ECEN 460
Power System Operation and Control
Spring 2025

Lecture 26:

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Special Guest Lecture by Sanjana Sanjana Kunkolienkar
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TEXAS A&M UNIVERSITY

Announcements

- Design project due at 9:30 am on May 1 (i.e., at the end of our final slot; no final)

Cost of Blackouts

- Electricity has varying value and hence the costs associated with blackouts can vary substantially
  - Momentary (less than five minutes) can have almost no impact for residential customers (certainly with exceptions!) while costing industrials potentially millions if production is interrupted
- Costs impact are sensitive to the duration and extent of the blackout as well
  - Long duration blackouts impacting a wide area are the worst case scenarios

Larger Scale Blackouts

- The North American Electric Reliability Corporation (NERC) requires reporting of events the interrupt more than 300 MWs or affect at least 50,000 customers
  - From 1984 to 2006 there were 861 events reported, but only about 300 met the criteria
  - Average of blackouts that met the criteria affected several hundred thousand customers, but large outages affected many more (like August 14, 2003 with more than 50 million people).

This data is now kind of dated, partially because of changes in the availability of information to researchers

Source: www.uvm.edu/~phines/publications/2008/Hines_2008_blackouts.pdf

Large Blackouts in North America By Event Size

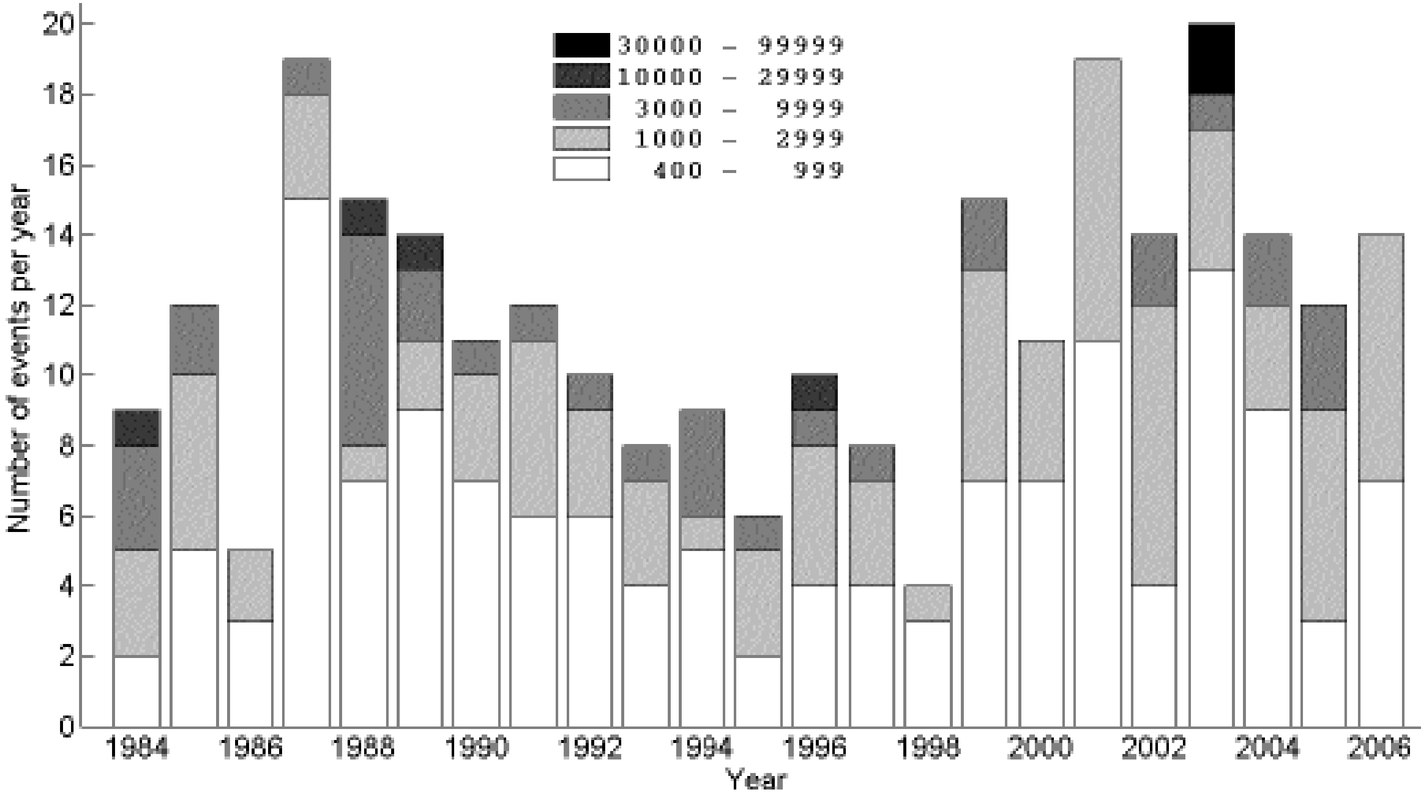


Figure 3. The number of large blackouts per year after removing small events, and controlling for increasing demand. Event size above is shown in year-2000 MW.

Source: www.uvm.edu/~phines/publications/2008/Hines_2008_blackouts.pdf

Causes of Large Blackouts

TABLE 2. STATISTICS FOR DATA CAUSE CATEGORIES

	% of events	Mean size in MW	Mean size in customers
Earthquake	0.8	1,408	375,900
Tornado	2.8	367	115,439
Hurricane/tropical storm	4.2	1,309	782,695
Ice storm	5.0	1,152	343,448
Lightning	11.3	270	70,944
Wind/rain	14.8	793	185,199
Other cold weather	5.5	542	150,255
Fire	5.2	431	111,244
Intentional attack	1.6	340	24,572
Supply shortage	5.3	341	138,957
Other external cause	4.8	710	246,071
Equipment failure	29.7	379	57,140
Operator error	10.1	489	105,322
Voltage reduction	7.7	153	212,900
Volunteer reduction	5.9	190	134,543

Source: www.uvm.edu/~phines/publications/2008/Hines_2008_blackouts.pdf

Weather Related Large-Scale Blackouts

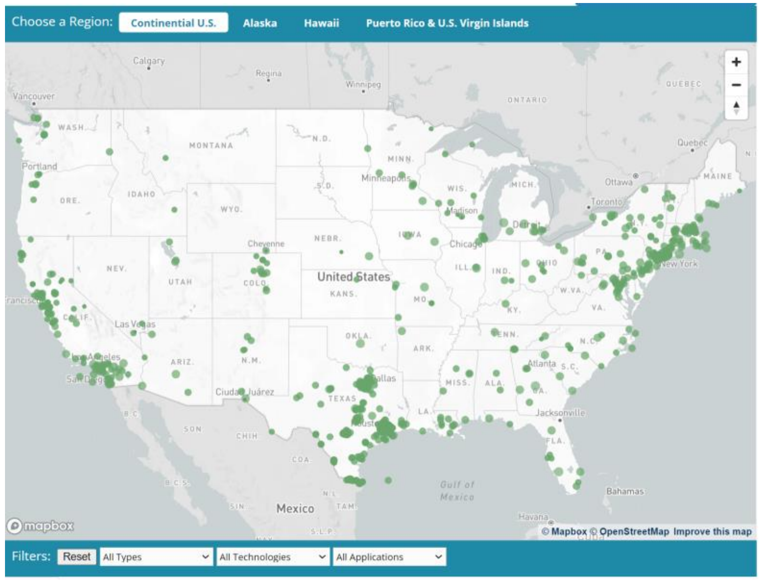
- A majority of the extremely large blackouts in the US are due to weather related causes
  - Hurricanes, ice storms, tornados are key causes
- Little can be done operationally for prevention
  - Operational changes can help with quicker restoration
- Prior planning can reduce the blackout extent
  - Tree trimming
  - Locating transmission/distribution underground can be effective but quite costly

Avoidable Transmission Level Blackouts

- Many major blackouts can be prevented.
- Time frames of the blackouts, minutes to hours, allow for operator intervention
  - Tokyo 1987 (20 minutes), WECC 1996 (six minutes), Eastern Interconnect 2003 (about an hour), Italy 2003 (25 minutes), India 2012
- And of course many are prevented, and hence do not make the news. For example, near voltage collapse in Delmarva Peninsula, 1999.

Blackouts and Micro-Grids/Distributed Generation

- The effects of short-term blackouts can be eliminated or reduced through the use of uninterruptible power supplies (UPSs) and backup generation
- Micro-grids, which have the ability to run autonomously from the main grid, offer the potential for additional reliability
  - Having sufficient generation capacity, and a long-term fuel source are key
- The DOE has a website that shows microgrid installations
  - https://doe.icfwebservices.com/microgrid
  - As of 2024 they noted 1174 operational microgrids with a total of 5.845 GW of reliable capacity



Year	Sites	Capacity (MW)
Unknown	36	147.1
Pre-1995	31	635.8
1995	3	59.6
1996	3	14.9
1997	3	42.4
1998	4	137.0
1999	17	50.1
2000	5	7.8
2001	6	18.8
2002	3	23.7
2003	12	61.3
2004	10	186.8
2005	12	333.0
2006	13	178.2
2007	11	40.8
2008	7	11.7
2009	16	93.7
2010	18	176.2
2011	14	79.4
2012	27	163.0
2013	61	510.6
2014	33	133.0
2015	33	173.4
2016	47	249.7
2017	96	264.8
2018	144	317.8
2019	97	588.9
2020	131	272.8
2021	82	151.7
2022	69	250.1
2023	71	262.2
2024	59	208.5
Total	**1,174**	**5,845**

U.S. installations as of December 18, 2024.

