New Developments in the Visualization of Wide-Area Electric Grid Information

Thomas J. Overbye
O'Donnell Foundation Chair III
Texas A&M University

University of Washington
April 29, 2021

Acknowledgments

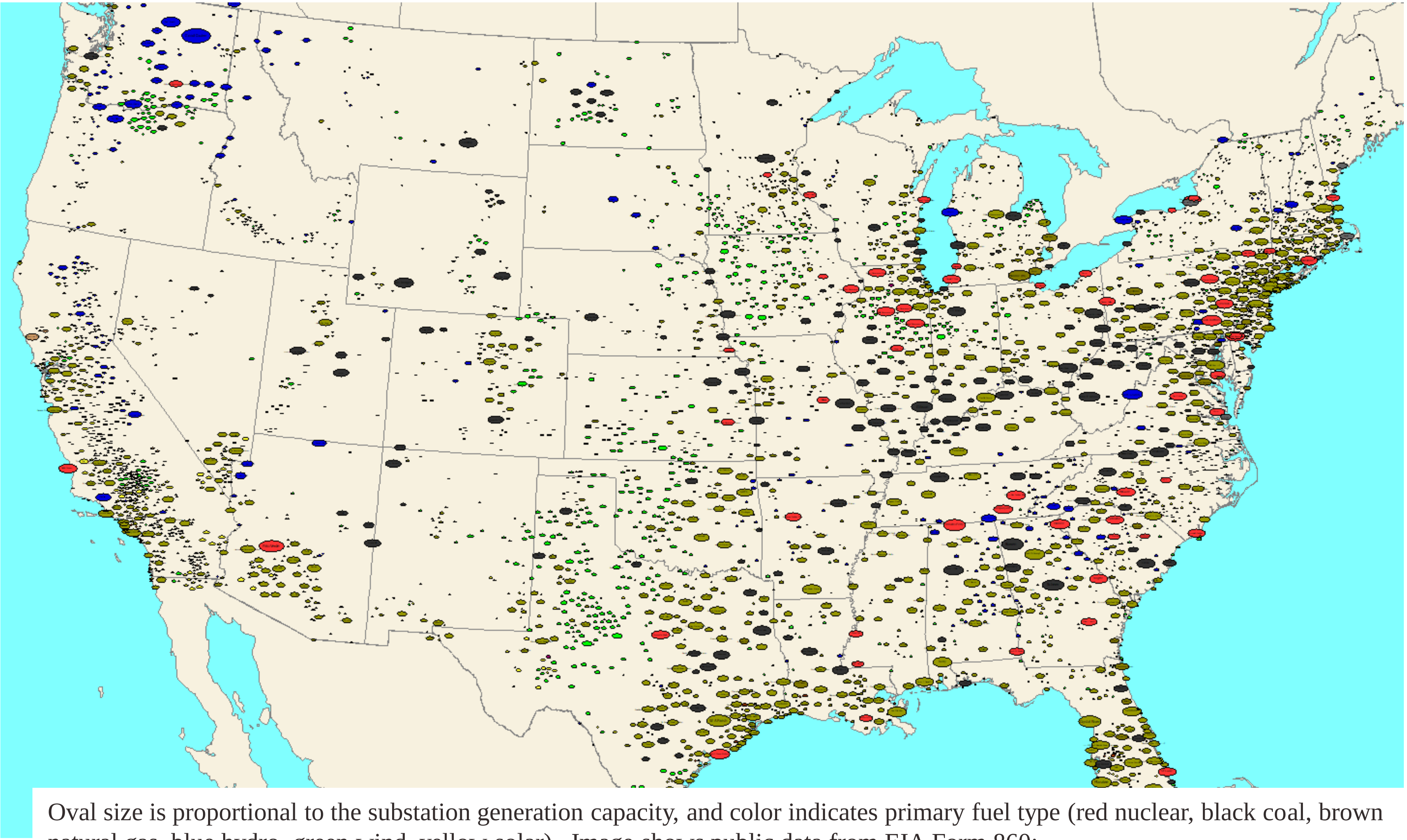
- Work presented here has been supported by a variety of sources including the Texas A&M Smart Grid Center, PSERC, DOE, ARPA-E, NSF, EPRI, BPA, and PowerWorld. Their support is gratefully acknowledged!
- Slides also include contributions from many of my students, postdocs, staff and colleagues at both TAMU and UIUC
- Thanks for human factor aspects from Prof. Esa Rantanen, Rochester Institute of Technology

Our Energy Future Could be Quite Bright!

- My professional goal is to help in the development of a sustainable and resilient electric infrastructure for the entire world.
- Electric grids are in a time of rapid transition, with lots of positive developments.
- I think our electric energy future could be quite bright! But there are lots of challenges with this transition, including maintaining human situational awareness, particularly during times of stress.

First a Little Background on the Texas Event of February 2021

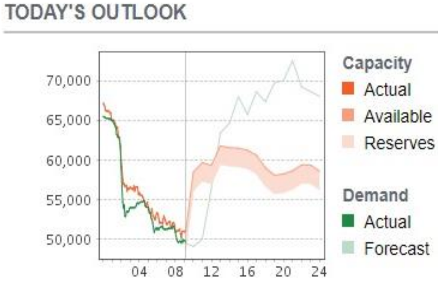
US Generation by Fuel Type



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;

A Quick Look Back at February

- Unfortunately electric grids often make the news for all the wrong reasons!

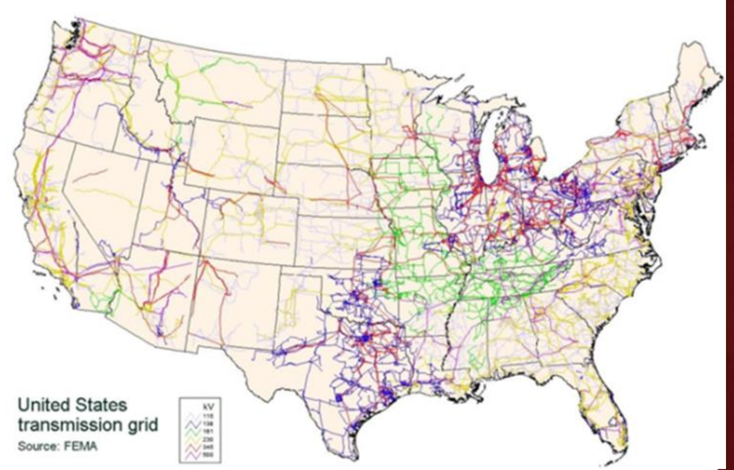


- Starting on Feb 14, 2021 statewide Texas had temperatures much below average, though not record cold
  - In College Station on Feb 15 is was 9°F and very windy (and 5°F on Feb 16)
  - Our record low is -3°F (1/31/1949), our coldest February temperature was 5°F (2/5/1951) and last single digit was 9°F (12/22/1989

- This stressed many infrastructures!

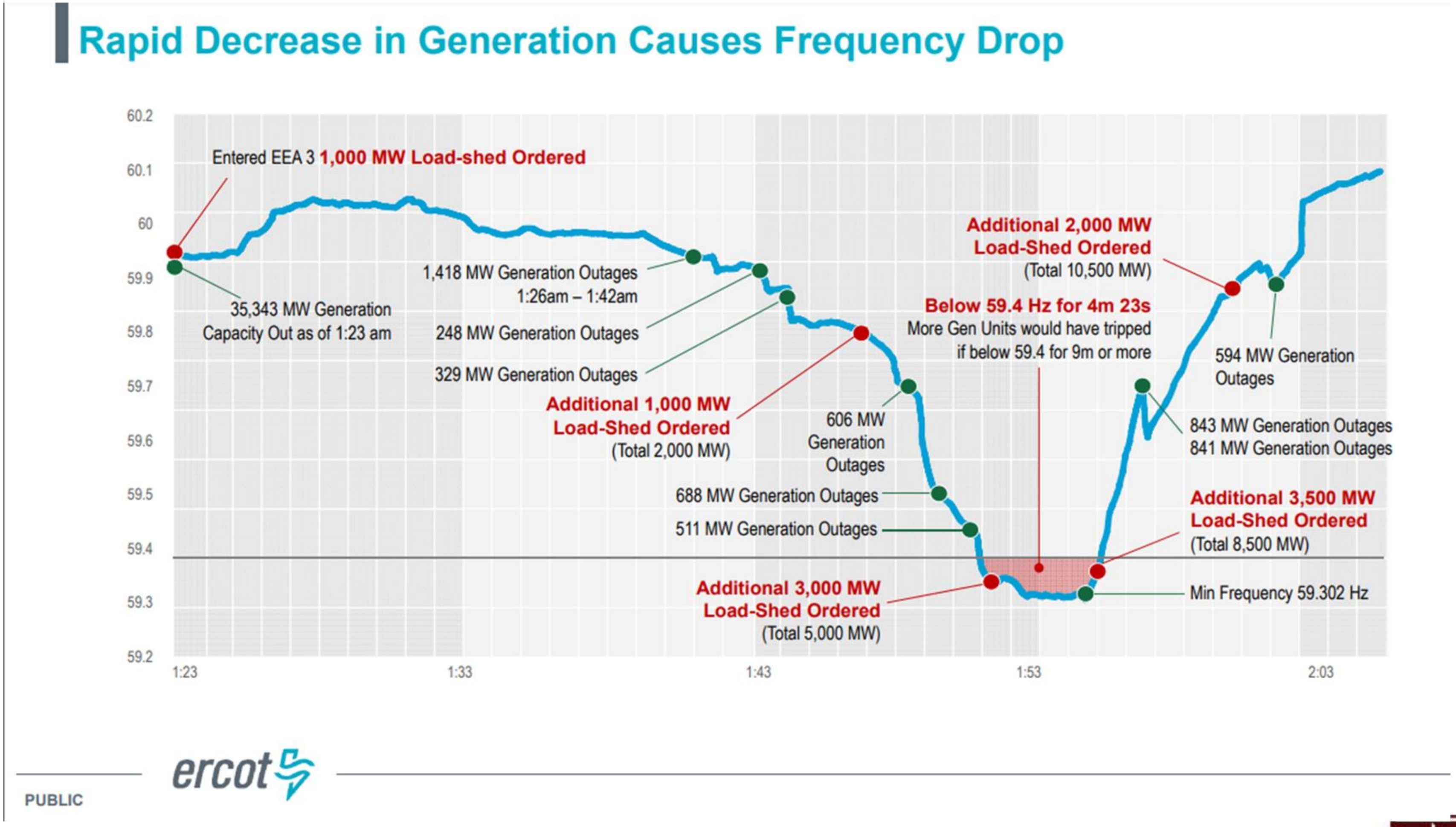
A Little Electric Grid Background

- Electricity cannot be economically stored
  - Generation must be continually adjusted to match changes in electric load and losses
- Electric power flows on high voltage transmission lines cannot usually be directly controlled
  - Control is mostly indirect, by changing generation



- Customers have been in control of their load
- Transmission system has finite limits; often operated close to its limit for economic reasons

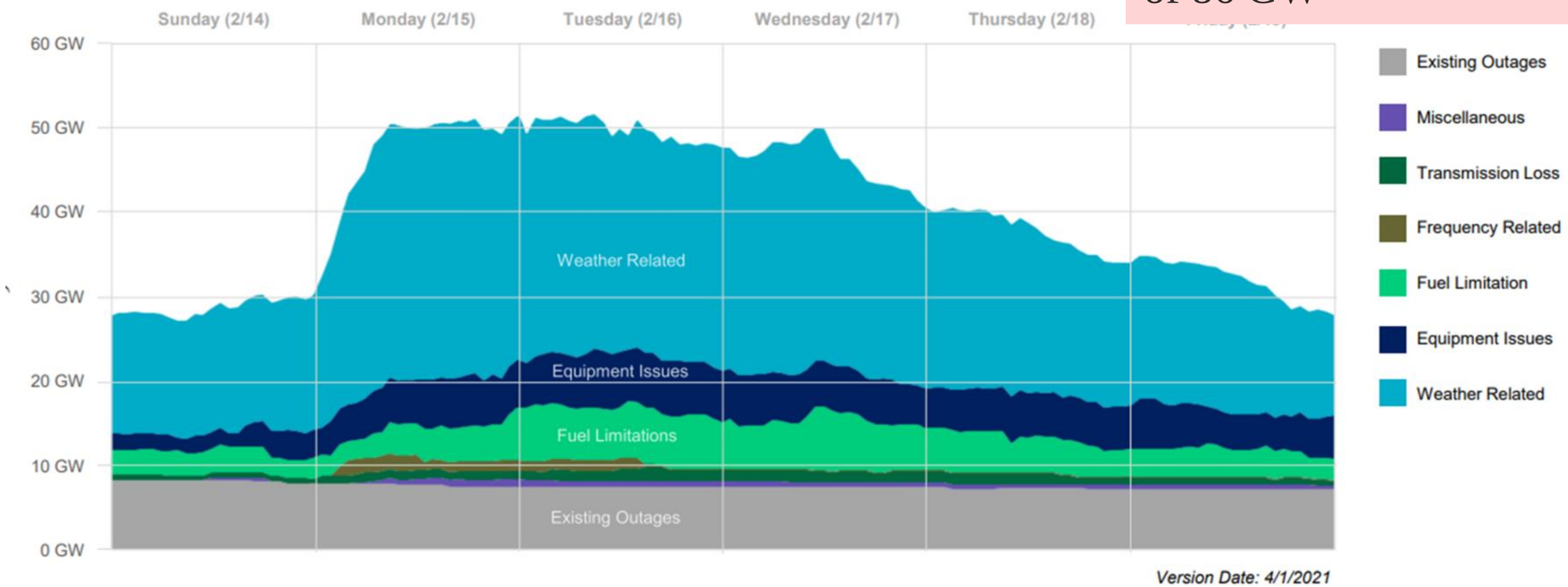
ERCOT Frequency, Feb 15, 2021



How Much Generation was Lost?

