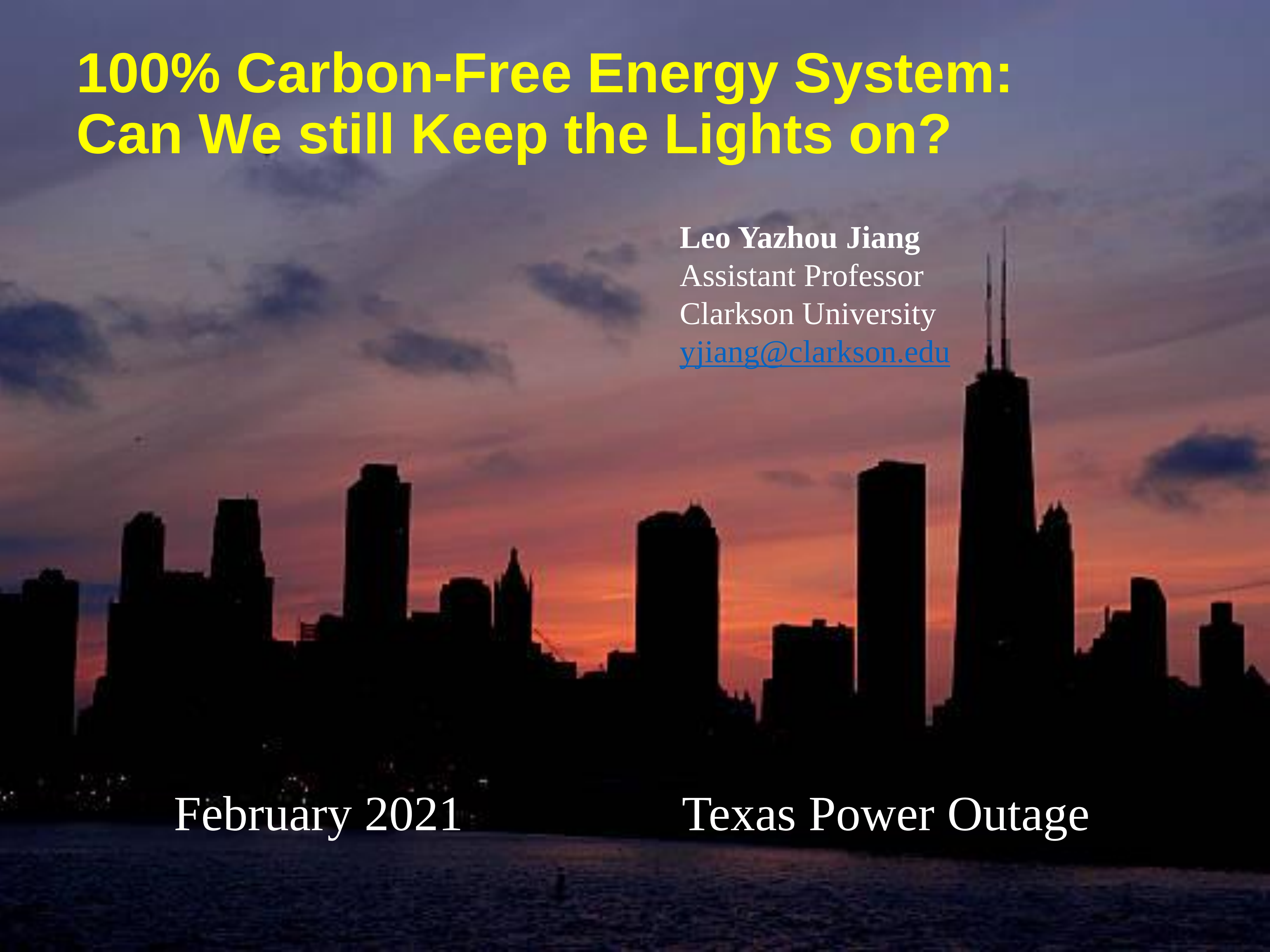
100% Carbon-Free Energy System: Can We still Keep the Lights on?



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February 2021

Texas Power Outage

Experience

2007

- ❑ Power

2012

- ❑ Power system restoration
- ❑ Distribution outage management
- ❑ GE DMS for smart city testbed

2016

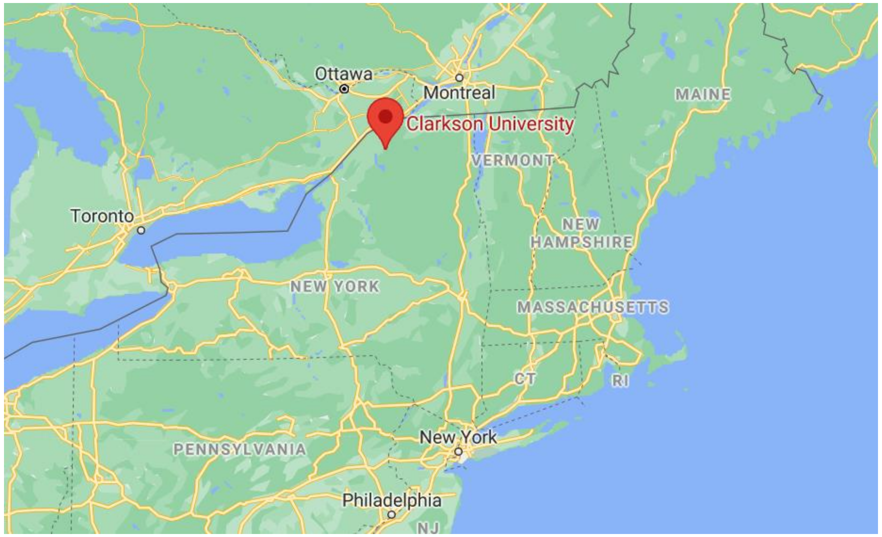
- ❑ Storage for improved grid reliability, dynamics and economics
- ❑ DG integration
- ❑ DERMS
- ❑ Flexible transformer for resiliency

2020

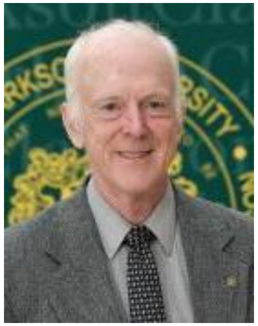
- ❑ Data analytics (intelligent alarms processing)
- ❑ Grid Operation under Uncertainties
- ❑ Fast power recovery
- ❑ Storage to support REWs

Disclaimer: no GE proprietary information has been included in this presentation.

Clarkson-Power Engineering



Center of Electric Power System Research
Core members



Tom Ortmeyer

Paul McGrath

Phil Barker

Jessica Zhang

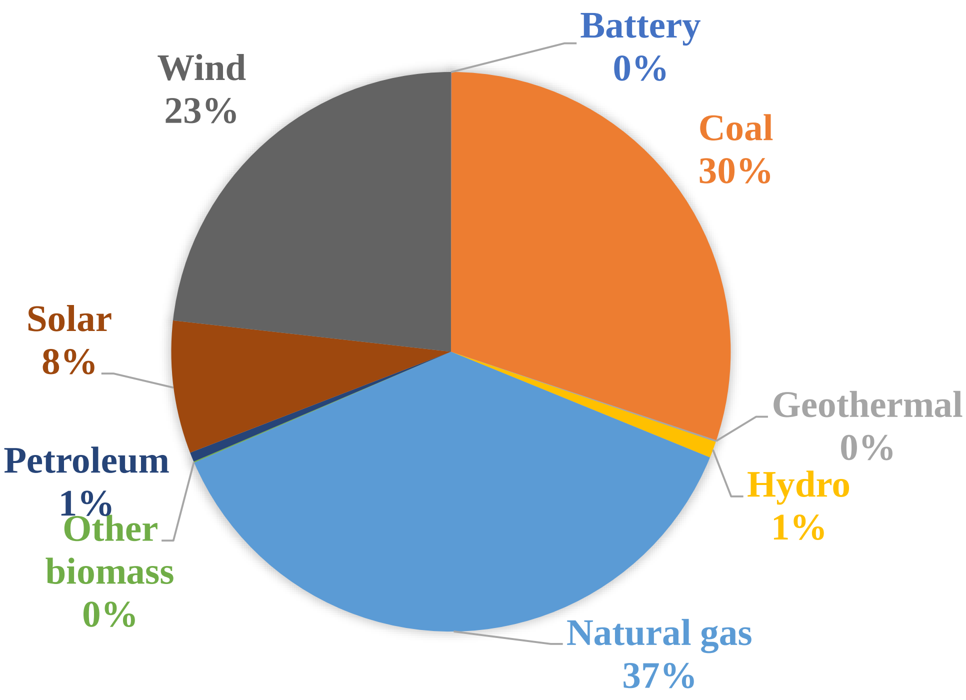
Leo Yazhou Jiang

Tuyen Vu

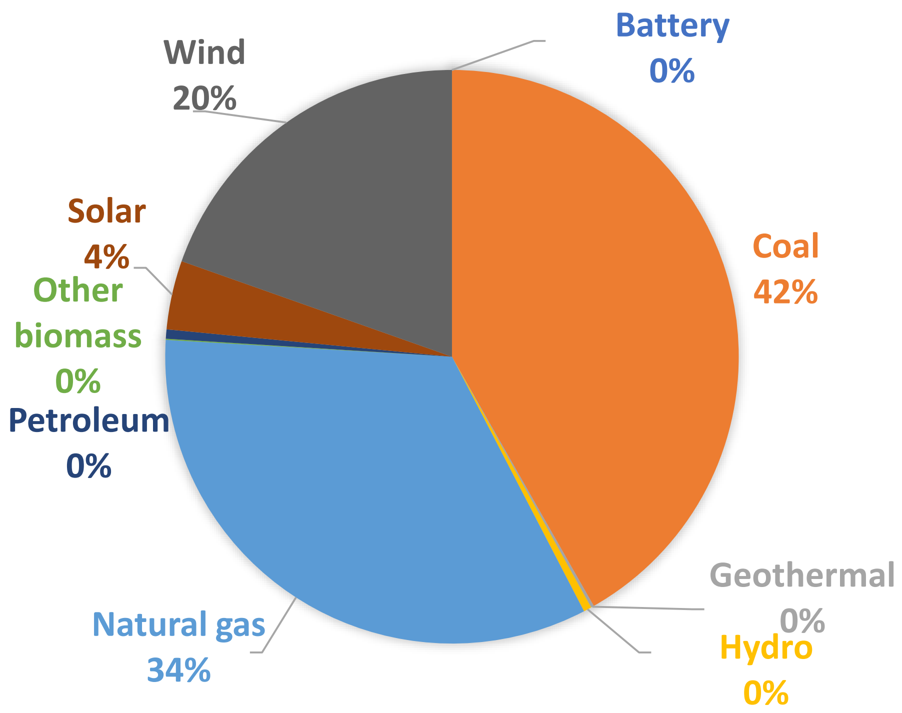
Long History of Power Engineering: a strength for future grid

