REINHOLD ENVIRONMENTAL ®

2023 Reinhold/PCUG Round Table Presentation

Cohosted by Duke Energy and Vistra in The Westin Hotel, Cincinnati, OH on June 26-27, 2023

Reliability During the Energy Transition

Challenges around the World

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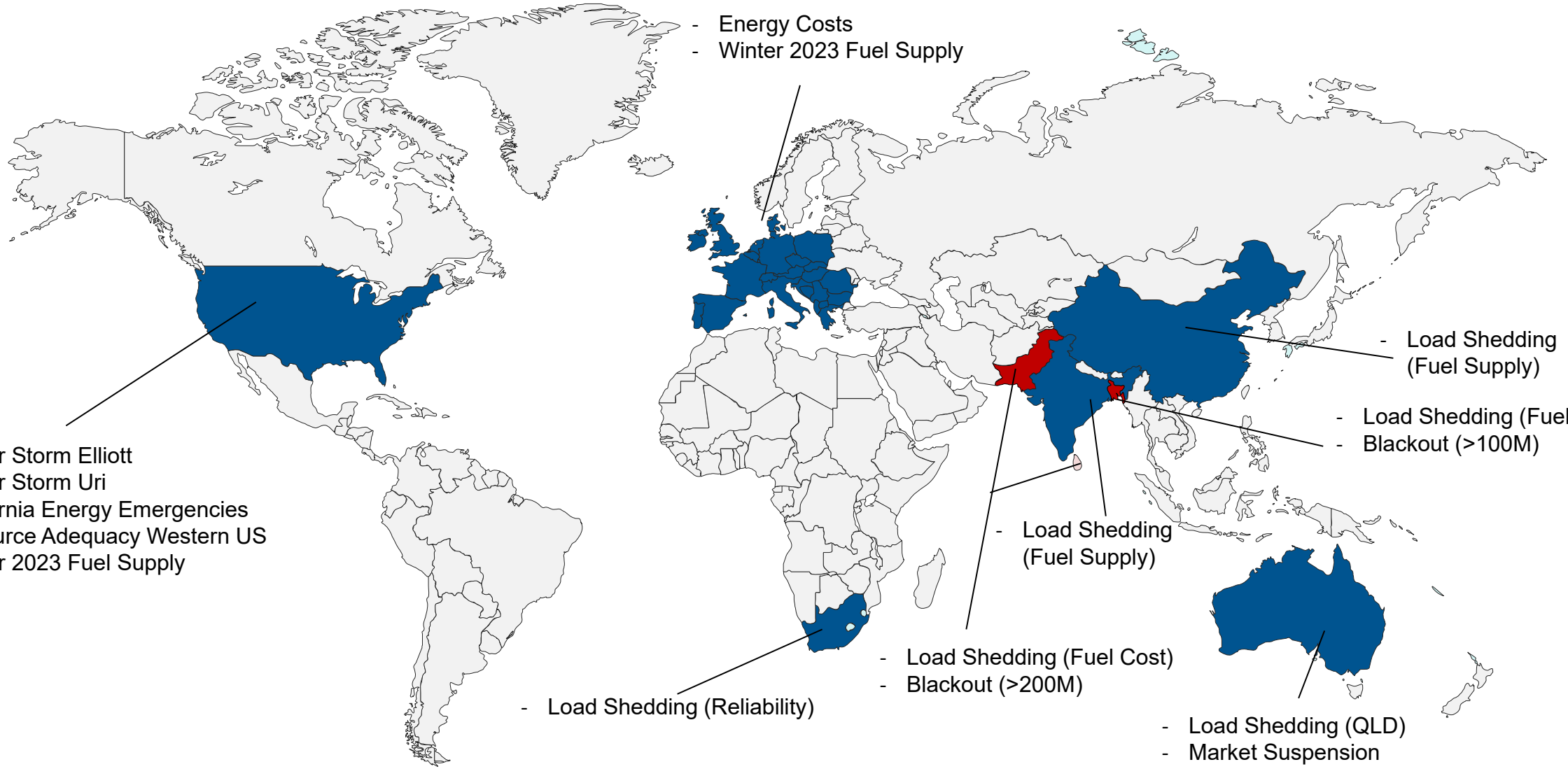
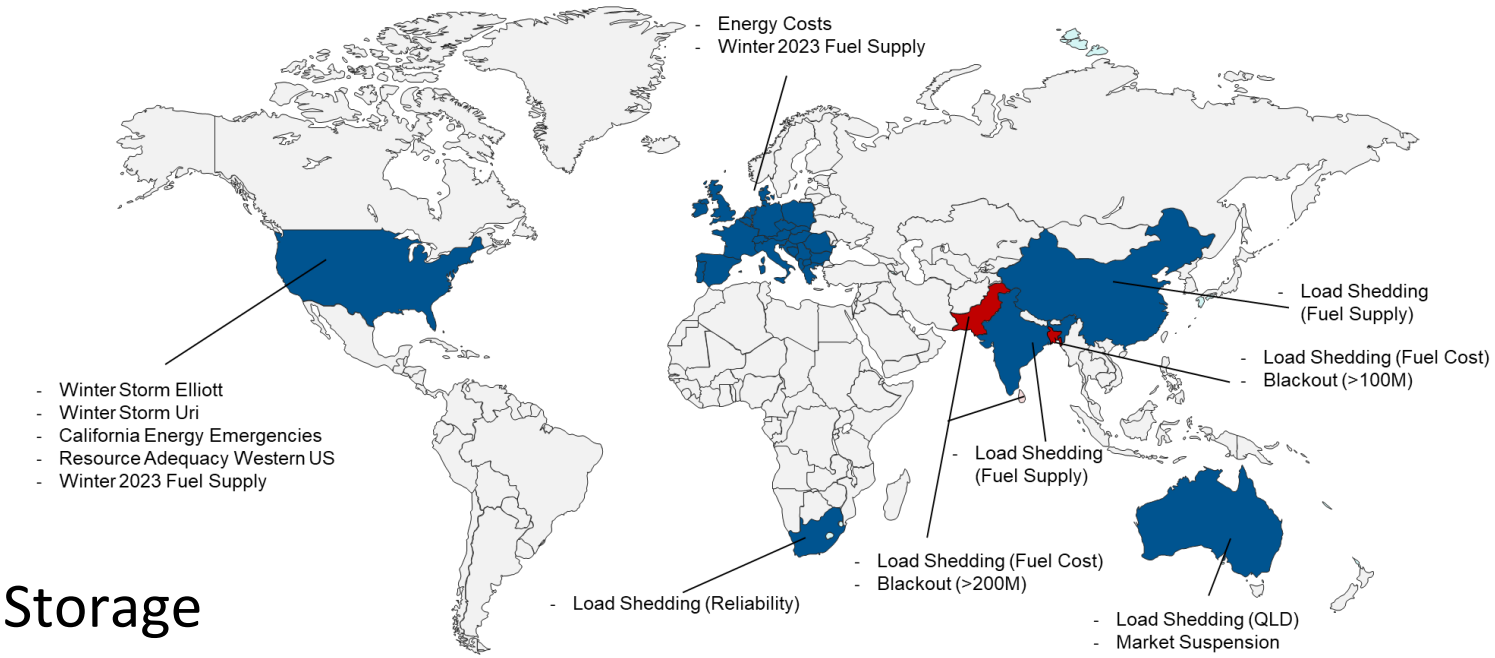
June 2023

Global Challenges



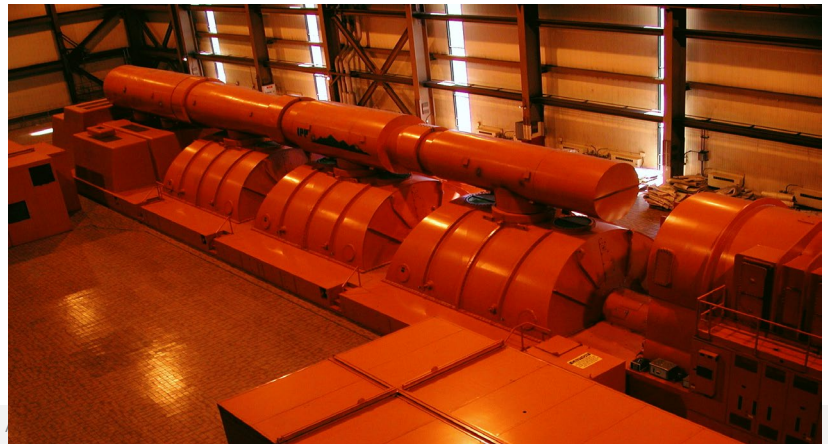
Energy Security

- Oil Security
  - Inventories (90 day)
- Natural Gas Security
  - Scenario Analysis
    - Pipelines / LNG Terminals / Storage
- Electricity Security
  - Minutes on Marginal Days
    - Interdependencies



50 or 60 Hz

Hz = Cycles per Second



Pipeline Electric Gas Compressors

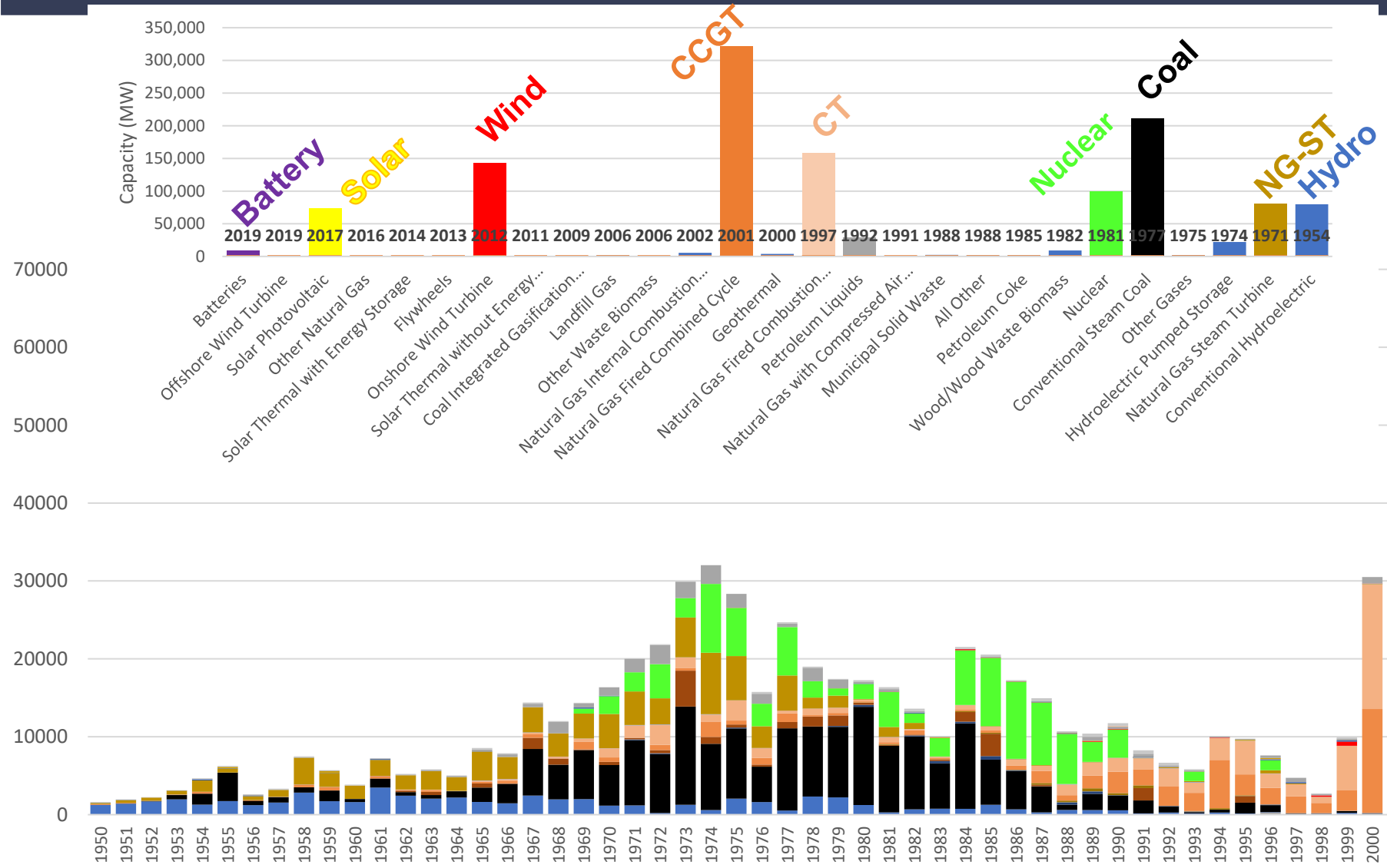
Battery Backup for Cellular Towers

USA
Evolving Fleet

US Capacity Details

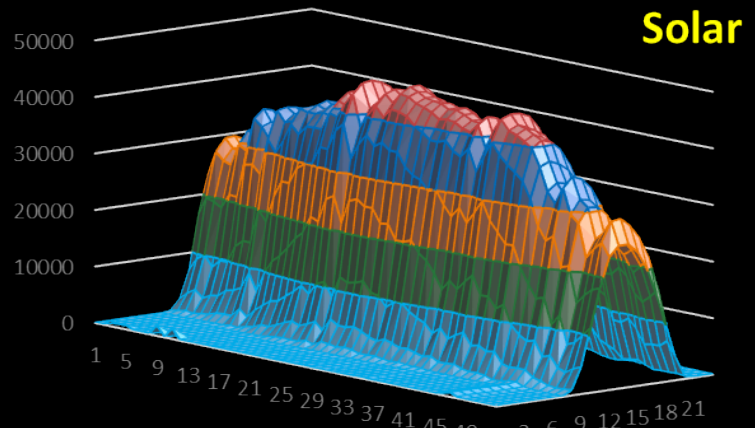
Few New Thermal Asset

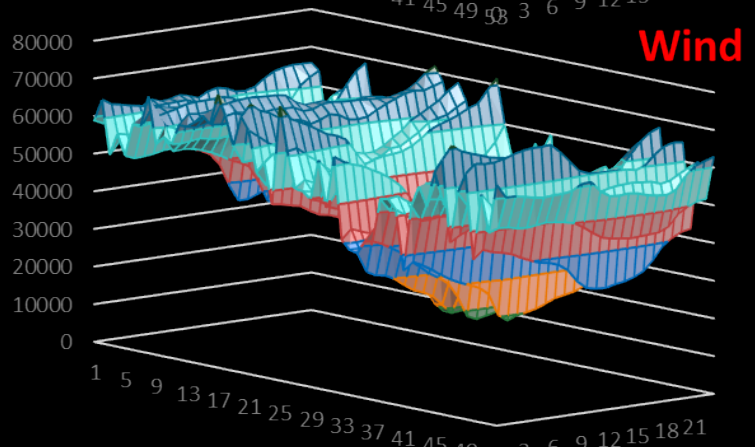
New Assets are more Variable

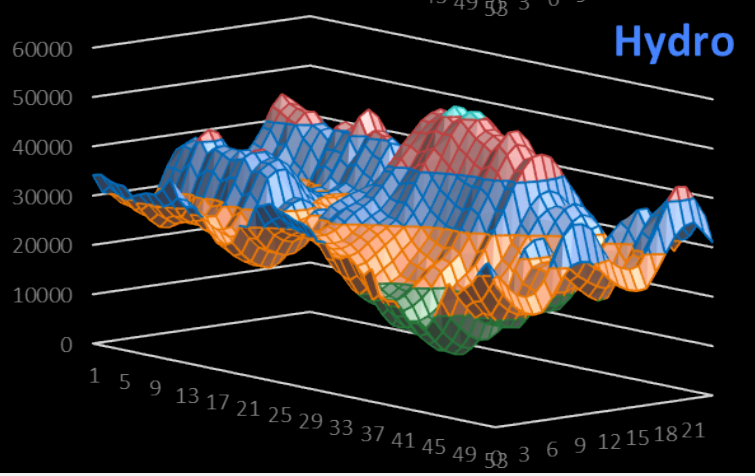


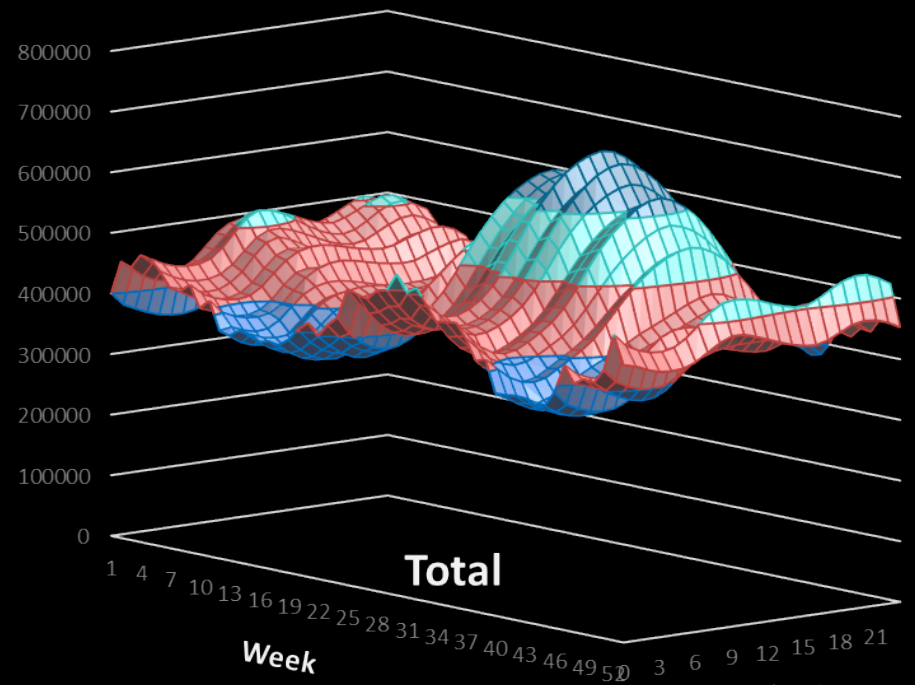
Wind and Solar outpacing all others 2019 forward, batteries beginning to pick up 2021