Restoration

- The cost of blackouts certainly increases the longer the power is out
- How quickly power can be restored depends on whether there was equipment damage
  - Downed lines take time to rebuild
  - Houses damaged by flooding need to be disconnected before service can be restored
  - Some generation, such as nuclear plants, can take days to restart
  - Damage to HEV transformers could be catastrophic!

Restoration, cont.

- For larger blackouts there appears to be little correlation between the size of the event and the restoration time

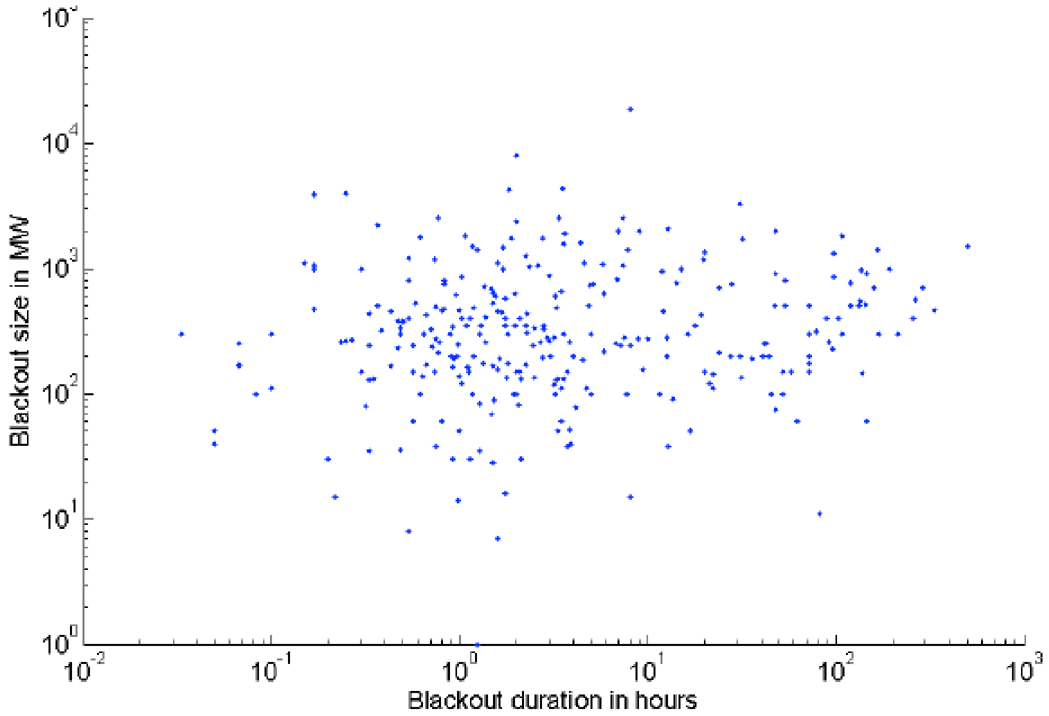


Figure 7. Blackout size in MW plotted against blackout duration. The two variables are almost perfectly uncorrelated. Correlation statistics shown in Table 4 shows the linear correlation. The log-log scale is used here for clarity—the linear scaled figure shows a similar relationship.

Source: www.uvm.edu/~phines/publications/2008/Hines_2008_blackouts.pdf

Black Start Restoration

- Power system restoration or black start (or blackstart)
  - A procedure to restore power in the event of a partial or total shutdown of the power system
  - A highly complex decision problem
- Object is to serve the load as soon as possible without violating operating constraints
  - Actions are time critical
- Primarily manual work by operators
- Offline restoration planning usually based on simulations

Background On Power System Black Start

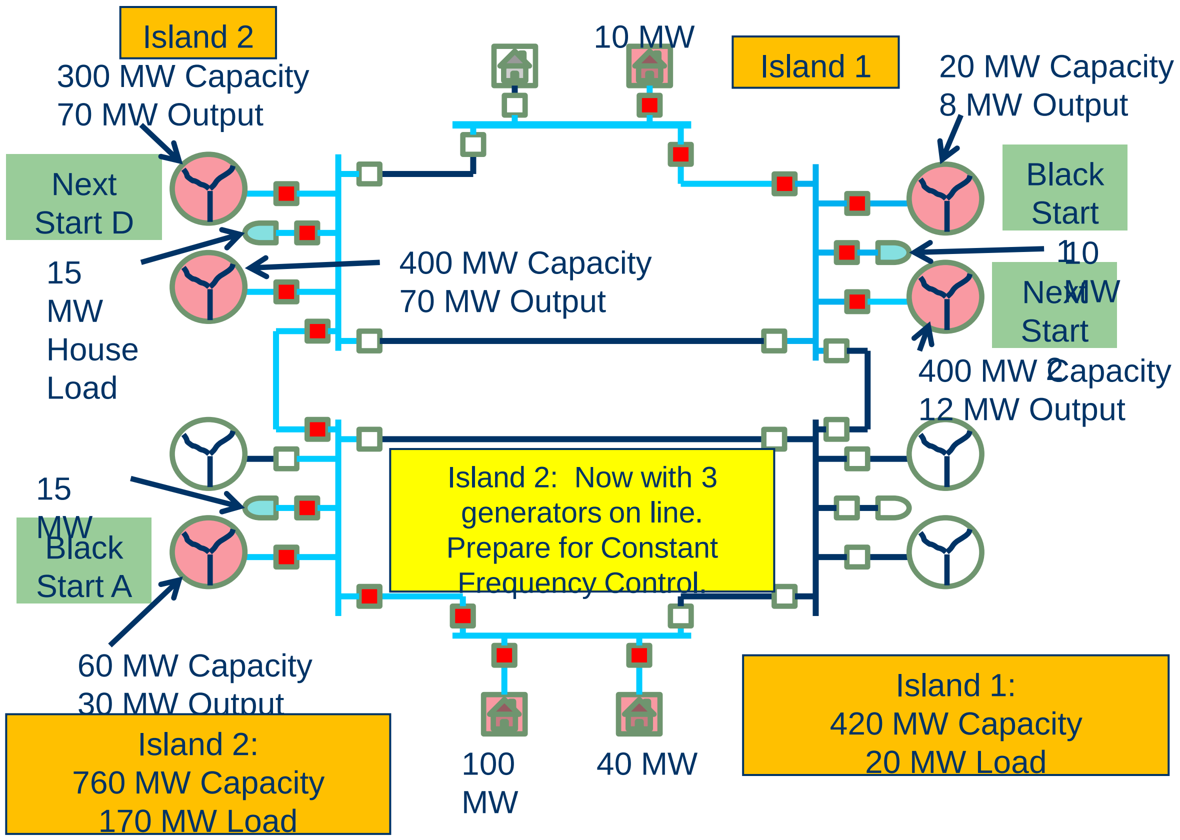
- Key NERC Standard is EOP-005, 2009
  - Transmission operators must have black start plans, verify them with steady-state and dynamic simulations, and run training exercises and testing
  - Parts of a black start plan
    - High level strategy for coordination and restoration
    - Nuclear power plant off-site power supply
    - Black start generating resources
    - Cranking paths to next-start units
    - Acceptable limits to voltage and frequency during restoration
    - Load restoration and prioritization process
    - Communication process and transfer of operational control
- Recent report covering black start:
  - J. G. O'Brien, M. Cassiadoro, T. Becejac, G. B. Sheble, J. D. Follum, U. Agrawal, E. S. Andersen, M. Touhiduzzaman, and J. E. Dagle, "Electric grid blackstart: Trends, challenges, and opportunities," Pacific Northwest National Lab, Richland, WA, Tech. Rep., 2021

Issues in Black Start Procedure Design

- Active power balance
  - Need to maintain system frequency within limits by system stability and protection settings
  - Accomplished by picking up loads in increments
- Frequency control
  - Initial black start islands are in isochronous control mode
  - Transition to droop control with AGC and appropriate frequency bias
  - Synchronizing islands, need to control frequency appropriately
- Reactive power balance and overvoltage control
  - Energizing few high voltage lines
  - Operating generators at minimum voltage levels
  - Deactivating switched shunt capacitors, connecting shunt reactors
  - Adjusting transformer taps, picking up reactive loads

General Stages of Black Start Restoration

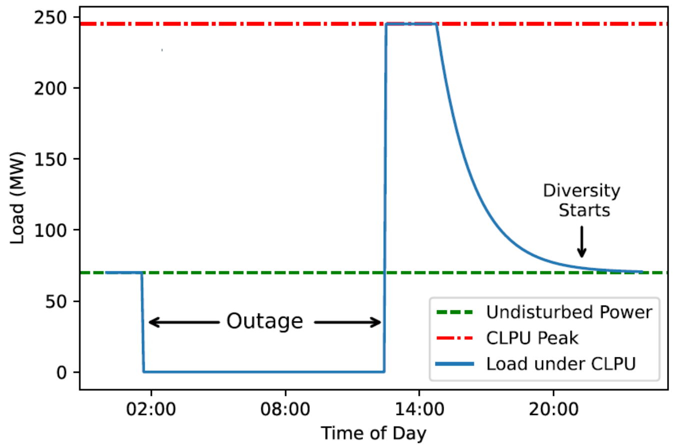
1. Ensure breakers are opened up to isolate the system
2. Start up black start units in separate islands, energizing associated buses on isochronous control
3. Add balancing loads and energize cranking paths to next-start units
4. Start up additional units and expand areas, transitioning to AGC control
5. Synchronize islands to reform transmission network
6. Continue to add load as additional generation comes online