Generation Mix in New Mexico

Generation Capacity by Fuel Type



Electricity by Fuel Type



Data Source: EIA

More engineering for grid decarbonization in NM

Clarkson

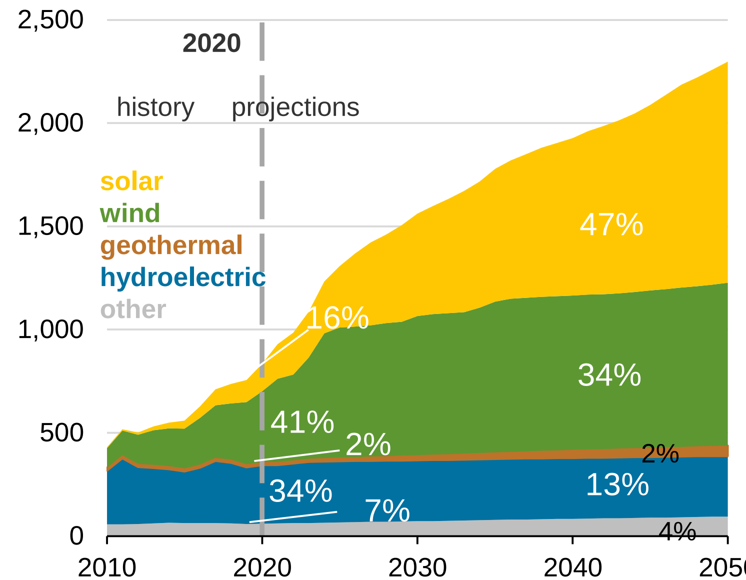
100% Carbon-Free in NM

RANK No.	TOTAL SCORE	SCHOOL
1	253.5	Rensselaer Polytechnic Institute
2	207.5	Missouri (Columbia)
3	196.0	Purdue
4	188.5	Pittsburgh
5	177.5	Texas (Arlington)
6	174.0	Massachusetts Institute of Technology
7	162.5	Iowa State
8	137.5	Southern California
9	127.5	Clarkson
10	119.5	Wayne State
11	119.0	Colorado
12	106.5	Texas Tech
13	101.5	Washington State
14	96.0	Missouri (Rolla)
15	94.5	Illinois
16	93.5	Tennessee
17	91.5	Ohio State
18	89.0	Northeastern
19	85.0	Virginia Polytechnic Institute
20	80.0	New Mexico State

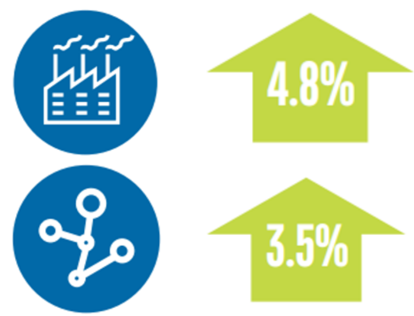
Figure 20 - Rank Based on Total Score in Twenty Criteria

L. Dwon, "Top 20 electric power engineering graduate schools and the selection parameters," IEEE Transactions on Power Apparatus and Systems, vol. 94, no. 1, 1975

U.S. renewable electricity generation



Source: 2021 U.S. EIA
2020 U.S. Energy Employment Report



Electric Power Generation Employment

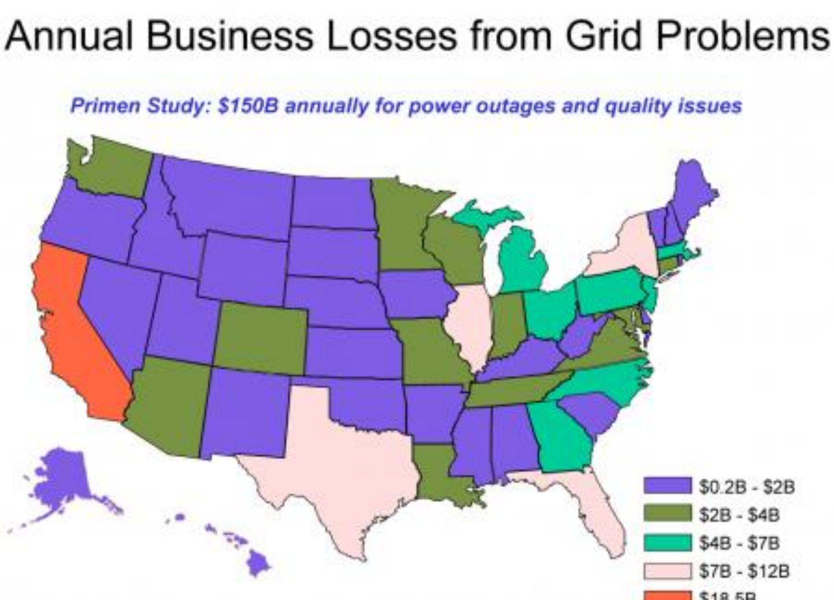
Transmission, Distribution and Storage

Rigorous Program for NM's goal of 50% renewable by 2030 and100% by 2045

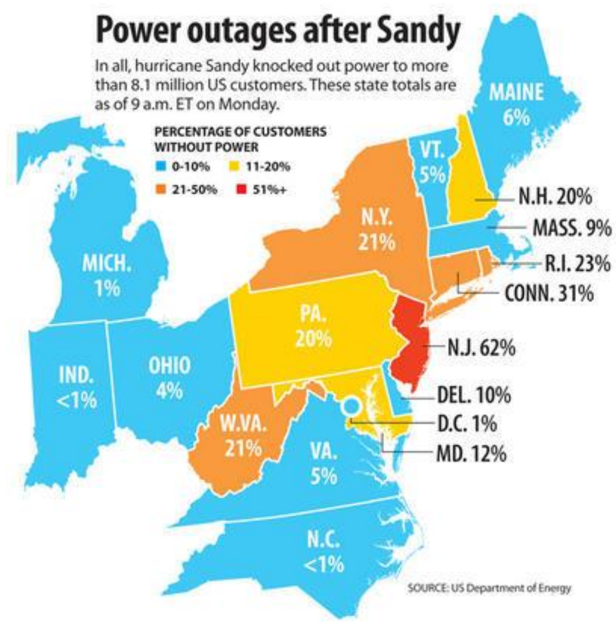
Blackouts

"…across all business sectors, the U.S. economy is losing between ***$104 billion*** and ***$164 billion*** a year to outages."

- Electric Power Research Institute (EPRI)



SOURCE-Forbes



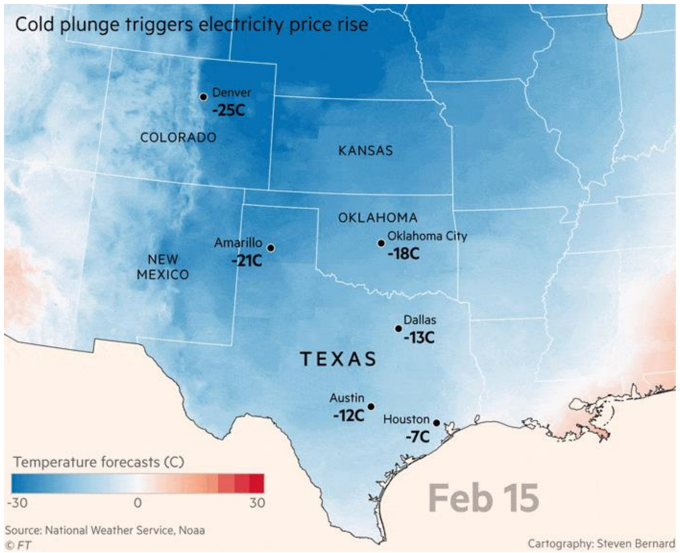
STATE	CURRENT CUTOMER OUTAGES
1. New Jersey	2,498,447
2. New York	1,967,874
3. Pennsylvania	1,267,512
4. Connecticut	626,440
5. Maryland	311,020
6. Massachusetts	298,072
7. Ohio	254,207
8. West Virginia	212,183
9. Virginia	182,811
10. New Hampshire	141,992
11. Rhode Island	116,308
12. Maine	90,727
13. Michigan	68,619
14. Delaware	45,137
15. Vermont	17,959
16. Indiana	7,537
17. North Carolina	4,005
18. District of Columbia	3,583

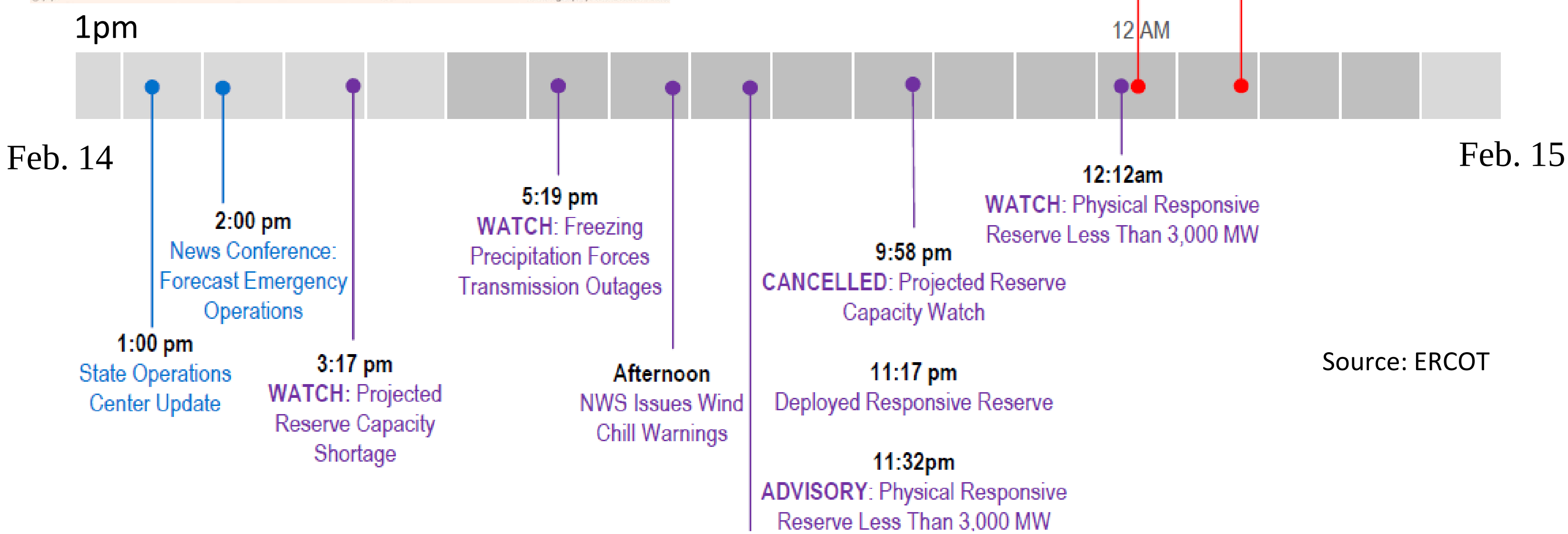
RICH CLABAUGH/STAFF

Ref: https://plus.google.com/104661774344420828388/posts/8RVM29NvkXT

Electricity: usually taken for granted until "Blackouts"