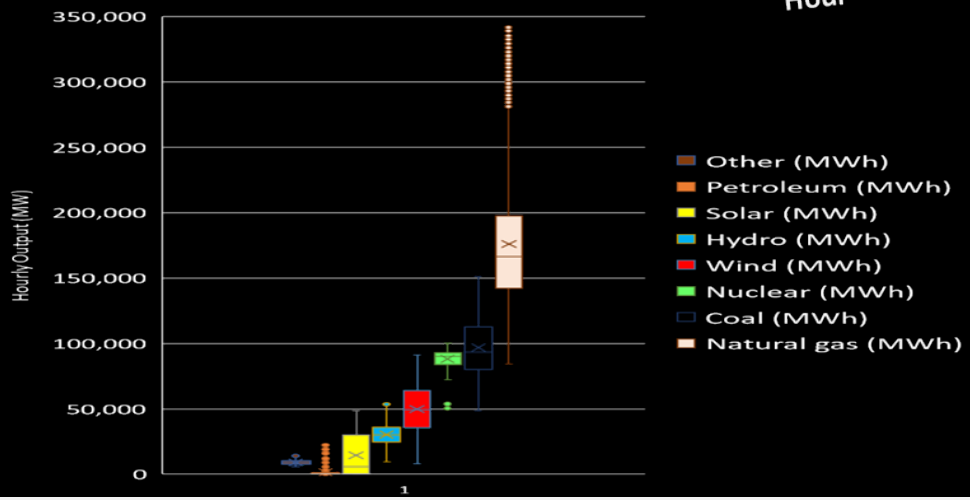
US Lower 48
2022 Shape of Generation

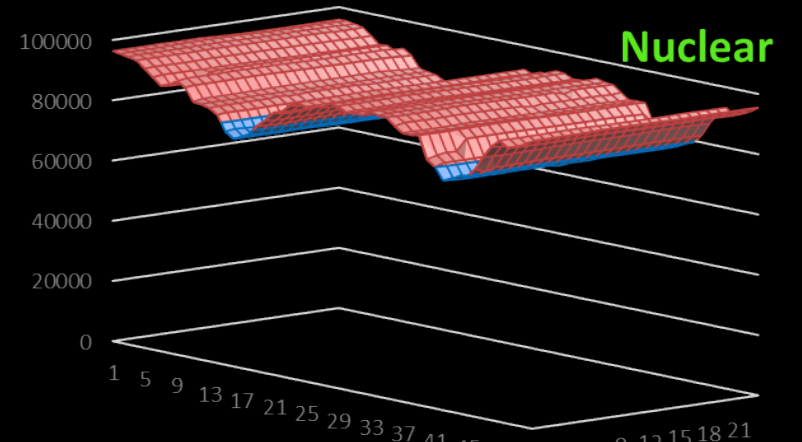


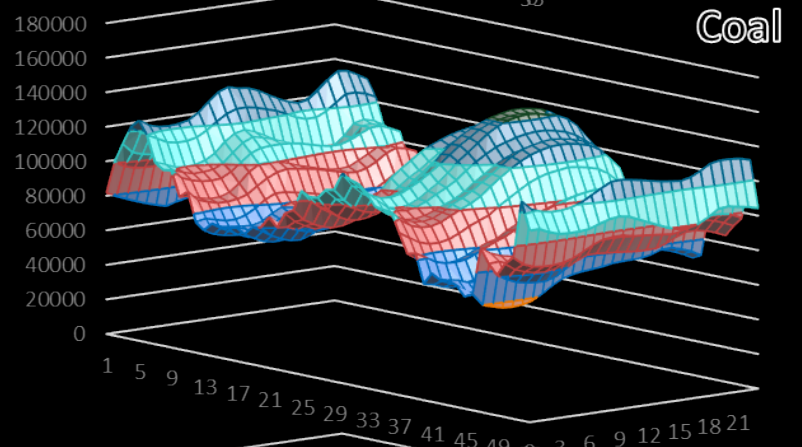


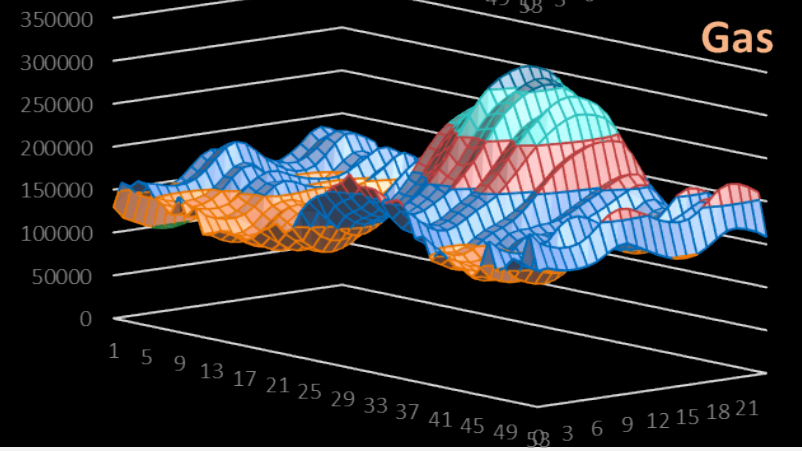












USA
Winter Peaks

Previous Winter Storms

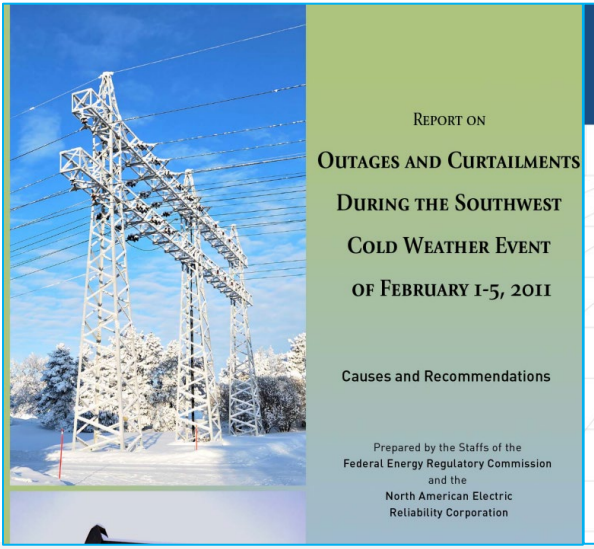
Transitions

Issues in each are not changing

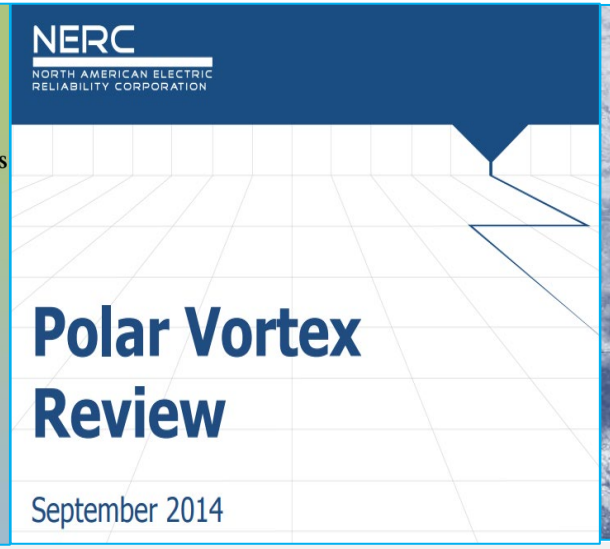
- Similar Issues each time …. but …
  - Uri impact in Texas was significantly worse outcomes than Elliott and preceding winter storms

Recurring themes …
Interplay of gas supply and electricity
Backup Fuel Supplies
Freezing instrumentation / equipment
Plants not designed for cold weather operation

2011 Southwest



2014 Central & Eastern

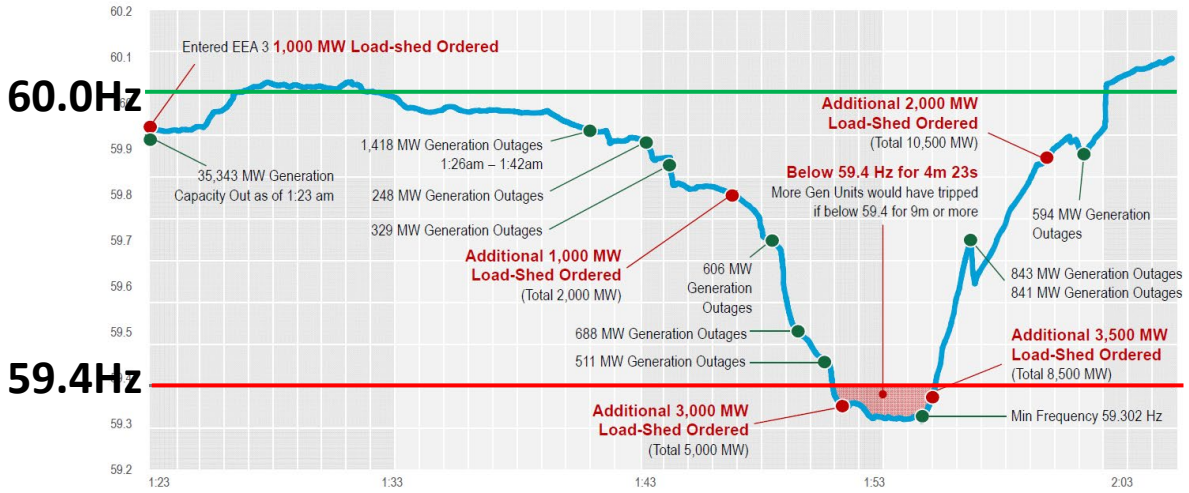


2018 South Central

2021 Texas & South Central

Texas February 2021

4 Minutes Away from Grid Collapse (Blackout)



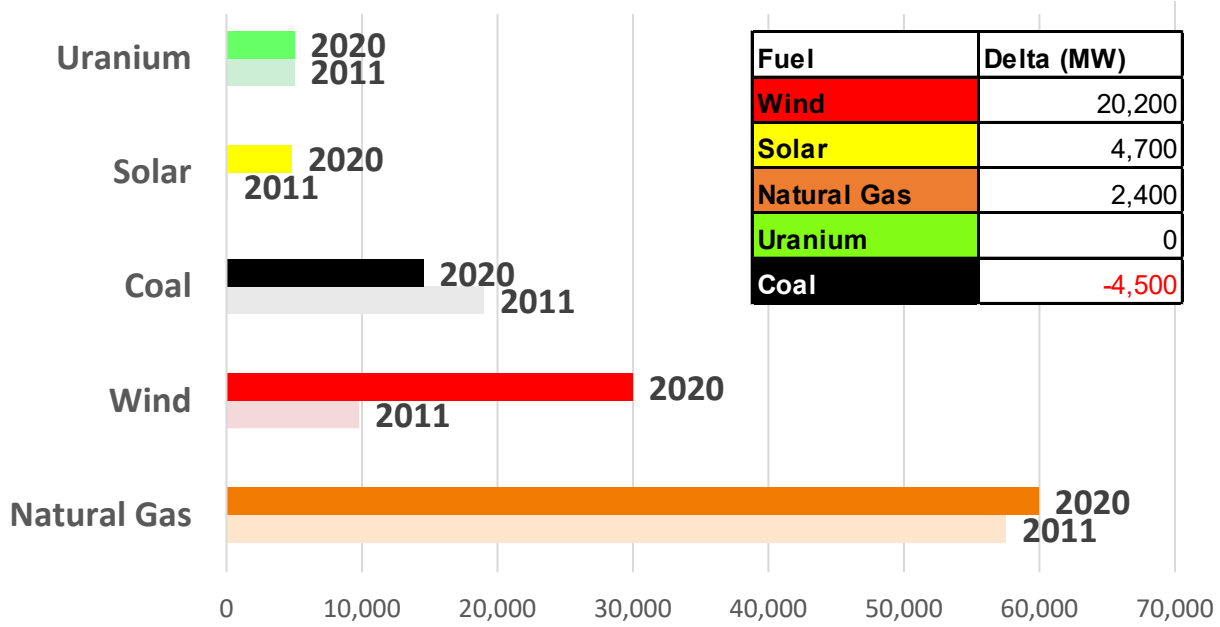
Cost of Winter Storm Uri could reach $300B USD
More than 200 deaths attributed to event

Significantly worse performance than 2011 Cold Snap

	2011	2021
Maximum generation capacity forced out at any given time (MW)	14,702	52,277
Generation forced out one hour before start of EEA3 (MW)	1,182	2,489
Cumulative generation capacity forced out throughout the event (MW)	29,729	46,249*
Cumulative number of generators outaged throughout the event	193	356
Cumulative gas generation de-rated due to supply issues	1,282	9,323
Lowest frequency	59.58	59.30
Maximum load shed requested (MW)	4,000	20,000
Duration load shed request (hours)	7.5	70.5
Estimated peak load (without load shed)	59,000	76,819

*Note: "Cumulative" values for 2021 were calculated using NERC 2011 report methodology. Cumulative amount for 2021 starts at 00:01 on February 14, 2021

Capacity by Fuel 2011 and 2020



Fuel	Delta (MW)
Wind	20,200
Solar	4,700
Natural Gas	2,400
Uranium	0
Coal	-4,500

Generation on Worst load Shed Hour Feb 15, 2021

Fuel Type	ERCOT MW	ERCOT Percent	MW 8pm Feb 15th	Percent Installed Cap.
Coal	14,703	11.9%	8,023	55%
Natural Gas	64,202	52.2%	30,917	48%
Nuclear	5,268	4.3%	3,785	72%
Other	1,268	1.0%	126	10%
Solar	6,202	5.0%	0	0%
Wind	31,414	25.5%	649	2%
TOTAL MW	123,057			