Source: ERCOT, *Frequency Control During Black Start Operations*, 2014

Cold Load Pick-Up Modeling

- When loads are energized after an extended outage, cold load pick-up (CLPU) is in effect
- This means the load's consumed power may be 3-10 times as large as the undisturbed load value
  - The reason for CLPU effects is the loss of load "diversity" – that is, loads such as air conditioners that ordinarily operate at different, small intervals will instead be operating all at the same time
  - This increased load may last for 30 minutes or longer, until load diversity starts back again
  - If an outage is shorter, the CLPU effects will not be as severe because there is not enough time for full loss of diversity



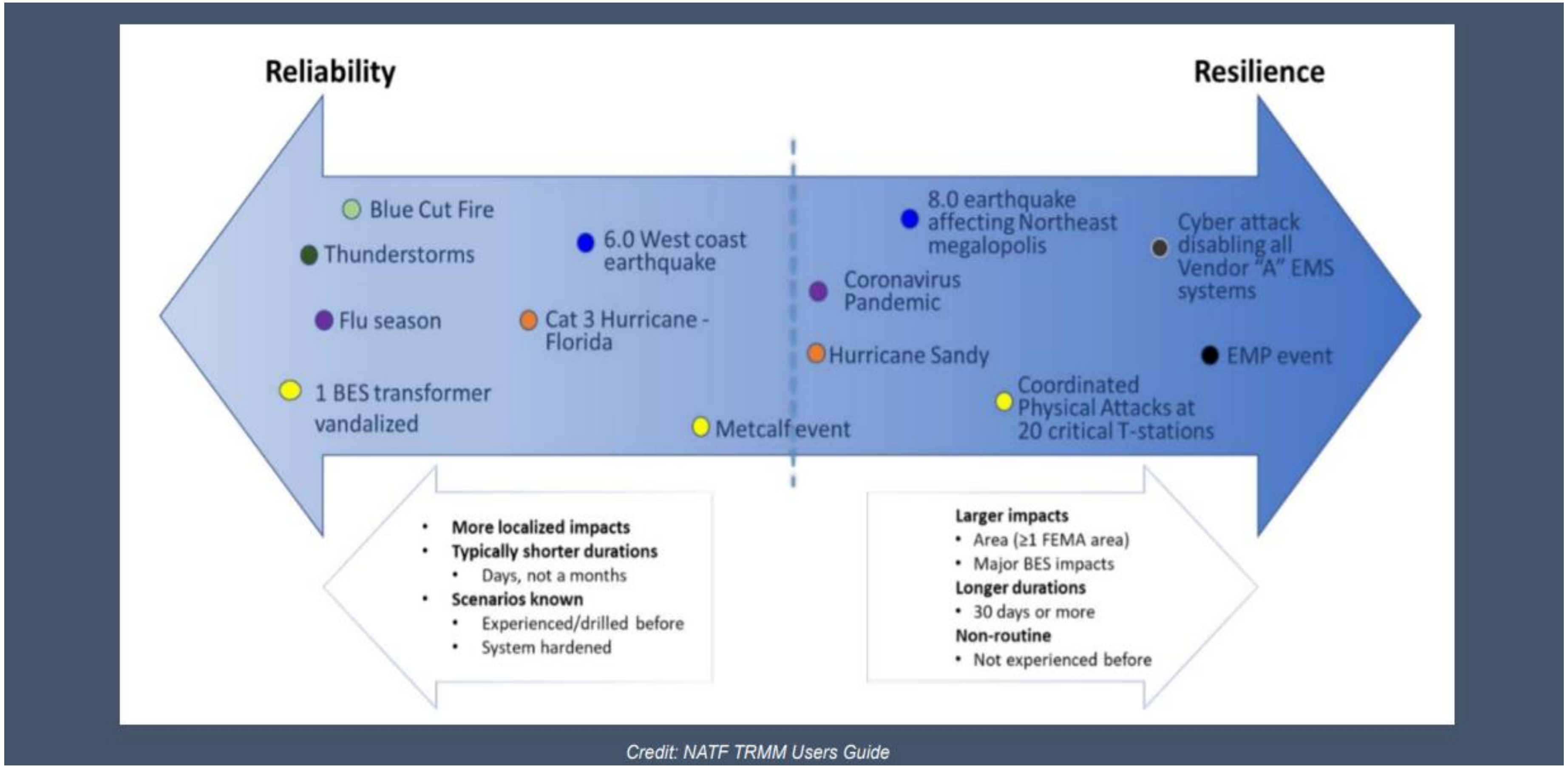
J. Penaranda and A. B. Birchfield, "Application and Parameter Sensitivities of a State-Space Cold Load Pickup Model for a Synthetic Restoration Test Case," *2022 North American Power Symposium (NAPS)*, Salt Lake City, UT, USA, 2022, pp. 1-6

Grid Resilience

- Grid resilience is currently a topic with lots of interest
- Resilience in general is defined as (Merriam Webster Dictionary)
  - "An ability to recover from or adjust easily to misfortune or change"
- EPRI & North American Transmission Forum (NATF)
  - The ability of the system and its components (… equipment and human …) to minimize damage and improve recovery from non-routine disruptions, including High Impact, Low Frequency (HILF) events, in a reasonable amount of time"
- The impact of blackouts is not linear!
  - Having 100 million people out of service can be more than tens times worse than 10 million out. A ten day blackout can be more than tens times worse than a one day blackout.

These definitions are from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021

Reliability – Resilience Continuum



Slide is from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021; credit NATF

High-Impact, Low-Frequency Events

- In order to enhance electric grid resiliencv we need to consider the almost unthinkable events
- These include what the North American Electric Reliability Corporation (NERC) calls High-Impact, Low-Frequency Events (HILFs); others call them black sky days, or severe resiliency events (SREs)
  – Large-scale, potentially long duration blackouts
  – HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) HEMPs

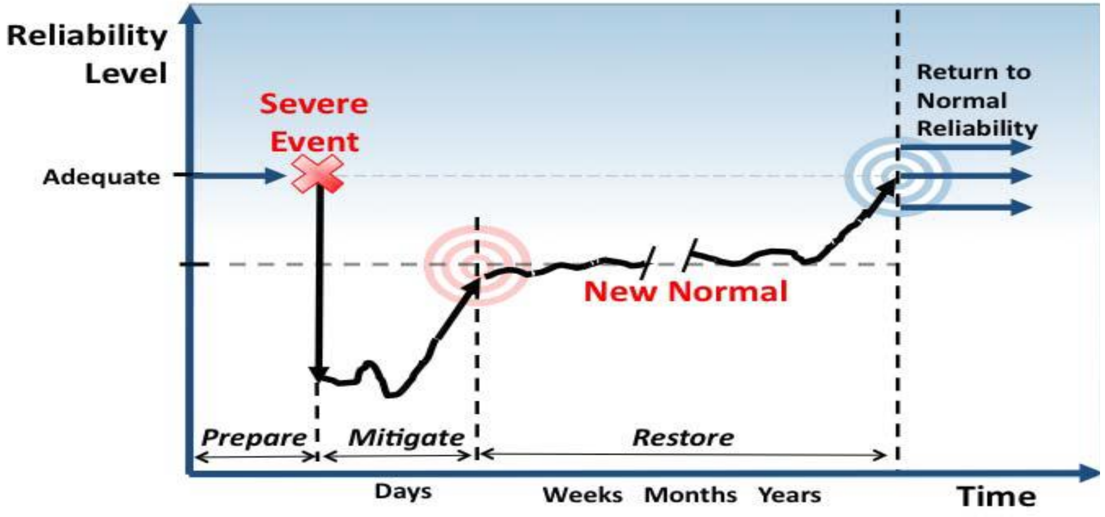
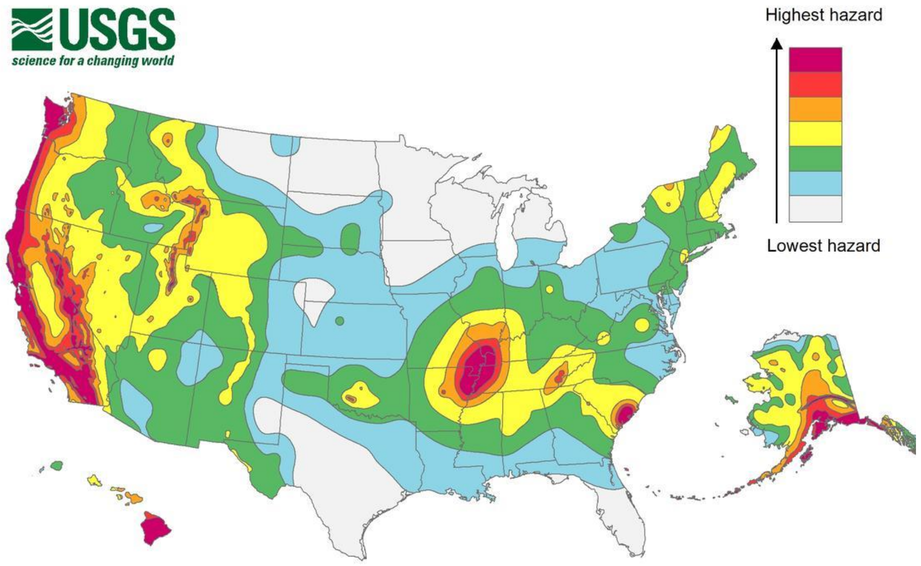