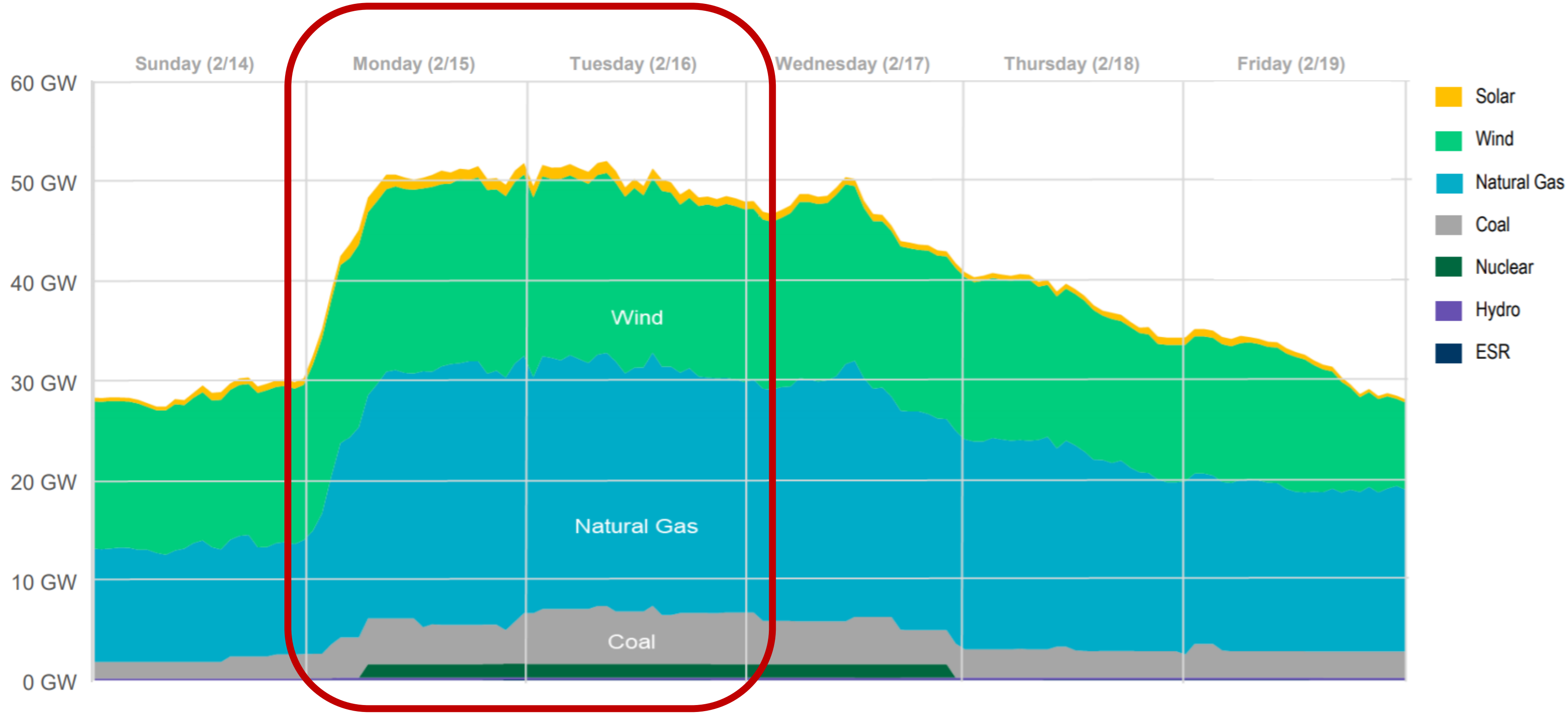
2021 Texas Blackout





Source: ERCOT

Net Generator Outages and Derates



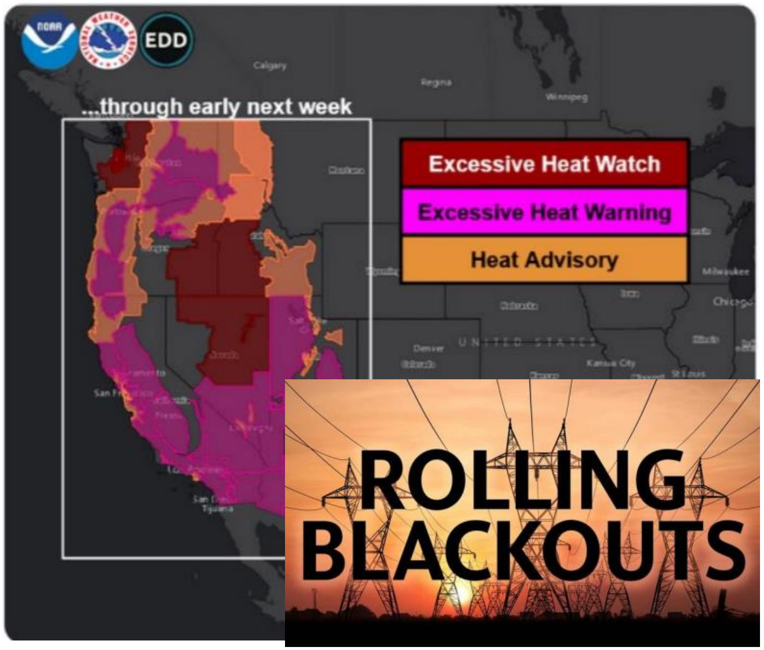
Source: ERCOT

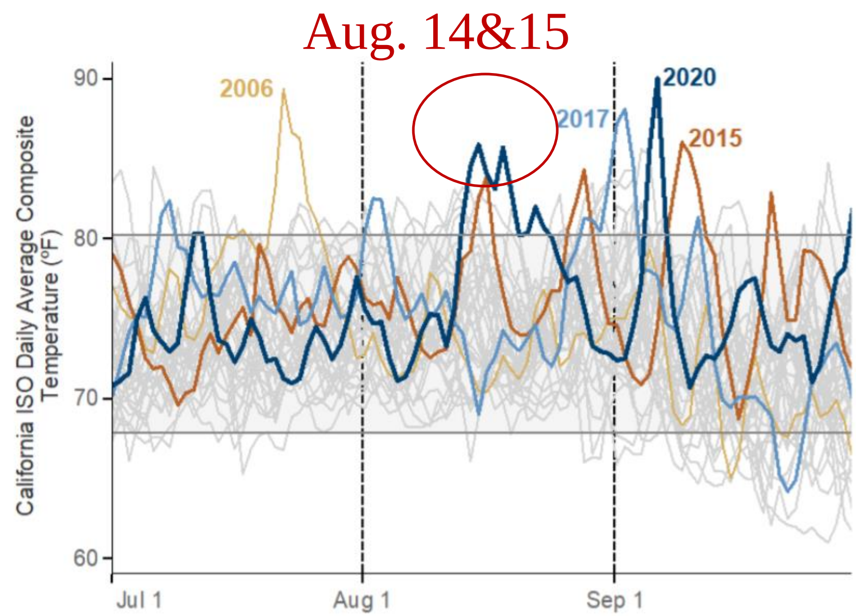
Peak Demand: ~75GW
Generation Capacity: ~107GW
Out Generation: ~52GW(48.6%)

~20GW Load Shedding

Insufficient generation to meet demand due to extremely cold weather

2020 California Rolling Blackout





Credit: final report, CEC

- ❑ The extreme heat wave experienced in August was a 1-in-30 year weather event in California
- ❑ This climate change-induced extreme heat wave extended across the Western United States

- ❑ Air conditioner was heavily used
- ❑ No demand response (reduction)
- ❑ Less efficient thermal generators (derated)
- ❑ Fires reduce solar generation
- ❑ State wide water resources 63% of average
- ❑ Variability of renewables

Heat wave led to reduced gen and increased demand!

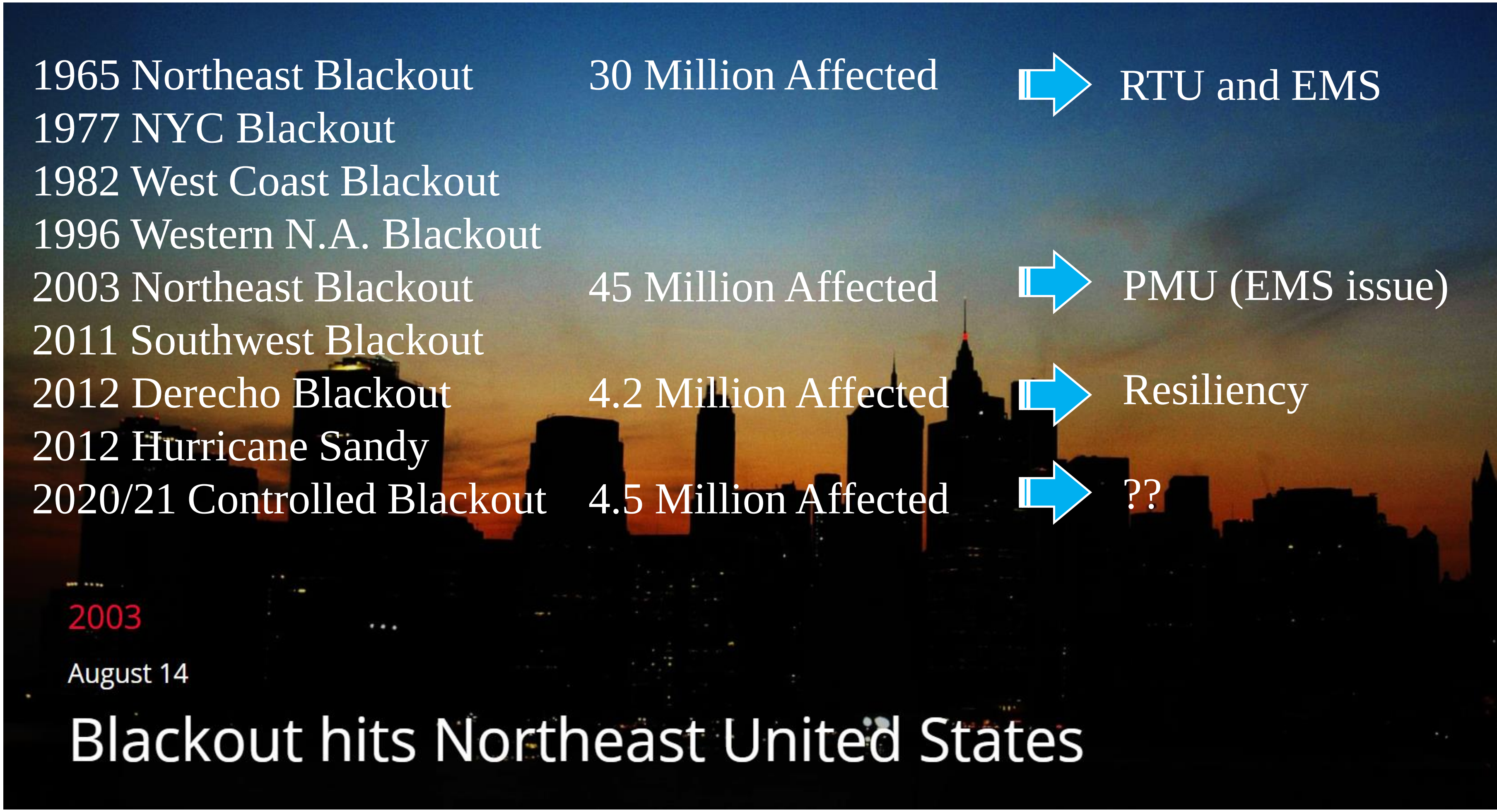
Blackouts in Texas and California

Blackouts	Texas	California
Cause	Extreme Cold Weather	Extreme Heat Wave
Generation	~52GW↓	Solar ↓, GT↓
Load	Load↑ (50% Texas homes use electricity for heating)	Load↑, air conditioning
Impact	Power outages for 4.5 million Texas homes (20 GW load shed)	~1GW load shed
Duration	Up to 4 days	Up to 1 hour