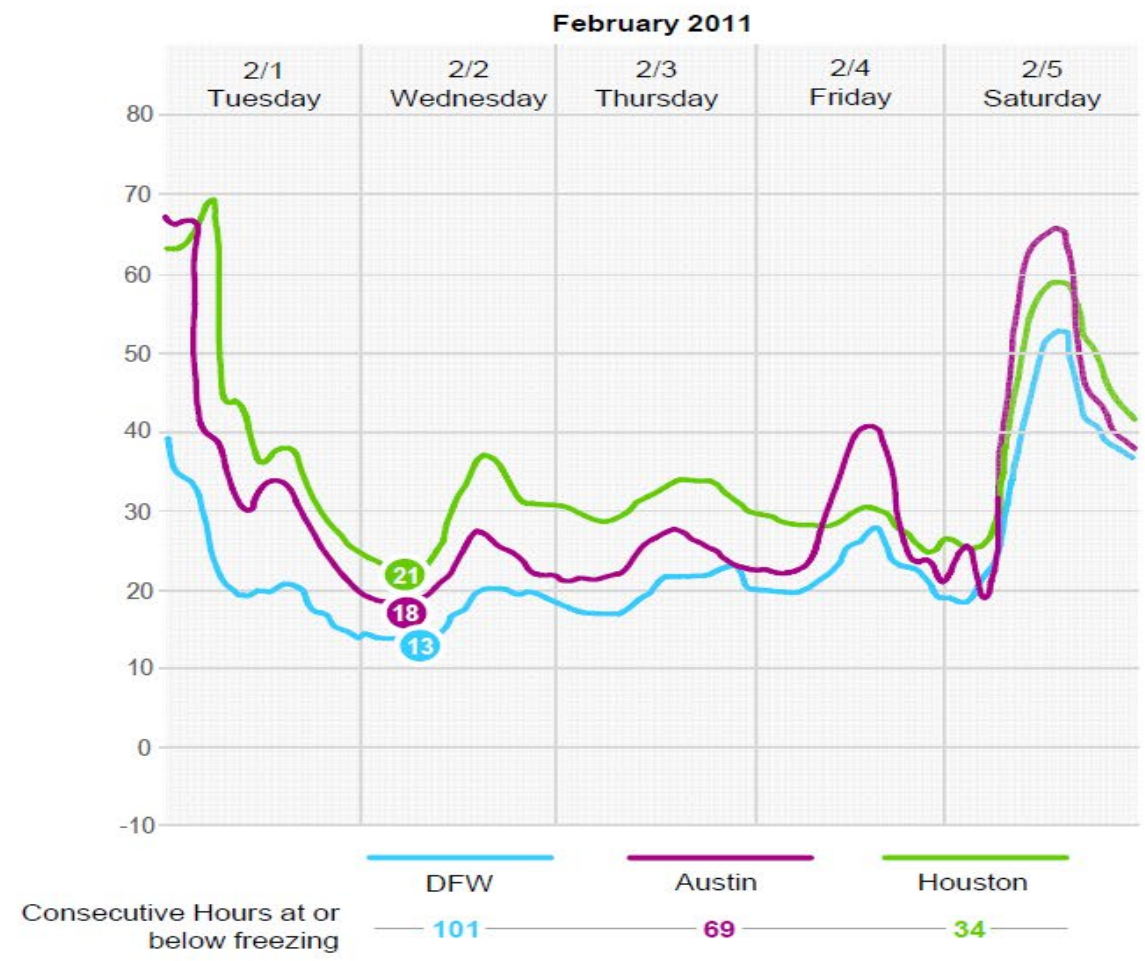
... shed additional firm load, peaking at 20,000 MW at 7:15 p.m. on February 15

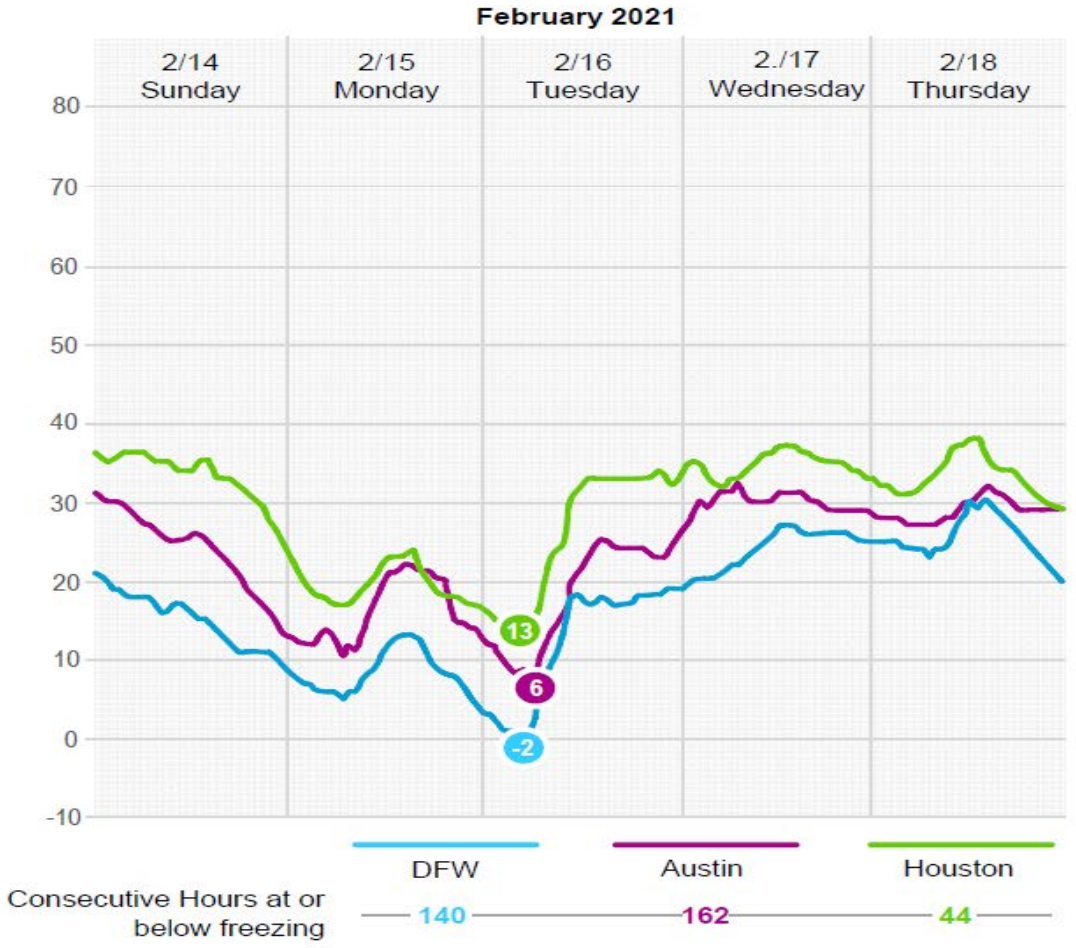
ERCOT Events

2011 vs 2021

Colder but Not that much colder and not for as long

2011 vs. 2021 Event Temperature Comparison





ERCOT Events

2011 vs 2021
Much Bigger Impact

2011 vs. 2021 Event Comparison

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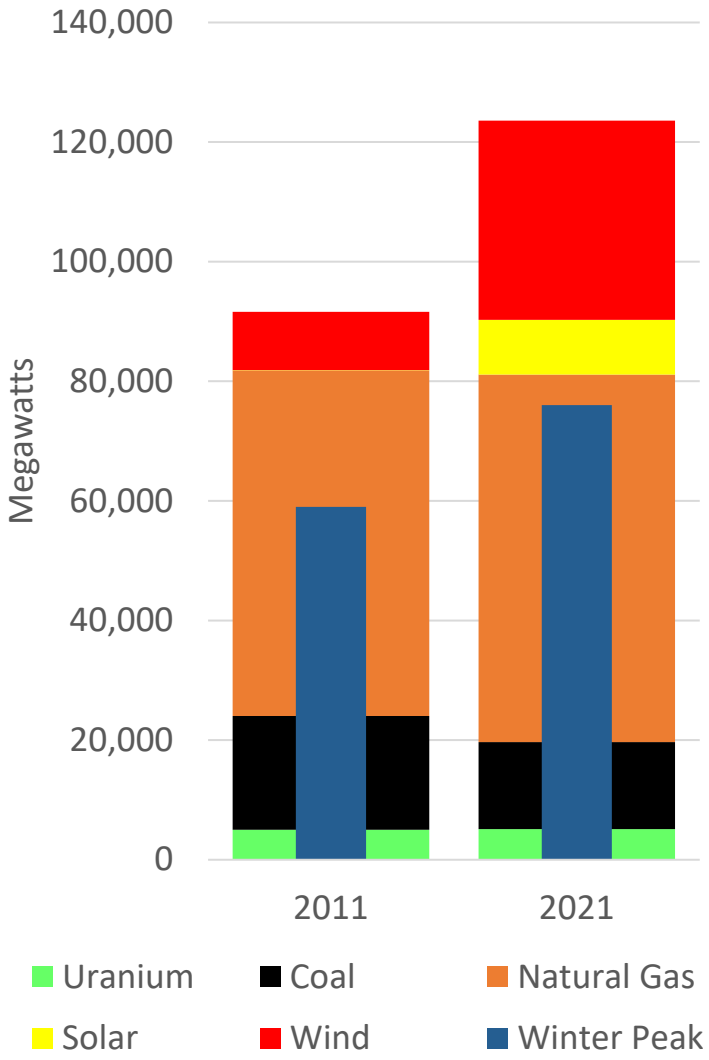
ERCOT 2011-2021

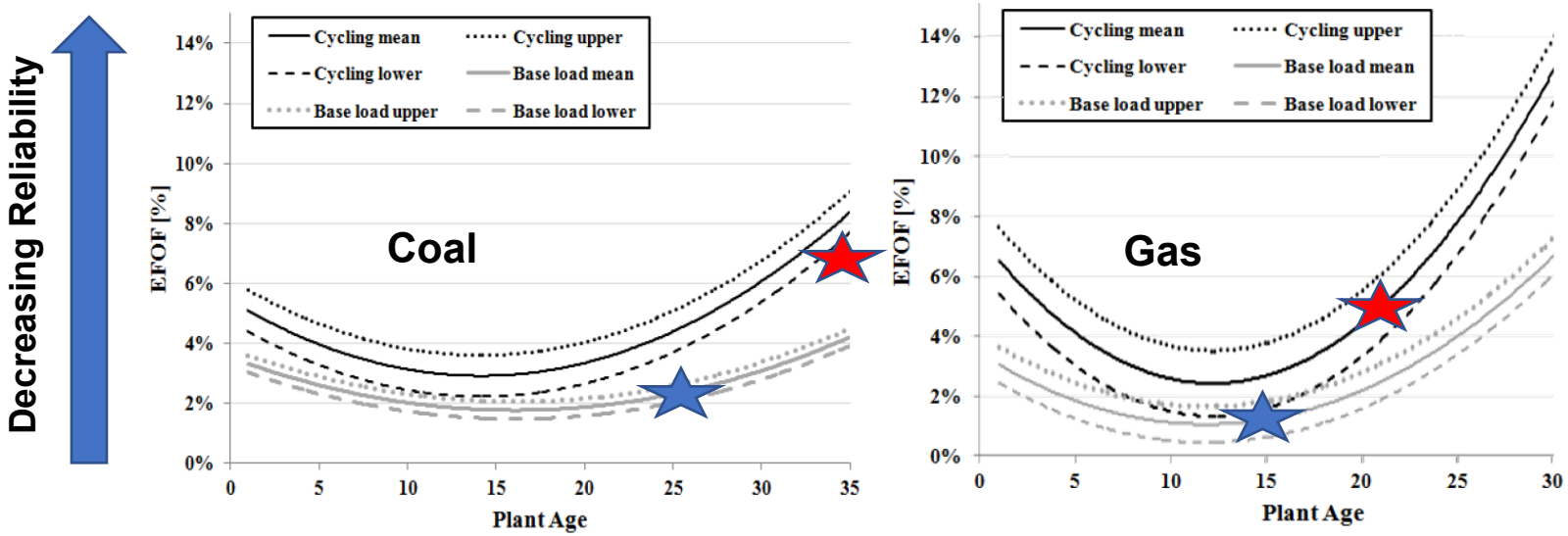
Dispatchable Reliability Assumptions



- Reducing Margin
  - Aging Dispatchable Assets
    - Lower Capacity Factors
    - Gas Supply common mode failure risk
      - Reliability Challenges
  - New Variable Assets
    - Hours of low output coincident with high demand