Image Source: NERC, 2012

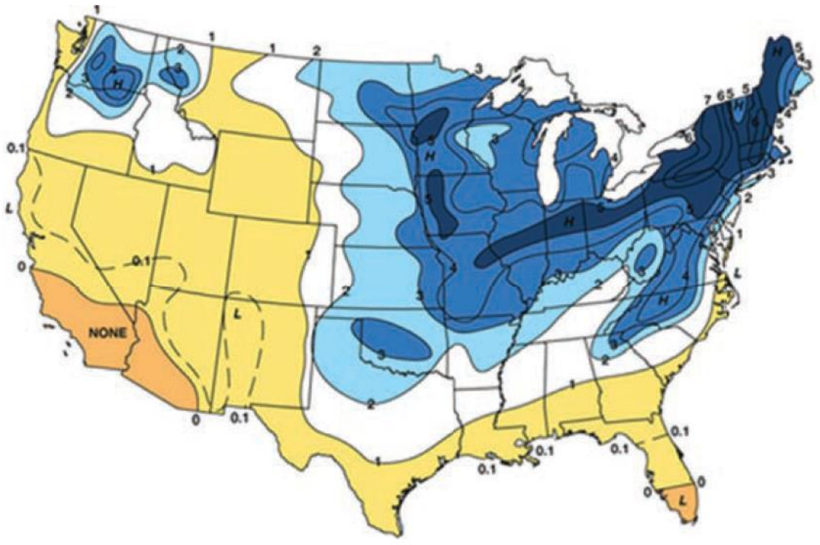
Resilient to What?

- A key question on resiliency is to determine the likely threats
  - Some are geographic, and may are hard to quantify

Earthquake Risk



Freezing Rain Risk



The impact of wind and solar output on the weather is also a growing concern

Source: *Enhancing the Resilience of the Nation's Electricity System*, 2017

Some Electric Grid Risks

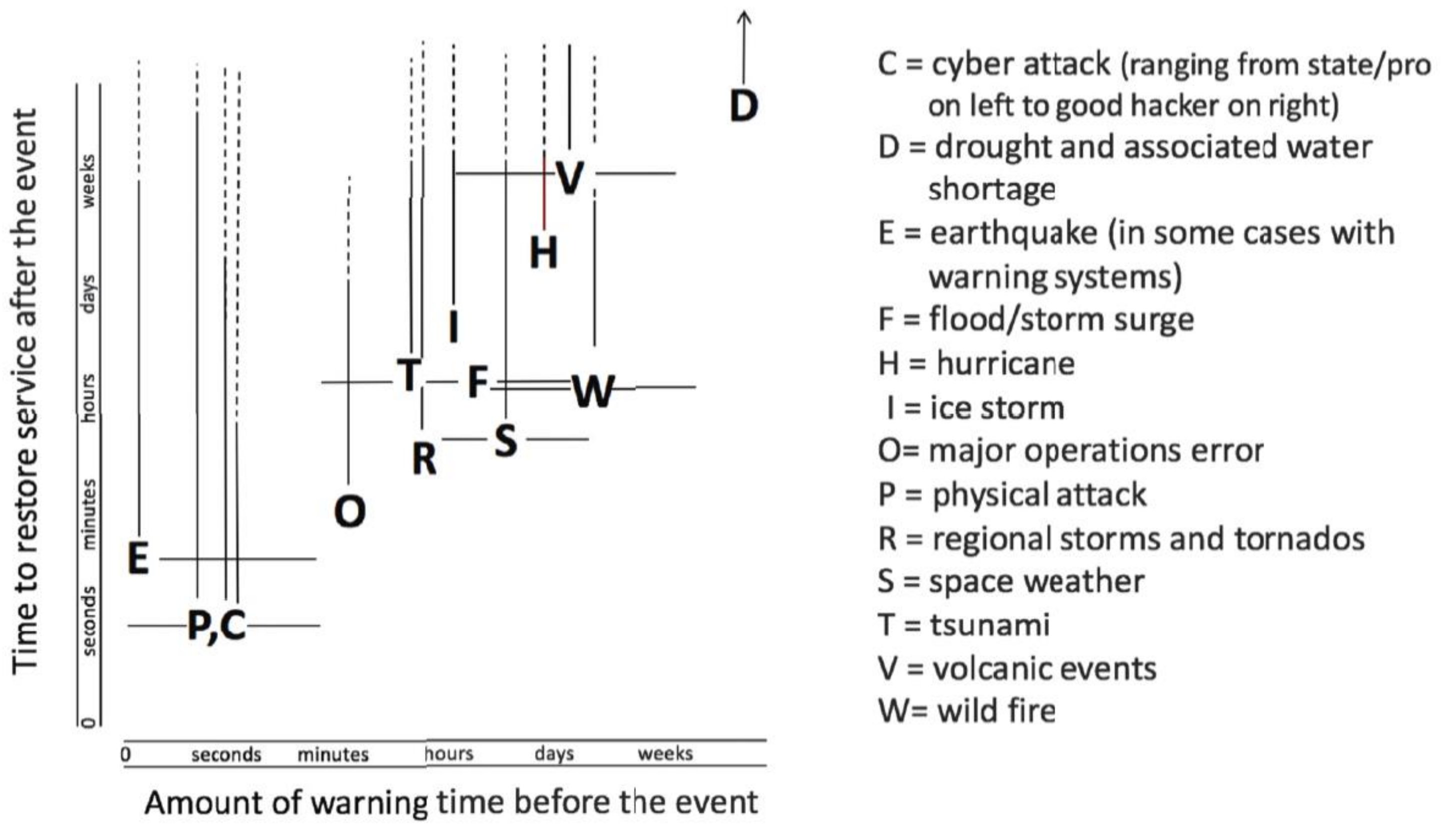


FIGURE 3.1 Mapping of events that can cause disruption of power systems. The horizontal placement provides some indication of how much warning time there may be before the event. The vertical axis provides some indication of how long it may take to recover after the event. Lines provide a representation

Source: *Enhancing the Resilience of the Nation's Electricity System*, 2017

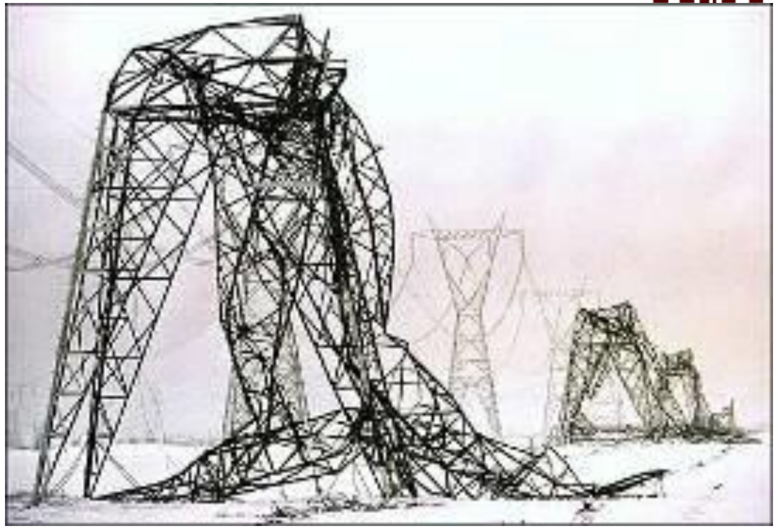
How to Approach HILF Events

- The goal in studying HILFs is seldom to replicate a specific event
  - Many have not occurred, and within each class there can be great variability (e.g., a physical attack)
- Nor is it to ensure there is no loss of service
- Rather, it is to be broadly prepared, and to be able to do at least a reasonable cost/benefit analysis
- HILF simulations can help in preparing for the unexpected
- Understanding, and ultimately enhancing resiliency, requires consideration during three periods 1) prior to an event , 2) during it 3) afterward
- Several techniques, such as improved control room rare event situational awareness and better black start procedures, are generally applicable