Engineering practices are challenged by extreme events to keep the lights on

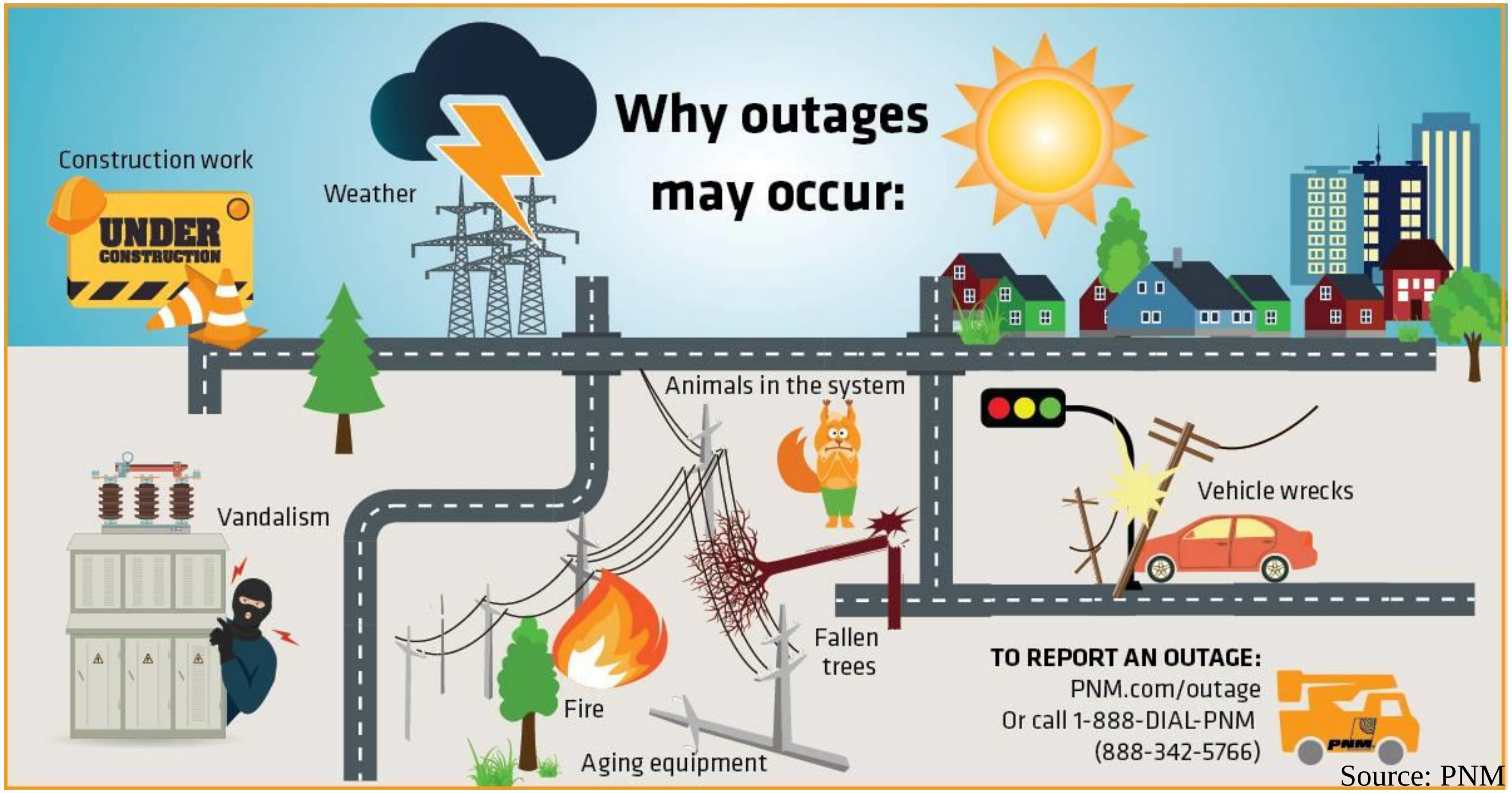
Historical Blackouts in the U.S.

1965 Northeast Blackout	30 Million Affected	RTU and EMS
1977 NYC Blackout		
1982 West Coast Blackout		
1996 Western N.A. Blackout		
2003 Northeast Blackout	45 Million Affected	PMU (EMS issue)
2011 Southwest Blackout		
2012 Derecho Blackout	4.2 Million Affected	Resiliency
2012 Hurricane Sandy		
2020/21 Controlled Blackout	4.5 Million Affected	??



Blackouts: a wakeup call for change of Grid

Root Causes of Power Outages



Source: PNM

Top 10 Root Causes of Outages

- Natural disasters
- Motor vehicle accidents
- Equipment failure
- Fallen trees
- Wildlife interference
- High energy demand
- Power line damage
- Damage from public
- Cyberattacks
- Planned power outages

Outage Management System (OMS) of Electric Power Distribution Systems

1. **Y. Jiang**, "Data-Driven Fault Location of Electric Power Distribution Systems with Distributed Generation," *IEEE Transactions on Smart Grid*, 2020
2. **Y. Jiang**, "Toward Detection of Distribution System Faulted Line Sections in Real-Time: A Mixed Integer Linear Programming Approach," *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 1039-1048, Jun. 2019
3. **Y. Jiang**, C. C. Liu, M. Diedesch, E. Lee, and A. Srivastava. "Outage Management of Distribution Systems Incorporating Information from Smart Meters," *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 4144-4154, Sept. 2016
4. **Y. Jiang**, C.C. Liu, and Y. Xu. "Smart Distribution Systems," *Energies*, vol. 9, no. 4, Apr. 2016

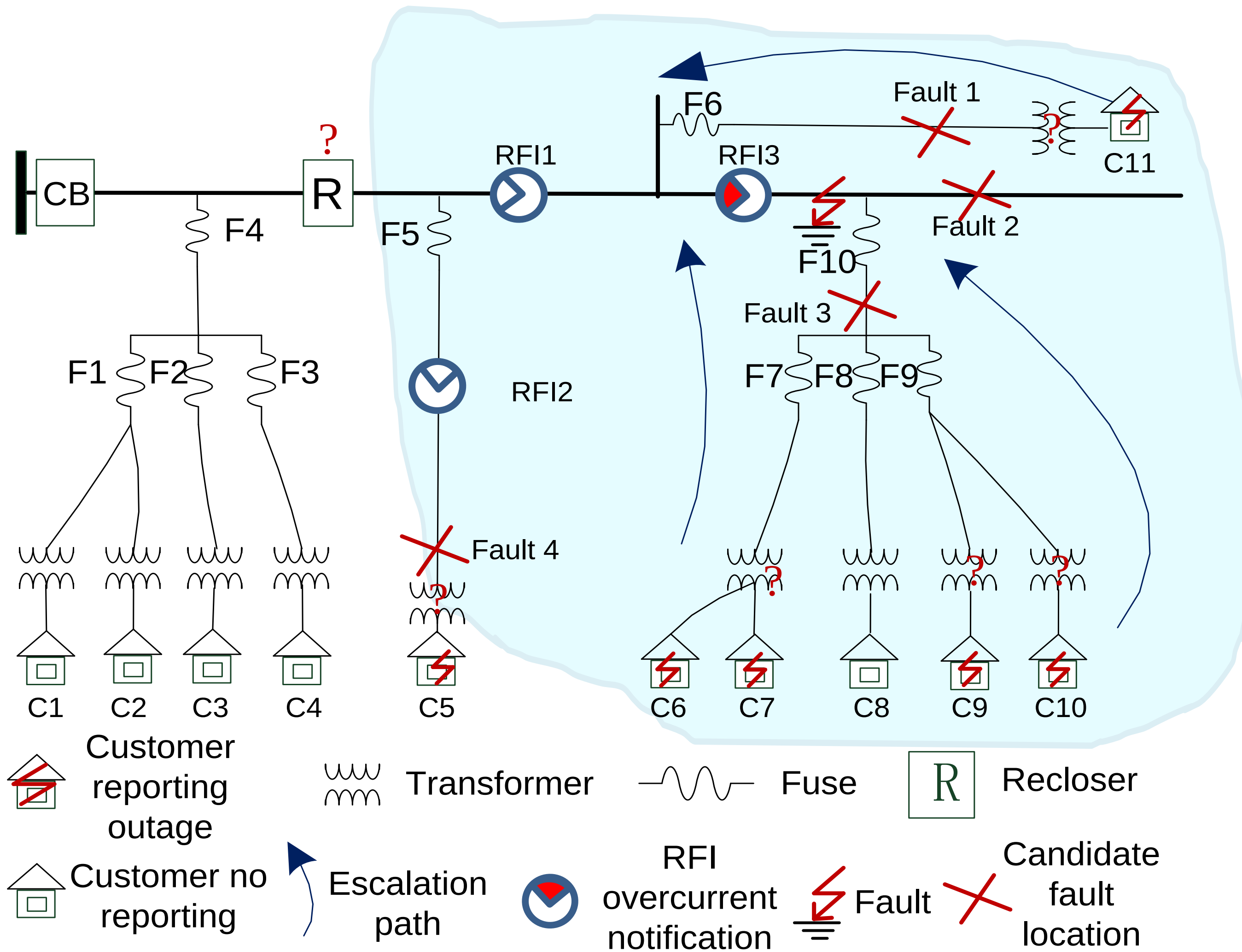
Energy Meters

Analog Meter	AMR Meter	Smart Meter
Electromagnetic Sensor	Digital IC sensor	Digital IC Sensor
Regular Visits for Maintenance and Meter Readings	Automated Meter Readings	Automated Meter Readings
	One-Way Communication	Customer’s Info.
		Two-Way Communications

New Mexico: **62% (665,660)** **26% (281,830)** **12% (131,043)**

~94.8 million smart meters have been installed in the U.S. by 2019

Outage Management of Distribution Systems



How to use meter data to infer the outage scenario?

