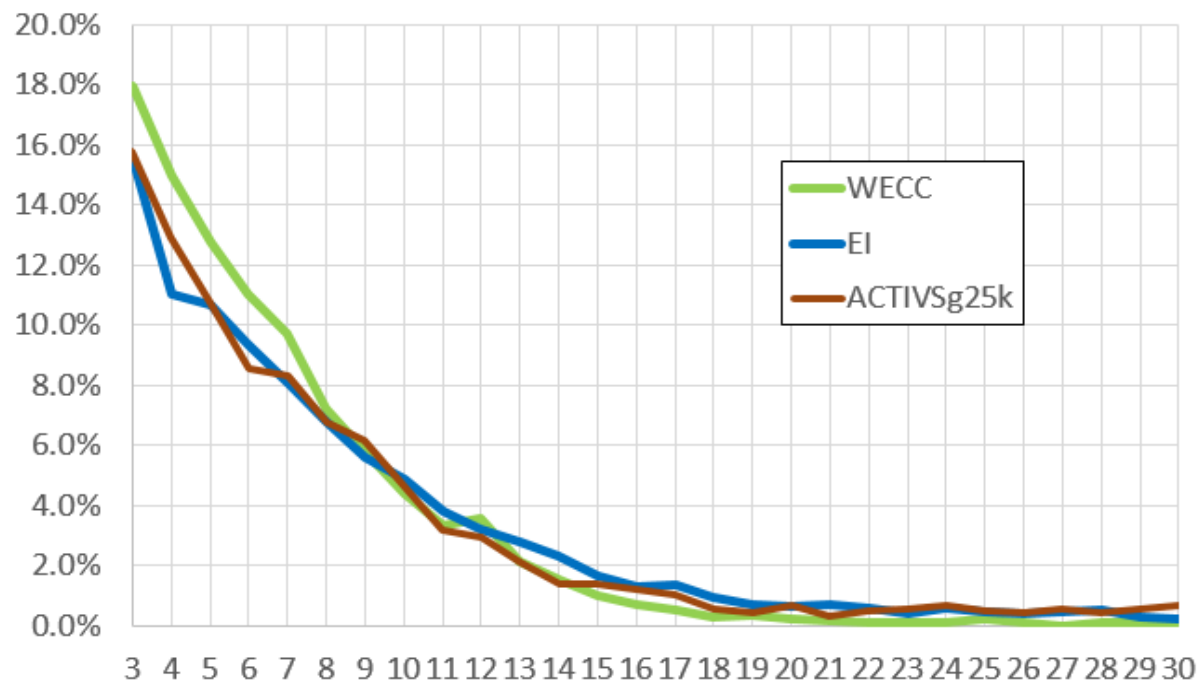
Validation: Insuring High Quality

- Based upon data from actual grids we've developed a large number of metrics that cover many aspects of both transmission and distribution 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



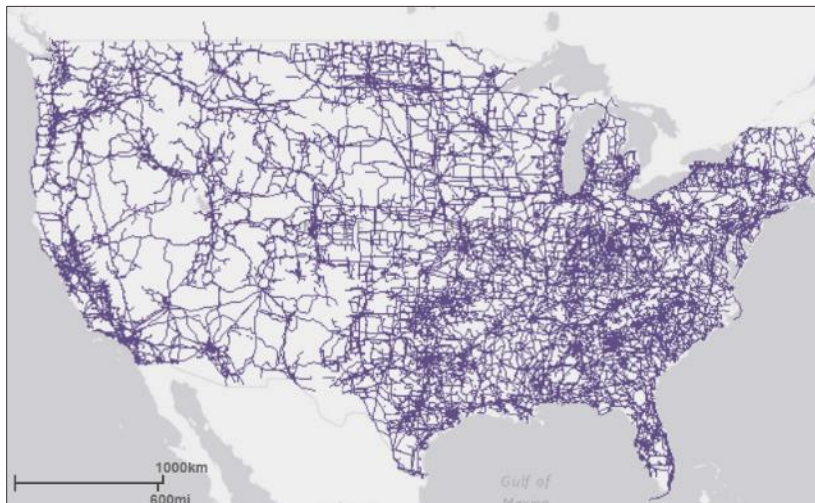
Validation Example: Cycle Sizes

- Cycles are use loops of connected buses. Power systems have many cycles and an important metric to match is to have a similar cycle basis