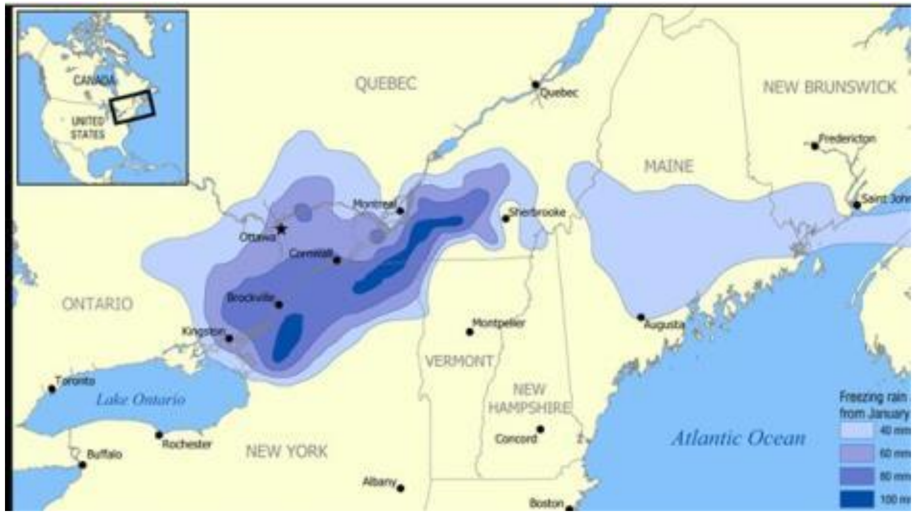
Challenges

- An all hazards approach to considering resiliency is crucial, but there is no a "one-size-fits-all" solution
- Identifying particular strategies to improve resiliency, to at least some degree, is relatively easy
- The challenge is developing appropriate priorities for actions, and determining the appropriate political and organizational support to make it happen
  - Just expecting electric utilities to make the investments necessary, while many are losing customer revenue to self-generation, might not be realistic
- HILFs (or perhaps Severe Resiliency Events [SREs] is better) come in a continuum of frequencies and impacts

Examples of Larger-Scale or Long Duration Outages



- Quebec geomagnetic disturbance blackout of 1989
- Northeast ice storm of 1998: A week long ice storm that resulted in more than three inches of ice on transmission lines, causing the collapse of 770 transmission towers and the replacement of 26,000 distribution poles
- Northeast blackout from August 14, 2003
- Hurricane Katrina (2005) with loss of service to 2.7 million customers, with 250,000 still out after 4 weeks
- Hurricane Maria (2017) in Puerto Rico,

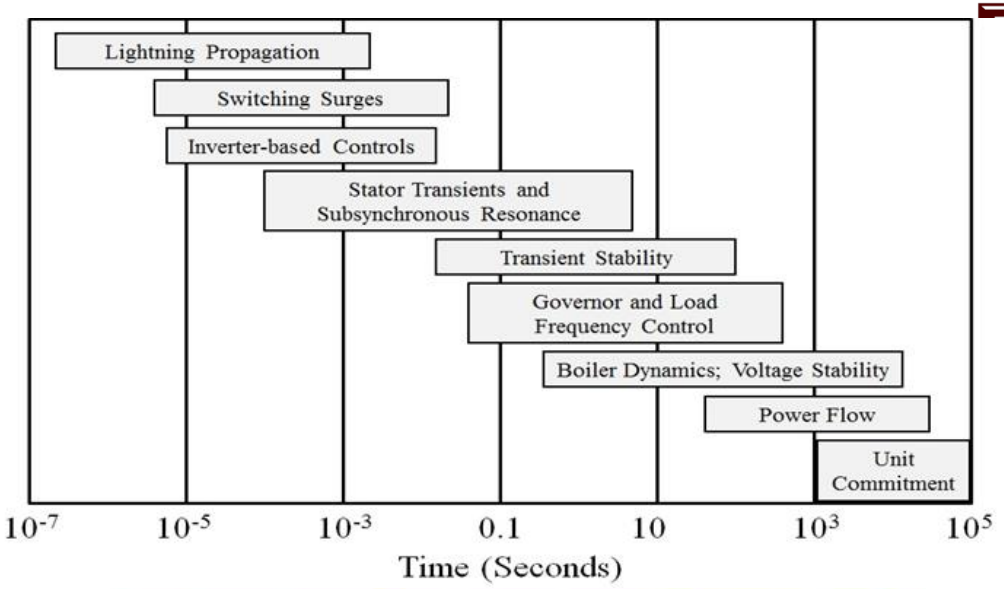


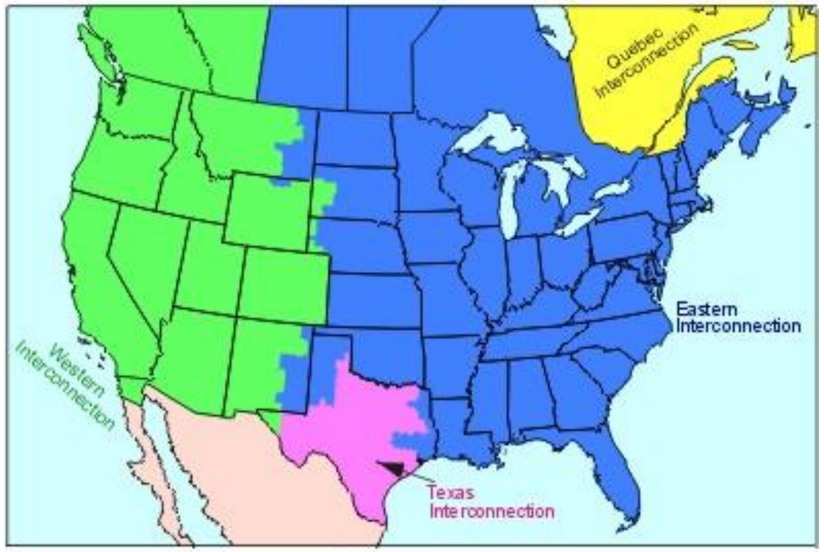
HILF Two Main Categories

- HILF events can be divided into two broad categories: 1) those not caused by human agents, and 2) those caused by human agents
- Modeling the non-human events is somewhat easier because the goal is to (at least generally) replicate what has occurred, or what could occur
- With human agent events the challenge is to protect the grid from potential events, without exposing vulnerabilities to an adversary or giving out potential mechanisms of attack
- Synthetic grids are good for both

Electric Grid Resiliency Modeling Challenges

- When considering resiliency events stability-level models often need to be used; this requires considering many different types of models
  - We recently did a study modeling a combined East-West grid, and it has 250 types of models
- The grid's operating point is constantly changing including the load, and generator and line/transformer statuses





Top Image: Sauer, P.W., M. A. Pai, Power System Dynamics and Stability, Stripes Publishing, 2007

General Grid Resilience Comments

- Understanding resilience requires considering how grids will respond to particular disturbances
- Substantially changing the topologies of existing grids is not an option
- In contrast to cyber security, there are seldom easy “patches” that can be applied to fix vulnerabilities
- Simplistic studies of how a grid disturbance could cascade often lead to incorrect conclusions; sequential power flows, sequentially taking out overloaded devices are not particularly helpful
- Full detail models of large-scale actual grids including the protection system usually don’t exist and modeling them would requiring knowing the associated remedial action schemes

Economic Valuation of Resilience

- While certainly challenging, metrics are needed to help determine the value of resilience to society
  - If we need to improve resiliency, someone needs to pay
- This is becoming a more challenging problem as more customers provide self-generation
  - Is the ability of some customers to self generate, at least for a period of time, a net gain to the grid's resiliency? How does one assess the resiliency of their systems?
- Given that both reliability and resilience are often desired, their needs to be a co-optimization of their benefits.

Example: Geomagnetic Disturbances (GMDs)

- GMDs are caused by solar corona mass ejections (CMEs), and range from minor and frequent to severe and extremely rare
- A GMD caused a blackout in 1989 of Quebec
- They have the potential to severely disrupt the electric grid by causing quasi-dc geomagnetically induced currents (GICs) in the high voltage grid
- Until recently power engineers had few tools to help them assess the impact of GMDs
- GMD assessment tools are now moving into the realm of power system planning and operations engineers

May 10 to 13, 2024 Geomagnetic Disturbance (GMD)

- A fairly large GMD caused just barely visible northern lights as far south as College Station, TX (latitude of 30.6°)
- While the Kp-index went up to its max value (9), it was not an overly severe GMD
  - nT/minute of < 100, where 500 would be a 1989 event, and 2500 for Carrington
- It caused more grid impacts than expected