Optimization for Outage Manageent

Maximize   the credibility of the outage scenario

Subject to:

i) the fault indicators sending flags should be upstream of the faulted line section

ii) the activated protective device should be upstream of the faulted line section

iii) the number and locations of multiple faults

iv) the number and locations of fault indicator failures

v) the number of protection miscoordination pairs

vi) missing outage reports from smart meters

vi) missing outage reports from smart meters

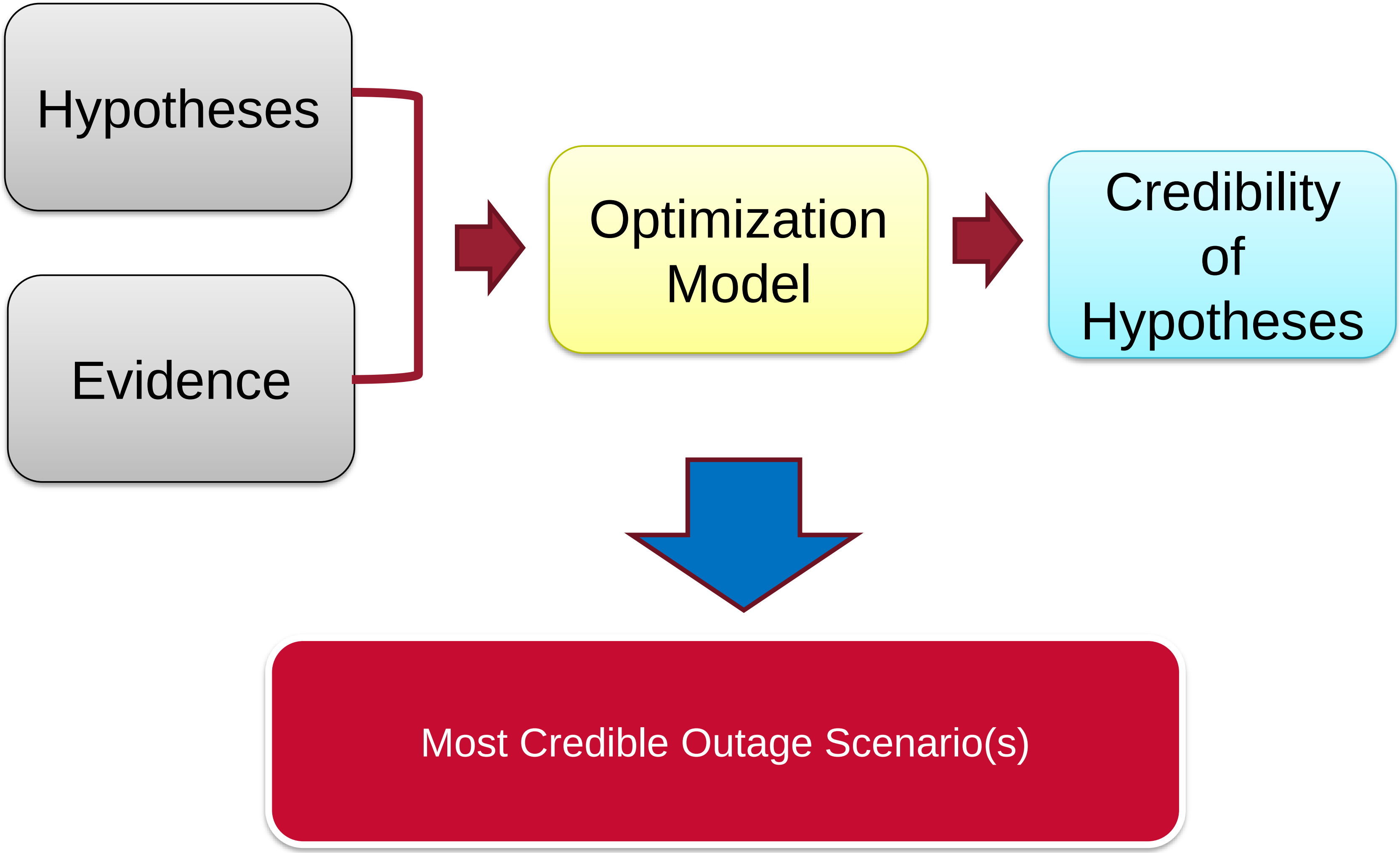
Logical constraints

Generate hypotheses

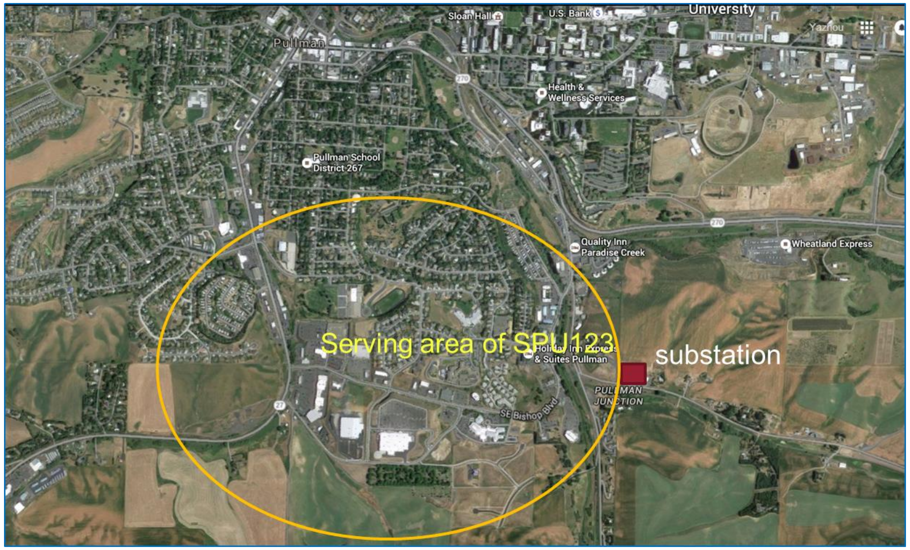
In objective function

Challenges: nonlinearity, computational complexity, local optimality

Multiple-Hypotheses Analysis

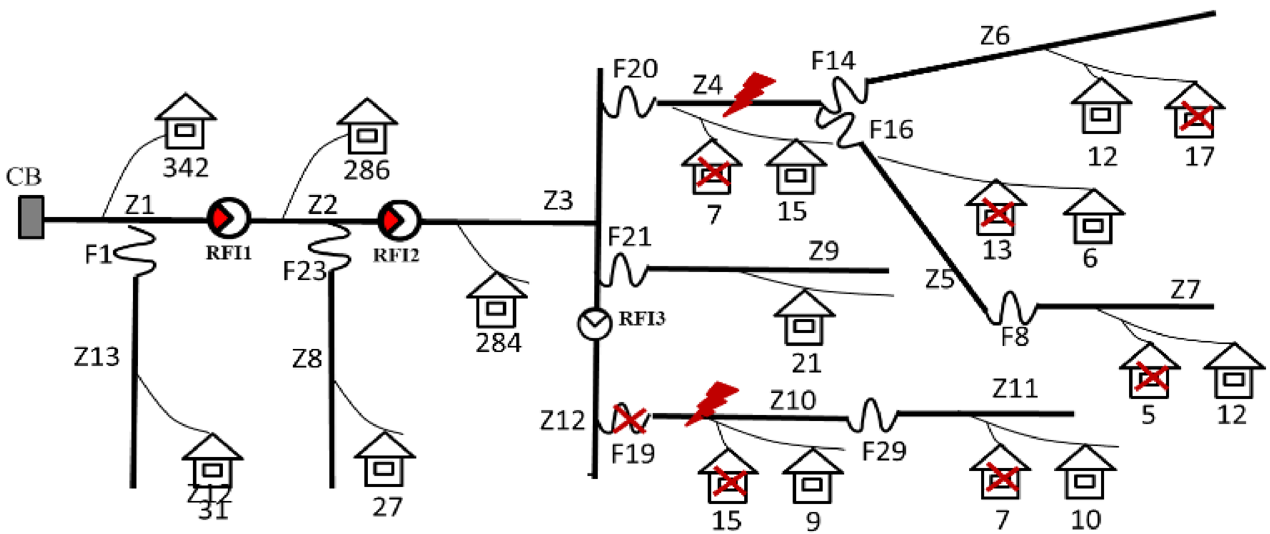


Real-World Distribution Feeders



True outage scenario:

- Two faults occur at Link4 and Link10;
- Fuse20 and Fuse19 are activated;
- 64 smart meter outage reports
- Fault current notifications from feeder sensors



Outage Management Results

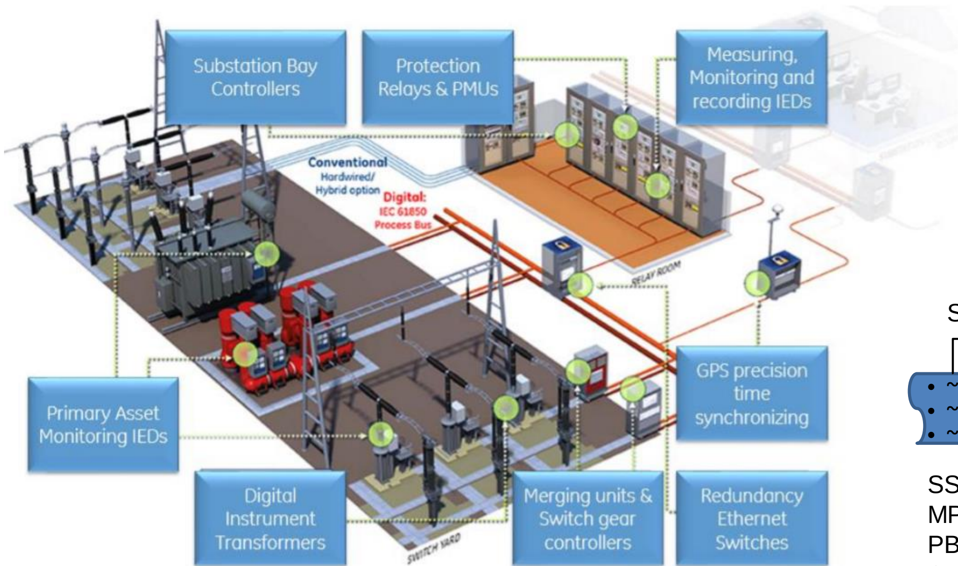
Hypo.	Actuated device(s)	Faulted section(s)	$N_{SM-Correct}$	$N_{SM-Unreport}$	$N_{SM-Incorrect}$	Abnormality of fault indicator failures and protection miscoor.	Cred.
1	Fuse19	Link10	22	19	44	$\varnothing$	0.232
2	Auto.R2	Link12	64	570	2	R2-R3 miscoor.	0.549
3	Auto.R2	Link3	64	570	2	R3 should not send a flag	0.424
4	Auto.R1	Link3	66	881	0	R2-R1 miscoor. and R3 should not send a flag	0.410
5	Fuse19 and Fuse20	Link4 and Link10	64	64	2	$\varnothing$	0.742
6	Auto.R2 and Fuse23	Link8 and Link12	66	595	0	R3-R2 miscoor.	0.550
7	Auto.R2 and Fuse23	Link3 and Link8	66	595	0	R3 should not send a flag	0.425
8	Auto.R2 and Fuse23	Link4/9 and Link8	66	595	0	Fuse20/21-R2 miscoor. and R3 should not send a flag	0.425