Intersections (Transmission Line Crossings)

- We've found it is important to match properties of electric grids that depend on their physical layout; for example transmission line crossings
 - Transmission line right-of-ways are available in EIA datasets; hence line crossings can be analyzed

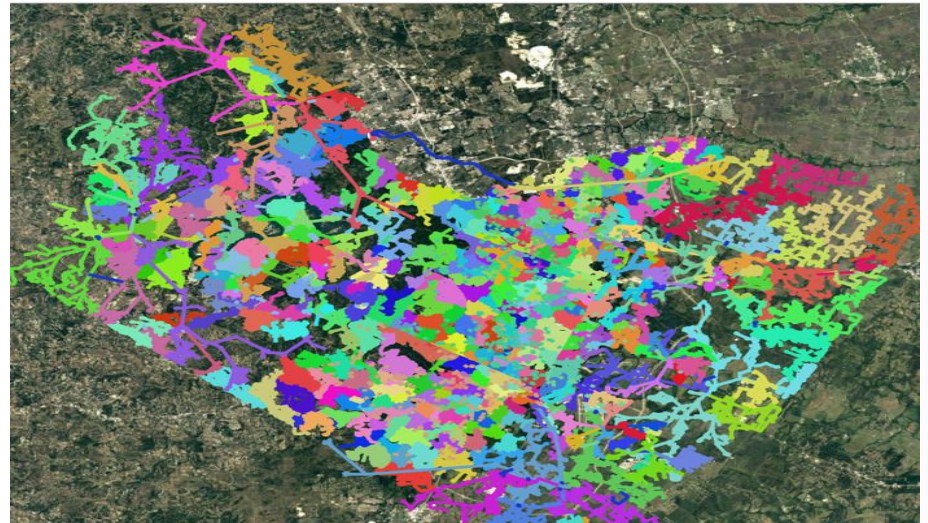


GEOGRAPHIC CROSSINGS FOR EIA DATASET VOLTAGE NETWORKS

Voltage class	Number of substations	Number of lines	Crossings, straight-line	
			Number	% of lines
765kV	40	42	1	2.4
500kV	529	732	67	9.2
345kV	1526	2171	297	13.7
230kV	4648	6233	935	15.1
161kV	2633	3172	405	13.0
138kV	8611	10684	1617	15.3
115kV	12826	15031	1485	10.2
100kV	894	1595	118	7.5
69kV	8022	8022	289	3.7

Detailed Transmission and Distribution Testing

- Full transmission and distribution system studies are being done using a co-simulation framework
 - PowerWorld Simulator is used to solve the transmission system and OpenDSS is used to solve each of the distribution circuits
 - The simulations are coupled together using the national lab developed HELICS package; one year of simulations took about 3 hours



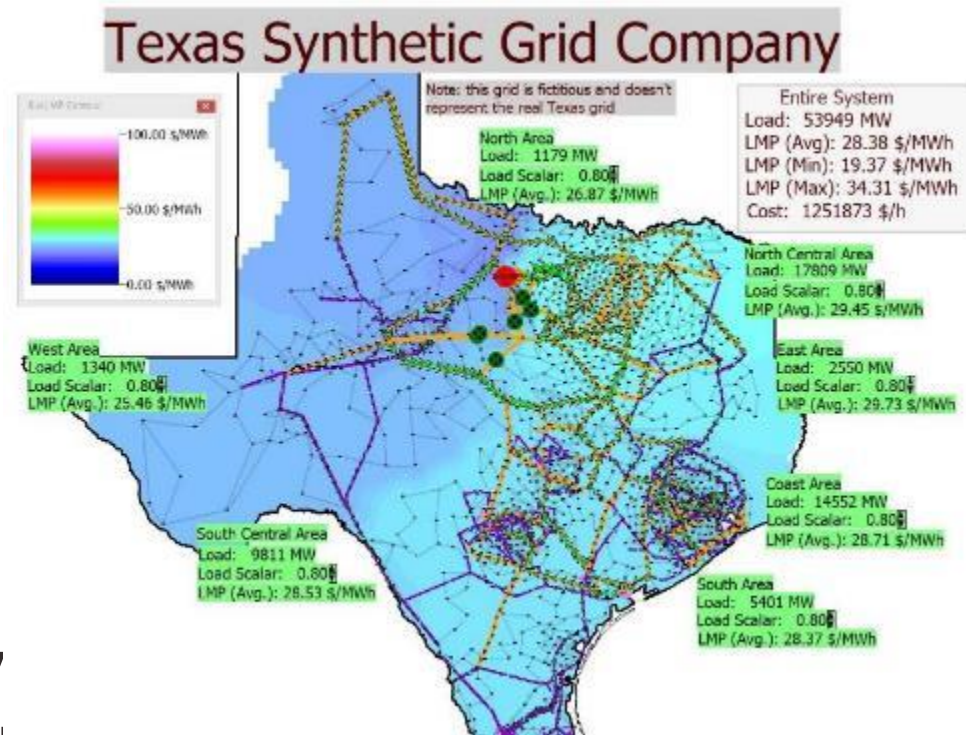
For Travis County (population 1.2 million) 307,236 meters are served by 488 distribution circuits