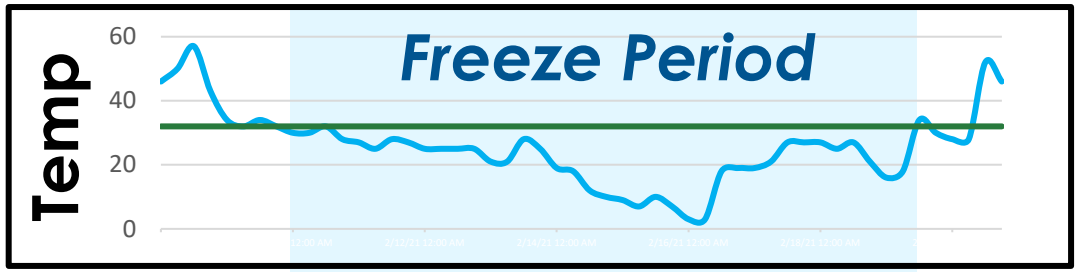
2021

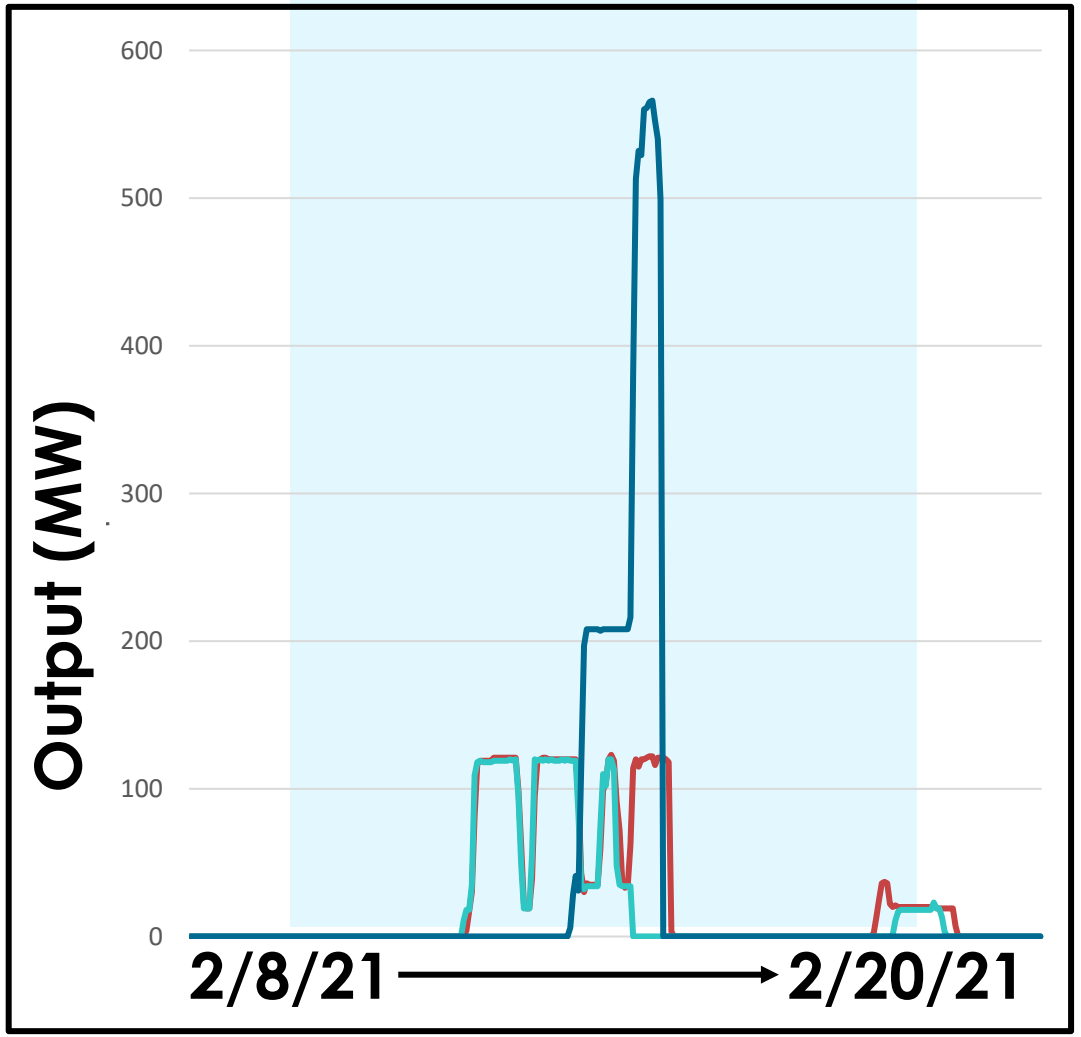
2011



Freeze Protection Challenges

Fr





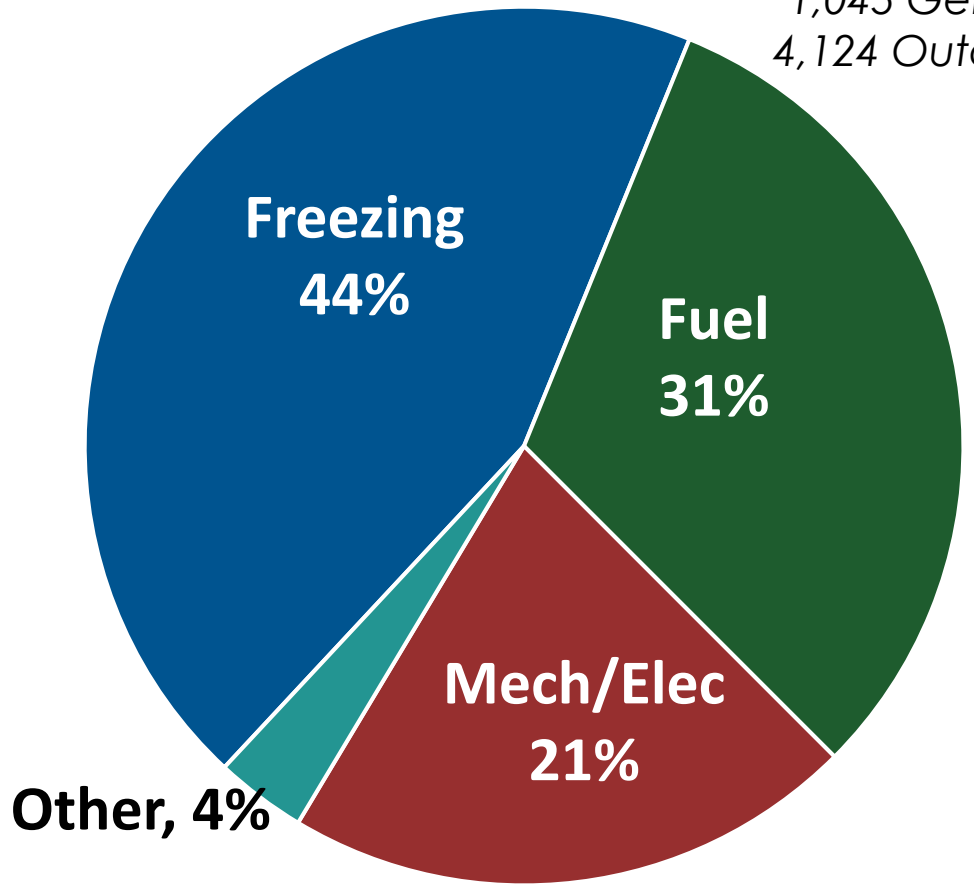
Open Air
Rarely Run (5% CF 2017-2020)
Called after Temperatures < 32F

2021 ERCOT Reliability

- Common Mode Failures
  - Gas Supply and Role of **Backup fuel**
  - Freeze Protection
  - Worse case hours for output
    - Just after sunset / before dawn + low wind (<2% of nameplate)
- Ability to ride through frequency deviations

Incremental Unplanned Generator Outages, Derates, and Star-up Failure by Cause

1,045 Generating Units
4,124 Outages/Derates



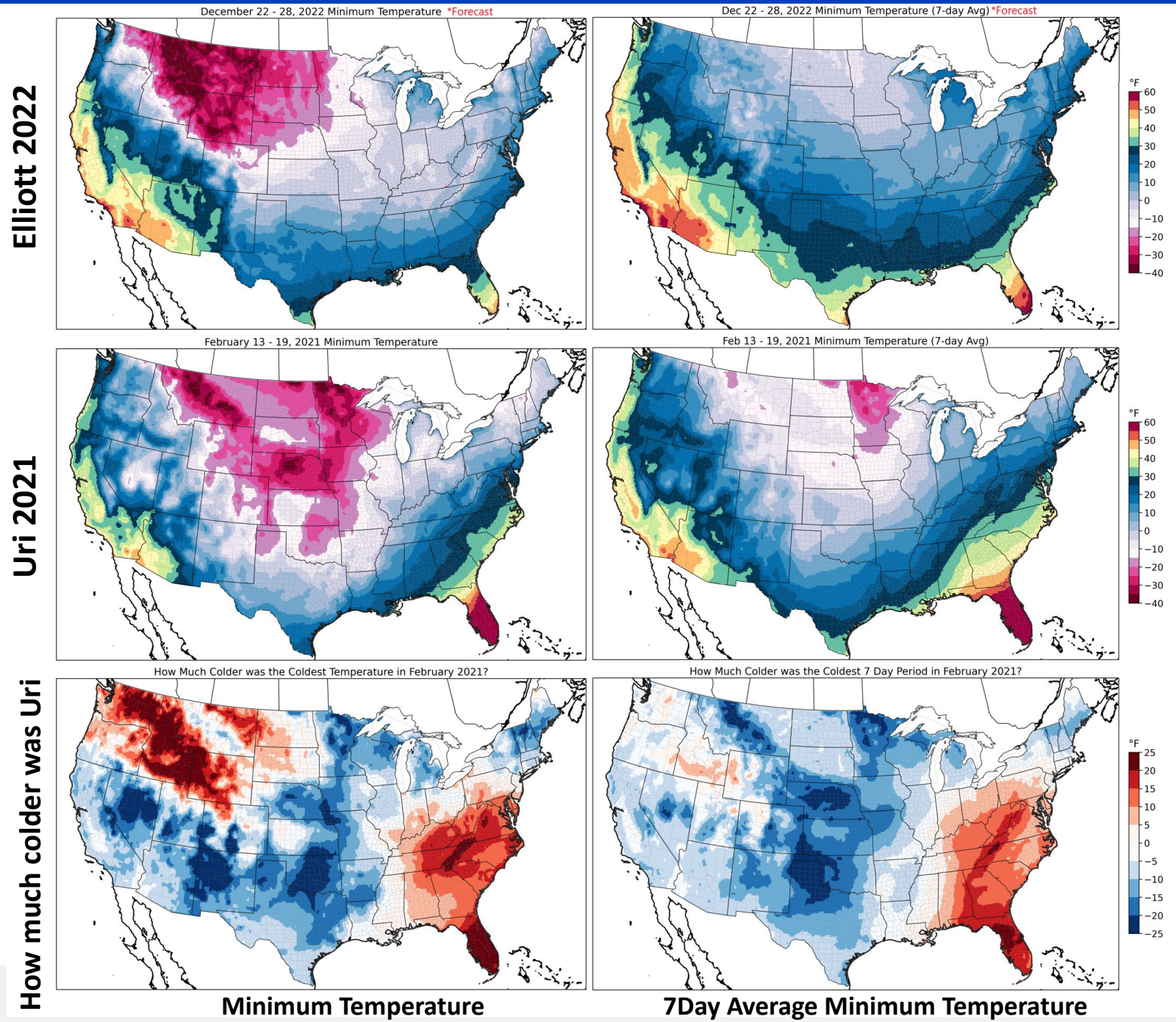
9GW of Gas Loss due to Fuel Supply

4GW of Coal/Gas Loss due Frequency

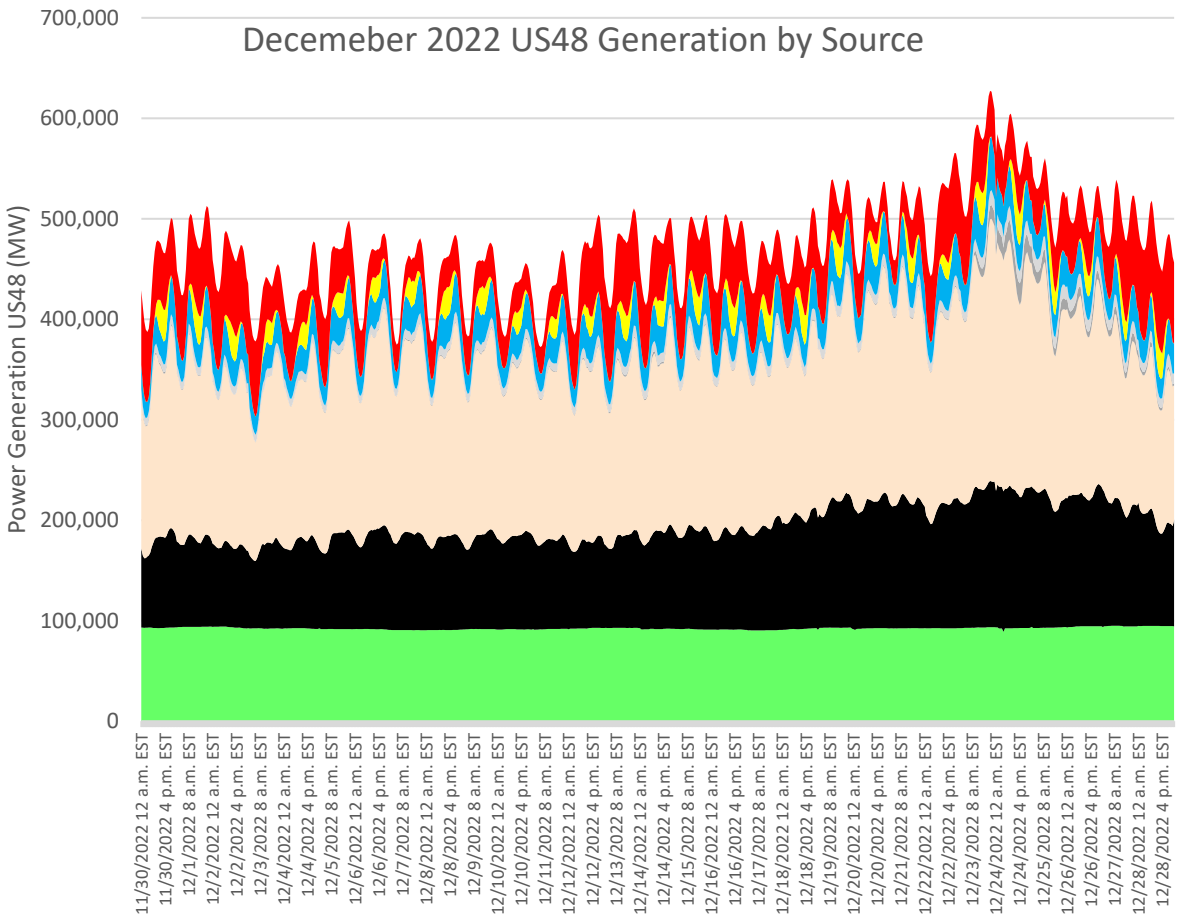
Comparison between the December 2022 and February 2021 cold air outbreaks

- Uri much colder in Texas, much warmer in Southeast and Northwest
- Uri regions impacted
  - Texas 20,000 MW / 70 hours of rolling outages
- Elliott regions impacted
  - Tennessee* and North Carolina* ~2,000 MW / ~12 hours of rolling outages each
  - Kentucky* ~1,000 MW / ~6 hours of rolling outages
  - Notable PJM EEA2
    - Elliott similar to 2014 Polar Vortex

*First rolling outages in the history of state



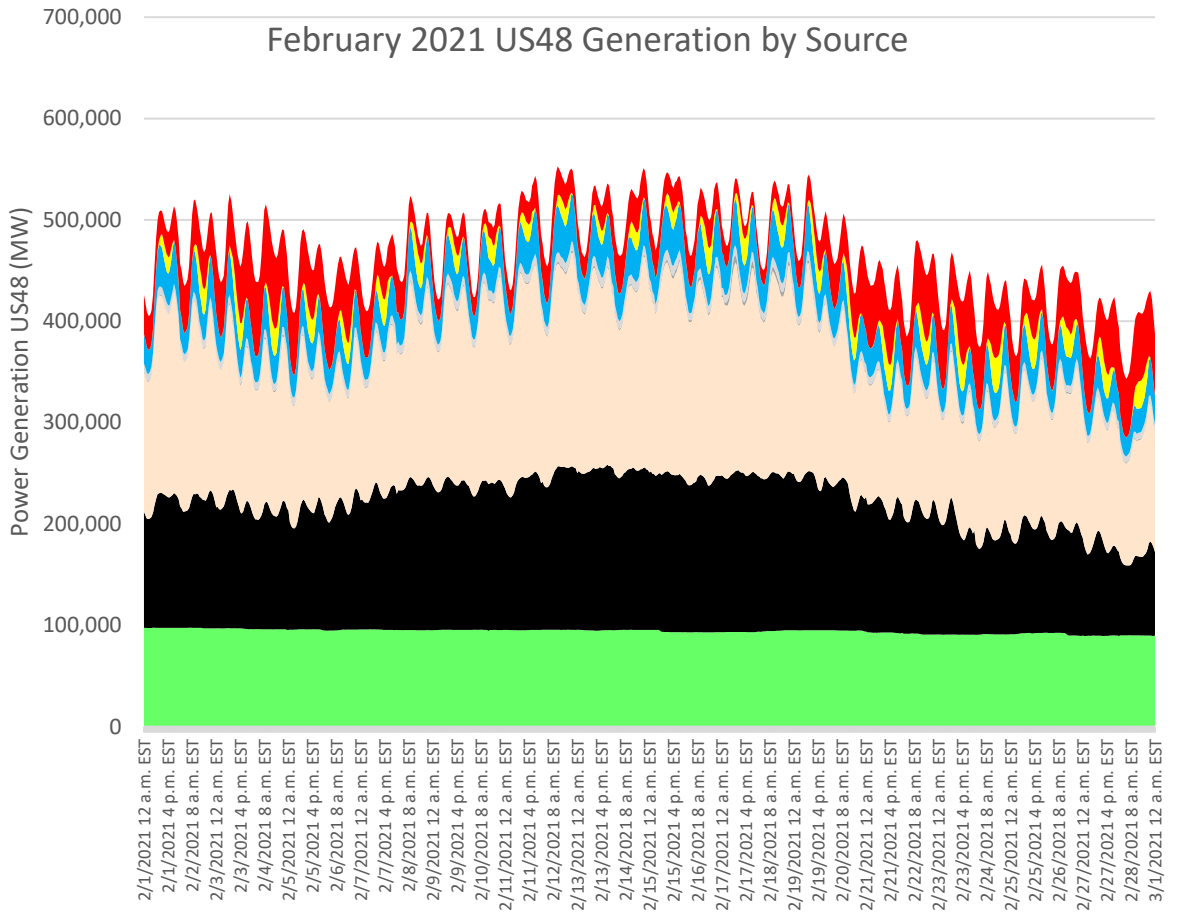
Generation by Source



Peak hour in the Month 12/23/2022 8 p.m. EST

	Wind	Solar	Hydro	Nat Gas	Coal	Nuclear	Total
% of Max Monthly Output	50%	2%	100%	100%	100%	99%	100%
MW at Peak demand hour	45,854	817	53,579	260,469	145,518	93,528	627,323
Peak MW in the Month	90,974	35,284	53,579	261,489	145,518	94,950	627,323