Total Winter capacity of 83 GW and Summer 2021 capacity of 86 GW

Net Generator Outages and Derates by Cause (MW)
February 14 – 19, 2021



Net generator outages at the beginning of each hour on February 14-19, 2021, by cause category.

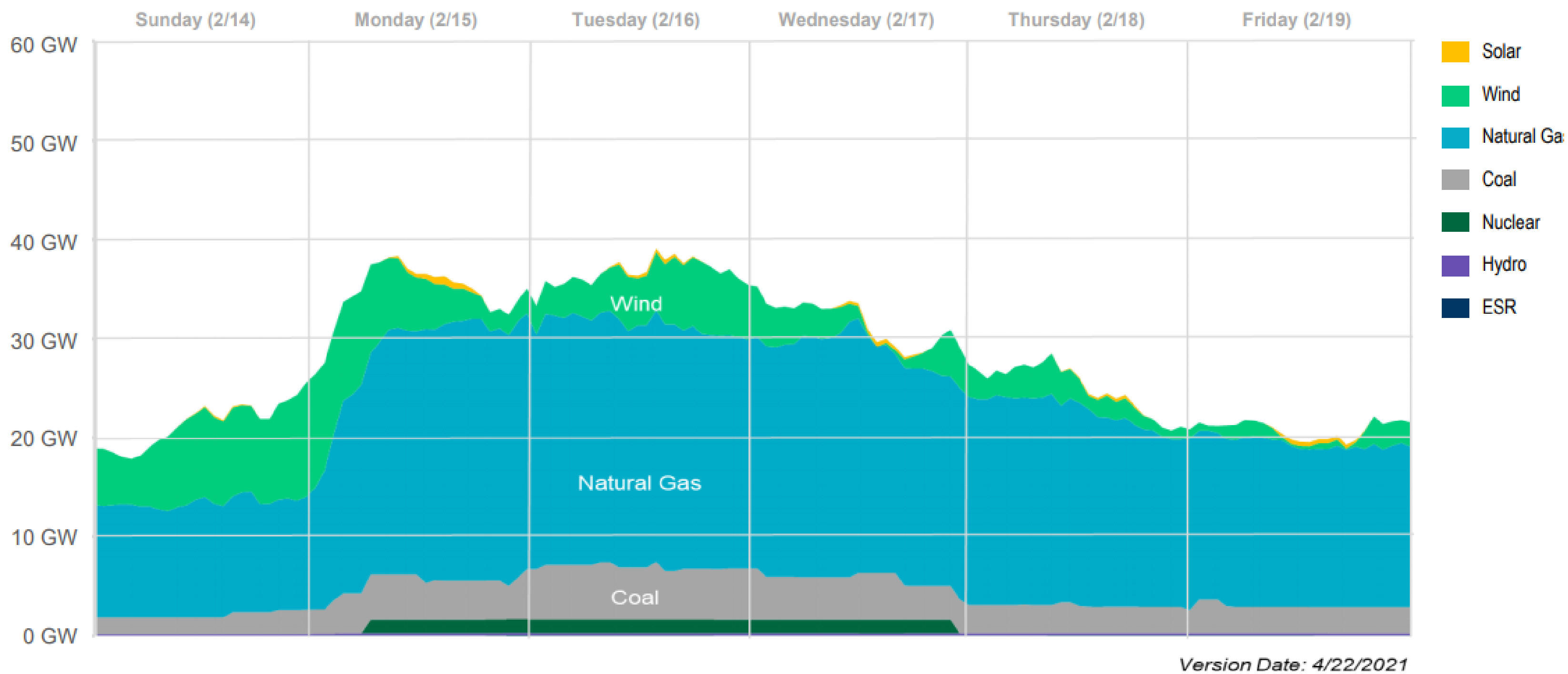
ercot

PUBLIC 4

A|M

Lost Generation by Fuel Type

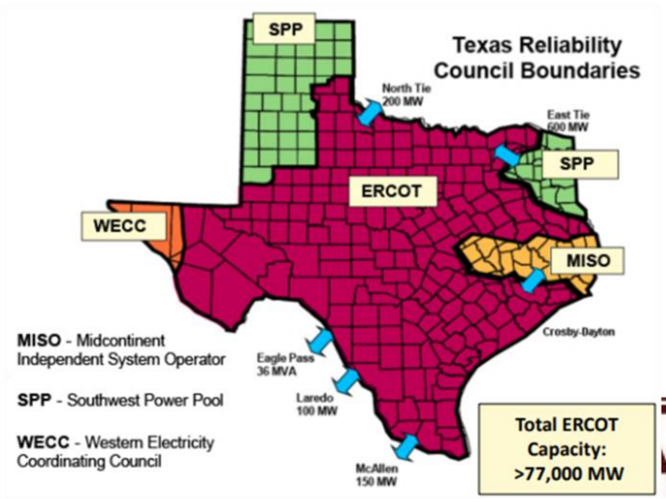
Net Generator Outages and Derates by Fuel Type (MW)



Wind and solar MW values based on estimated lost output due to outages and derates from slides 15 and 16.

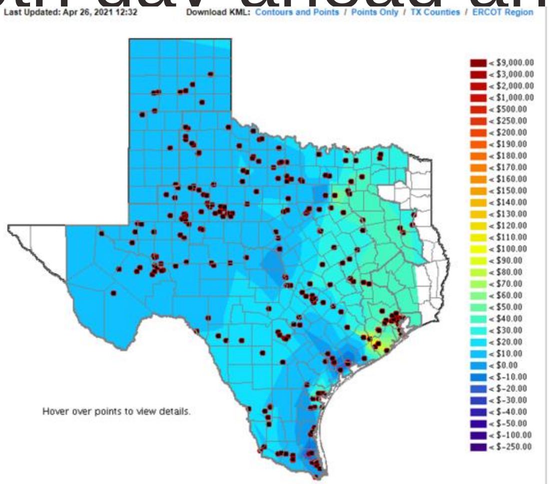
Why is ERCOT Separate?

- ERCOT operates asynchronous from the rest of North America, but has high voltage dc (HVDC) ties with the Eastern Interconnect and Mexico
- The advantage is ERCOT avoids some federal regulation. The legal basis for this is complex, based on the US Constitution, the Federal Power Act, the 5/4/76 midnight connection, other legislation, court rulings, and FERC decisions



Why Were Electric Prices High?

- In ERCOT, like much of the rest of the country, electricity is priced using a locational marginal price (LMP) market, that has both day-ahead and real-time markets
  - The price of electric varies by location and time of day
- Usually the price is relatively low at say $30/MWh



- It had been capped at $9000/MWh but this was lowered in March 2021 to $2000/MWh
  - Operating for days at price was considered unlikely!

What about Summer 2021?

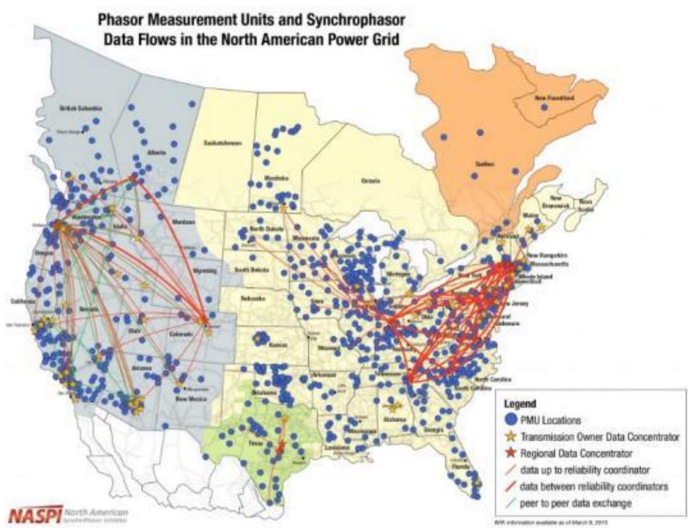
- On April 14 ERCOT reported tight grid conditions because of lots of generator outages and low wind/solar, but did not call for energy conservation
- News articles on April 15 reported there could be shortages this summer, but much of this was due to ERCOT studying more severe scenarios (high economic growth, drought, low solar and generation generation)
- With a more traditional approach the forecasted peak is 77 GW and generation capacity of 87 GW
  - The reserve margin during summer 2021 should be higher than in 2020 or 2019

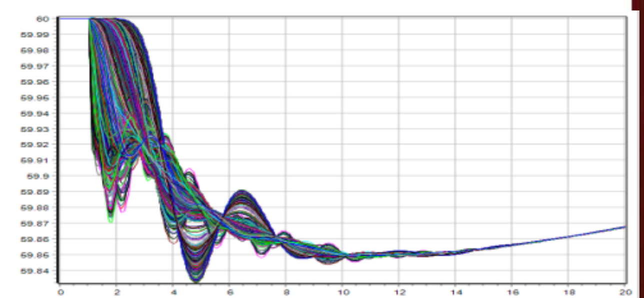
Visualization Overview

- Presentation focuses on wide-area electric grid visualization
- Grids are getting increasingly complex, particularly with many more automatic controls, and there is a concern about whether anybody fully really knows what's going on
- How data is transformed into actionable information is a crucial, yet often unemphasized, part of the software design process
- Focus here is more on visualization for engineers, as opposed to operators

Examples of Power System "Big Data"

- Power system operations and planning are a rich source of data
  - SCADA has traditionally provided a grid data at scan rates of several seconds
  - Thousands of PMUs are now deployed providing data at 30 times per second
  - In planning many thousand of studies are now routinely run, with a single transient stability run creating gigabytes





A Specific Example: One Dynamics Study

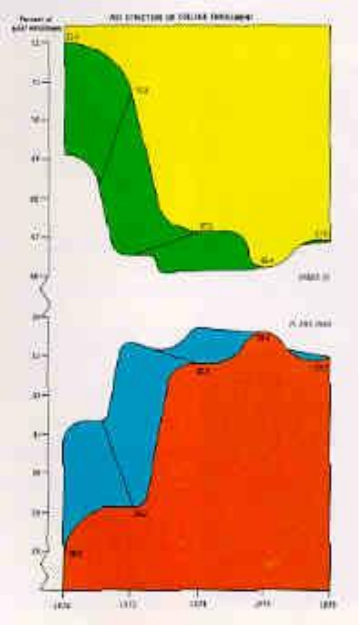
- One of our projects is looking at dynamic aspects of an ac interconnection of the Eastern Interconnect and the WECC
- We're doing lots of dynamic simulations (some 30 seconds, soon to be much longer)
- The Model has 110,000 buses, 244 different types of dynamic models, 48,000 model instances and 194,000 states
- A human factors challenge in doing a study is for the engineer to know what happened

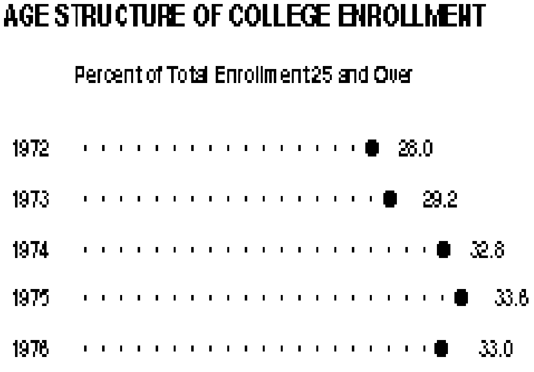
Visualization Software Design

- Key question: what are the desired tasks that need to be accomplished?
  - Needs for real-time operations might be quite different than what is needed in planning
- Understanding the entire processes in which the visualizations are embedded is key
- Software should help humans make the more complex decisions, i.e., those requiring information and knowledge
  - Enhance human capabilities
  - Alleviate their limitations (adding up flows into a bus)

Visualization Cautions!

- Just because information can be shown graphically, doesn't mean it should be shown
- Three useful design criteria from 1994 EPRI visualization report:
  1. Natural encoding of information
  2. Task specific graphics
  3. No gratuitous graphics





Tufte: "may well be worst graphic ever"

Source: E. Tufte, The Visual Display of Quantitative Information, Graphics Press, Cheshire, CT, 1983.

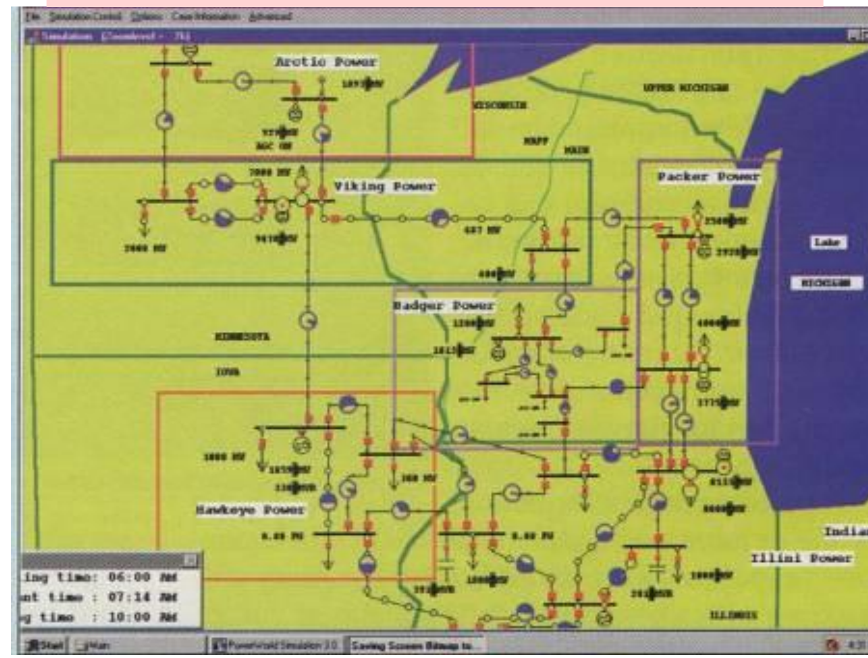
Synthetic Models and Visualization

- Access to actual power grid models is often restricted (CEII), and this 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 with other researchers, and even presenting results can be difficult
- A solution is to create entirely synthetic (fictitious) models the mimic characteristics of actual models
  - Kudos to the US DOE ARPA-E for funding work over the last five years in this area

Early Synthetic Grids

- Synthetic electric grids are models of electric grids that do not represent any actual electric grid

A pseudo-geographic grid



A non-geographic grid

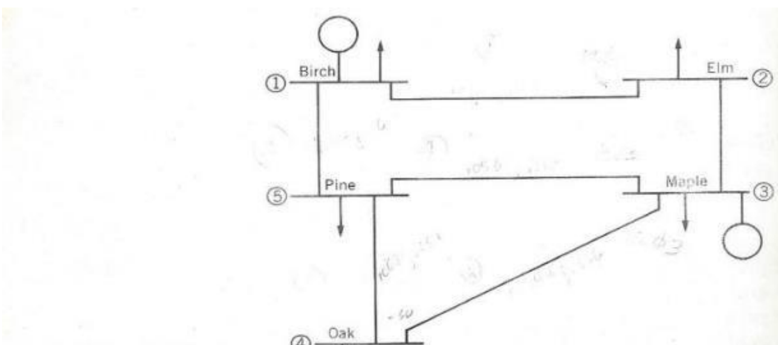


Figure 8.1 One-line diagram for Example 8.1.