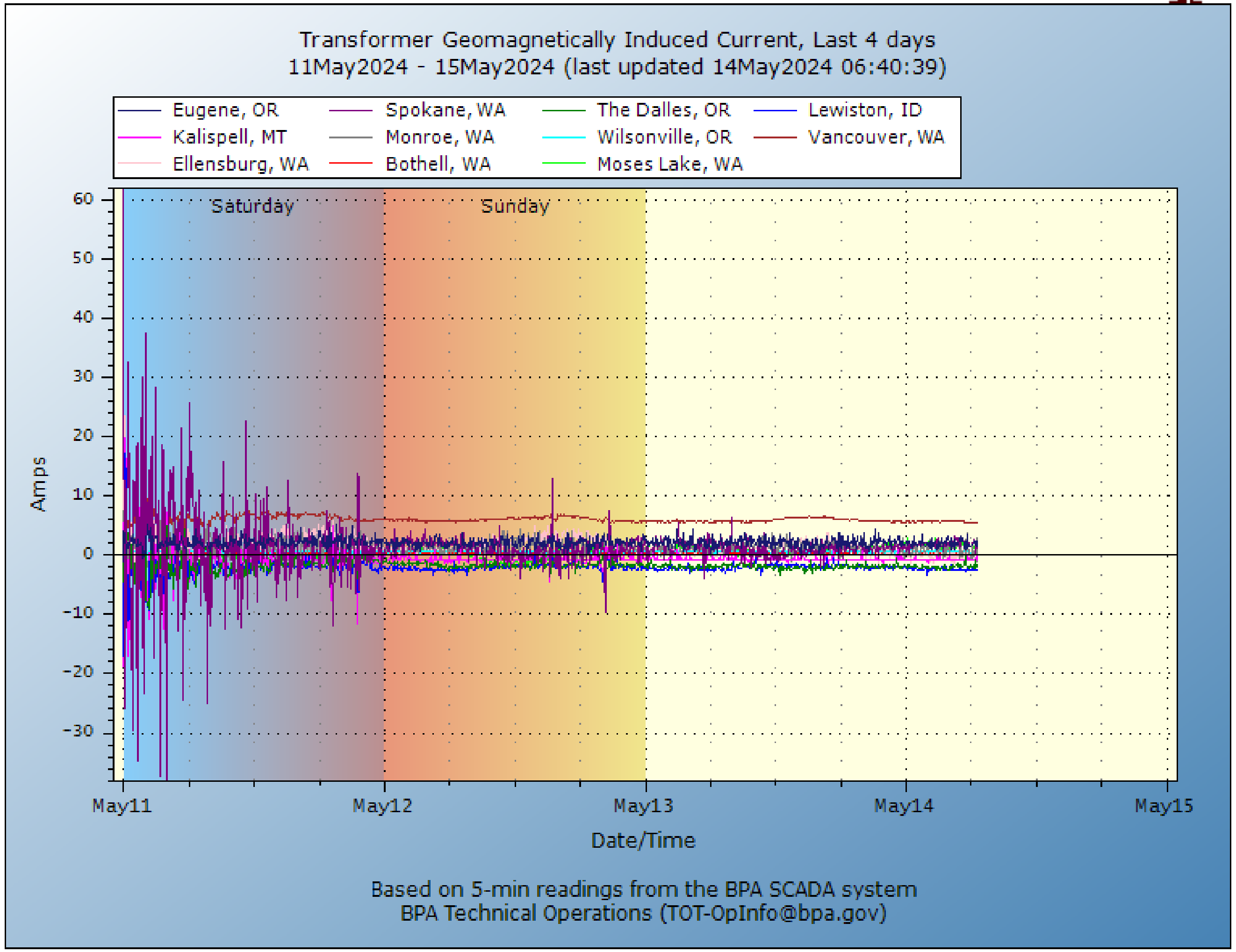
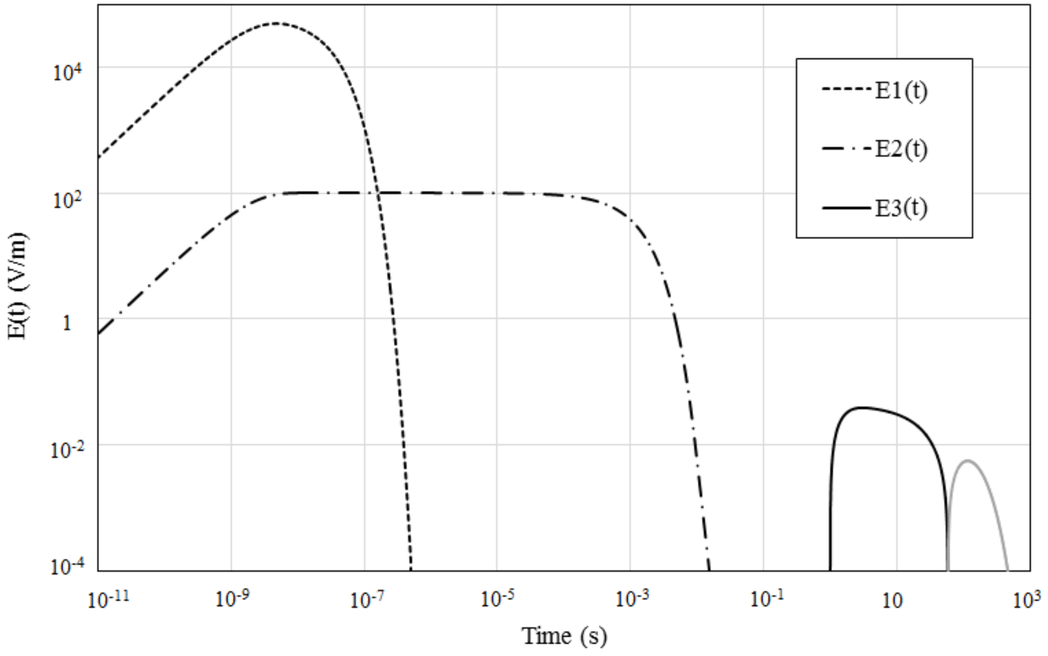


Image: transmission.bpa.gov/Business/Operations/gic/gic.aspx

HILF Example: Nuclear EMPs

- Broadly defined, an electromagnetic pulse (EMP) is any transient burst of electromagnetic energy
- High altitude nuclear explosions can produce continental scale EMPs; called HEMPs
- The impacts of an HEMP are typically divided into three time frames: E1, E2 and E3
  - E1 impacts electronics, E2 is similar to lightning, E3 is similar to a very large, but short duration GMD



Nuclear EMP History

- The presence of EMPs was theorized by Enrico Fermi prior to the first explosion in July 1945
  - Many wires were shielded, but still some data was lost due to EMP
- Starfish Prime was an explosion of a 1.44 megaton nuclear weapon at an altitude of 400 km over the Pacific Ocean in July 1962
  - Part of series of tests known as Operation Fishbowl
  - The EMPs were much larger than expected, driving instruments off scale
  - Impacts seen in Honolulu (1445 km away), including knocking out about 300 street lights, setting off alarms, and damaging a microwave link
  - Some low earth orbit satellites were also damaged

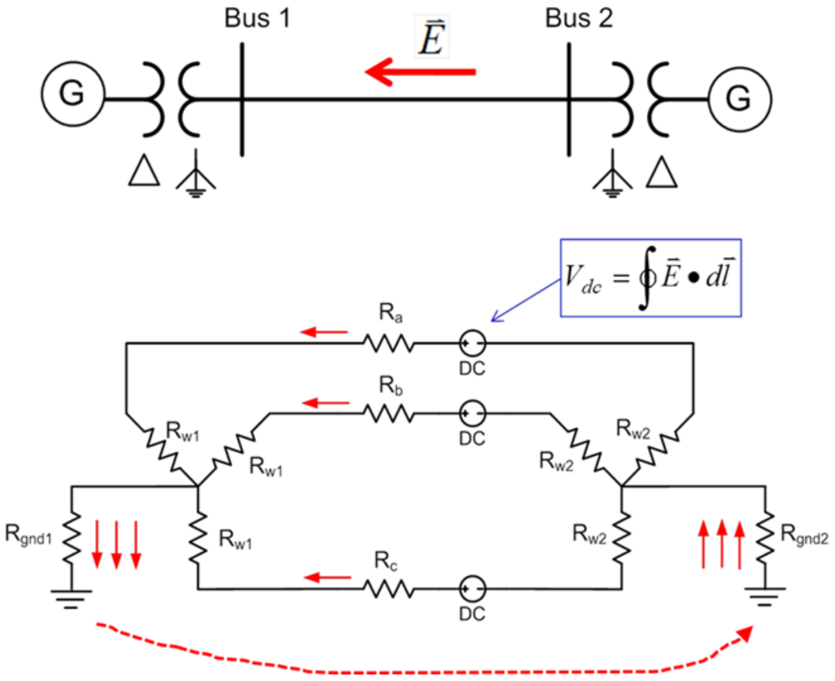
Starfish Prime observed on Maui in 1962, Source US EMP Commission Report, 2017

Electric Fields and Geomagnetically Induced Currents (GICs)