Different Levels of Modeling

- Just because we have detailed grids, doesn't mean we always simulate the coupled transmission and distribution models. Other options are
 - Transmission only
 - Distribution only
 - Full transmission with distribution topology; this can be quite useful for doing multi-infrastructure simulation in which we just need to know what parts of the distribution system are out-of-service

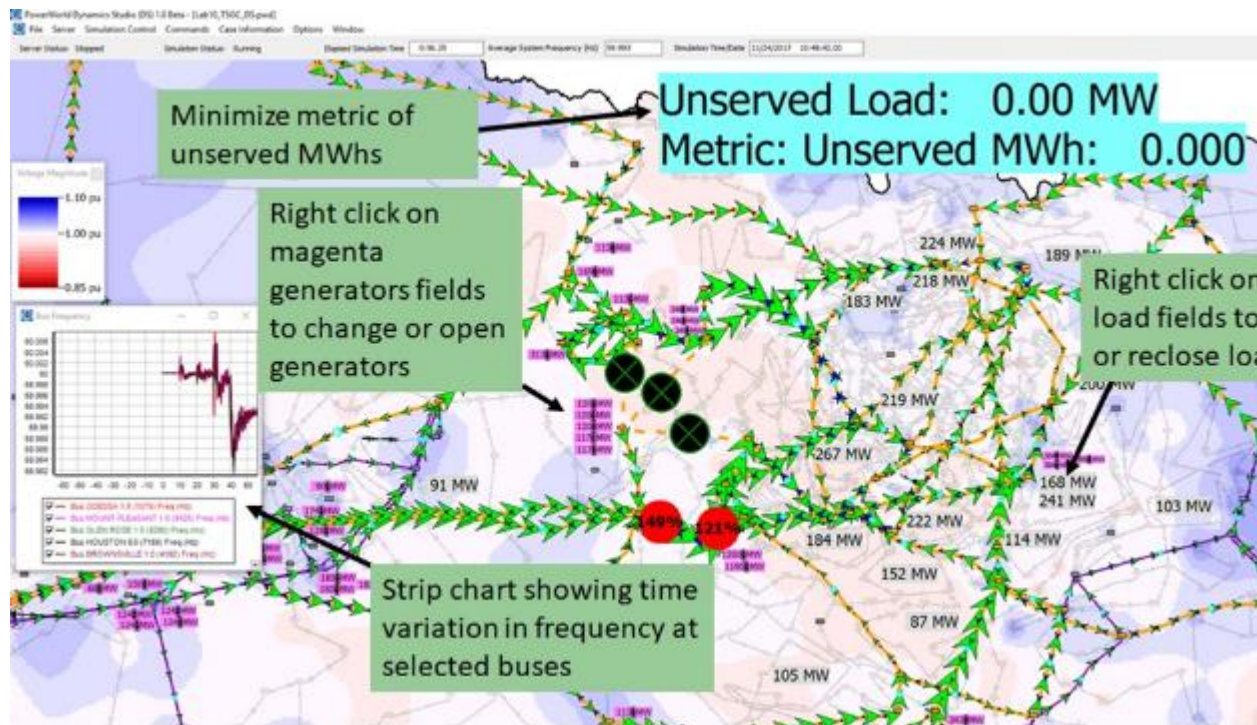
Synthetic Grid Applications: Innovative Electric Power Education

- Lab assignments involving a 2000 bus case have been integrated into Texas A&M's power classes
- Class includes large-system exercises for power flow, economic dispatch, contingency analysis, SCOPF, and transient stability