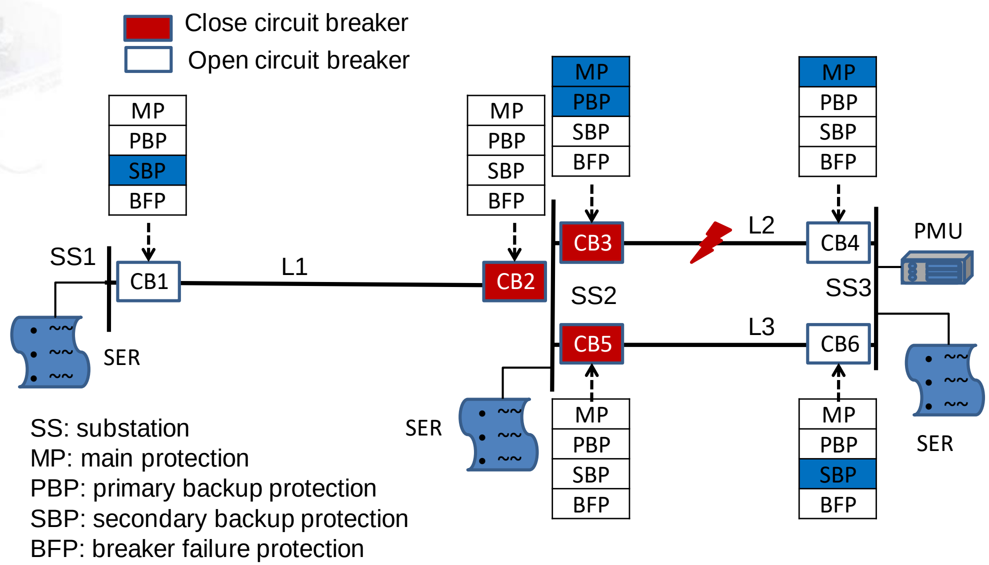
- The true outage scenario that Fuse19 and Fuse20 melted to isolate the faulted line sections of Link4 and Link10 is captured;
- The two false outage reports from smart meters are identified.

Outage Management of Transmission Systems

1. **Y. Jiang,** and A. Srivastava, "Data-Driven Event Diagnosis in Transmission Systems with Incomplete and Conflicting Alarms Given Sensor Malfunctions," *IEEE Transactions on Power Delivery*, 2019
2. **Y. Jiang**, S. Chen, C.C. Liu, W. Sun, X. Luo, S. Liu, N. Bhatt, S. Uppalapati, and D. Forcum, "Blackstart Capability Planning for Power System Restoration," *International Journal of Electrical Power & Energy Systems*, vol. 86, pp. 127-137, Mar. 2017
3. **Y. Jiang**, G. Wang, S. Roy, and C.C. Liu, "Power System Severe Contingency Screening Considering Renewable Energy," *Proceedings of the 2016 IEEE PES General Meeting*, Boston, MA

Transmission Automation





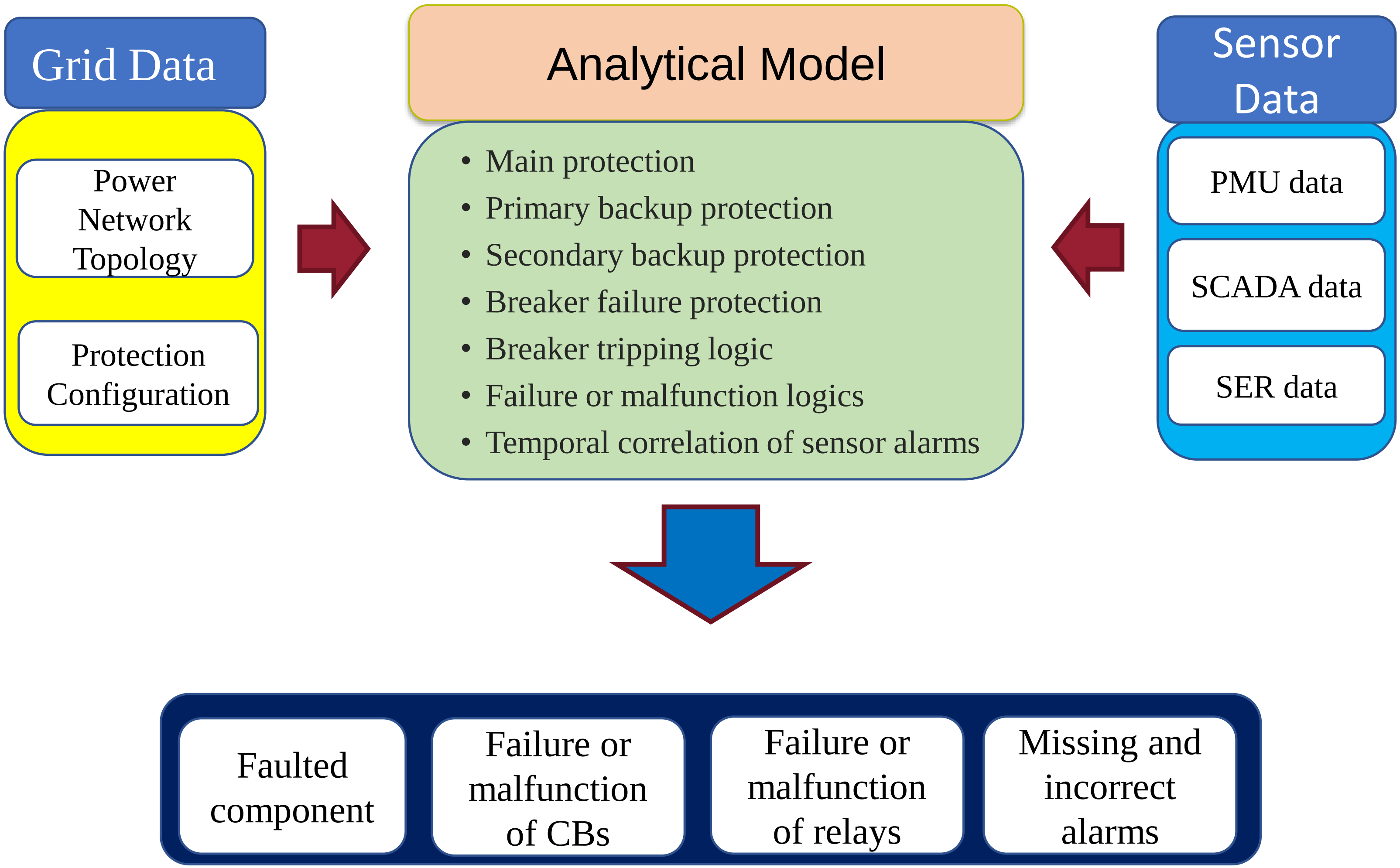
Source: Securing IEDs against Cyber Threats in Critical Substation Automation and Industrial Control Systems by Pubudu Eroshan Weerathunga and Anca Cioraca

- Phasor Measurement Unit (PMU)
- Digital Relays
- Intelligent Electronic Device (IED)

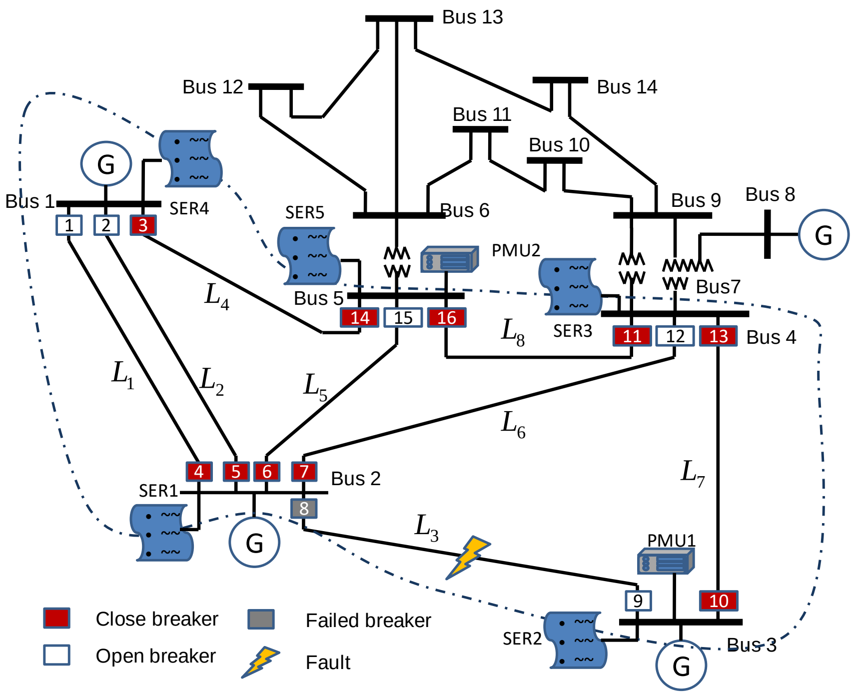
- Protection for grid assets
- Main protection
- Primary backup protection
- Secondary backup protection
- Breaker failure protection

Data analytics + domain knowledge for grid challenges.

Transmission Event Diagnosis



Event Diagnosis Results



Alarms	Time Tags	Alarms at Control Center
SERs	11:12:1:200	MP of CB9 operated
	11:12:1:233	CB9 operated to open
	11:12:1:700	SBP of CB12 operated
	11:12:1:701	SBP of CB1 and CB2 operated
	11:12:1:702	SBP of CB15 operated
	11:12:1:734	CB1 and CB2 open
	11:12:1:735	CB15 operated to open
	11:12:1:835	CB12 open
PMU	11:12:1:233	CB9 tripped open from PMU1
	11:12:1:735	CB15 tripped open from PMU2
SCADA		CB1, CB2, CB9, CB12, CB15 open

Fault occurrence t	11:12:1:200
Faulty Component	L3
Failed Relay	Main Protection and Primary Backup protection for CB8
Malfunctioned relay	None
Failed CB	None
Malfunctioned CB	None
Missing alarm	None
Incorrect time tag	CB12

Handle complex scenarios with abnormalities

What if cascading events leading to system wide blackouts?