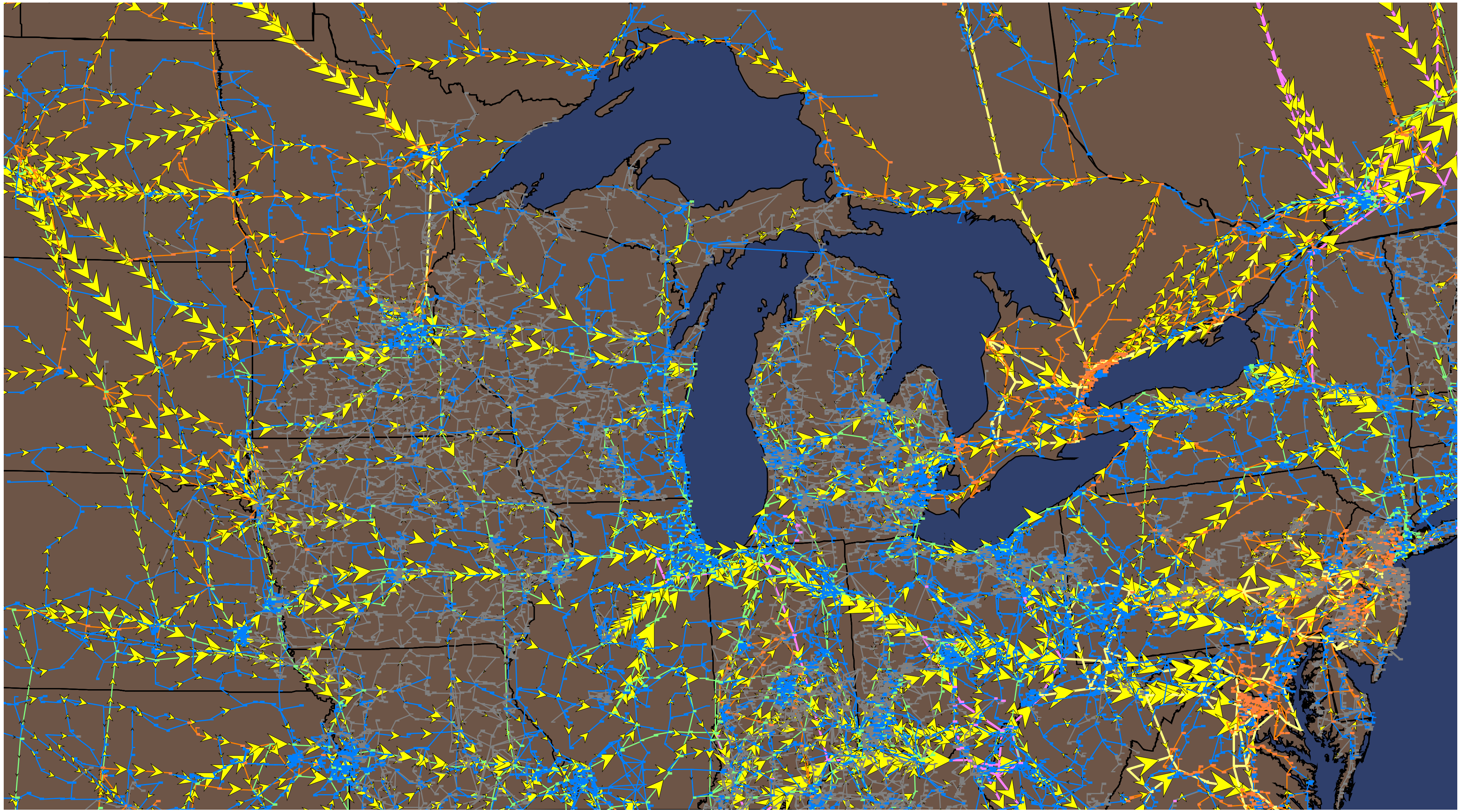
- The induced electric field at the surface is dependent on deep earth (hundreds of km) conductivity
  - Electric fields are vectors (magnitude and angle); values expressed in units of volts/mile (or volts/km);
  - A 2500 nT/minute storm could produce 5 to 10 volts/km
- The electric fields cause GICs to flow in the high voltage transmission grid
- The induced voltages that drive the GICs can be modeled as dc voltages in the transmission lines.
  - The magnitude of the dc voltage is determined by integrating the electric field variation over the line length
  - Both magnitude and direction of electric field is important

Geomagnetically Induced Currents (GICs)

- Both GMDs and HEMPs cause electric fields, with values dependent on the deep earth conductivity
- Along length of a high voltage transmission line, electric fields can be modeled as a dc voltage source superimposed on the lines
- These voltage sources produce quasi-dc geomagnetically induced currents (GICs) that are superimposed on the ac (60 Hz) flows



Simulated GICs in High Voltage Transmission Grid



The Impact of a Large GMD From an Operations Perspective

- Would be maybe a day warning but without specifics
  - Satellite at Lagrange point one million miles from earth would give more details, but with less than 30 minutes lead time
  - Could strike quickly; rise time of minutes, rapidly covering a good chunk of the continent
- Reactive power loadings on hundreds of high voltage transformers could rapidly rise

- Increased transformer reactive loading causes heating issues and potential large-scale voltage collapses
- Control room personnel would be overwhelmed
- The storm could last for days with varying intensity

GIC Mitigation

- Tools are needed to determine mitigation strategies
  - Cost-benefit analysis
- GIC flows can be reduced both through operational strategies such as opening lines, and through longer term approaches such as installing blocking devices
- Redispatching the system can change transformer loadings, providing margins for GICs
- Algorithms are needed to provide real-time situational awareness for use during GMDs

Integrating Weather (and Other Resiliency Events) into Electric gird Planning

- Human activity depends on the weather, and this has always been reflected in the electric load
- Traditionally some power flow parameters have depended on the weather (e.g., line ratings, turbine max MW, line resistance)
- Over the last several decades this dependence has grown substantially with the increase in wind and solar generation
  - They now provide about 17% of US electric energy (> 30% in ERCOT); there are times when most of the electricity in regions is supplied by these sources
  - They are extremely dependent on the weather
- Major power system input parameters are now heavily weather dependent (e.g., wind and solar generator Max MW)

Availability of Weather Information

- We started this effort three years back by using historical weather station measurements (mostly identified by their ICAOs [International Civil Aviation Organization], e.g. KLIT, KCLL)
  - We had lots of data, but much of it had missing values; we also only had surface wind values and no direct solar measurements
  - Such measurements at specific locations can still be very useful (e.g., at electrical substations)
- There are many other sources of free weather information, with good coverage provided by *Weather DataSet Needs for Planning and Analyzing Modern Power Systems*, Energy Systems Integration Group (ESIG), October 2023
  - www.esig.energy/wp-content/uploads/2023/10/ESIG-Weather-Datasets-summary-report-2023.pdf

ESIG Report (10/2023)

- "These widespread changes lead to the increasing weather-dependence of supply and demand, making power system planning dramatically more complex and requiring much more comprehensive weather data for robust system planning."
- "The work required to achieve a long-term solution to weather data needs is not trivial, but it is manageable and is much less costly than blindly building trillions of dollars of infrastructure without the basic tools to cost effectively optimize it and assess its reliability."
- PowerWorld had started working in planning weather integration about a year before the ESIG report appeared, but much progress has been made in the last year

TABLE 2

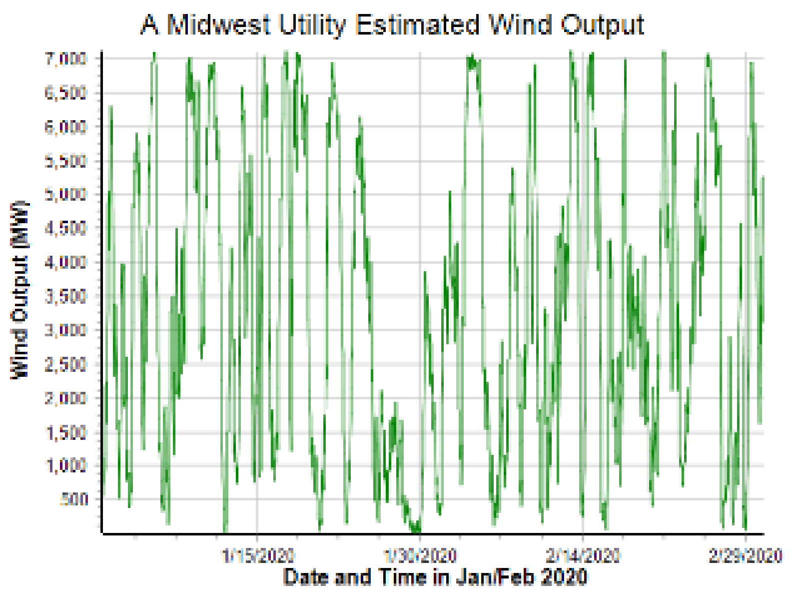
Summary of Current Power System Modeling Weather Input Data Sources