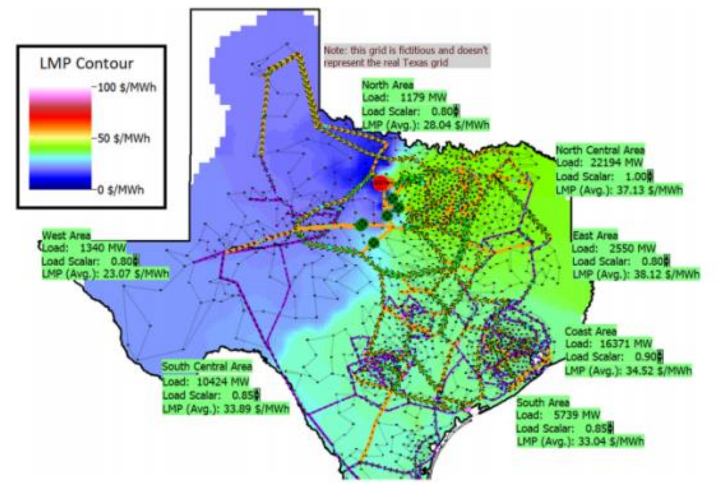
Left Image Source: W.D. Stevenson, *Elements of Power Systems*, Fourth Edition, McGraw-Hill Book Company New York, 1982 (the first edition was in 1955)

Synthetic Models Used Here

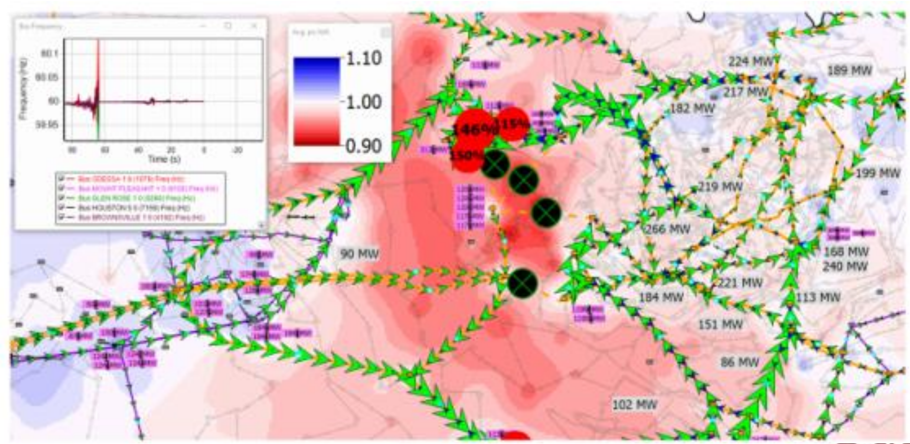
- Examples presented here will be based on either a 42-bus grid, a 2000-bus synthetic grid covering the ERCOT footprint, or an 80,000-bus synthetic grid modeling separate US east and west grids combined by a few ac interties
- All grids have embedded geographic coordinates
- The inclusion of geographic coordinates in actual electric grid models has increased rapidly over the last few years, driven in part by their requirement for geomagnetic disturbance (GMD) impact studies

2000 Bus Texas Synthetic Grid

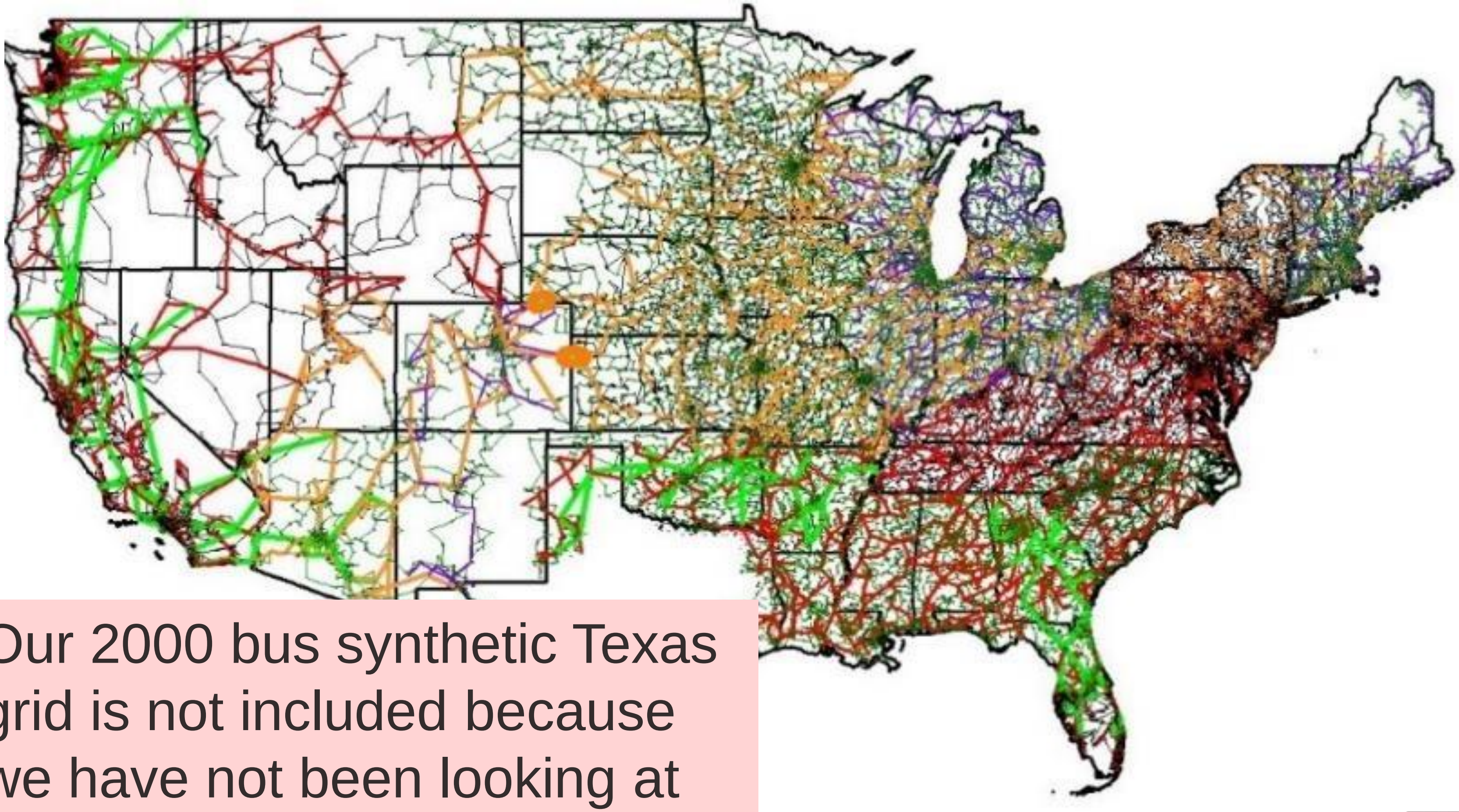
- This fictional grid, which has 2000 buses, is designed to serve a load similar to the ERCOT load with a similar geographic distribution
  - The grid was designed using a 500/230/161/115 kV transmission to be different from the actual grid
  - Public generator information is used



6. Diagram display for optimal power flow lab on the fictitious synthetic 2000-bus system. Green fields provide controls for the load scalar in seven of th
m areas, and report the average LMP for these areas. The background contour [45] shows that the locational marginal prices.



80,000 Bus Synthetic Grid for East-West Interconnection Studies



Our 2000 bus synthetic Texas grid is not included because we have not been looking at an ac intertie for Texas

Decision Making, Data, Information, Knowledge

- Ultimate goal is to help humans make better decisions
- Competing definitions for the process of taking raw “data” and producing something useful
  - Understanding, decisions, wisdom
- Data: symbols, raw, it simply exists
- Information: Data that is given meaning, often in a relational context; some how processed
- Knowledge: Application of information to answer “how.” Connecting patterns.
- Understanding, and/or wisdom at top

Understanding the Entire Process is Key

- Understanding the entire processes in which the visualizations are embedded is key.
  - What is the “information access” cost?
  - How will the information be used and shared?
  - Is it raw data, or derived values?
  - Should the visualizations sit on top of a model, or is a standalone process sufficient?
  - Ultimately, what are the desired tasks that need to be accomplished?
- We’ll start with a brief coverage of some traditional approaches (tabular, graphs and onelines, then go into some newer ones)

Example: Tabular Displays

- In many contexts, tabular displays (particularly with interactive features such as sorting, filtering, drill-down, and the ability to enter data) can be a great way to show data

	Number	Area Name	Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num	Zone Name	Zone Num
1	1001	Far West	ODESSA 2 0	115.00	0.98089	112.802	-30.18	20.78	5.89				0.00	0.00	1	Far West T	9
2	1002	Far West	PRESIDIO 2 0	115.00	1.01218	116.400	-24.75	15.41	4.37				0.00	0.00	1	Far West T	9
3	1003	Far West	O DONNELL 1	115.00	1.00832	115.956	-25.02						0.00	0.00	1	Far West T	9
4	1004	Far West	O DONNELL 1	230.00	1.01000	232.301	-26.84			158.25	-29.07		0.00	0.00	1	Far West T	9
5	1005	Far West	BIG SPRING 5 (	115.00	1.00790	115.908	-22.77						0.00	0.00	1	Far West T	9
6	1006	Far West	BIG SPRING 5	13.80	1.00147	13.820	-20.60			25.73	-4.94		0.00	0.00	1	Far West T	9
7	1007	Far West	VAN HORN 0	115.00	1.01973	117.268	-25.10	7.01	1.99			0.00	0.00	0.00	1	Far West T	9
8	1008	Far West	IRAAN 2 0	115.00	1.00133	115.153	-13.78						0.00	0.00	1	Far West T	9
9	1009	Far West	IRAAN 2 1	13.80	1.00000	13.800	-10.41			61.87	-2.55		0.00	0.00	1	Far West T	9
10	1010	Far West	PRESIDIO 1 0	115.00	1.01933	117.223	-23.46					0.00	0.00	0.00	1	Far West T	9
11	1011	Far West	PRESIDIO 1 1	22.00	1.01958	22.431	-22.12			7.50	0.00		0.00	0.00	1	Far West T	9
12	1012	Far West	SANDERSON (	115.00	0.98899	113.734	-29.67	2.99	0.85			9.29	0.00	0.00	1	Far West T	9
13	1013	Far West	MONAHANS 2	115.00	1.00167	115.192	-21.95	29.23	8.28				0.00	0.00	1	Far West T	9
14	1014	Far West	GRANDFALLS (	115.00	1.00324	115.373	-18.04	2.22	0.63				0.00	0.00	1	Far West T	9
15	1015	Far West	MARFA 0	115.00	1.02132	117.451	-24.87	7.51	2.13				0.00	0.00	1	Far West T	9
16	1016	Far West	GARDEN CITY (	115.00	1.01758	117.022	-21.94	2.89	0.82			31.06	0.00	0.00	1	Far West T	9
17	1017	Far West	ODESSA 4 0	115.00	0.98205	112.936	-28.53	18.34	5.20				0.00	0.00	1	Far West T	9
18	1018	Far West	NOTREES 0	115.00	0.99128	113.997	-27.25	0.07	0.02				0.00	0.00	1	Far West T	9
19	1019	Far West	MIDLAND 4 0	115.00	1.00078	115.090	-29.70	61.78	17.50			143.20	0.00	0.00	1	Far West T	9
20	1020	Far West	BIG SPRING 1 (	115.00	1.02190	117.519	-21.73					80.13	0.00	0.00	1	Far West T	9
21	1021	Far West	BIG SPRING 1	13.80	1.00000	13.800	-15.11			149.63	-25.59		0.00	0.00	1	Far West T	9
22	1022	Far West	O DONNELL 2	115.00	1.01132	116.302	-24.18						0.00	0.00	1	Far West T	9
23	1023	Far West	O DONNELL 2	13.80	1.01000	13.938	-15.27			135.00	3.21		0.00	0.00	1	Far West T	9
24	1024	Far West	ODESSA 6 0	115.00	0.99425	114.338	-26.17	63.04	17.86				0.00	0.00	1	Far West T	9
25	1025	Far West	BIG SPRINGS 0	115.00	1.01805	117.076	-20.73						0.00	0.00	1	Far West T	9
26	1026	Far West	BIG SPRINGS 1	13.80	1.00000	13.800	-11.21			93.15	-4.41		0.00	0.00	1	Far West T	9
27	1027	Far West	MIDLAND 2 0	115.00	1.01258	116.447	-32.98	101.21	28.68			76.90	0.00	0.00	1	Far West T	9
28	1028	Far West	COAHOMA 0	115.00	1.01371	116.577	-25.80	10.01	2.84				0.00	0.00	1	Far West T	9
29	1029	Far West	MIDLAND 3 0	115.00	1.00868	115.998	-31.93	83.18	23.57			40.70	0.00	0.00	1	Far West T	9