Power System Restoration

Generator Restoration → System Restoration → Load Restoration

Generator Restoration

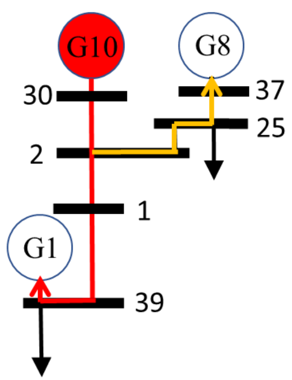
1. Determine system status
2. Restart generators
3. Identify cranking paths

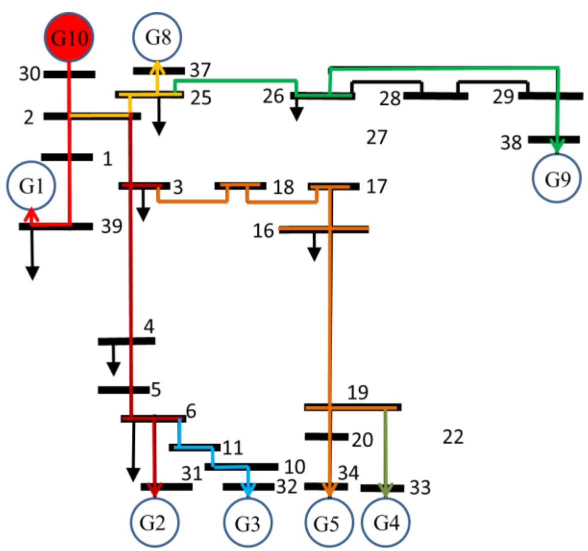
System Restoration

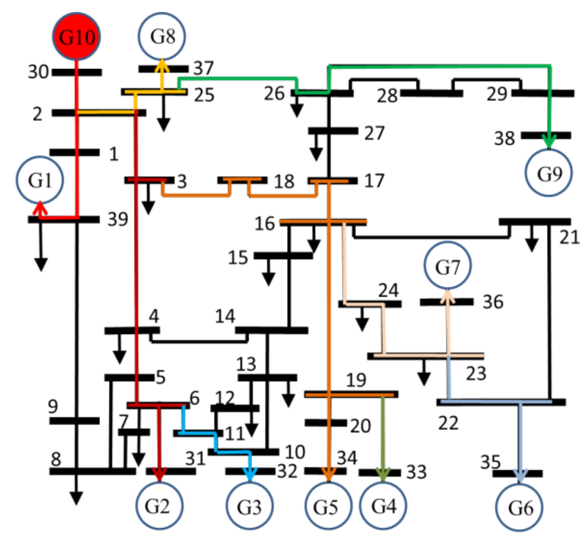
1. Energize networks
2. Restore sufficient loads
3. Synchronize islands

Load Restoration

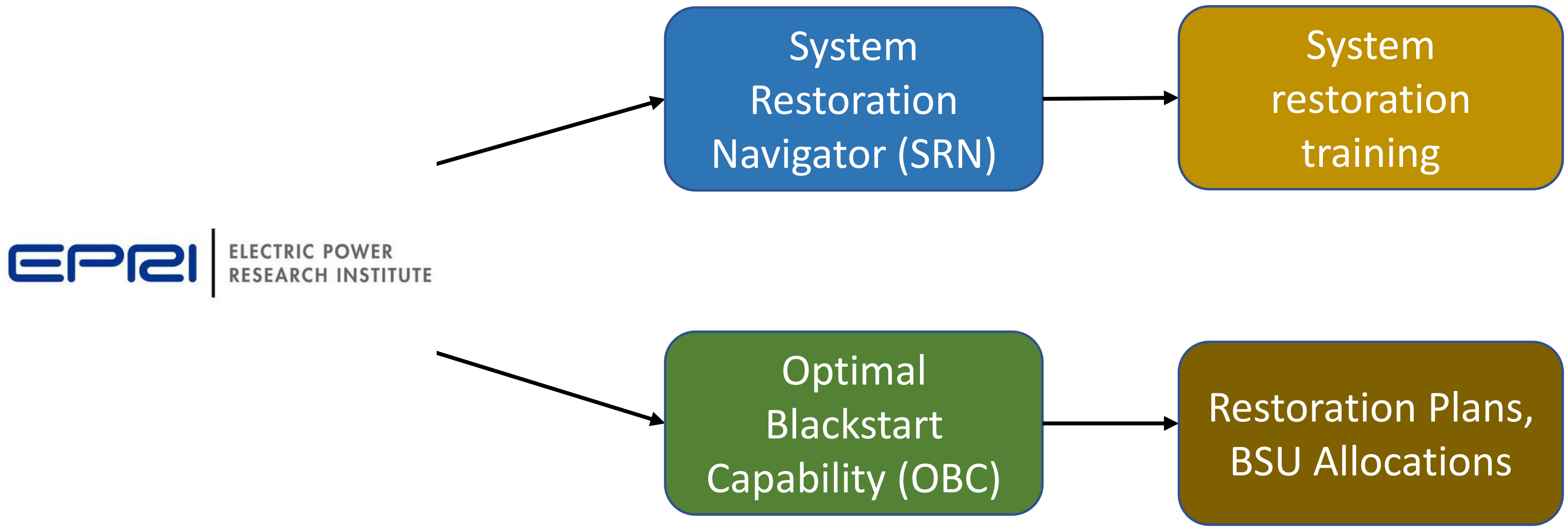
1. Schedule load pickup
2. Minimize unserved loads







Optimal Blackstart Capability (OBC)



EPRI – OBC Tool

Case Study-Blackstart Unit Allocation

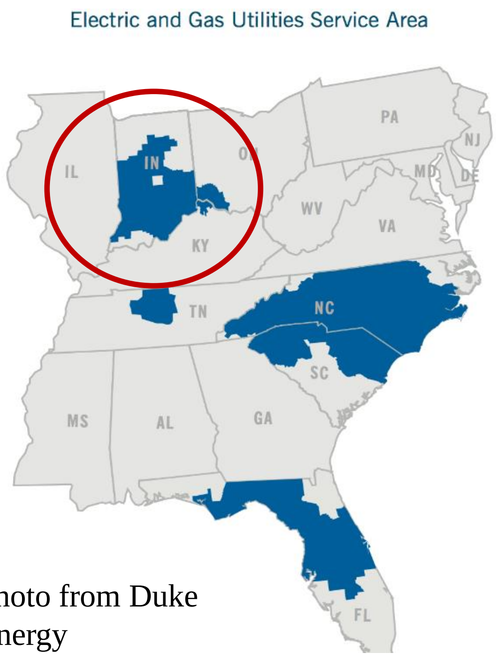
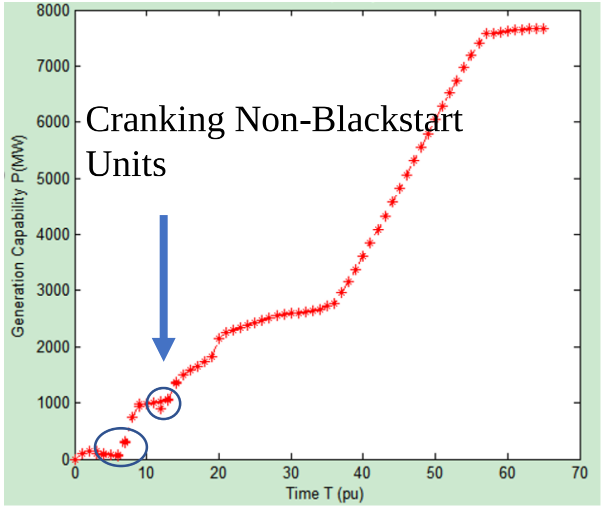
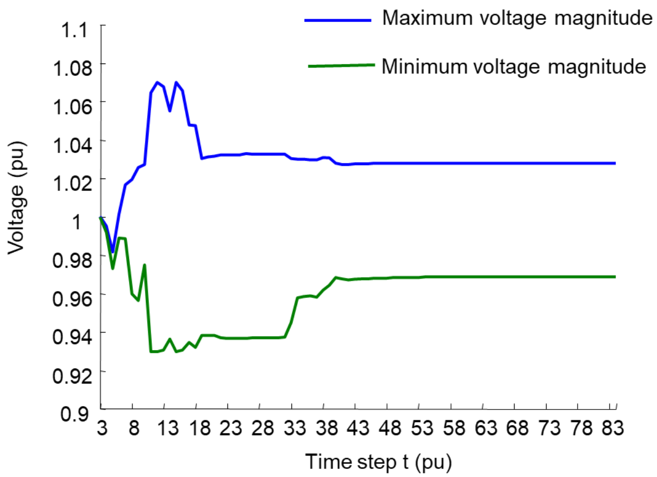


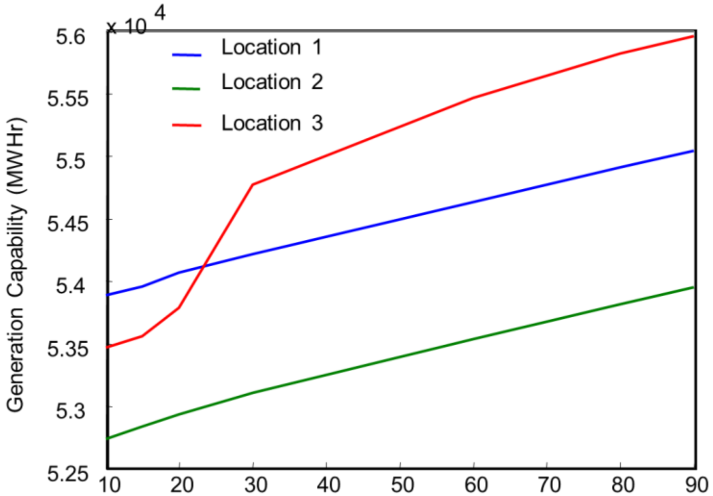
Photo from Duke Energy





Duke-Energy Indiana System

- 37 NBSUs,
- 348 buses
- 397 transmission lines



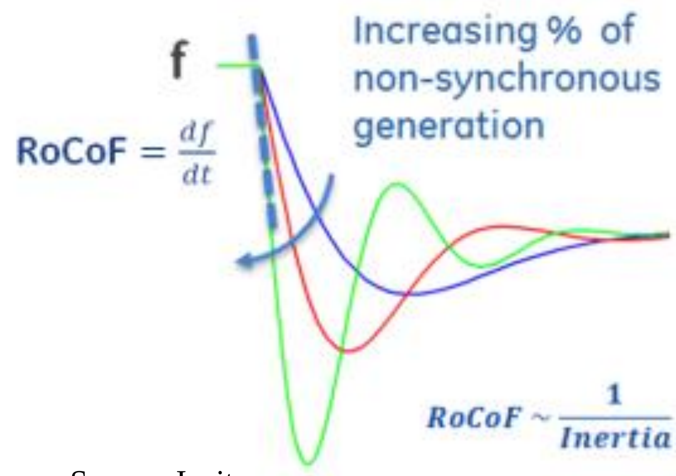
- Location 3 is more superior than other locations if the capacity of BSU is greater than 24 MW.