Innovative Electric Power Education

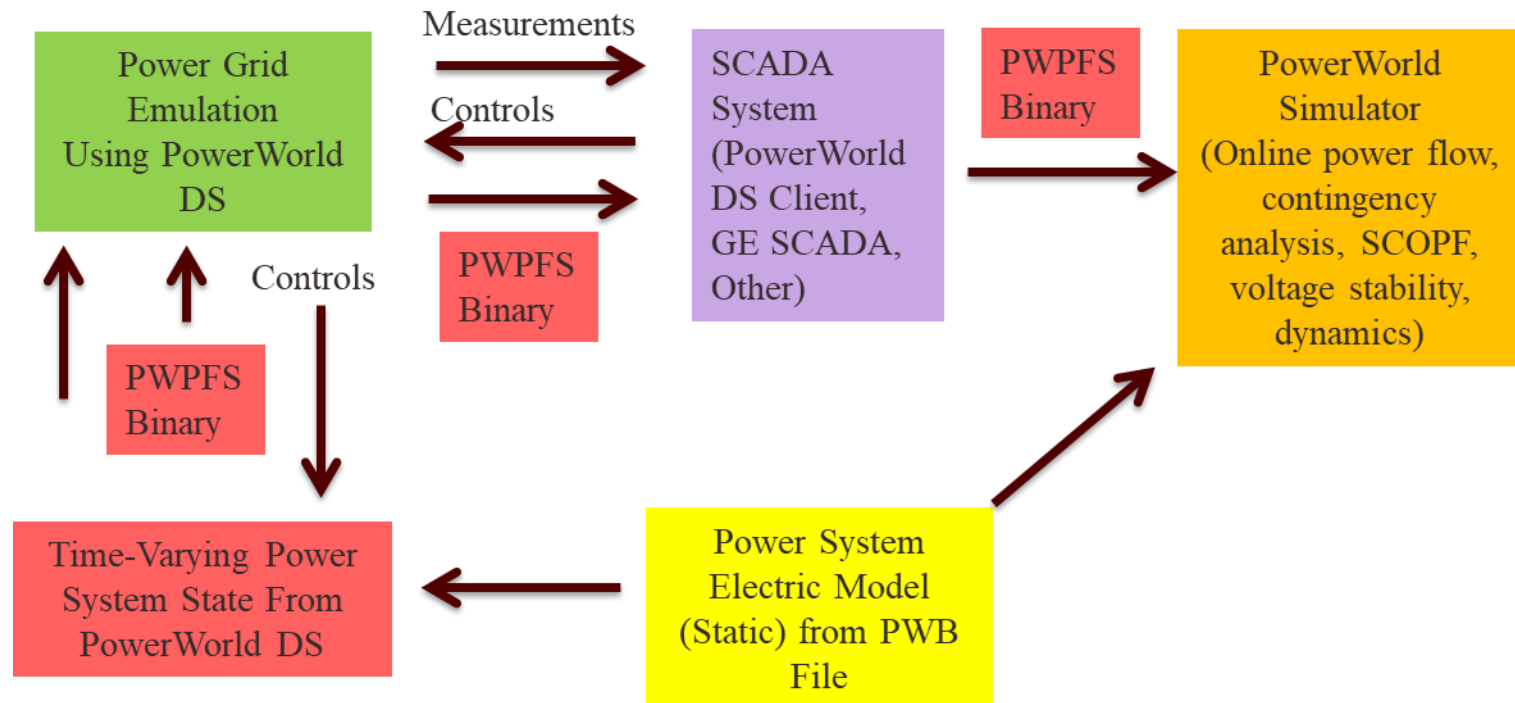
- One lab challenges students to save the synthetic Texas grid from voltage collapse following a simulated tornado in real-time!



The lab was introduced in Fall 2017; in Fall 2018 it was expanded to be a multi-user simulation. However it did not involve integrated analysis.

Fall 2019: EMS In-A-Box

- Starting this semester during the event students will use an integrated power flow and the OPF to determine the optimal system controls to use.