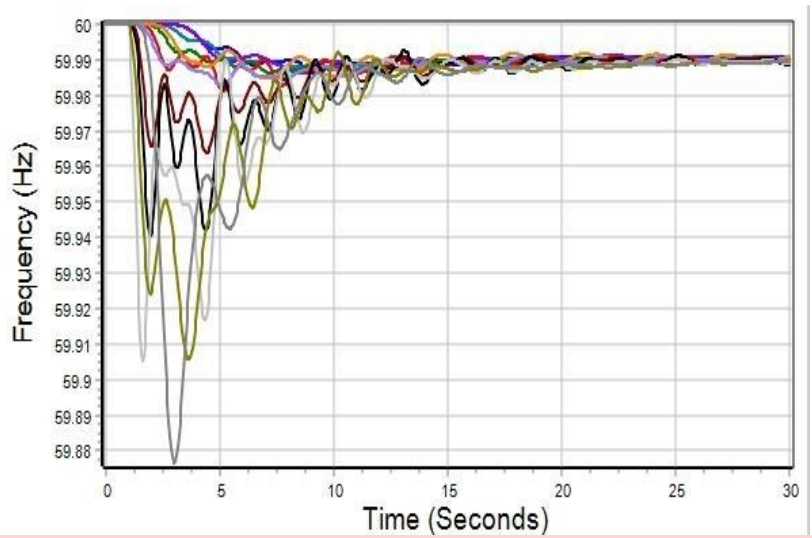
Use of Color

- Some use of color can be quite helpful
  - 10% of male population has some degree of color blindness (1% for females)
- Do not use more than about ten colors for coding if reliable identification is required
- Color sequences can be used effectively for data maps (like contours)
  - Grayscale is useful for showing forms but not values
  - Multi-color scales (like a spectrum) have advantages (more steps) but also disadvantages (effectively comparing values) compared to bi-color sequences

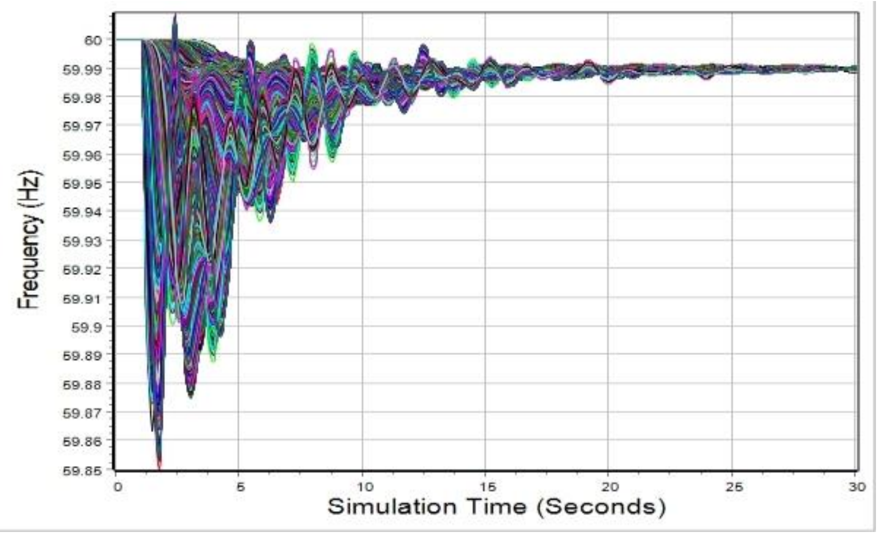
The book by Colin Ware is a great resource

Graphs

- Graphs are also a great way to show information, particularly for time-variation
- The number of curves needs to match the task

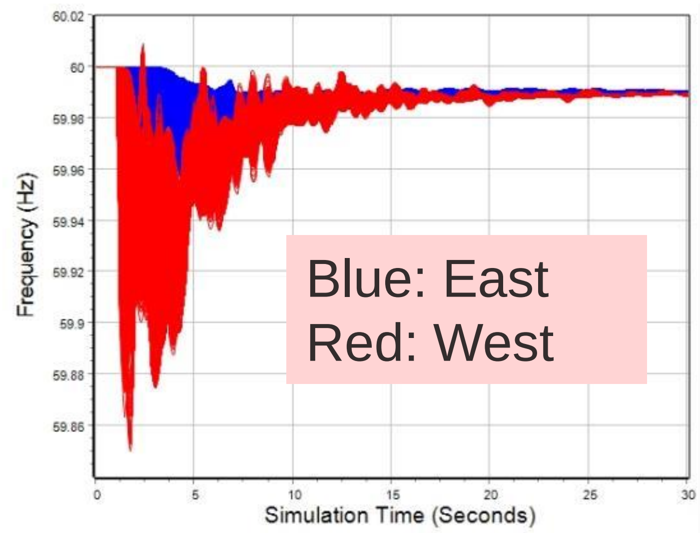


A few curves, detail of each visible, key can identify objects (several thousand values)

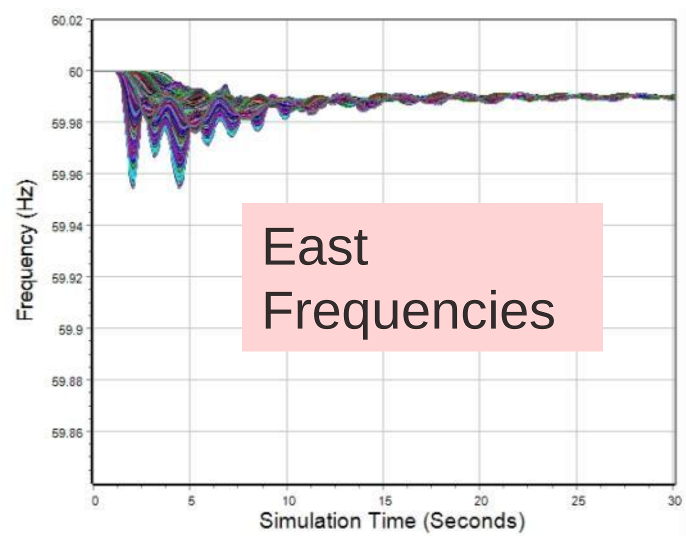


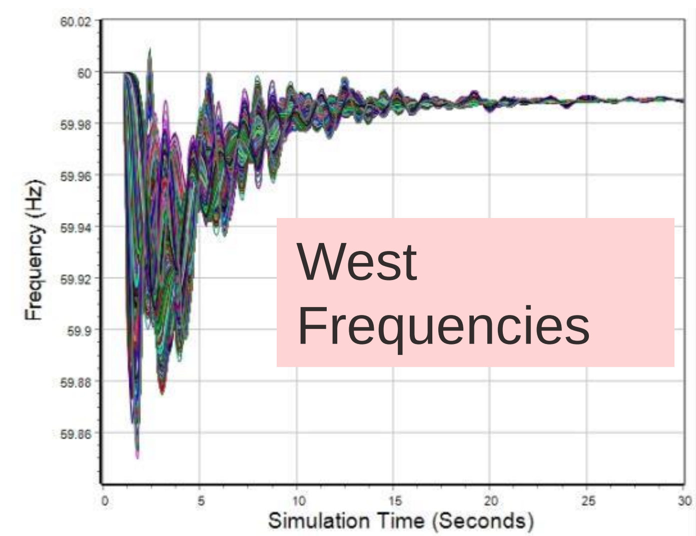
Envelope of response for the 80k bus, 40,000 substation frequencies (24 million values)

Graphs: 40,000 Substation Examples



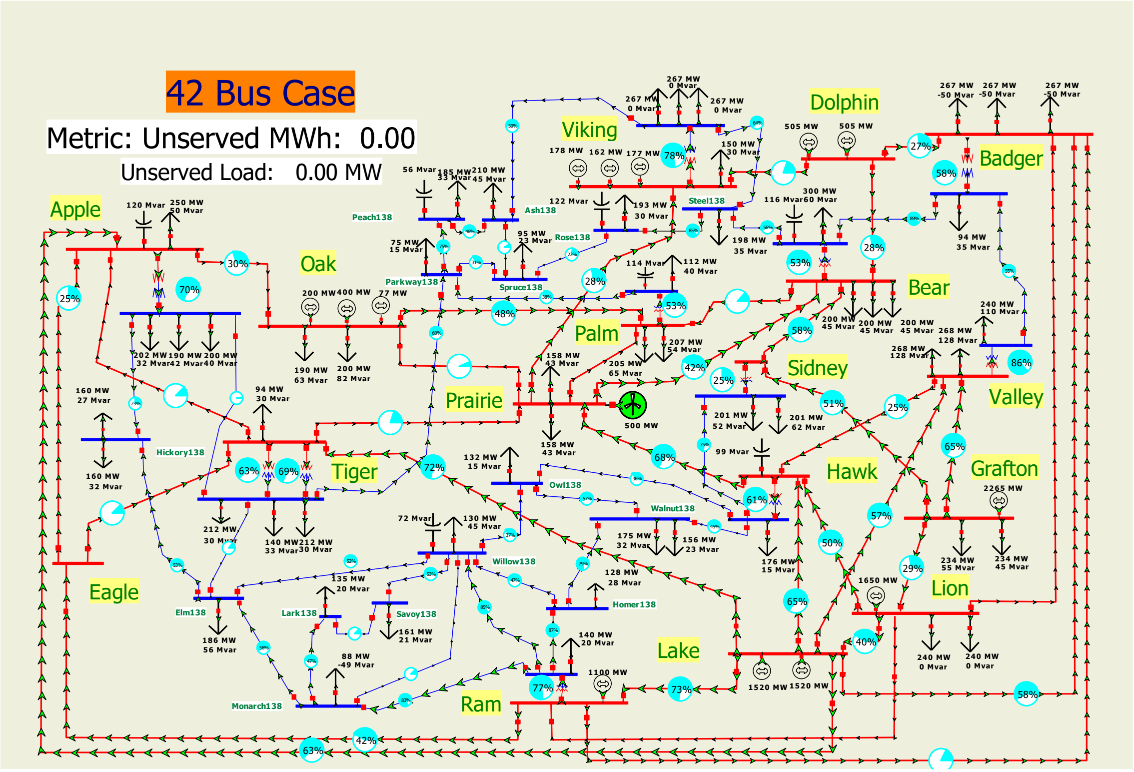
For the 40,000 substation plot, color can be helpful in showing the East response (blue) versus West (red) but the curve order matters. It is probably better to use two plots, with one for the East and one for the West (obviously using the same scale)





Onelines

- Widely used and can be quite effective for showing substations (or local regions) or smaller grids; can be slow on larger systems



Visualization Background: Preattentive Processing

- When displaying large amounts of data, take advantage of preattentive cognitive processing
  - With preattentive processing the time spent to find a “target” is independent of the number of distractors
- Graphical features that are preattentively processed include the general categories of form, color, motion, spatial position