Nuclear Generation (MWh) | Coal Generation (MWh)
Natural gas Generation (MWh) | Petroleum Generation (MWh)
Other Generation (MWh) | Hydro Generation (MWh)
Solar Generation (MWh) | Wind Generation (MWh)



Peak hour in the Month 2/12/2021 11 a.m. EST

	Wind	Solar	Hydro	Nat Gas	Coal	Nuclear	Total
% of Max Monthly Output	36%	28%	97%	95%	99%	98%	100%
MW at Peak demand hour	28,781	9,813	46,473	200,142	161,297	95,540	553,033
Peak MW in the Month	79,073	34,753	47,719	210,955	163,350	97,616	553,033

Nuclear Generation (MWh) | Coal Generation (MWh)
Natural gas Generation (MWh) | Petroleum Generation (MWh)
Other Generation (MWh) | Hydro Generation (MWh)
Solar Generation (MWh) | Wind Generation (MWh)

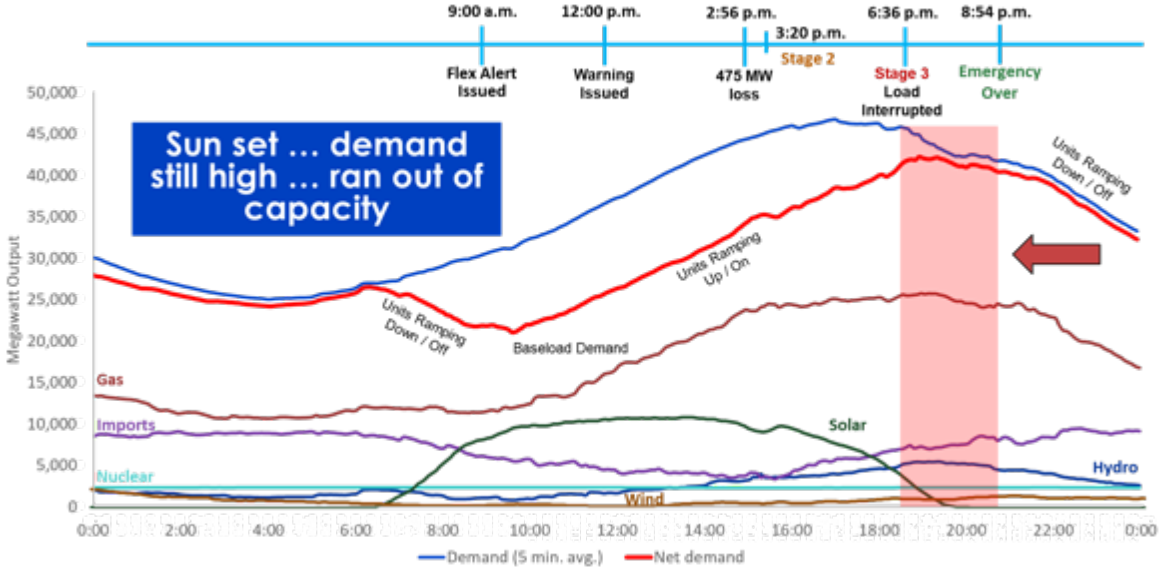
USA
Summer Sunset

California Late Summer

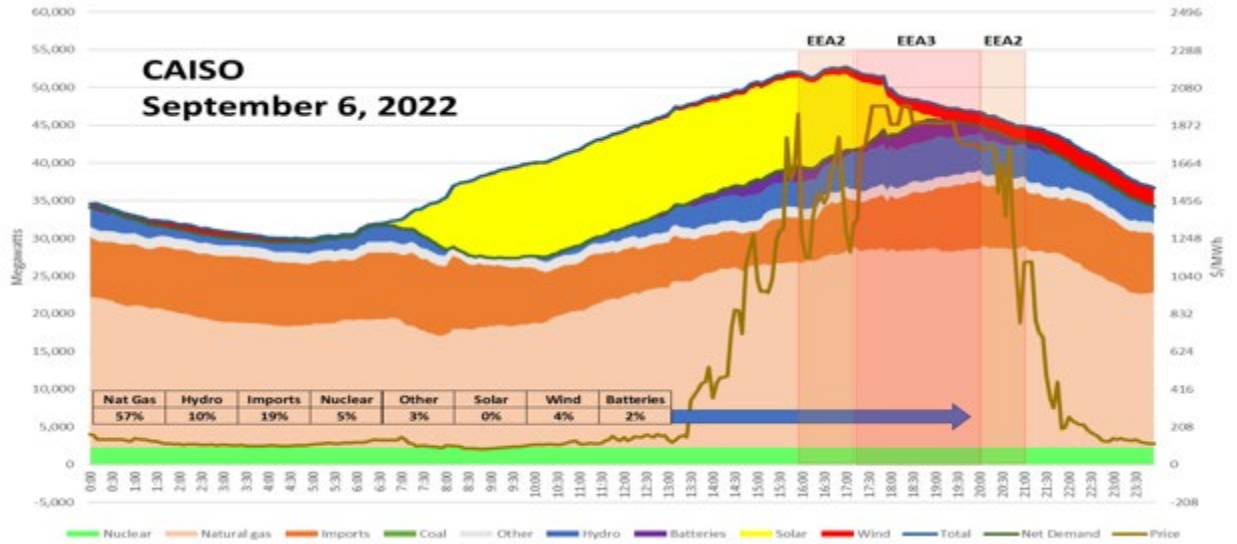
Transitions

Setting Sun … Persistent Demand

CAISO August 14, 2020 – Rolling Outages 6:36pm-7:56pm



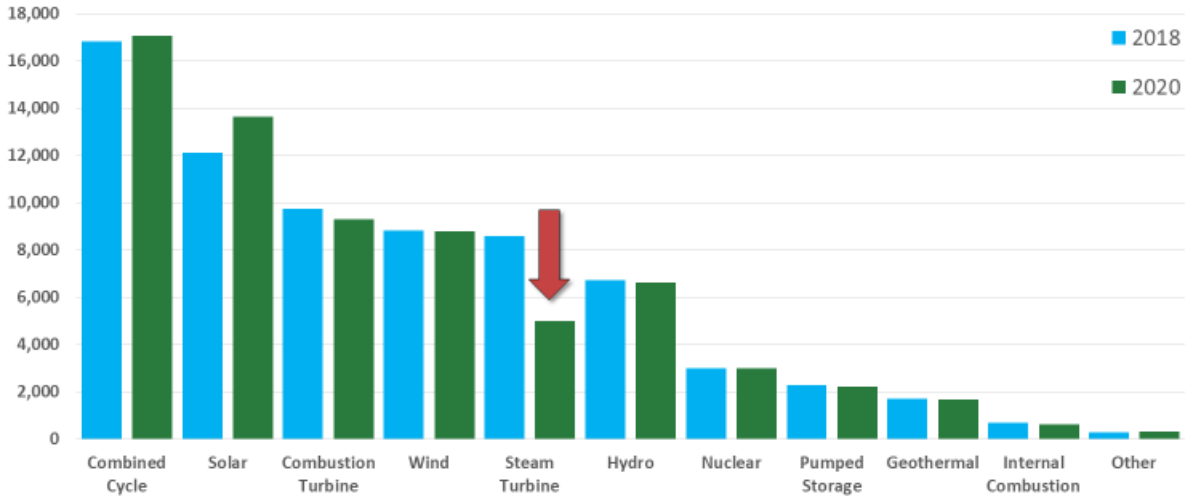
CAISO September 6, 2022 – Energy Emergency Alert 3



- **When sun sets in Summer short on energy**
- **12.2 gigawatts (GW) emergency backup generators**
  - About 15% of California's entire electricity grid (majority are diesel-fueled) – October 2021 Study
- 07/01/2022 ***"California Gov. Gavin Newsom (D) signed a controversial measure yesterday that would delay the closure of natural gas plants and expedite energy generation projects in an effort to avoid blackouts over the next five summers."***
- **>$2B USD Cost**

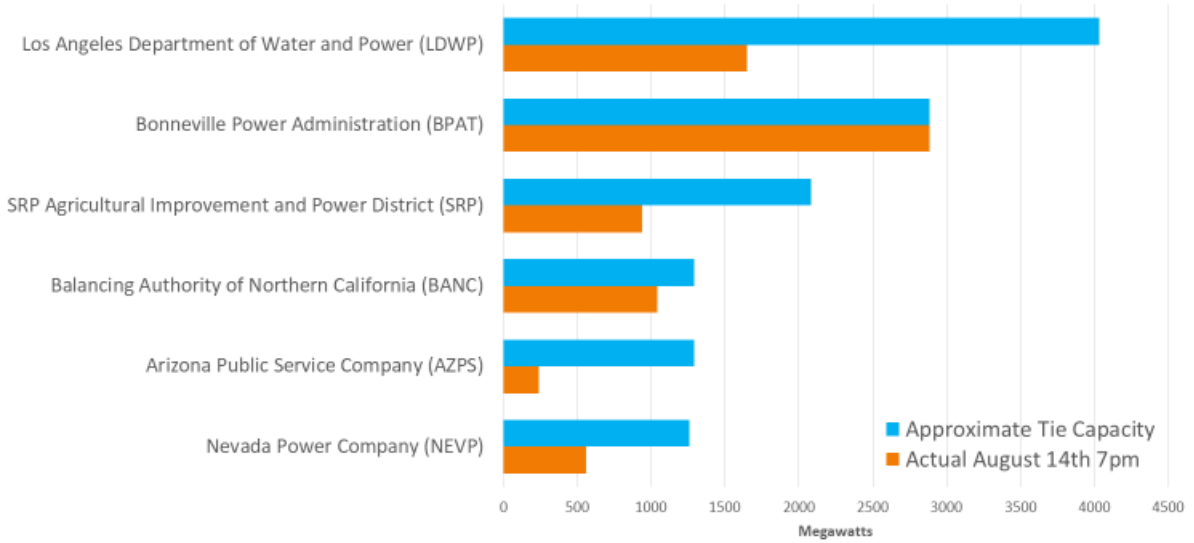
Net Demand is Electricity Demand after the demand met by variable energy resources

CAISO Capacity 2018 versus 2020

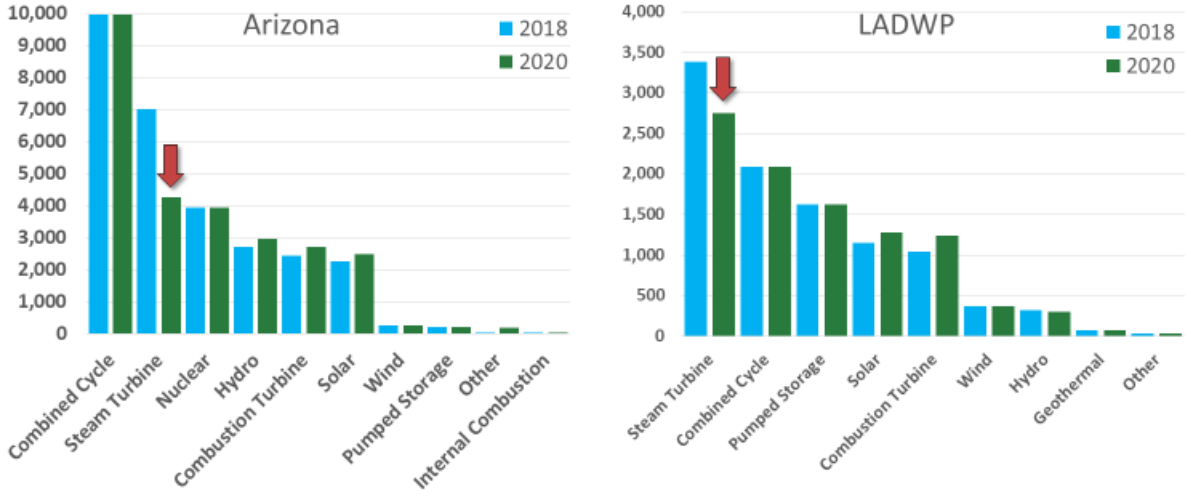


Down over 4000 MW in Dispatchable Capacity

Interchange Electricity Flow to CAISO

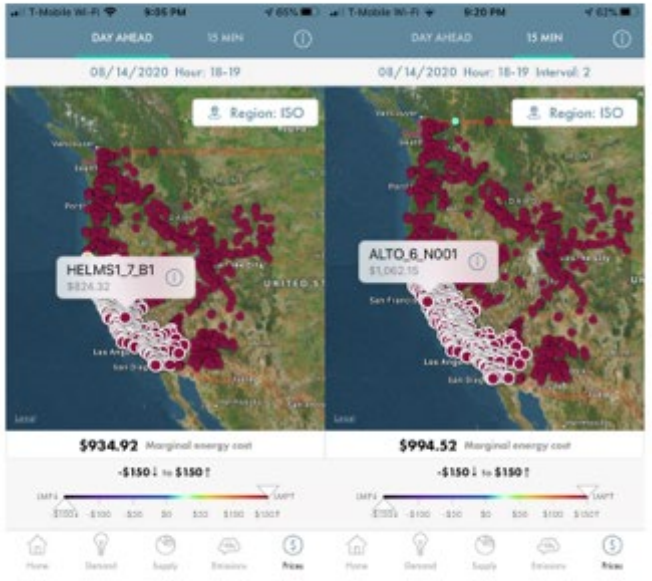


Capacity 2018 versus 2020



Down over 3000 MW in Dispatchable Capacity

Price Incentive



- Day ahead, 15 minute, and real time prices were all about $1000 / MWh
  - If additional power was available from adjacent markets the price would incentivize operation
- At the start of Stage 3 there was ~3000 MW utility scale PV generating, within 1 hour that was <100 MW

CAISO 2020 Reliability Insights

- Sunset Hours were critical
  - Need to identify critical hour and base investments as such
    - Key reliability hour – output enhancements?
    - California adjusted Effective Load Carrying Capacity for new PV downward
- Need to pay attention to Neighbors Energy Supply Mix – Price signals may not be sufficient, especially if Supply Mix is similar

Hourly Dispatch Critical – Cost to Ratepayers can increase significantly to deliver reliable power if retirements outpace ability to meet all hours

California to open 5 natural gas plants to avoid blackouts

Friday, August 20th 2021

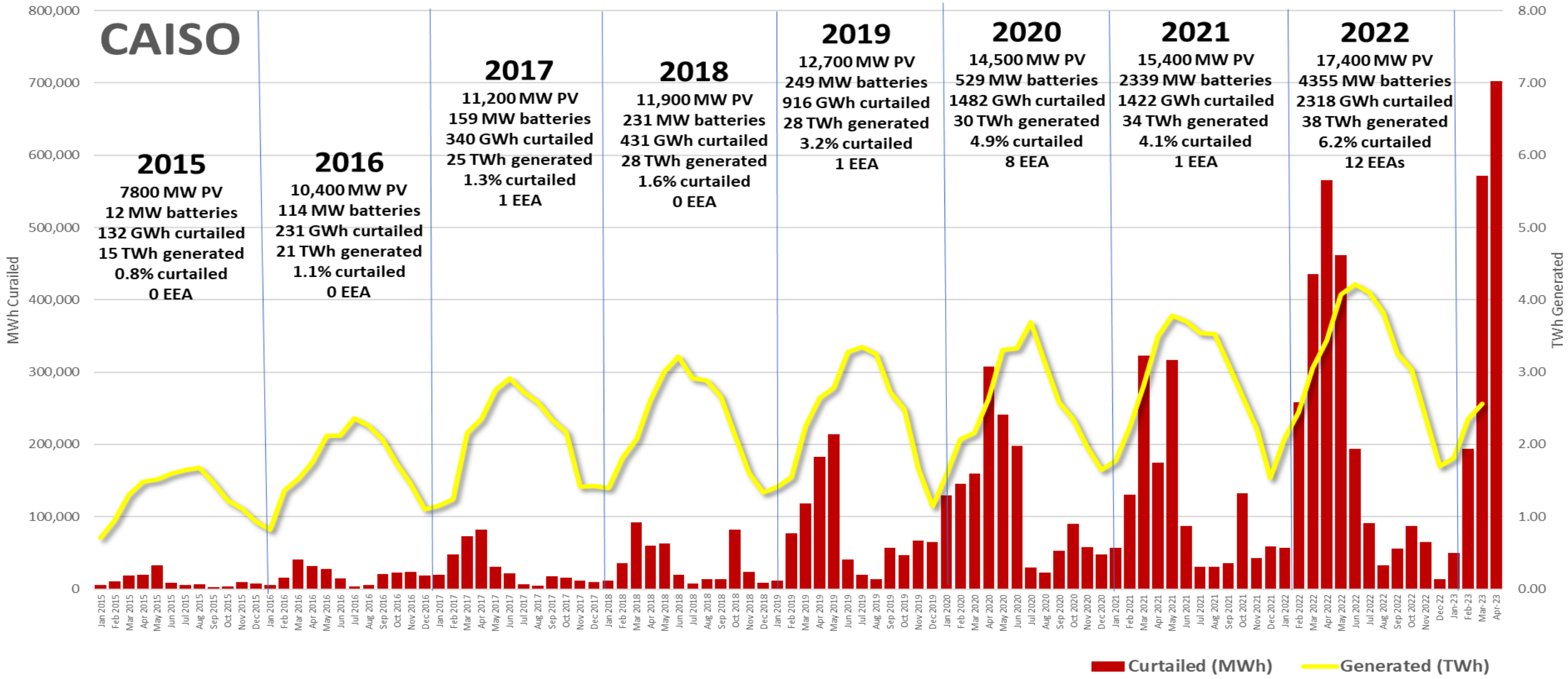
… price tag of $171.5 million, each unit will produce about 30 MW of power for a total of 150 MW …

https://kmph.com/news/local/california-to-open-5-natural-gas-plants-to-avoid-blackouts