Giving Students (and Others) Experience In Grid Operations

- Most electric power students have little or no experience in actually operating an electric grid (real or simulated)
- One of our goals is to provide such an experience both in an individually and as part of a team
- Developing this involves a combination of the electric grid, the scenario, and the associated simulation environment, and the path to give the users experience with the environment
- This also generates data



The Simulation Environment



Applications: Visualization Research

- With the now wide spread availability of large-scale, geographically based public synthetic grids, there has been increased need for better wide-area visualizations
- Visualizations involve many trade-offs, with the best approach ultimately application dependent
- Recent research using the synthetic grids is focused on how to maximize display space, while retaining some geographic context



Pseudo-Geographic Mosaic Displays Can Maximize Screen Usage

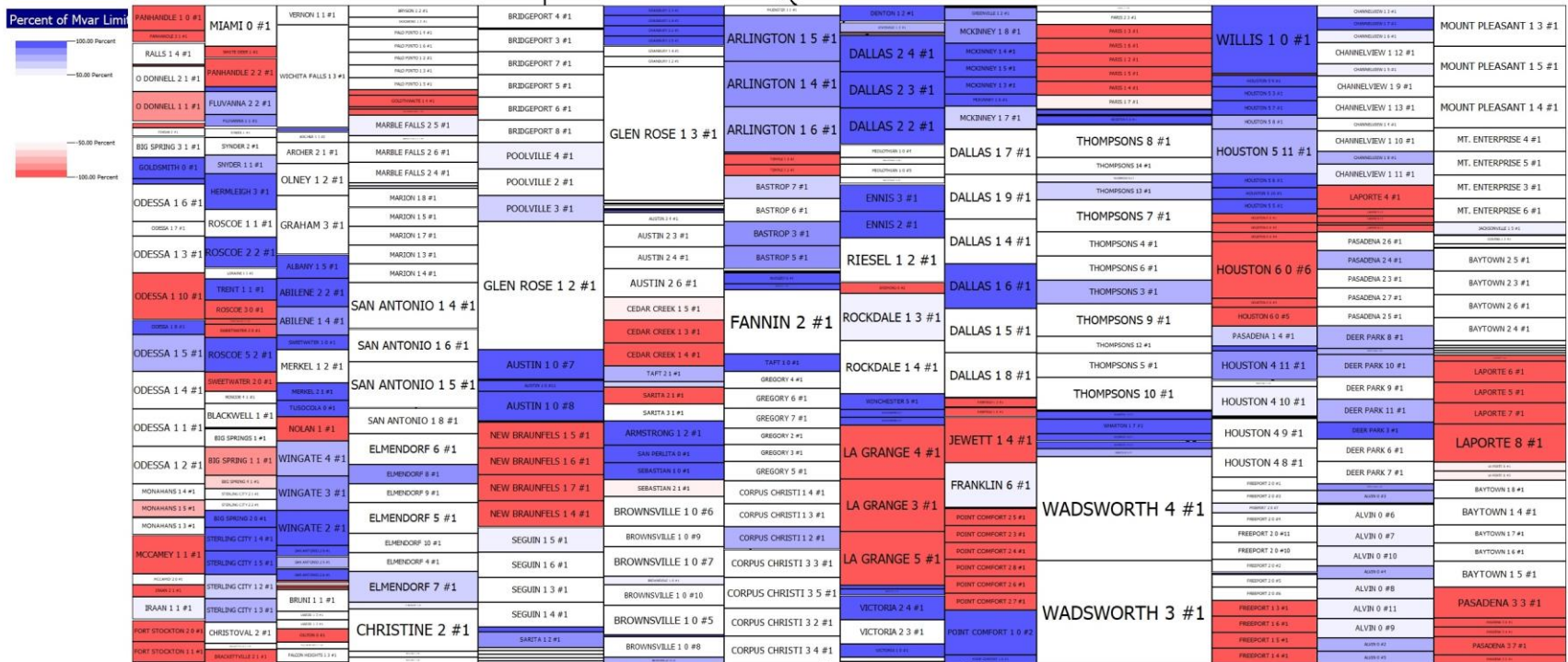
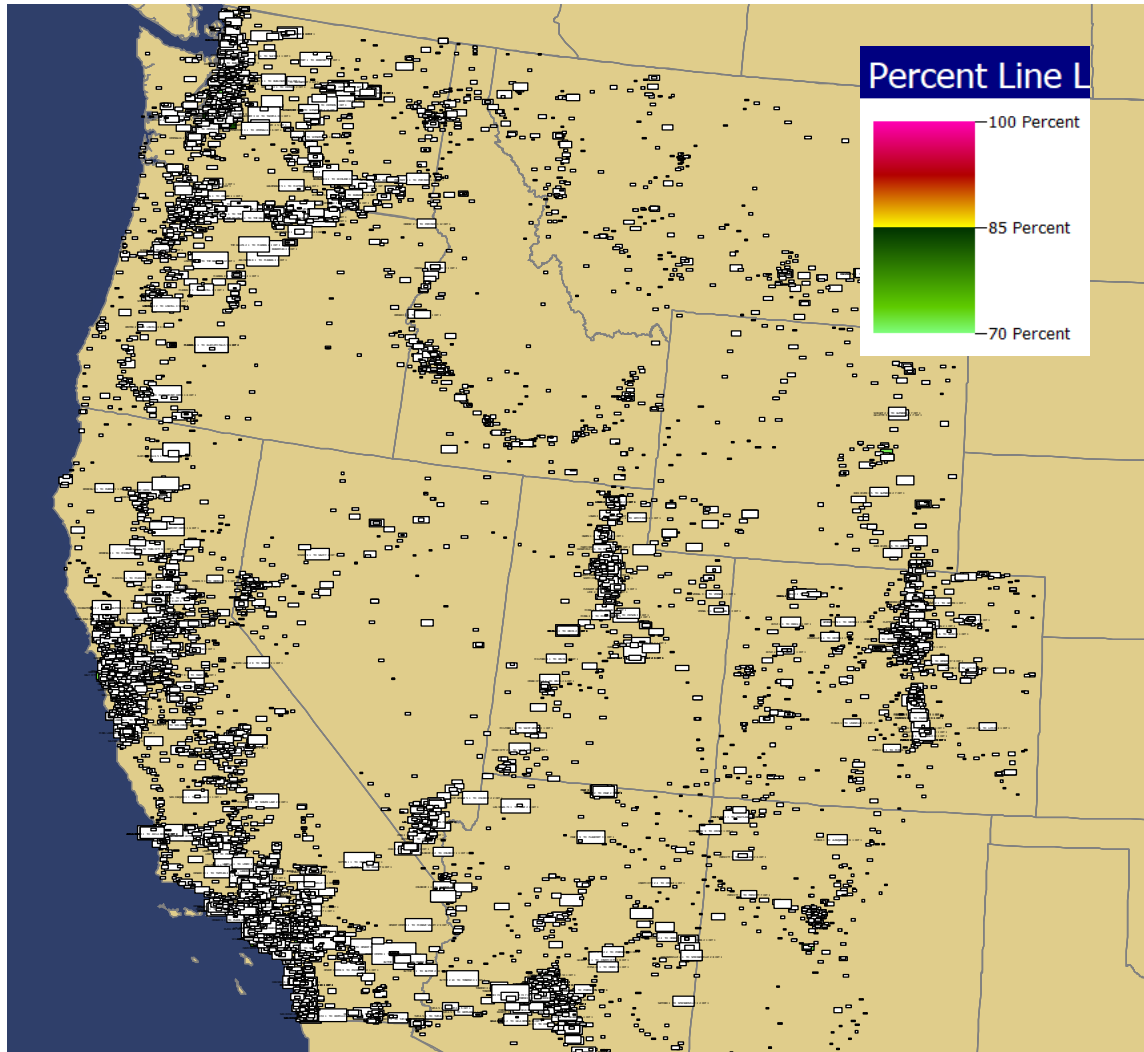