Preattentive Processing Examples

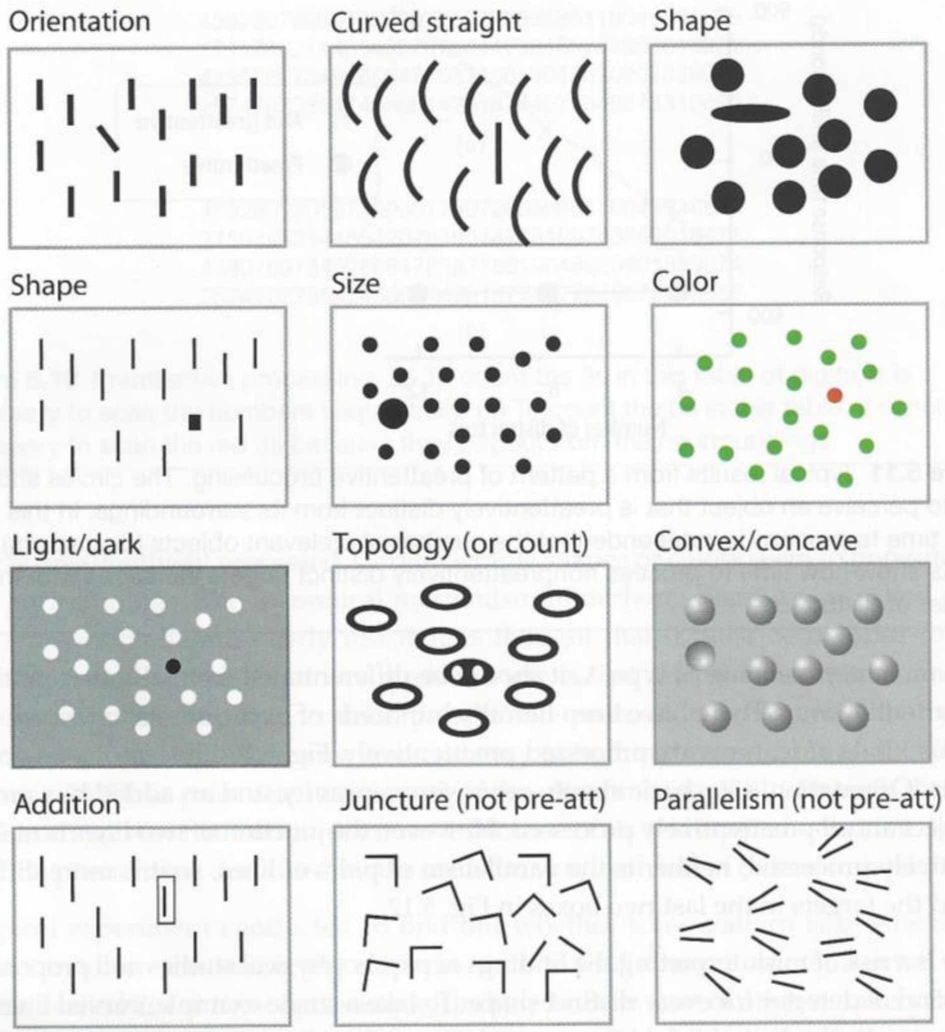
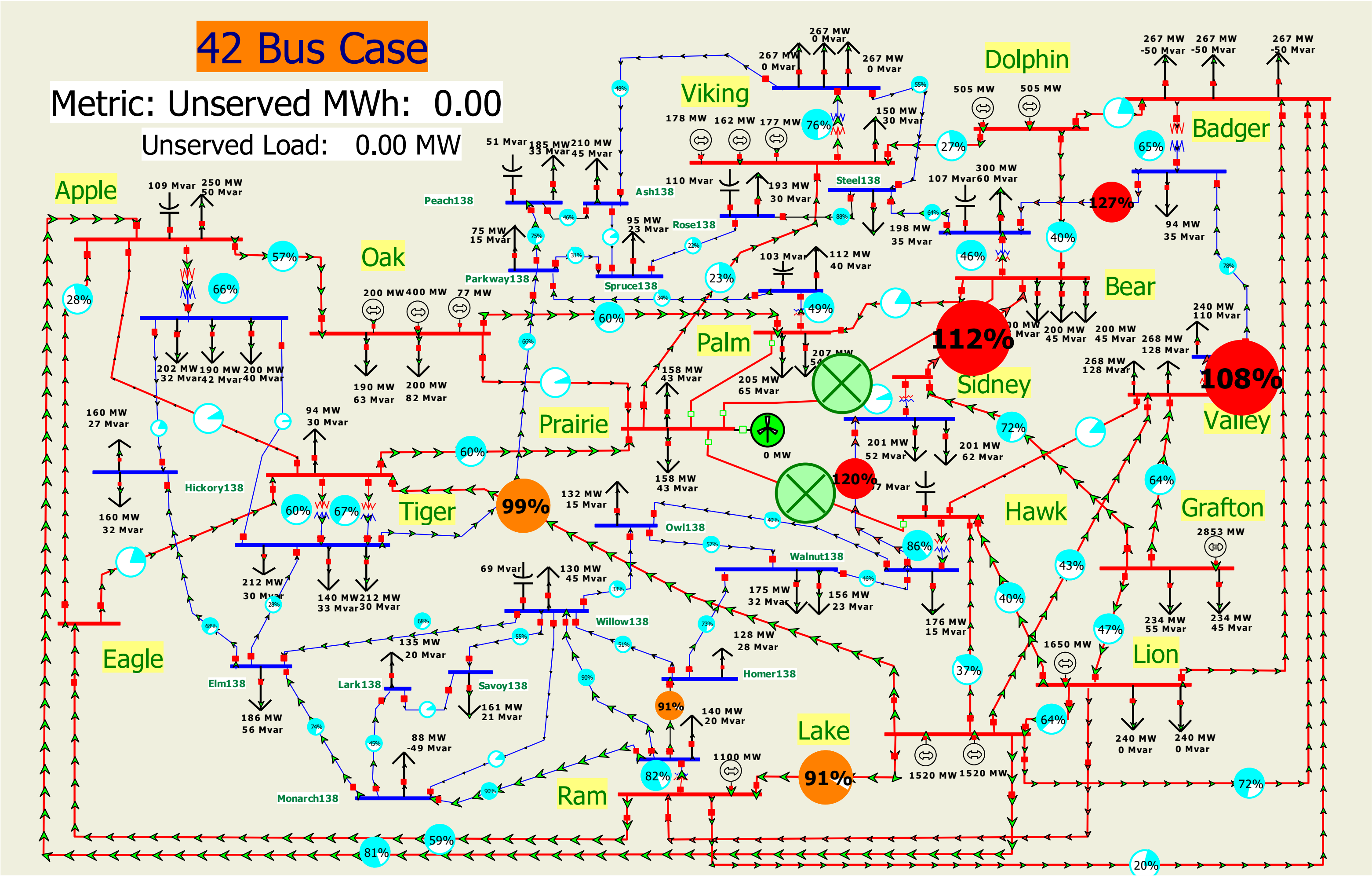


Figure 5.12 Most of the preattentive examples given here can be accounted for by the processing characteristics of neurons in the primary visual cortex.

All are preattentively processed except for juncture and parallelism; however too many can defeat their purpose

Source: *Information Visualization* (Fourth Edition) by Colin Ware, Fig 5.12

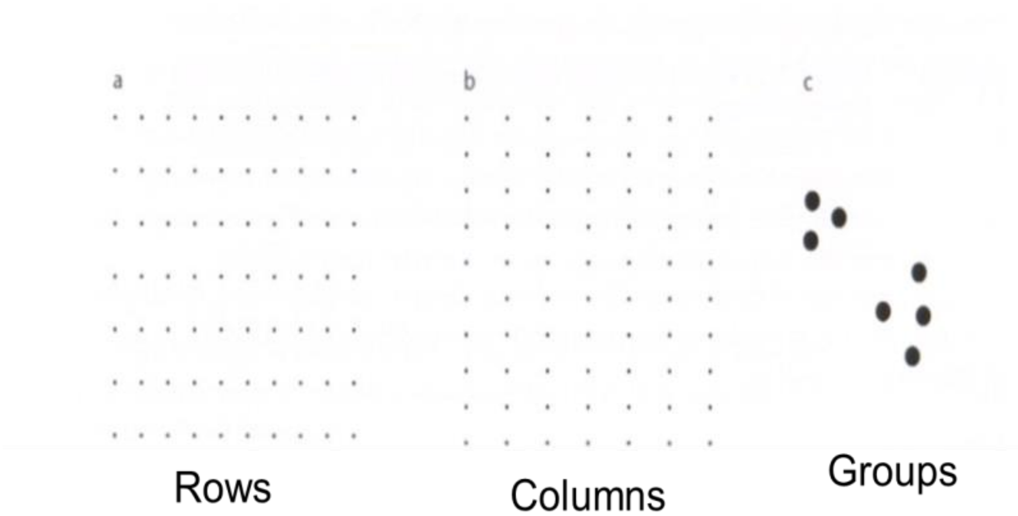
Preattentive Processing with Color & Size

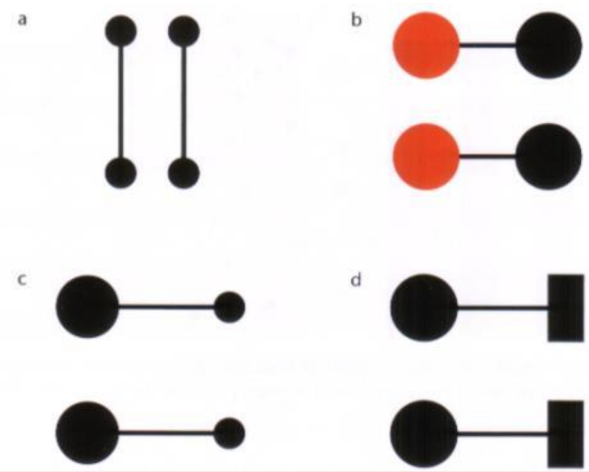


Detecting Patterns

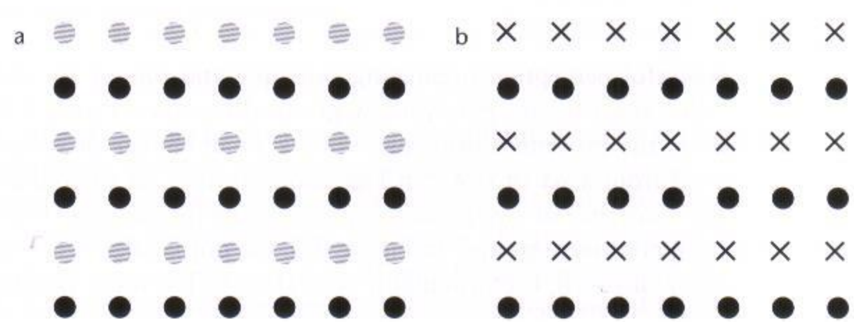
- A large portion of information visualization is associated with detecting patterns
- Gestalt (German for “pattern”) Laws
  - Proximity
  - Similarity (we didn’t discuss color)
  - Connectedness
  - Common Fate (flows)

Proximity, Similarity, Connectedness,





Connectedness is stronger than proximity, color, shape

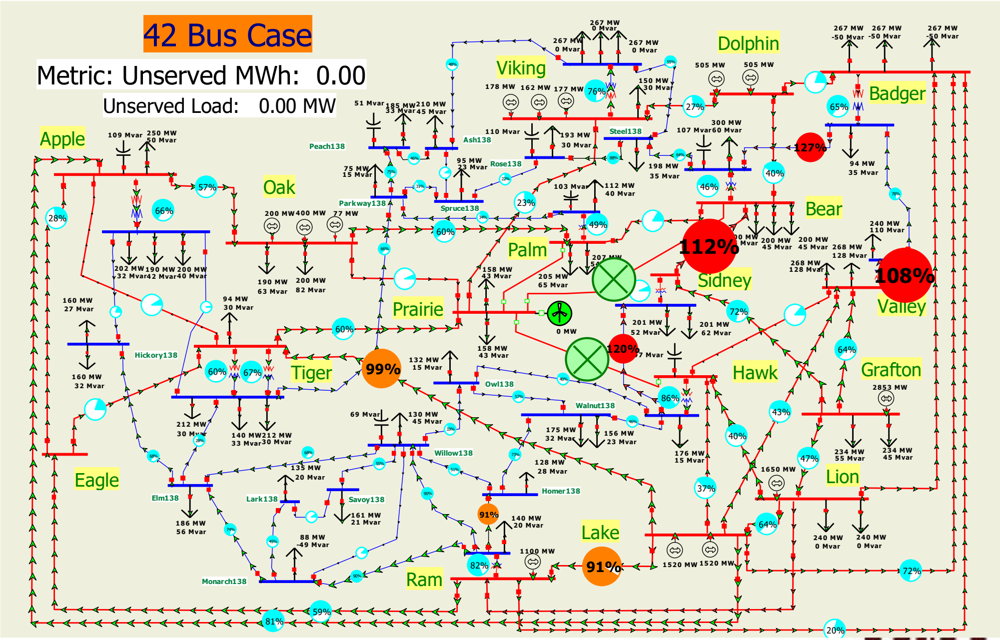


Similarity makes all perceived as rows

Source: *Information Visualization* (Fourth Edition) by Colin Ware, Chapter 6 Images

Common Fate: Patterns in Motion

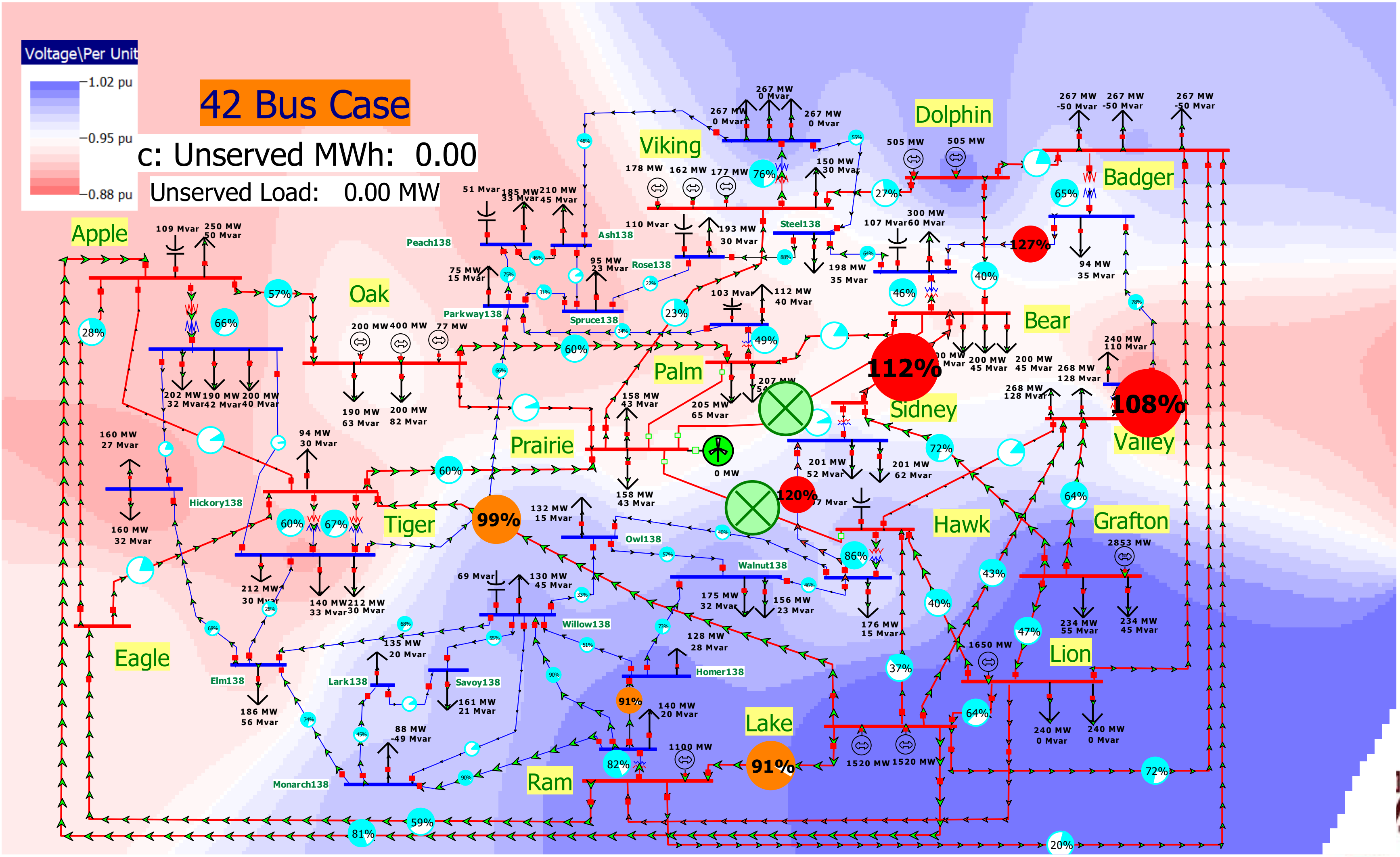
- Motion can be a very effective means for showing relationships between data
- People perceive motion with great sensitivity
- Motion can also be used to convey causality (one event causing another)
- However, too much motion can be a distractor