California Curtailment

Transitions

Seasonal Demand / Output Mismatches



Electricity Security

NERC Reliability Assessments

North America

Regional Reliability Concerns

Energy Emergency Alert 1 (EEA1)
Energy Emergency Alert 2 (EEA2)
Energy Emergency Alert 3 (EEA3)

EEA3 Rotating Outages may occur

https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2023.pdf

Summer 2023 Reliability Assessment
California Late Summer EEA3

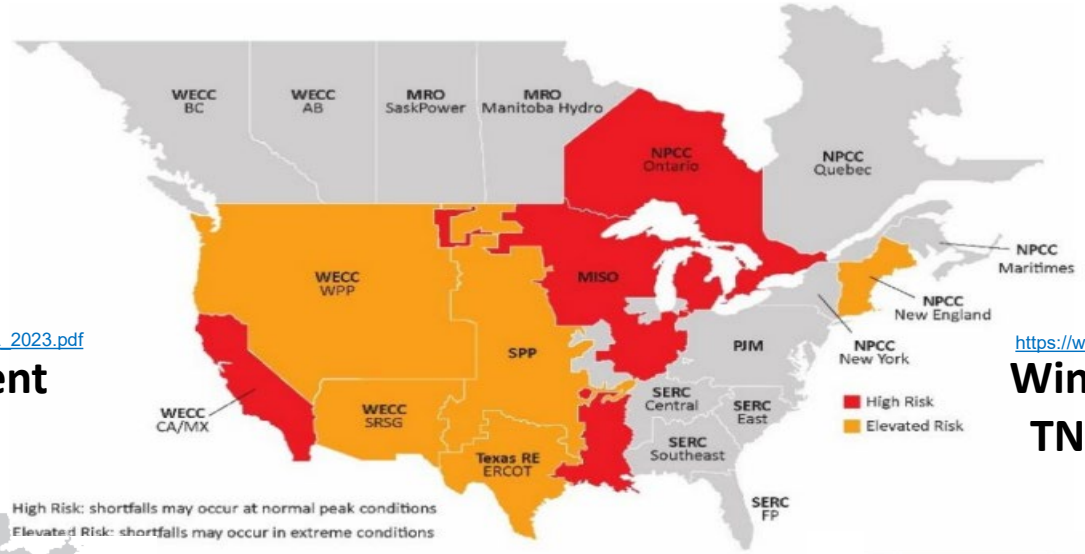


Figure 1: Risk Area Summary 2023–2027

https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_WRA_2022.pdf

Winter 2022/23 Reliability Assessment
TN and NC Winter Storm Elliott EEA3

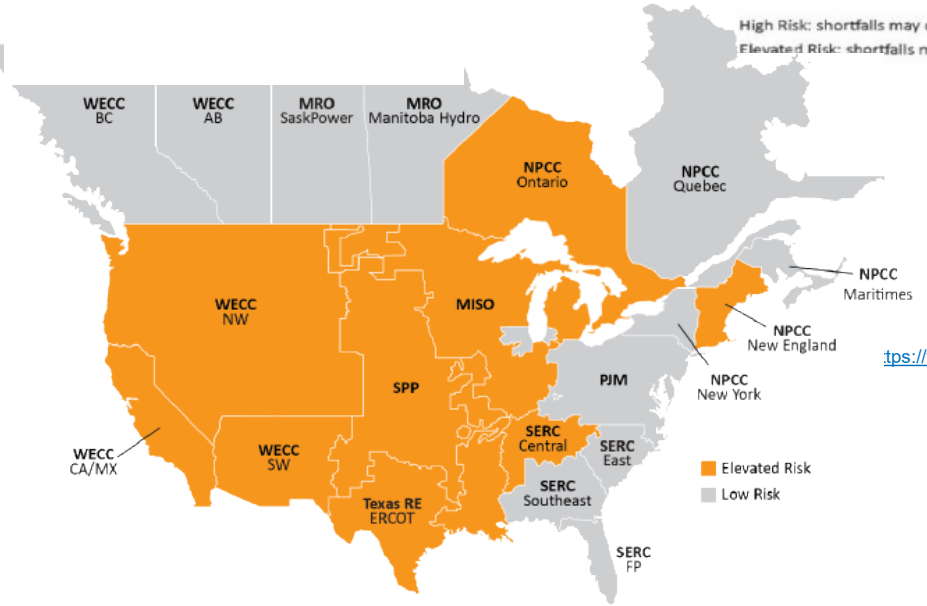


Figure 1: Summer Reliability Risk Area Summary

2022 Long-Term Reliability Assessment
Many Regions At Risk

:tps://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf

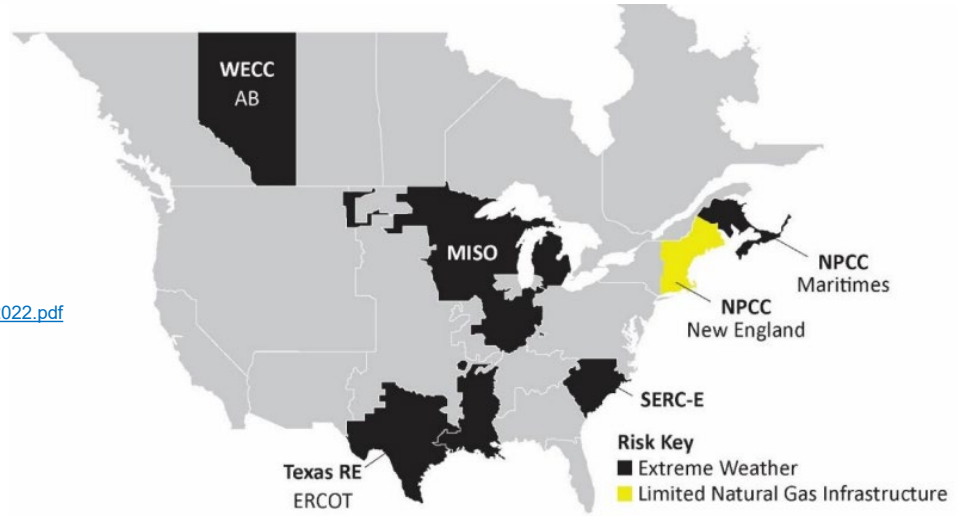
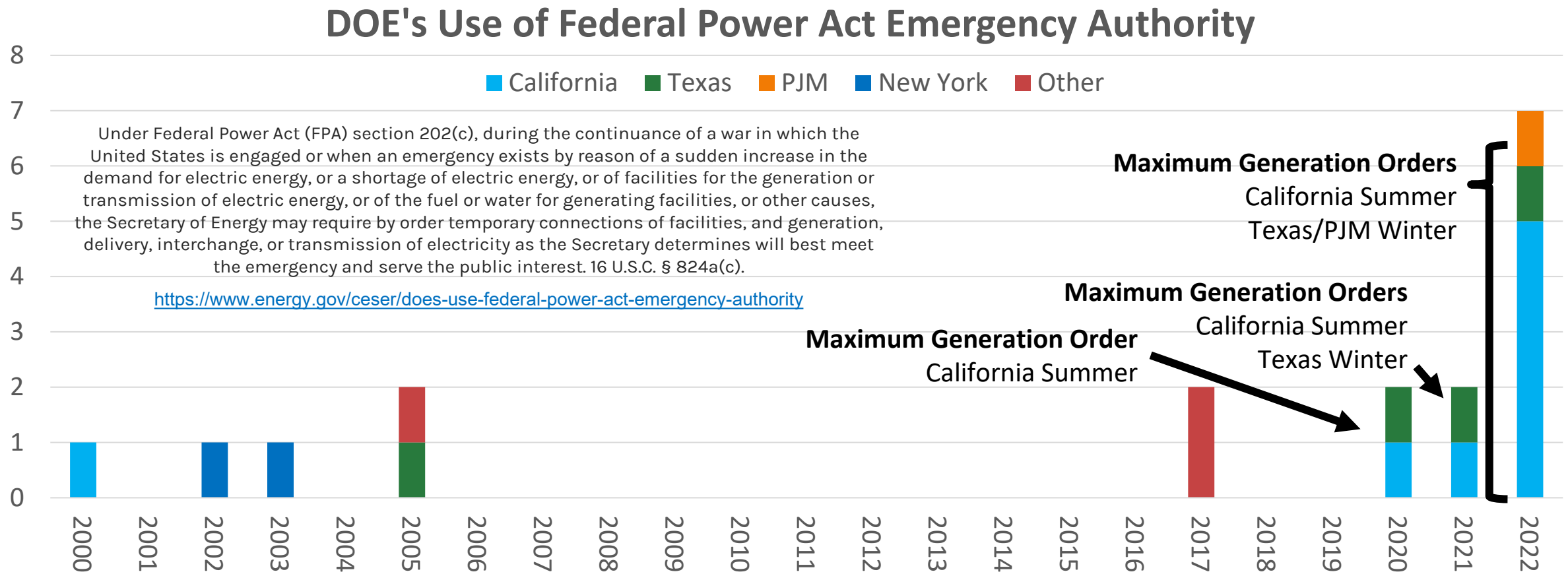


Figure 1: Winter Reliability Risk Area Summary

Use of Federal Power Act Emergency

On Marginal Days System is Stretched to Limits

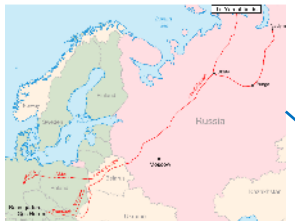


Typical Max Generation Order: The CAISO "requests that the Secretary issue the requested emergency order by Friday, September 2, 2022, or a[s] soon as possible thereafter, authorizing specific electric generating resources (Covered Resources) located within California to operate at their maximum generation output levels between 2:00 p.m. and 10:00 p.m., when directed to do so by the CAISO, notwithstanding air quality or other permit limitations."

Europe

European Spot Market Gas Prices

Actions and reactions



Recent Europe Headlines

Energy Mix Resilience varies by Energy Sources
Currently Europe Crisis is Affordability – but Winter Shortages seem very possible

Germany Has Three Months to Save Itself From a Winter Gas Crisis

https://www.bloomberg.com/news/articles/2022-08-01/germany-heading-to-gas-emergency-with-russia-keeping-nord-stream-flows-reduced

Spain puts limits on air conditioning and heating to save energy

https://amp-theguardian-com.cdn.ampproject.org/c/s/amp.theguardian.com/world/2022/aug/02/spain-puts-limits-on-air-conditioning-and-heating-to-save-energy

France to Curb Nuclear Output as Europe's Energy Crisis Worsens

- High river temperatures restrict EDF's ability to cool plants
- Temperatures to reach 36 degrees Celsius in Paris on Wednesday

https://www.bloomberg.com/news/articles/2022-08-03/edf-to-curb-nuclear-output-as-french-energy-crisis-worsens#xj4y7vzkg

Fossil fuels surpass renewables as EU's top power source - Eurostat

https://www.reuters.com/markets/europe/fossil-fuels-surpass-renewables-eus-top-power-source-eurostat-2022-06-30/

"British household energy bills to be at 'devastating' levels until 'at least 2024'"

https://www.ft.com/content/77e6de25-5d59-4e51-a835-8b4fa0a50a6e

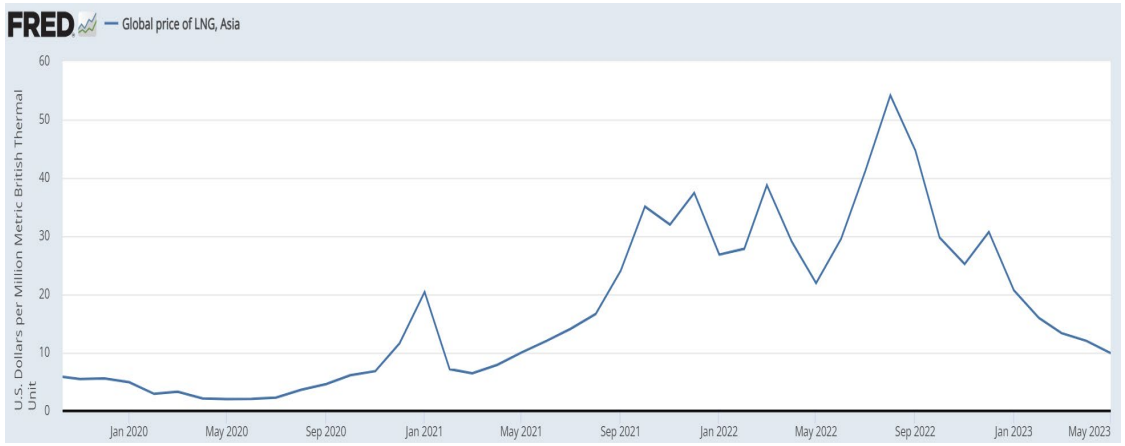
UK braces for even higher bills as Norway threatens electricity export cut

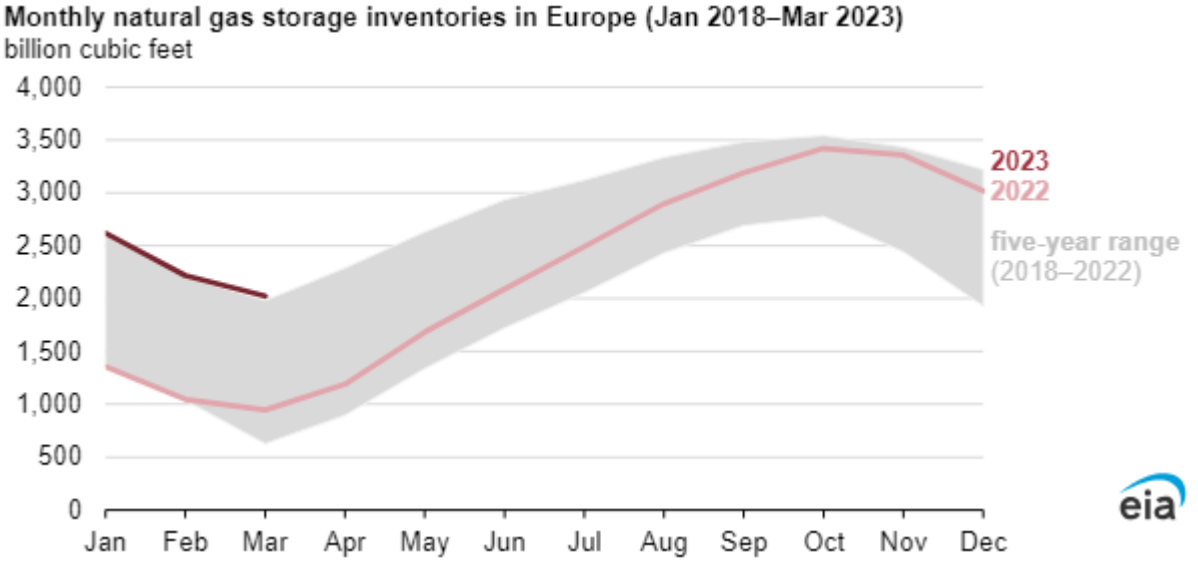
https://www.theguardian.com/money/2022/aug/08/uk-braces-for-even-higher-bills-as-norway-threatens-electricity-export-cut