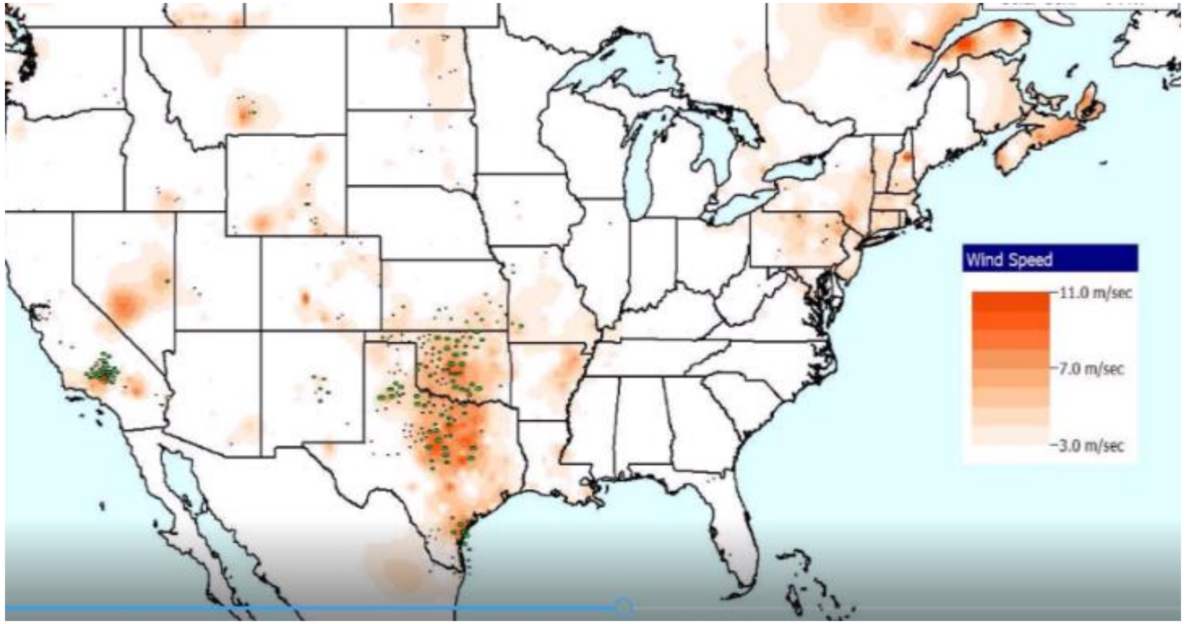
	Spatial Resolution	Temporal Resolution	Length	Continuously Extended	Correct Variables/ Levels	Coincident and Coherent	Validated/Uncertainty Quantified for Power System Use	Detailed Documentation	Future-Proofed	Availability/ Ease of Access	Curation and Advice	Region Covered
MERRA-2[a]	~60 km	60 min	1980–present	Yes	Yes/No	Yes	No		Probably		Basic	Global
ERA5[b]	~30 km	60 min	1940–present	Yes	Yes/No	Yes	Some		Yes		Good	Global
HRRR[c]	3 km	15 min	2014–present	Yes	Yes/No	Yes/No	No		Unideal		Basic	U.S.
WIND Toolkit[d]	2 km	5 min	2007–2014	No	Yes/Yes	Yes	Yes		No		Basic	Various
WTK-LED[e]	2 km/4 km	5 min	3 year/20 year	No	Yes/Yes	Yes	Not yet	Not yet	No	Unknown, dataset not yet available		Various
NSRDB[f]	4 km/60 km	30 min	1998–present	Yes	Yes/No	Solar only	Yes		Yes		Basic	Most of globe
CERRA[g]	11 km/5.5 km	60 min	1980–present		No/Yes	No solar	Yes		Possibly		Basic	Europe
CONUS404[h]	4 km	60 min/15 min (precip)	1980–2020	No	Unknown/Probably	Yes	Not the intended use					Continental U.S.
BARRA[i]	12 km/1.5 km	60 min	1990–2019	No	Yes/Probably	Yes				Fee-based		Australia/New Zealand
Public Observing Networks[j]	Non-uniform, variable density	1 hr or less	Variable	Yes	Yes/No	Mostly	Varies. Not for power systems	Varies	Usually	Usually easy	Varies	Global
Renewable Energy Project Data[k]	Non-uniform, variable density	Usually minutes	Variable but rarely more than 10 years	Varies	Yes/Usually	Yes	Usually	Varies, but usually poor	Varies	Usually poor	Usually none	Very limited
Proprietary Statistically Derived VRE Shapes[l]	Non-uniform, variable density	Usually hourly	Variable. Rarely reliable long records.	Varies	Usually incomplete	No	Partial	See note	No		None	Very limited

Fully Met · Close to Being Met · Partially Met · Met in a Very Limited Way · Not Met at All · Not Enough Info. for Determination

Weather Resiliency Example: Renewable Resource Droughts

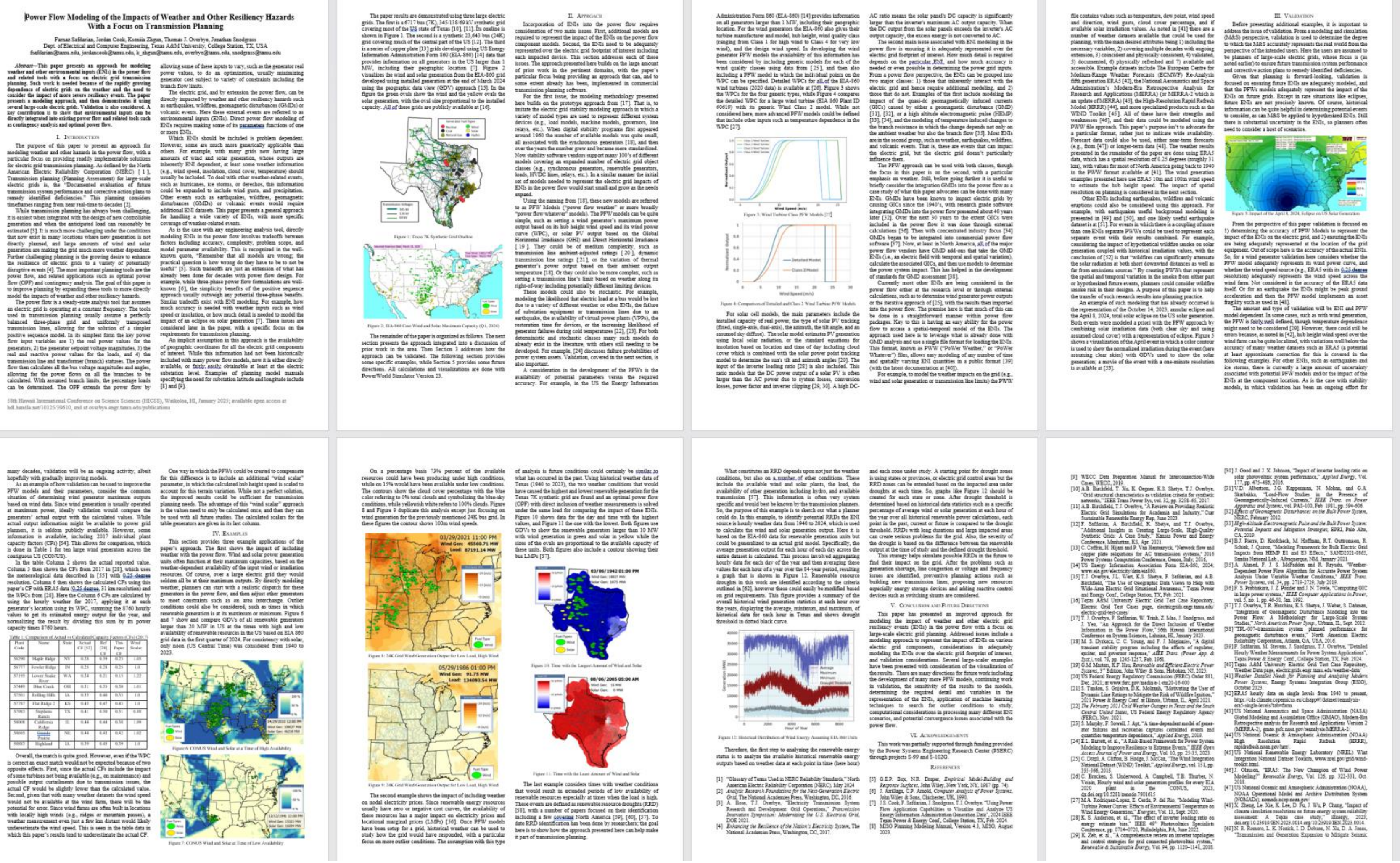
- With the rapid growth in wind and solar resources, a growing concern is how to handle wind and solar "droughts" with the generic term of renewable resource droughts used to describe them
- The below example is a wind drought that occurred in the Midwest in late January 2020





HICSS 2025 Paper on Power Flow Weather Modeling

- There is a paper from the 59th Hawaii International Conference on System Sciences (HICSS) titled, "Power Flow Modeling of the Impacts of Weather and Other Resiliency Hazards With a Focus on Transmission Planning,"; it is available at **overbye.engr.tamu.edu/publications**



Some Strategies to Prepare: Component Hardening, Physical Security

- Electric grids are comprised of components, and resiliency can be enhanced by hardening particularly vulnerable components
  - Transmission lines in likely icing location, undergrounding some lines, transformers with better handling of geomagnetically induced currents (GICs), water protection
  - This needs to be done considering the cost versus benefit
  - Vegetation management should also be considered
- Physical security is an area of increased concern, with unmanned aerial vehicles being a fast rising threat

Enhancing Bulk Grid Simulations to Handle HILF Scenarios

- The stressed operation associated with the high impact, low frequency events presents modeling challenges
- Luckily, over the last several years the software is being enhanced to deal with these situations
  - My next presentation goes in-depth on geomagnetic disturbance (GMD) and high altitude electromagnetic pulse (HEMP) modeling
- There is also a need to consider high voltage transmission system design that lessens the likelihood of cascading outages
- Improving situational awareness during times of extreme grid stress is key

Adaptive Islanding

- One promising resiliency technique is to design interconnected grids to split (island)
  - This is known as controlled islanding and can be enhanced to be adaptive islanding
  - A distribution system example is a microgrid
- The islands need to be chosen so they have sufficient generation to match load
- Often control is still centralized
- A more involved islanding issue is to setup the grid so smaller parts can function with full autonomy

Resiliency and Coupled Infrastructures

- As our societies become more dependent on electricity, short and small duration blackouts become more concerning, and large-scale, long duration outages can be catastrophic
- There are many couplings between electric grids and other infrastructures such as natural gas, water, cyber, and increasing transportation
- These couples need to be more fully considered in electric grid resiliency modeling and simulation