Scattered Data Interpolation (Colored Contouring)

- For wide-area visualization, contours can be effective for showing large amounts of spatial data
  - Takes advantage that as humans we perceive the world in patterns (sometimes even when none exist!)
  - Now widely used
- Scattered data interpolation algorithms are needed to take the discrete power system data and make it spatially continuous
  - Various algorithms can be used include a modified Shephard's and Delaunay triangulation
- A color mapping is needed

Shepard's Algorithm, Blue/Red Discrete Color mapping

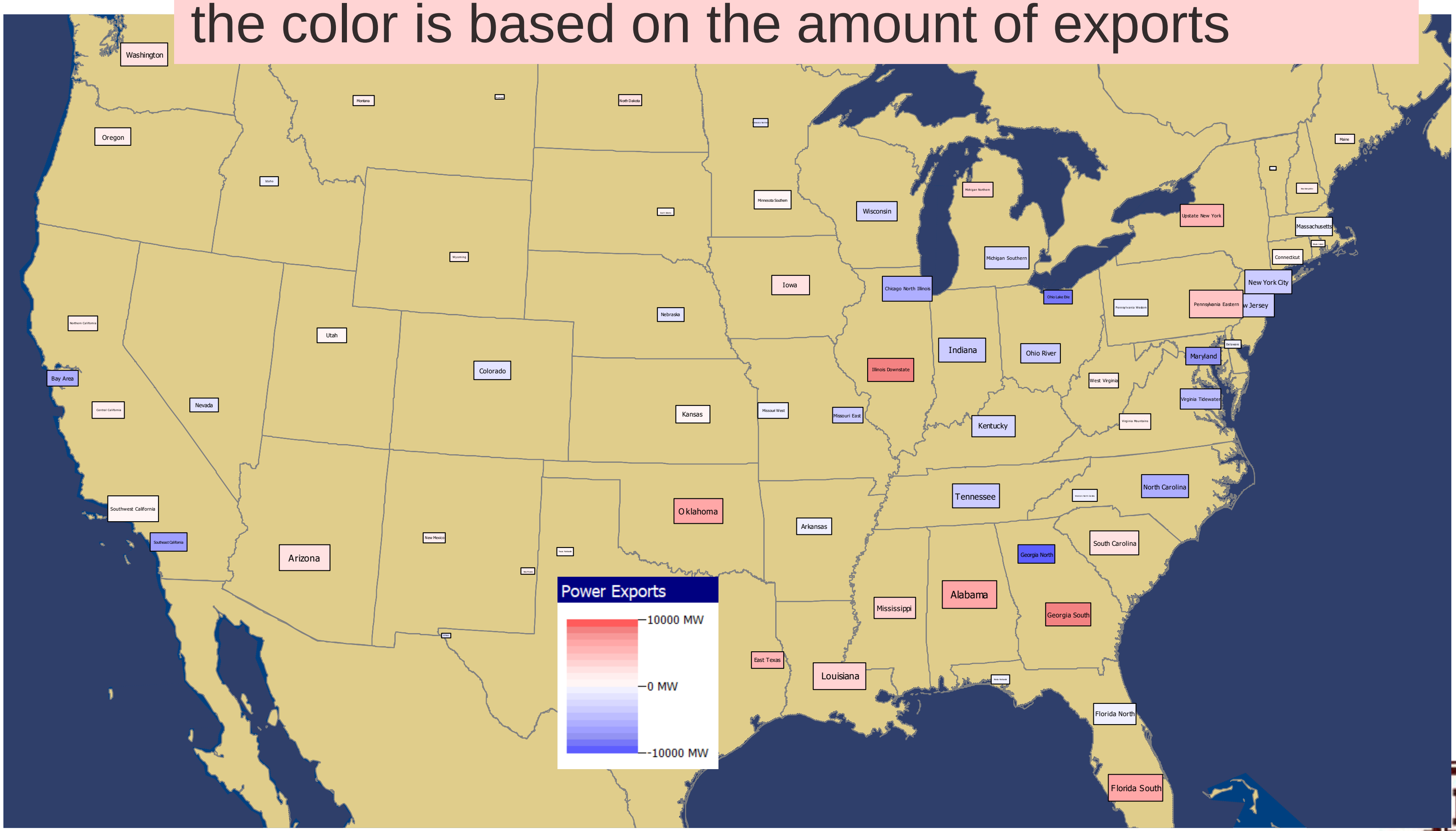


Geographic Data Views

- One way to make visualizations more interactive is to use underlying geographic information to quickly auto-create displays
  - Known as geographic data views (GDVs)
- GDVs can be used either on individual objects (like generators, buses, or substations), or on aggregate objects (like areas and zones)
- The GDV display attributes (e.g., size, color) can be used to show object data
- The GDV displays can be saved for later use and links to the underlying objects allow for drilldown

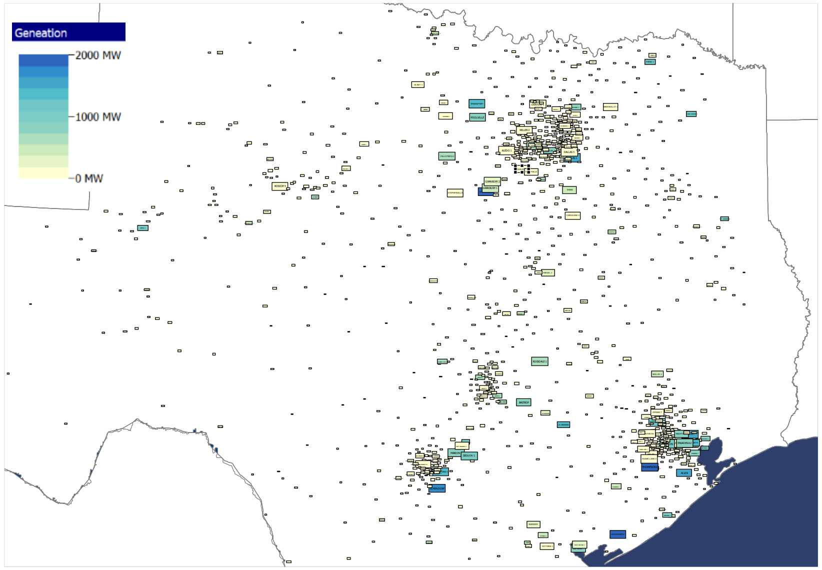
80,000 Bus System Area GDV Example

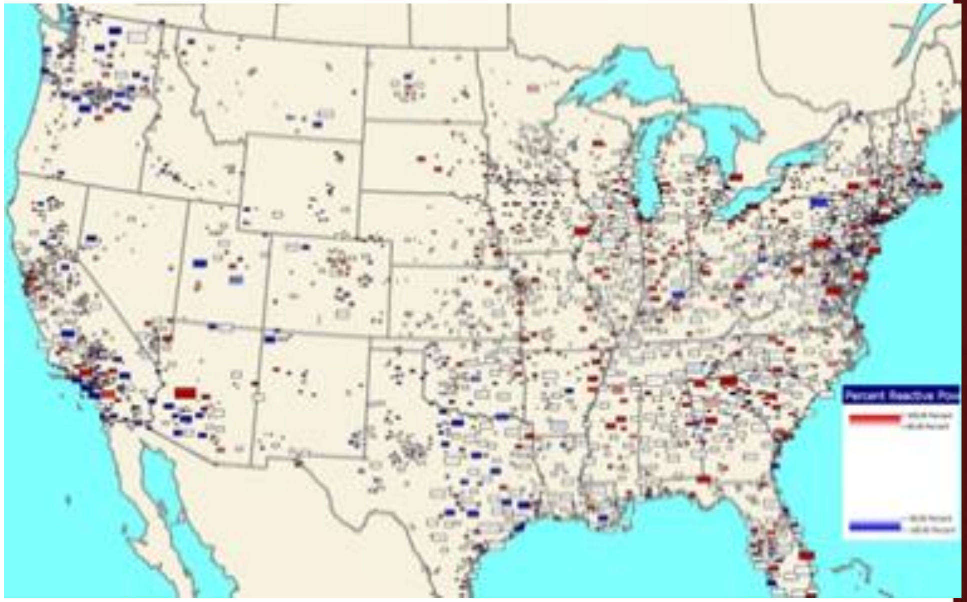
Size is proportional to the area's generation, while the color is based on the amount of exports



2K and 82K Substation GDV

Size is proportional to a substation value (MW throughput on left, generation on the right) while the color is based on the amount of substation generation (left of reactive power output on right)





Some Techniques for Dealing with Time-Varying Data

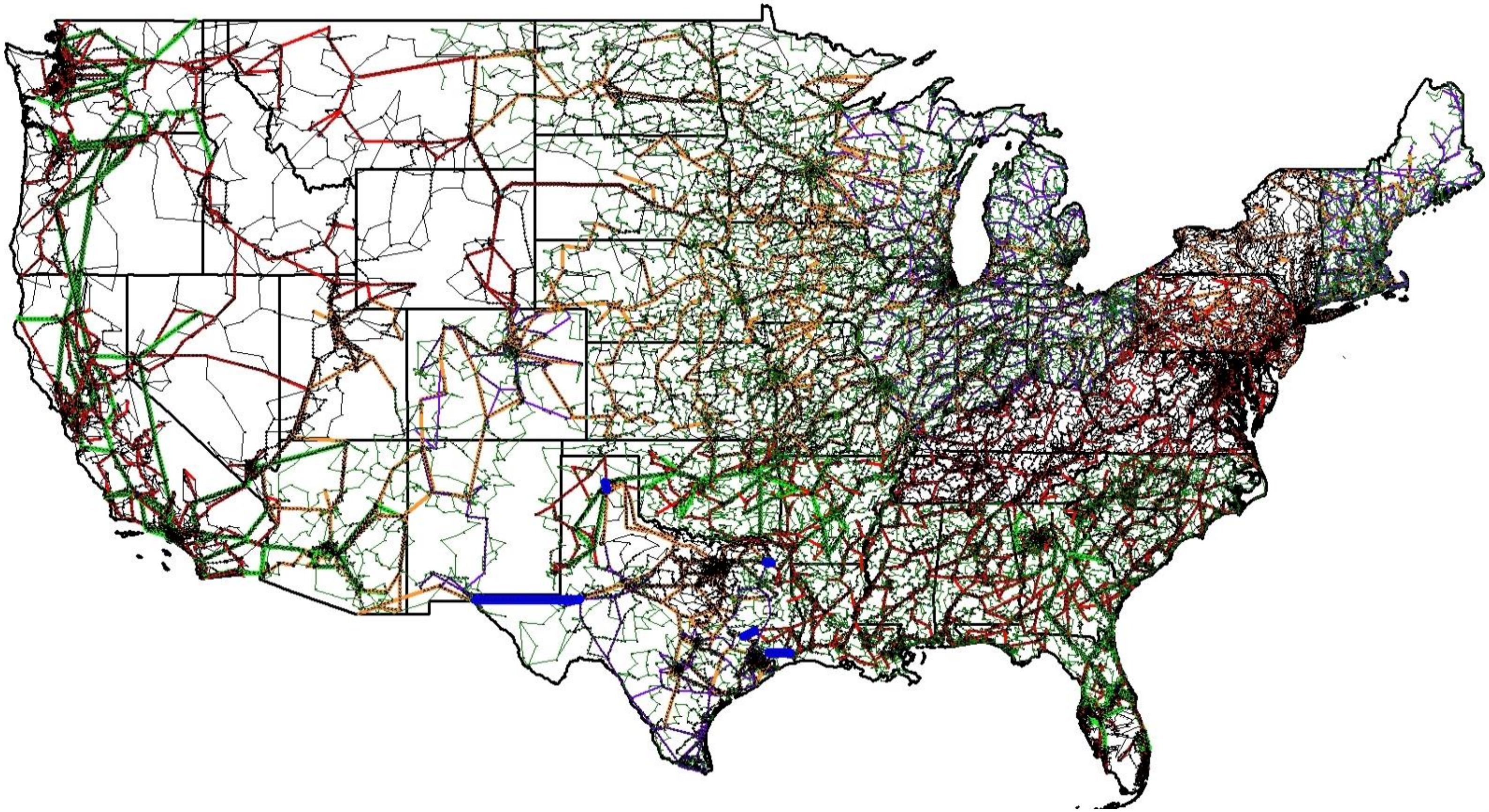
- Need to keep in mind the desired task!
- Tabular displays
- Time-based graphs (strip-charts for real-time)
- Animation loops
  - Can be quite effective with contours, but can be used with other types of data as well
- Data analysis algorithms, such as clustering, to detect unknown properties in the data
  - There is often too much data to make sense without some pre-processing analysis!

Animation loops

- Animation loops trade-off the advantages of snapshot visualizations with the time needed to play the animation loop
  - A common use is in weather forecasting
- In power systems applications the length/speed of the animation loops would depend on application
  - In real-time displays could update at either SCADA or PMU rates
  - Could be played substantially faster than real-time to show historical or perhaps anticipated future conditions

Visualizing Line Flows: Is This Display Useful

- The image shows the 82,000 bus synthetic transmission grid used in the paper.