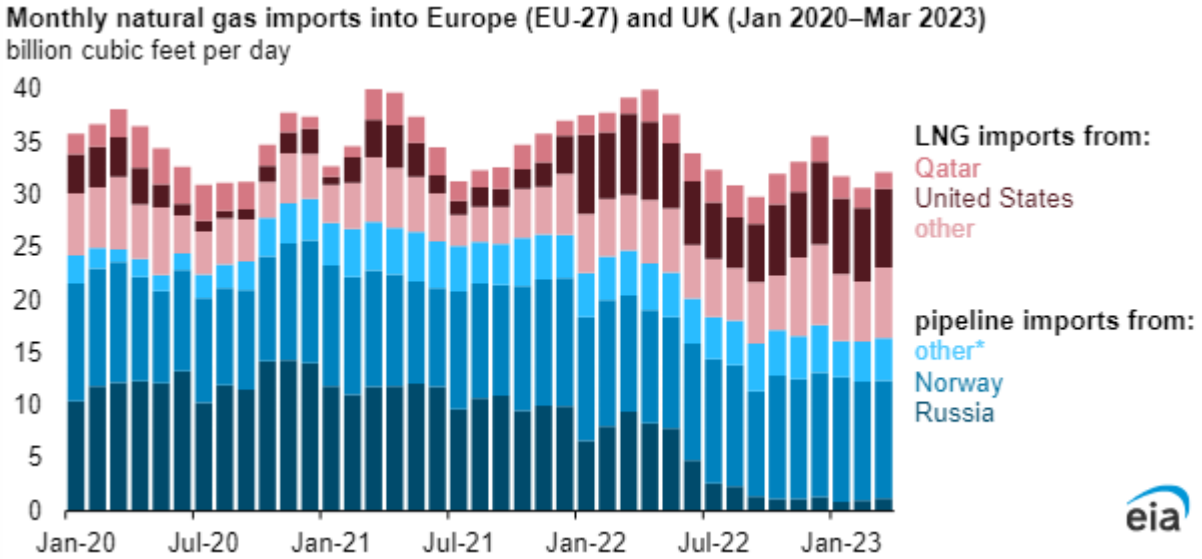
Europe ended winter 2022–23 with the most natural gas in storage on record

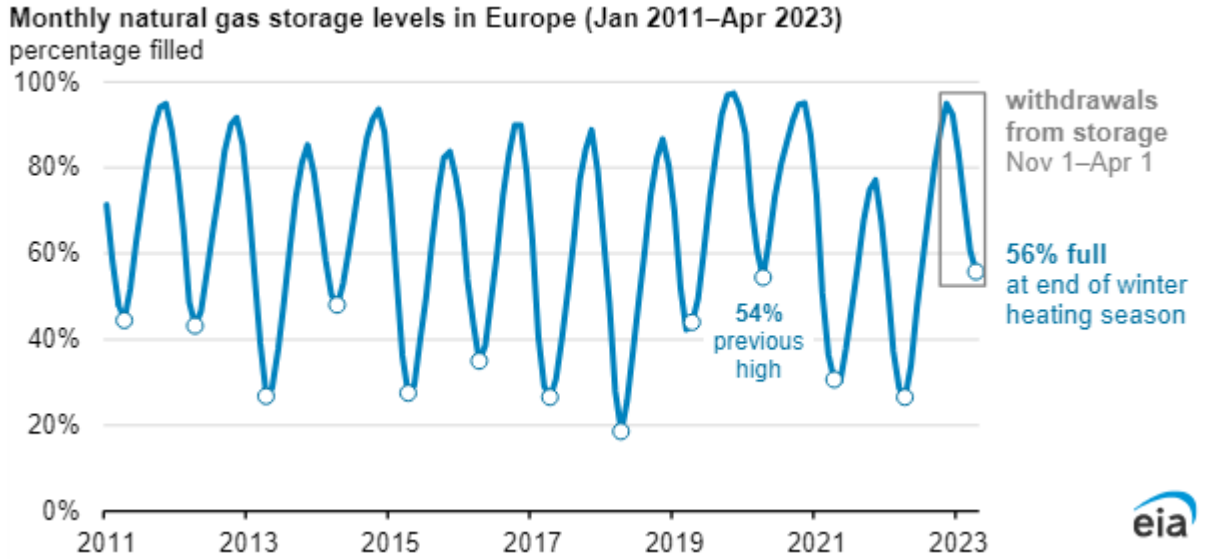
2023 Warm European Winter

- European LNG imports drove up Asia prices



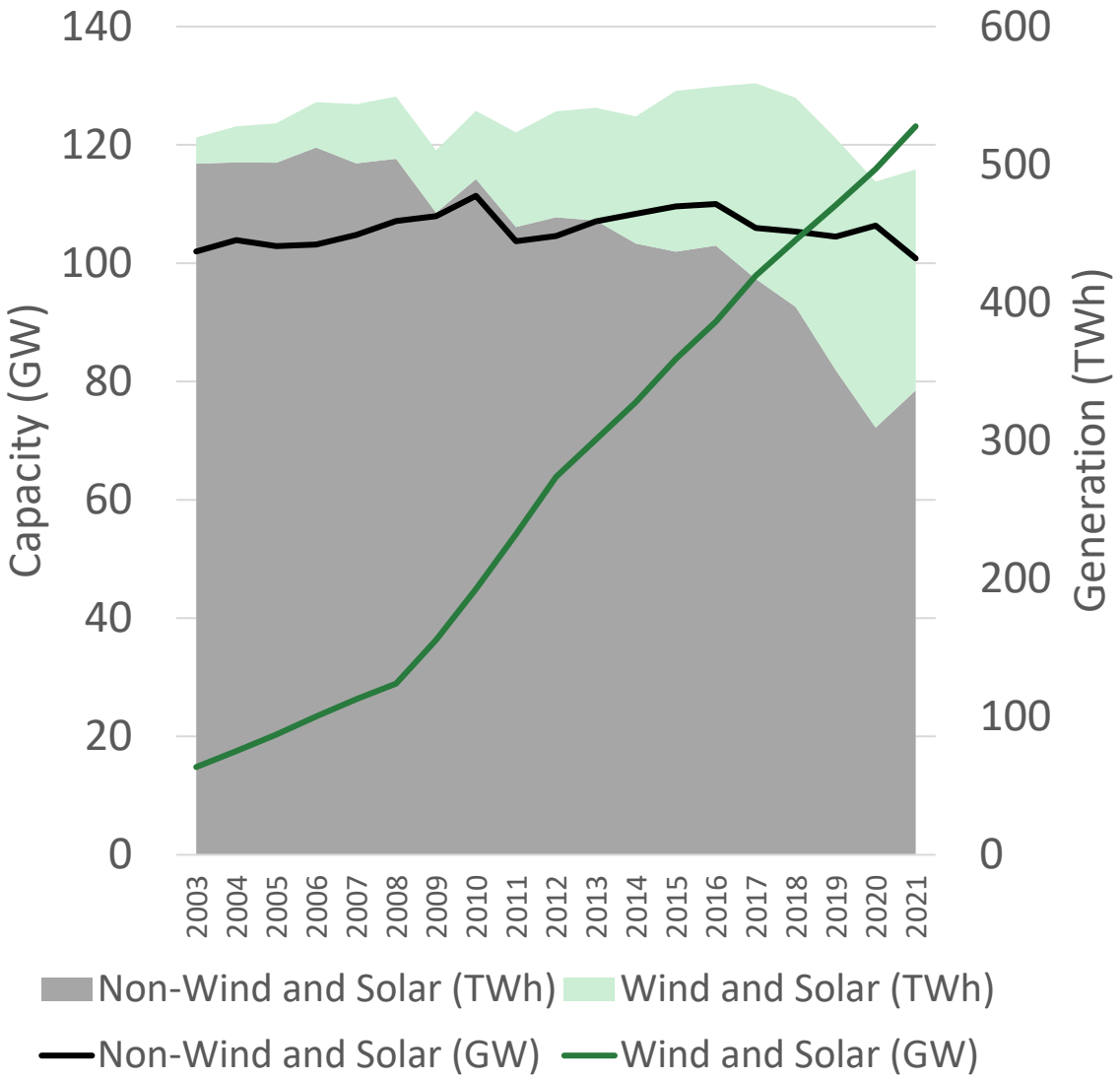




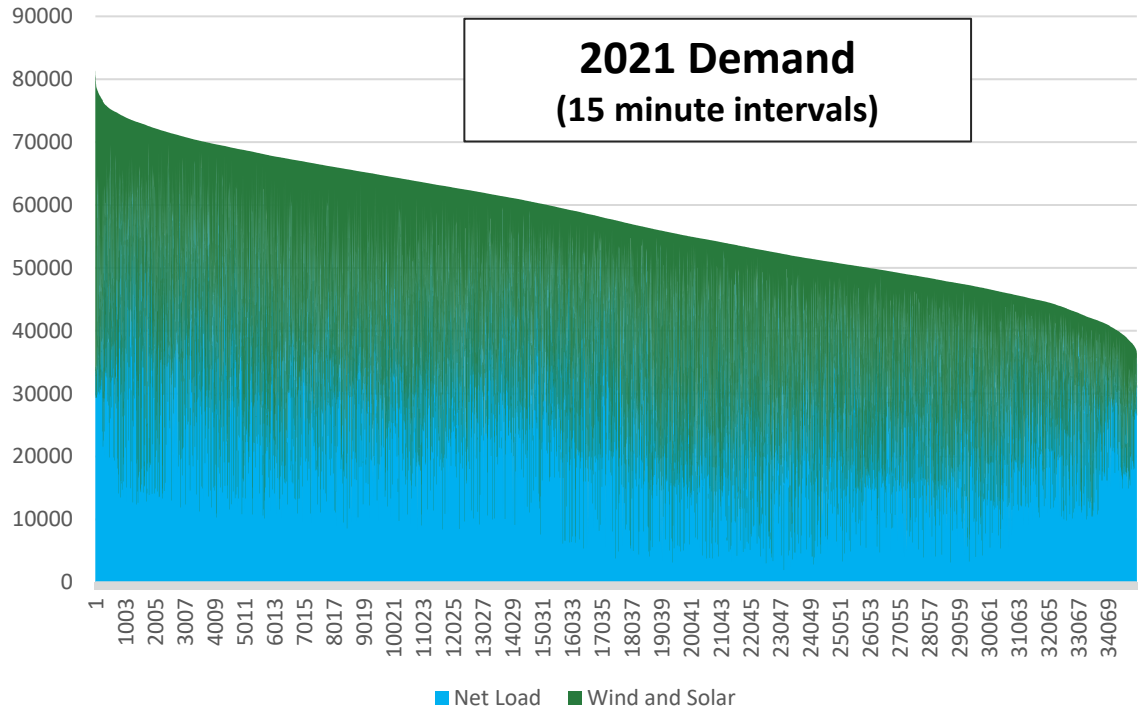


https://www.eia.gov/todayinenergy/detail.php?id=56400#:~:text=On%20April%201%2C%20natural%20gas,22)%20average%20of%201.21%20Tcf.

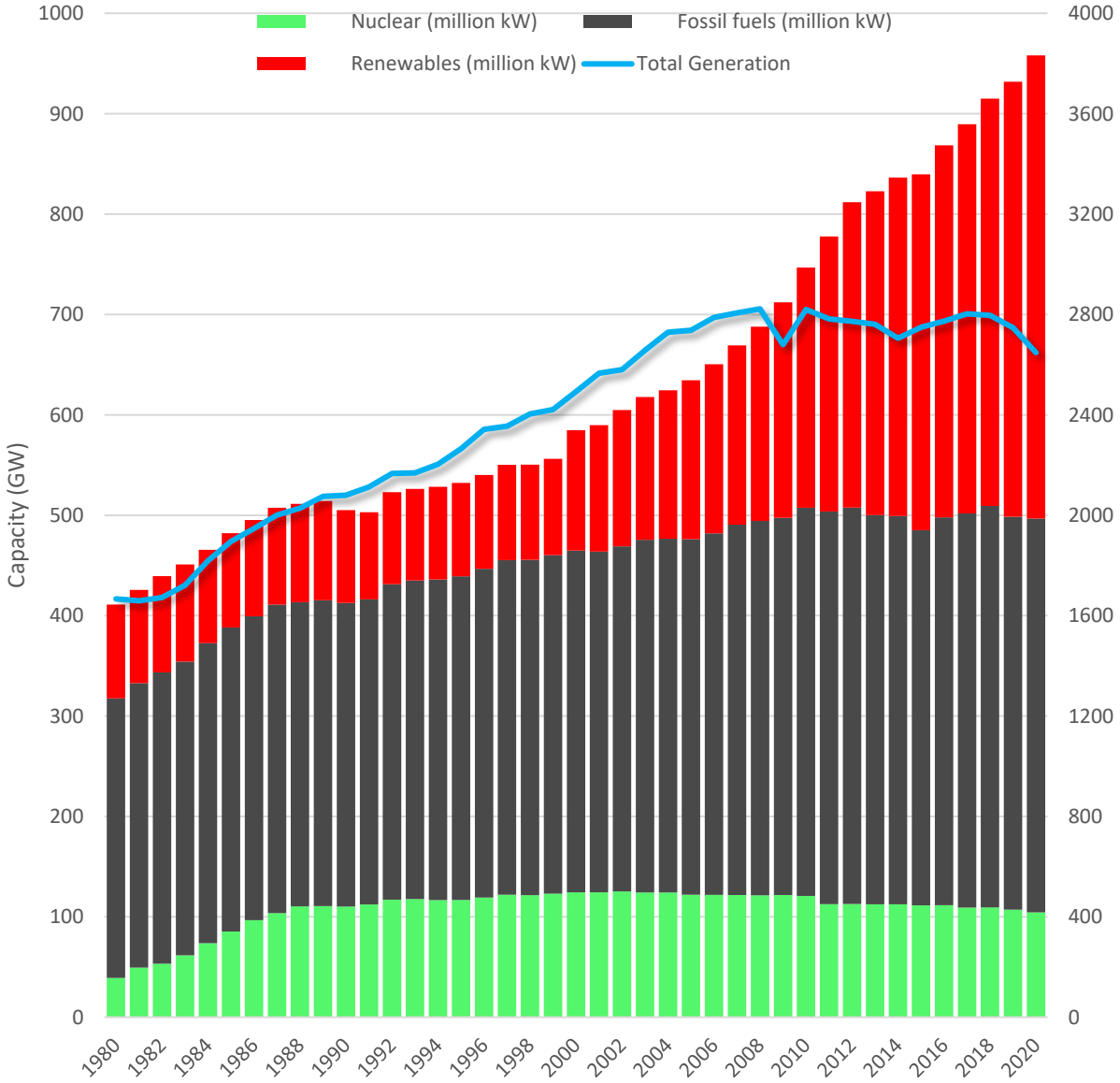
Germany Installed Capacity, 2021 Generation Needs