A tool to assist in blackstart resource allocation

Grid of the Future: Challenges

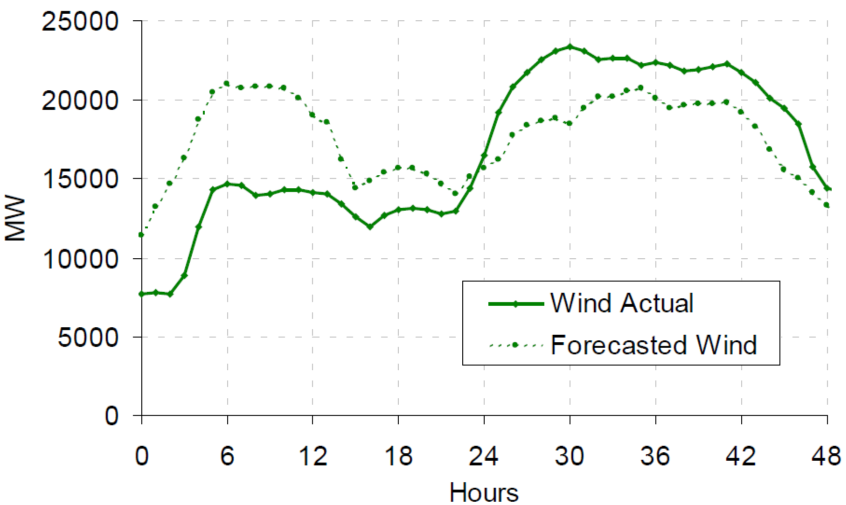
- ❑ Low Inertia
- ❑ Variability
- ❑ Uncertainties

- ❑ Engineering practices/controller based on conventional generation resources

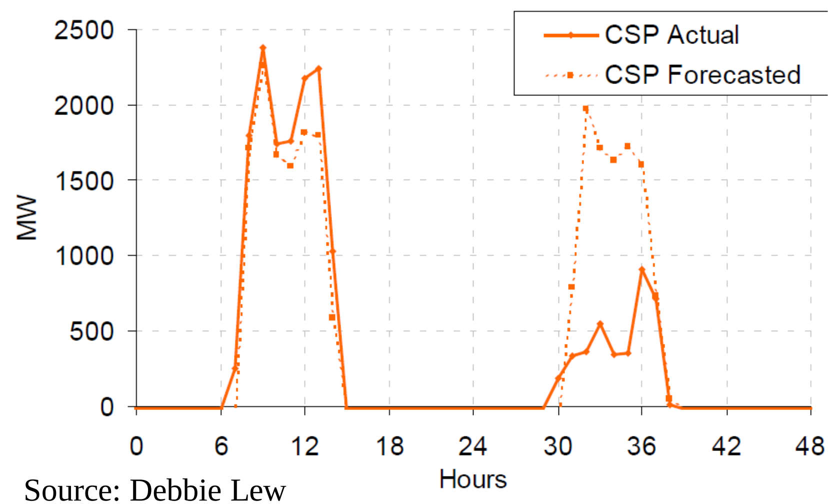


Source: Incite

Uncertainty



Variability



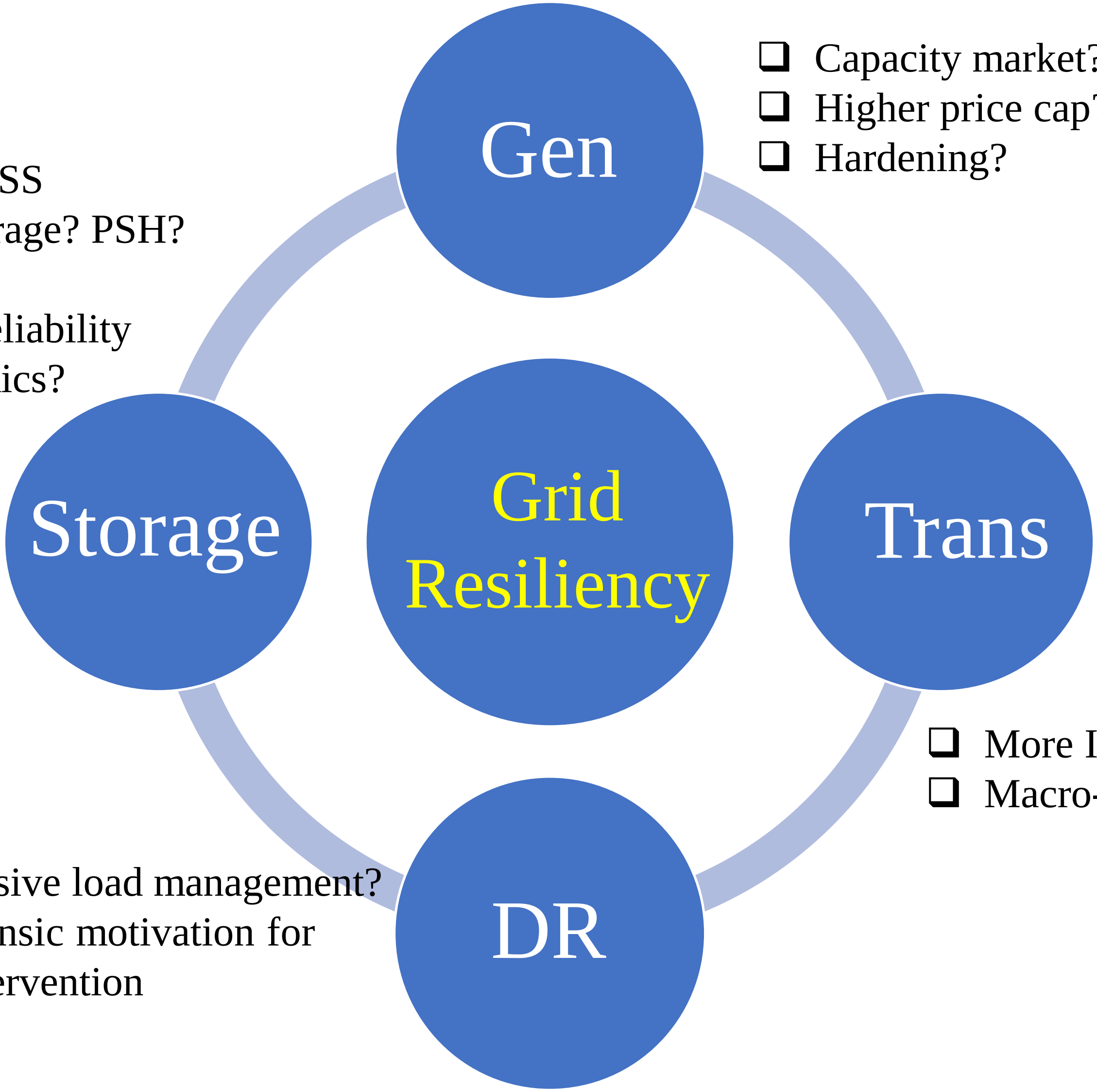
Source: Debbie Lew

Complex system behavior is a challenge

Keep the Lights On?

- ❑ Short-term BESS
- ❑ Long-term storage? PSH? Hydrogen?
- ❑ Dispatch for reliability versus economics?

- ❑ Capacity market?
- ❑ Higher price cap?
- ❑ Hardening?

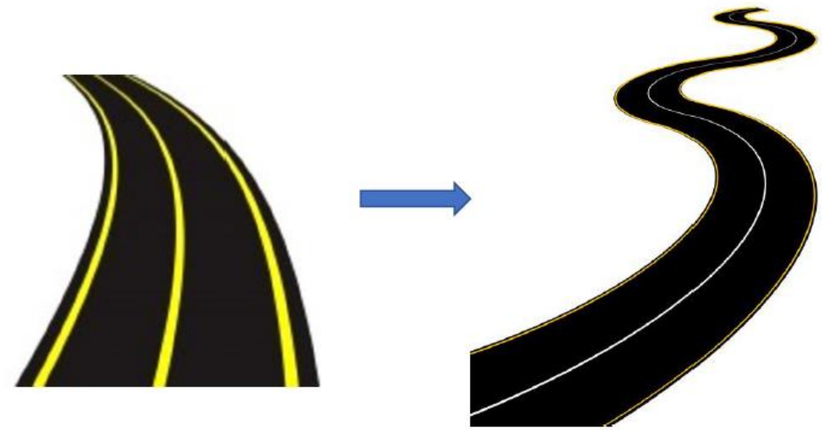


- ❑ More Inter-tied?
- ❑ Macro-grid?

- ❑ Price responsive load management?
- ❑ Internal/intrinsic motivation for behavior intervention

Resilient Carbon-Free Power Grid of the Future

**100% Carbon Free Energy System:
can we still keep the lights on?**

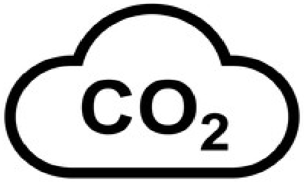


- ❑ Dream big
- ❑ Act on science/engineering

Lower Energy **Cost**

Keep the **Lights On**

Reduce **Carbon Emission**



Further Reading

1. **Y. Jiang**, “Probabilistic Fault Location of Electric Power Distribution Systems with Data Uncertainties,” *IEEE Transactions on Smart Grid*, 2021
2. **Y. Jiang**, “Data-Driven Fault Location of Electric Power Distribution Systems with Distributed Generation,” *IEEE Transactions on Smart Grid*, 2020
3. **Y. Jiang**, “Toward Detection of Distribution System Faulted Line Sections in Real-Time: A Mixed Integer Linear Programming Approach,” *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 1039-1048, Jun. 2019
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5. **Y. Jiang**, S. Chen, C.C. Liu, W. Sun, X. Luo, S. Liu, N. Bhatt, S. Uppalapati, and D. Forcum, “Blackstart Capability Planning for Power System Restoration,” *International Journal of Electrical Power & Energy Systems*, vol. 86, pp. 127-137, Mar. 2017
6. **Y. Jiang**, C. C. Liu, M. Diedesch, E. Lee, and A. Srivastava. “Outage Management of Distribution Systems Incorporating Information from Smart Meters,” *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 4144-4154, Sept. 2016
7. **Y. Jiang**, C.C. Liu, and Y. Xu. “Smart Distribution Systems,” *Energies*, vol. 9, no. 4, Apr. 2016
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Clarkson