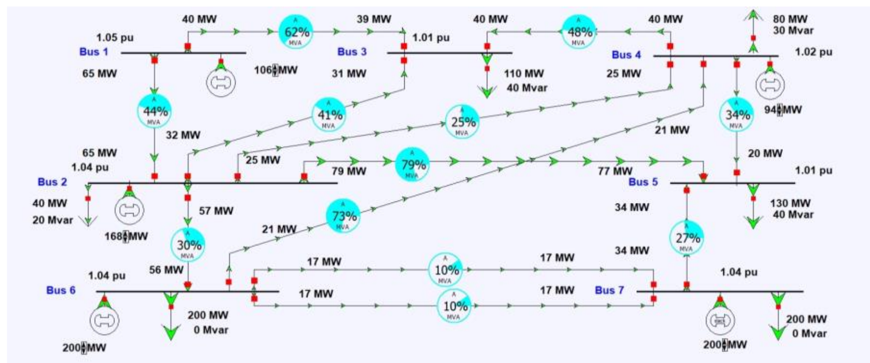


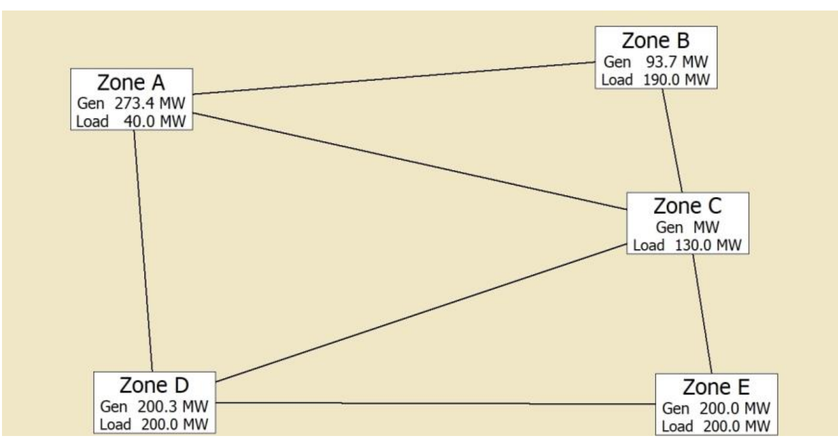
Simplifying Line Flows

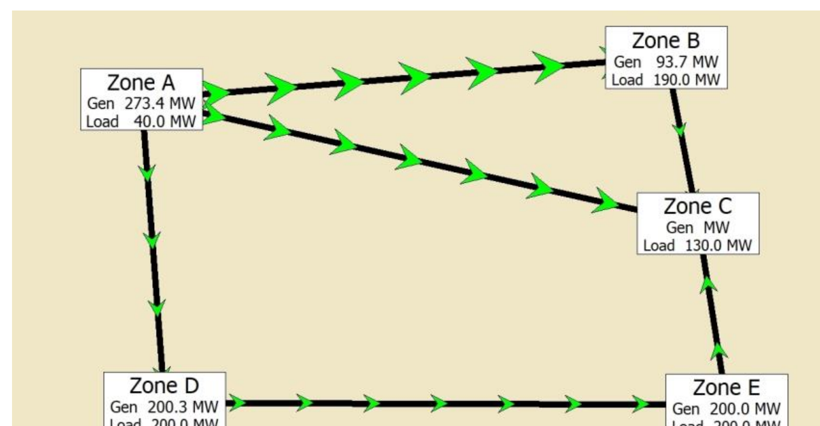
- A new technique from KPEC is an algorithm for visualizing power system flows using a Delaunay triangulation approach (giving a planar graph)
- The algorithm is simple and fast
  - Assume *n* buses, *m* bus groups and *b* branches joining the buses, with geographic info. available for buses
  - Map each branch to its terminal bus group(s)
  - Do a Delaunay triangulation of the *m* bus groups to create a set *S* of segments
  - For each branch quickly determine a segment path between its terminal bus groups adding it to the list for each segment

Seven Bus Example

- This can be illustrated with a seven bus example with five bus groups, A={1,2}, B={3,4}, C={5}, D={6}, E={7}







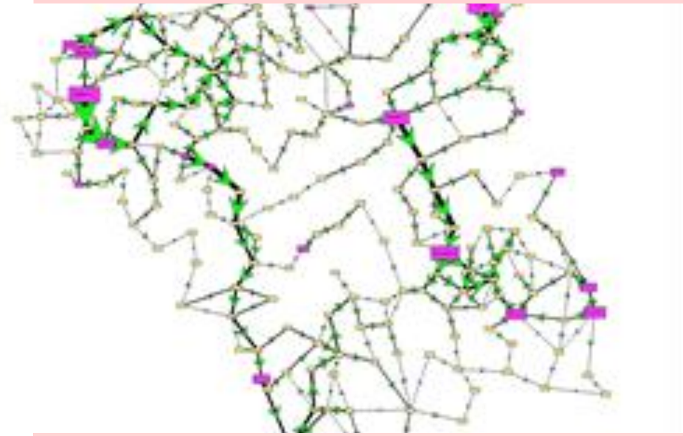
Computing Path Between Two Groups

- In general calculating the path between two bus groups is not exceptionally fast (given that is has to be applied to each branch)
- However, when the graph is based on a Delaunay triangulation paths can be calculated very quickly
- Different algorithms exist to do this
  - We've been using a Greedy Routing algorithm
- Determining the path for a branch between its terminal bus groups has three options
  1. Both ends in same group so branch is ignored
  2. Ends are in first neighbor groups so simple
  3. Use the Greedy Routing algorithm

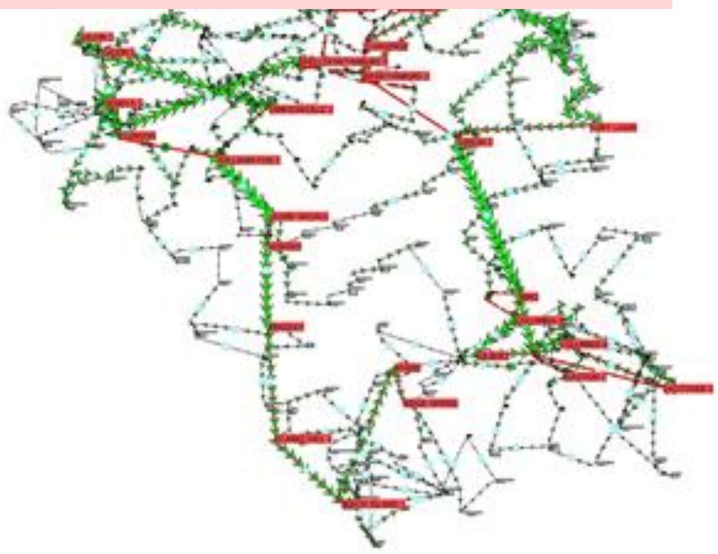
500 Bus Example

- Slide shows the original network with several intersecting branches an then two applications of the algorithm

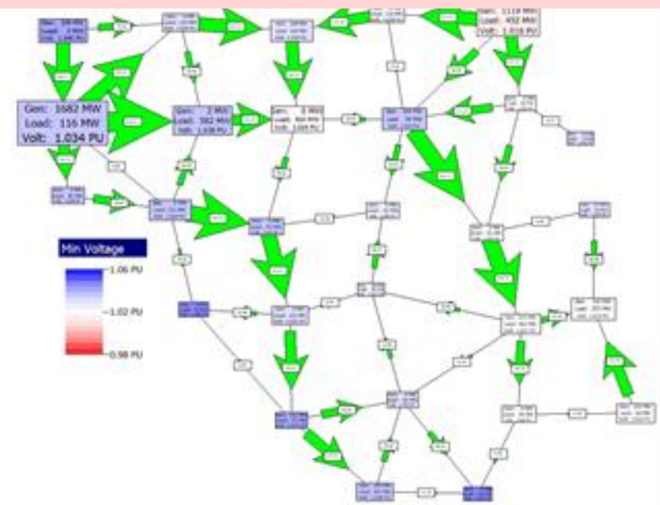
Algorithm m =208, s=311



Original System, b=599



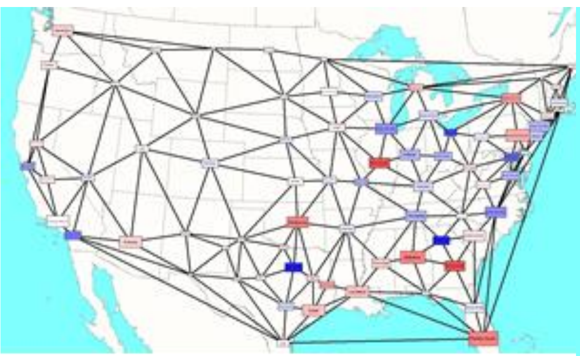
Algorithm m =28, s=49

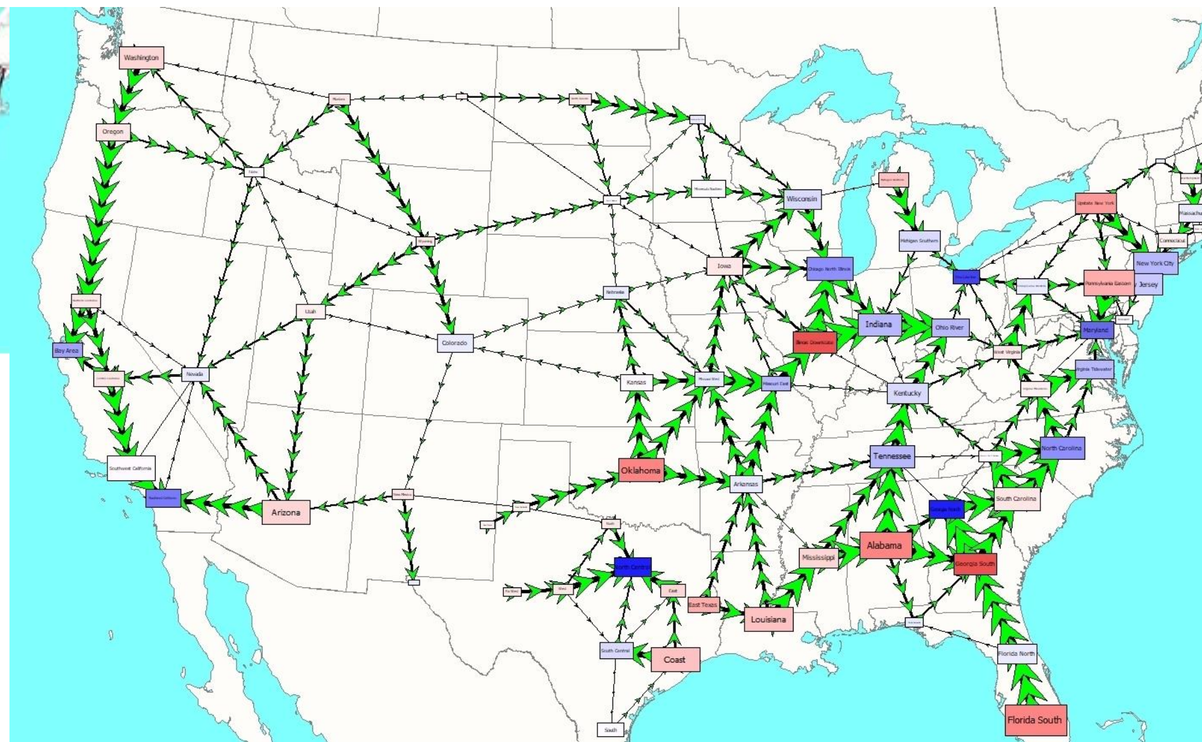


Algorithm on 82,000 Bus Grid

- In all cases for the following slides the algorithm took less than one second

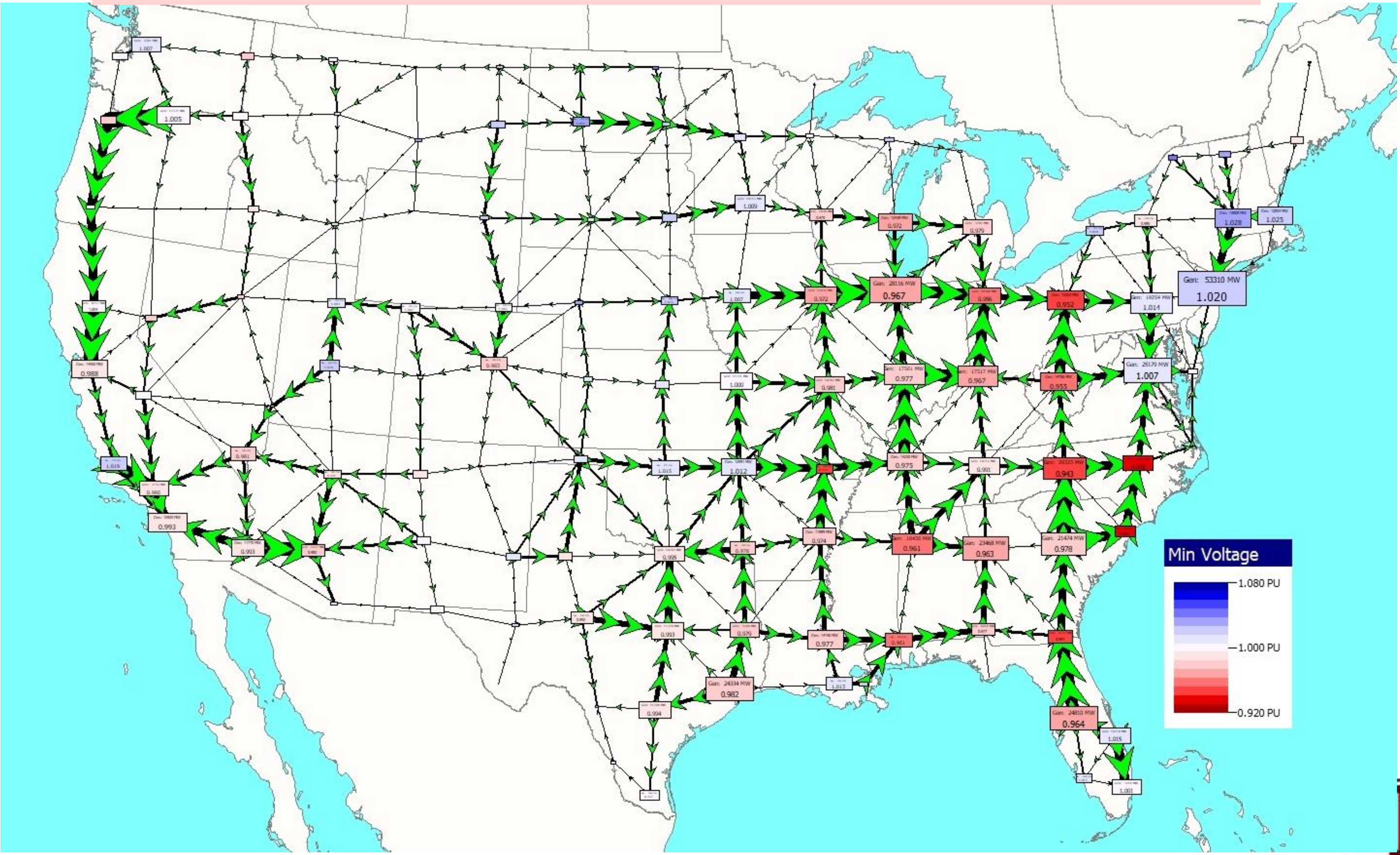
Algorithm m =76, s=114 (after removing zero branch segments)