Image visualizes percentage generator reactive power output. Image source: Overbye, Wert, Birchfield, Weber, "Wide-Area Electric Grid Visualization Using Pseudo-Geographic Mosaic Displays," Proc. 2019 North American Power Symposium (NAPS), Wichita, KS, Oct 2019

Visualizing 12,700 Line Flows:



Large-scale synthetic grids can help guide new visualization solutions. This image attempts to show 12,700 line flows, with object size based on the line's MVA flow and its coloring based on percentage loading.

Visualizing 12,700 Line Flows:

Visualization using a pseudo-geographic mosaic approach with all rectangles linked to provide drill-down details

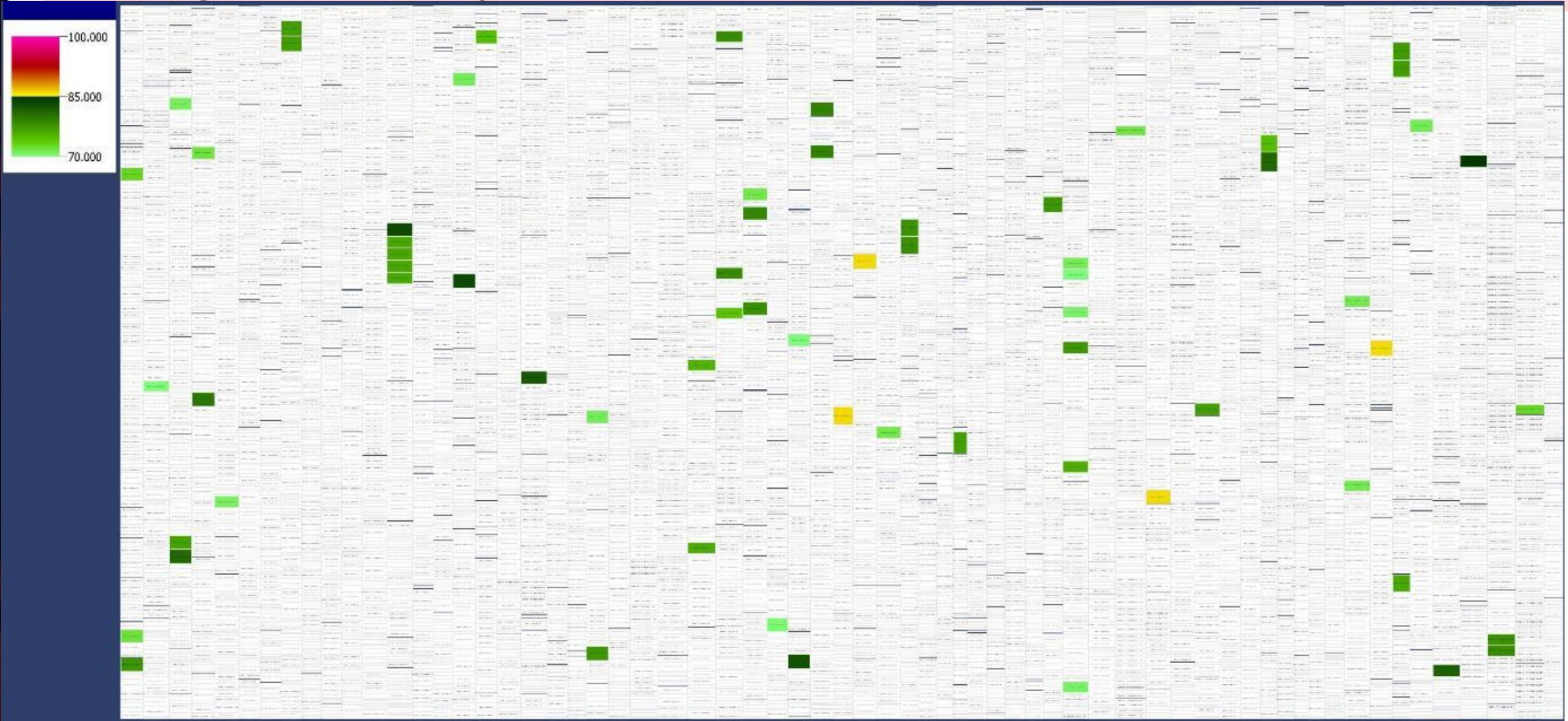
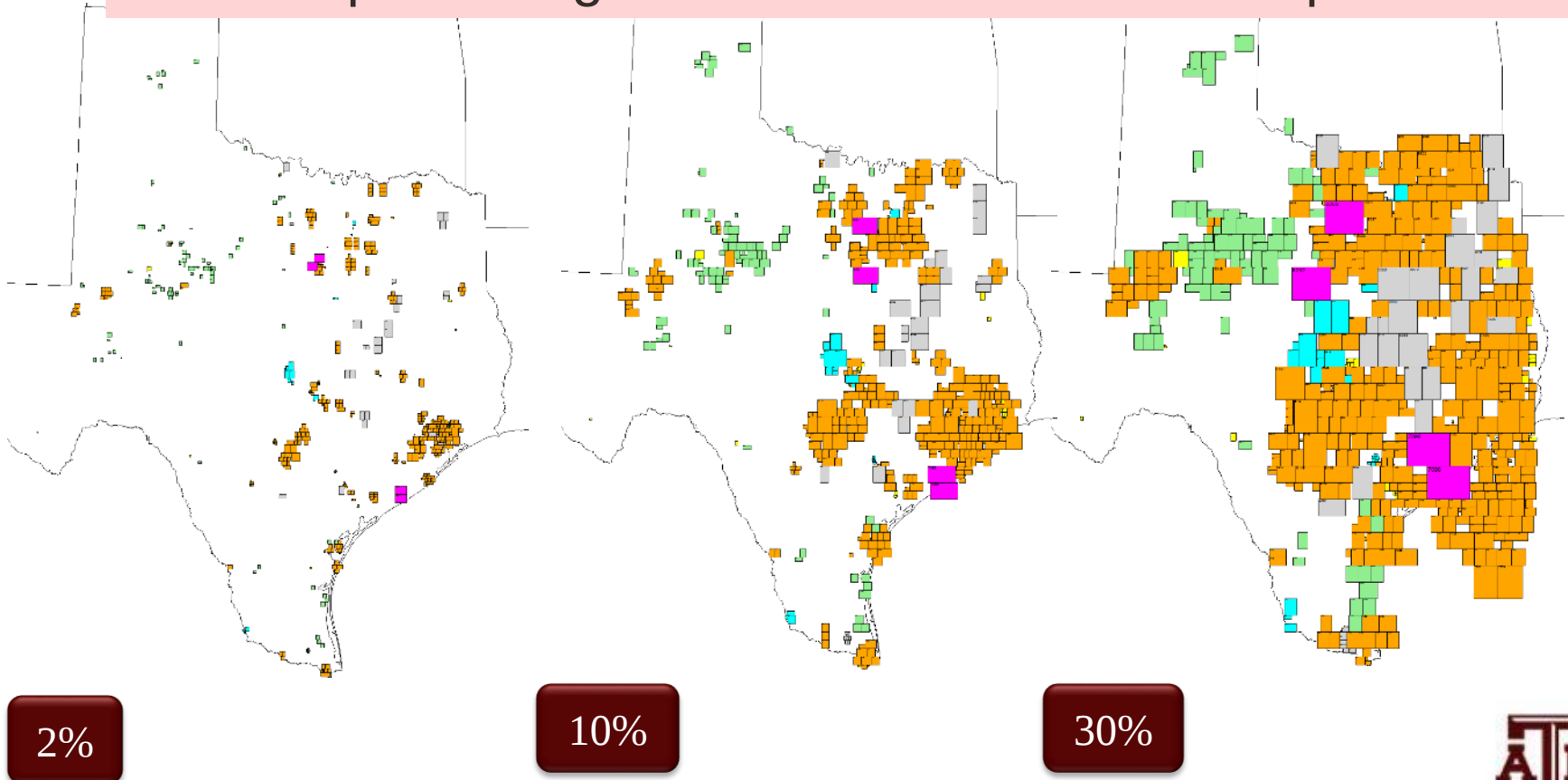