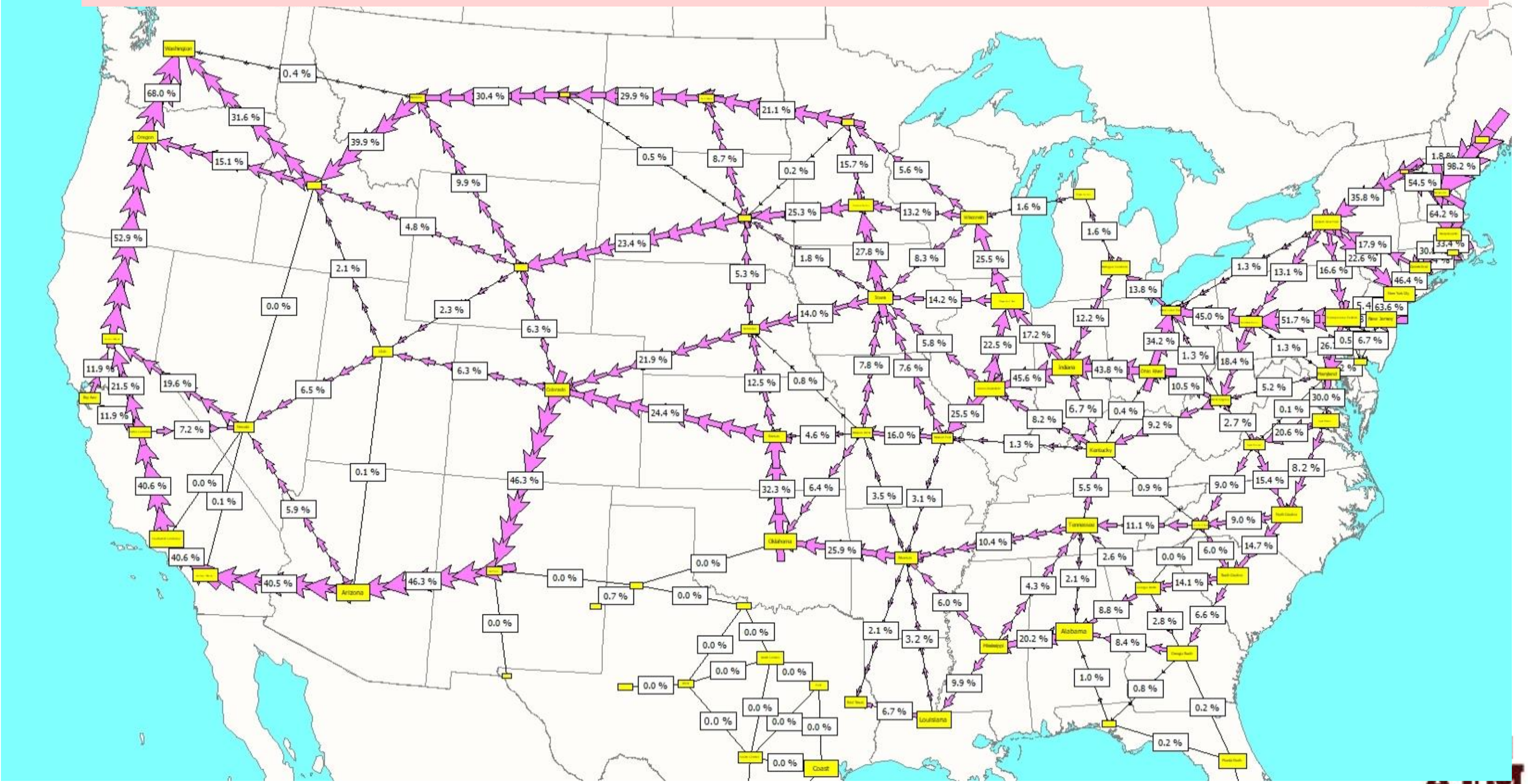
Algorithm on 82,000 Bus Grid

Algorithm using a 10 by 16 latitude/longitude grid



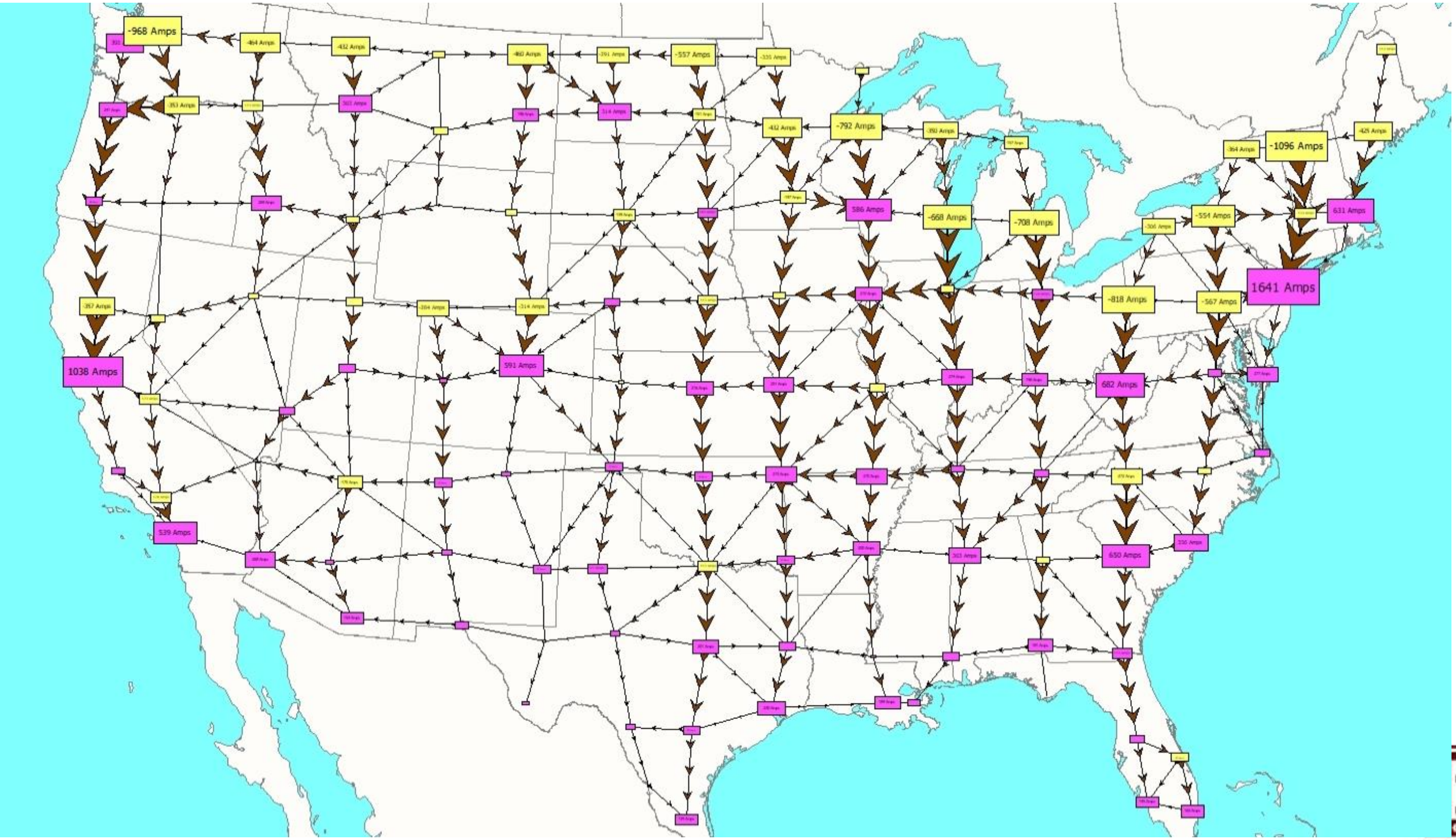
Algorithm on 82,000 Bus Grid, PTDFs

Algorithm using areas for the bus groups with labels added to show the exact PTDF values (Maine to Univ. Washington)



Algorithm on 82,000 Bus Grid, GICs

The impact of the assumed North-South electric field is readily apparent; yellow indicates GIC sources, magenta sinks

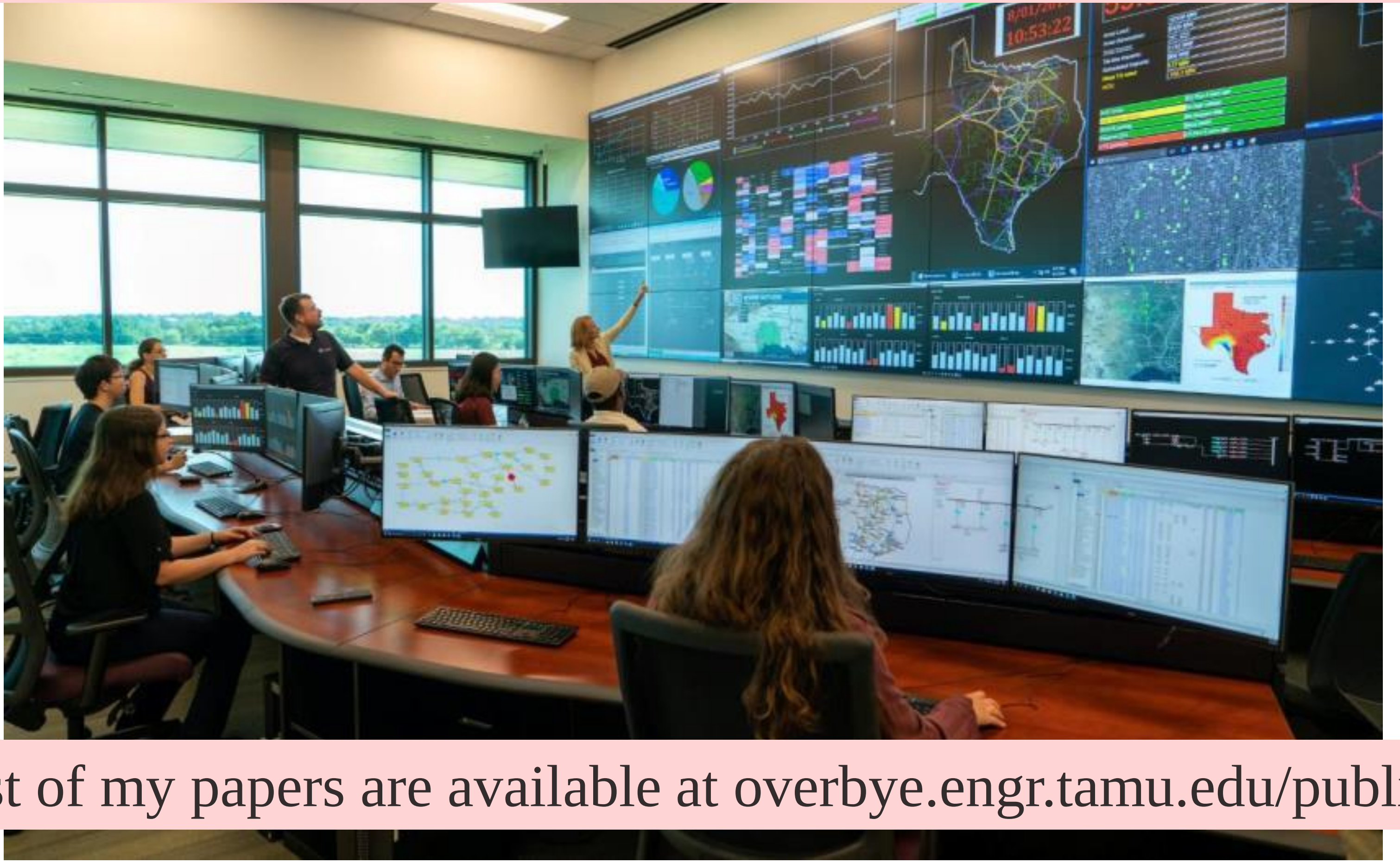


Conclusions

- We've reached the point in which there is too much data to handle most of it directly
  - Certainly the case with much time-varying data
- How data is transformed into actionable information is a crucial, yet often unemphasized, part of the software design process
- There is a need for continued research and development in this area
  - Synthetic power grid cases, including dynamics, are now emerging to provide input for this research

Thank You! Questions?

Also, please join us in person at Texas A&M for NAPS 2021 on November 14-16 in College Station, with papers due July 15, 2021



Most of my papers are available at overbye.engr.tamu.edu/publications/