Image source: Overbye, Wert, Birchfield, Weber, "Wide-Area Electric Grid Visualization Using Pseudo-Geographic Mosaic Displays," Proc. 2019 North American Power Symposium (NAPS), Wichita, KS, Oct 2019

Auto Screen Layout Designed to Percentage Screen Fill

Images show generation by capacity and fuel type using different percentages of the available screen space



2%

10%

30%



Image source: Adam Birchfield

Applications: Coupled Infrastructures and Extreme Events

- Since the highly detail synthetic grids are linked to actual parcels, they can be used in coupled infrastructure simulation
 - Metadata is used to indicate the number of people at a meter and other attributions
- By partnering with the Texas Transportation Institute (TTI) we're moving forward with coupled electric grid/transportation studies
 - Blackouts affect people, and large blackouts can affect a lot of people, causing transportation impacts
 - Studies can be done looking at different rates of transportation electrification



Summary

- Thanks to investment primarily by ARPA-E, large-scale, highly detailed synthetic grids are a reality
 - Ongoing research on enhancements and applications
- These can be used to generate large amounts of context-aware data, helping to enable a large amount of power system research
- Coupled infrastructure research is now potentially available to a much broader audience
- Lots of opportunities for PSERC involvement in this exciting and impactful area!!



Thank You!

Questions?