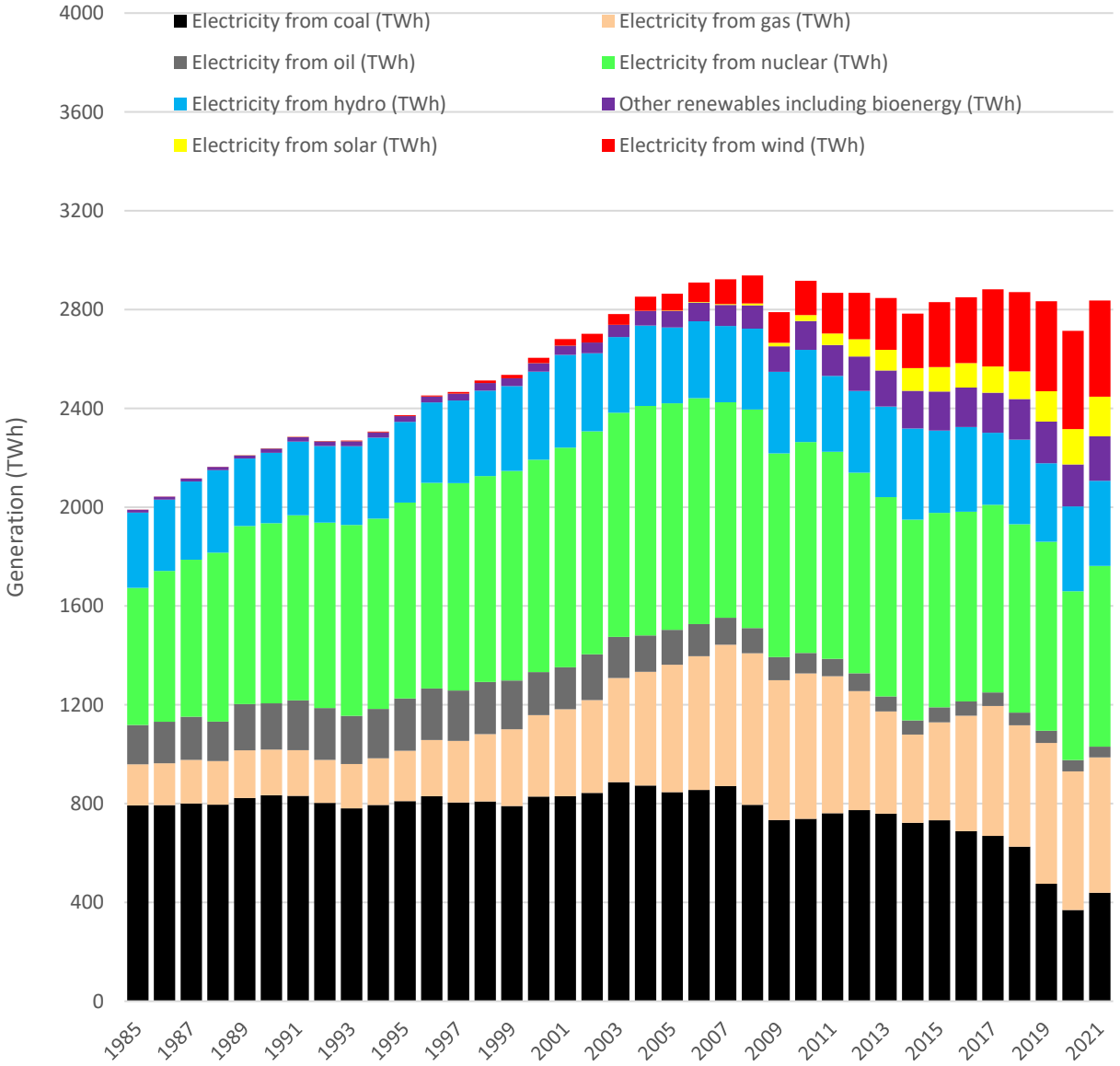


- Peak Demand 2021 – 81GW
- Peak Net Demand 2021 – 71GW
  - Reduction in Peak 13.1%
- Wind and Solar delivered 31.9% of Total Electricity Generation



European Union Capacity (GW) and Generation (TWh)





China / India / Asia

China

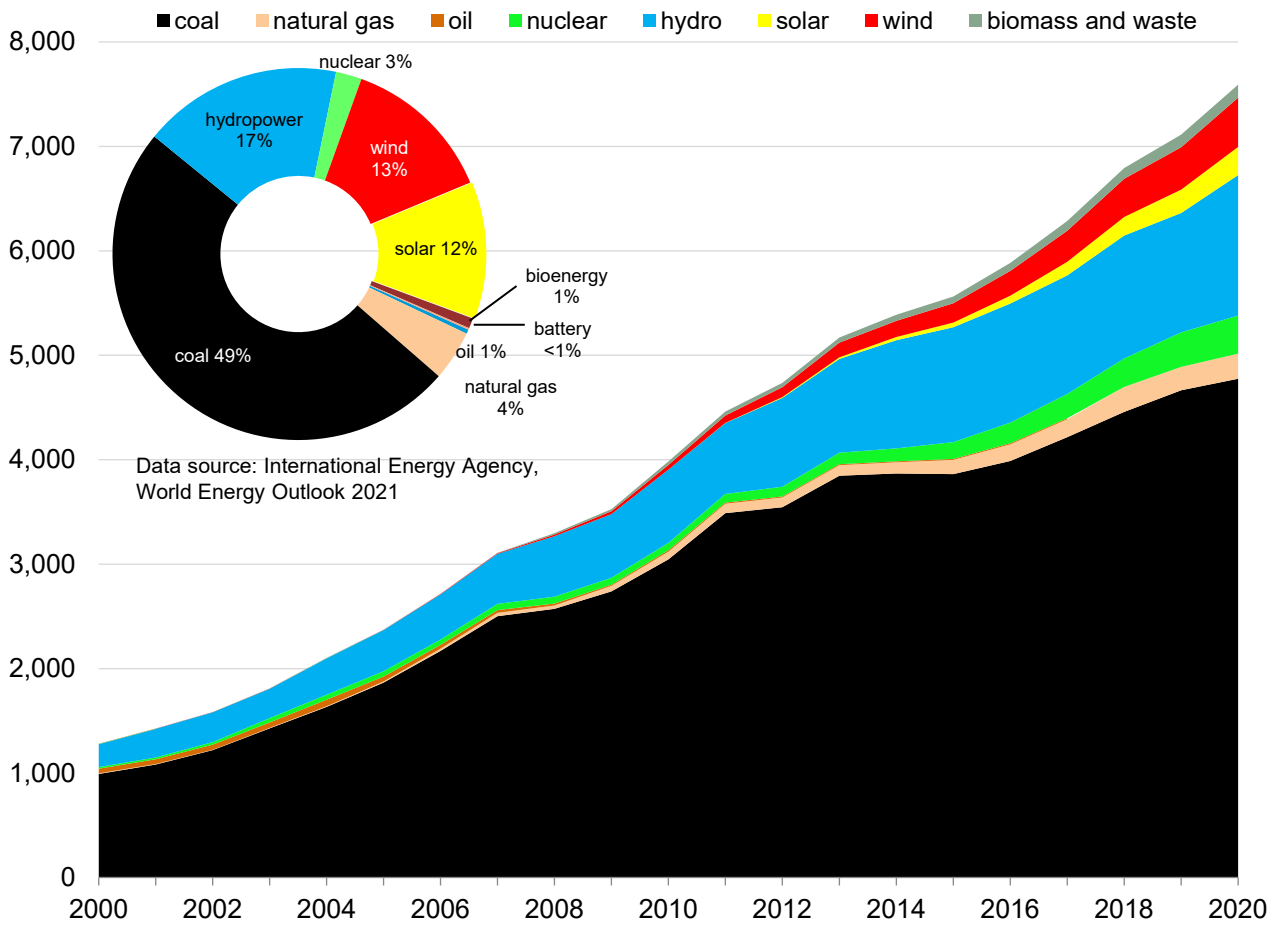
- **China Cuts Power to Factories, Homes as Reservoirs Fall**
  - August 17, 2022

- This year's crisis is a result of two factors that is, "abnormally hot weather" and a lack of rainfall.
- Last year, power generation plants cut back on production due to high coal costs they could not offset with fixed electricity sales and provincial governments rationed power usage in an effort to meet yearly emissions targets.

- **Power Shortages Resolved in China**
- Fri 17 Dec, 2021
- Beijing and Shanghai face blackouts in deepening power crunch
- Rolling outages come as factories suspend work and water supply unstable

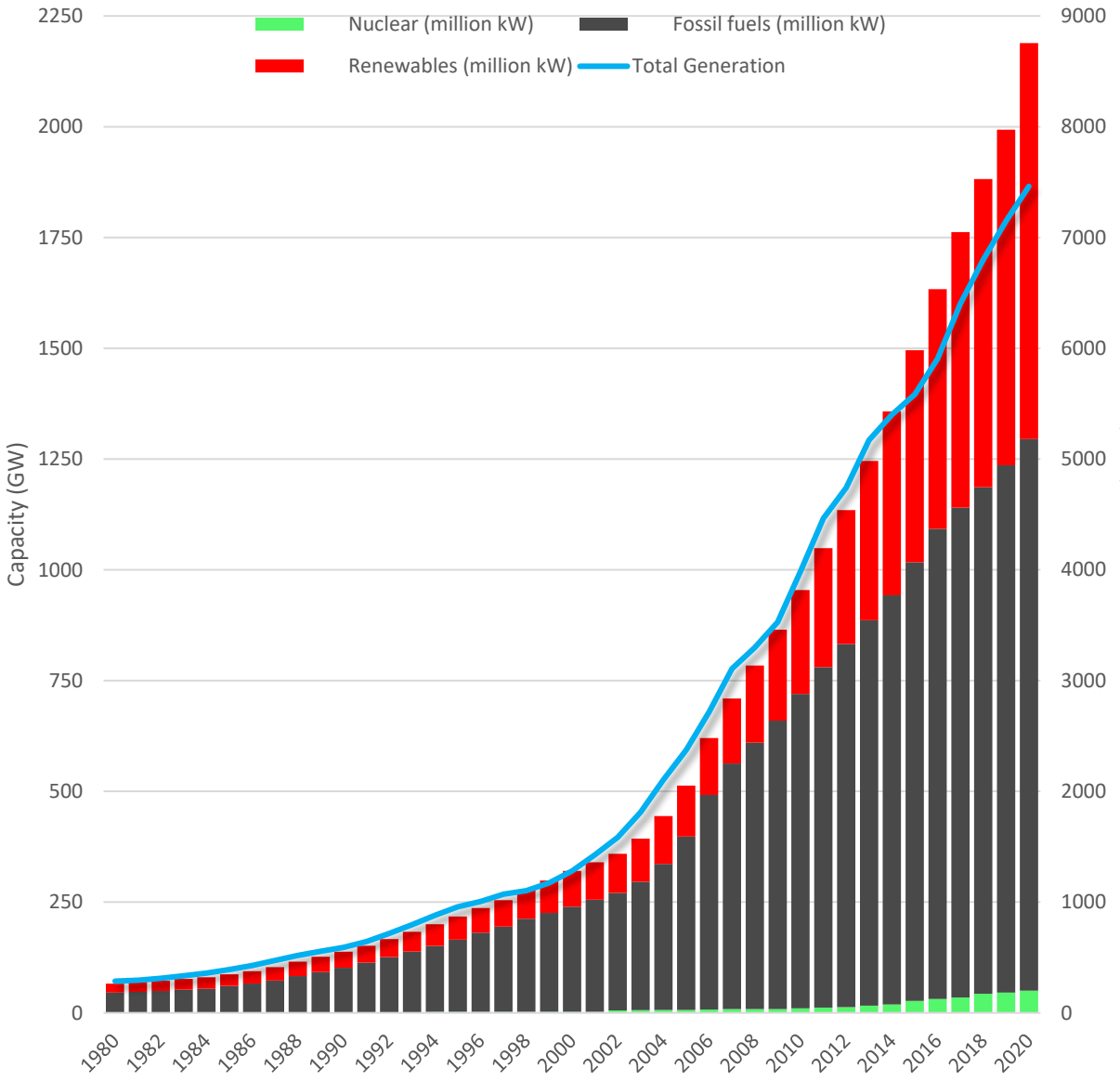
Figure 7. China's net electricity generation by fuel type, 2000–2020

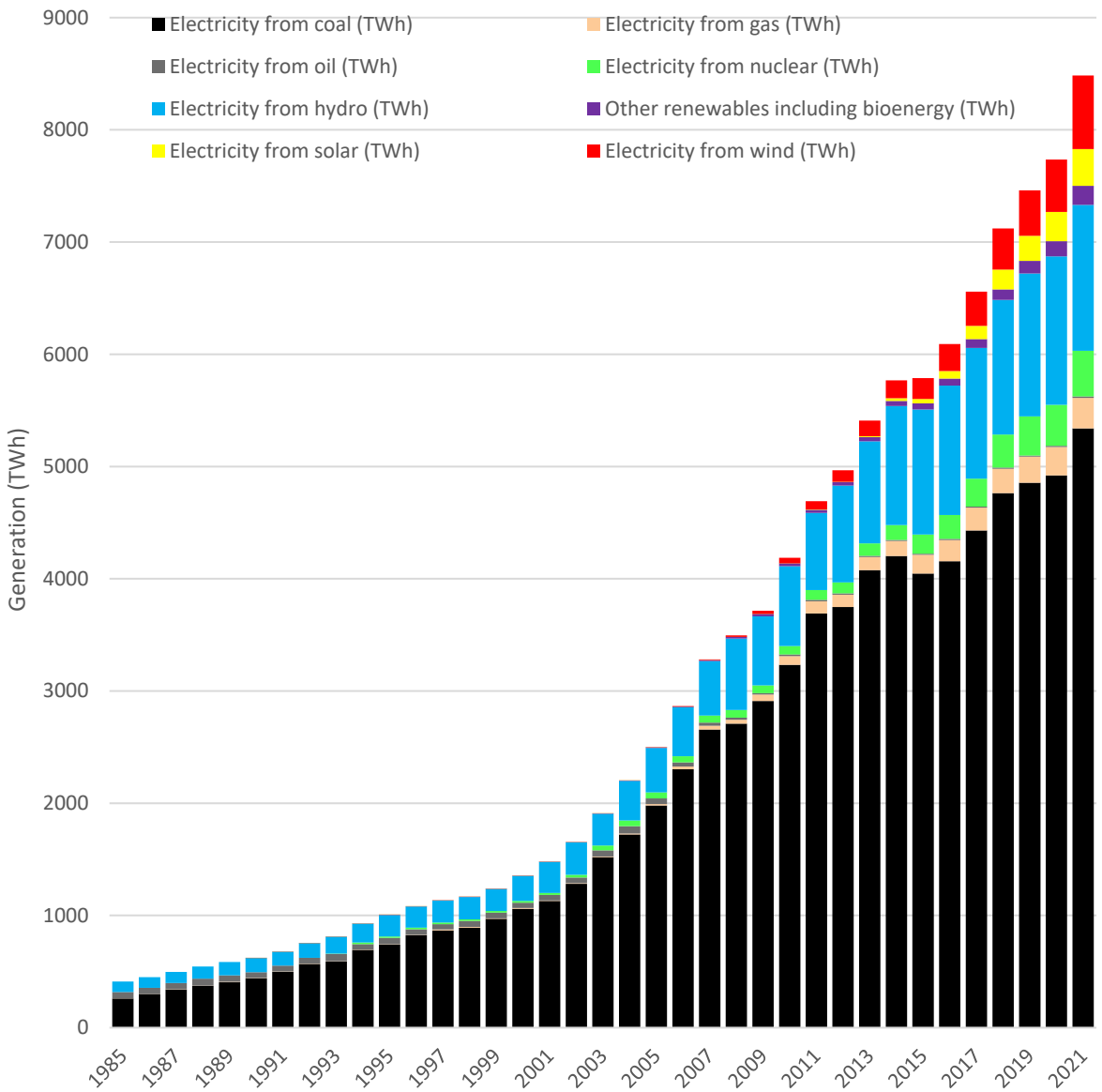
terawatthours (TWh)



Data source: U.S. Energy Information Administraion, *International Energy Statistics*

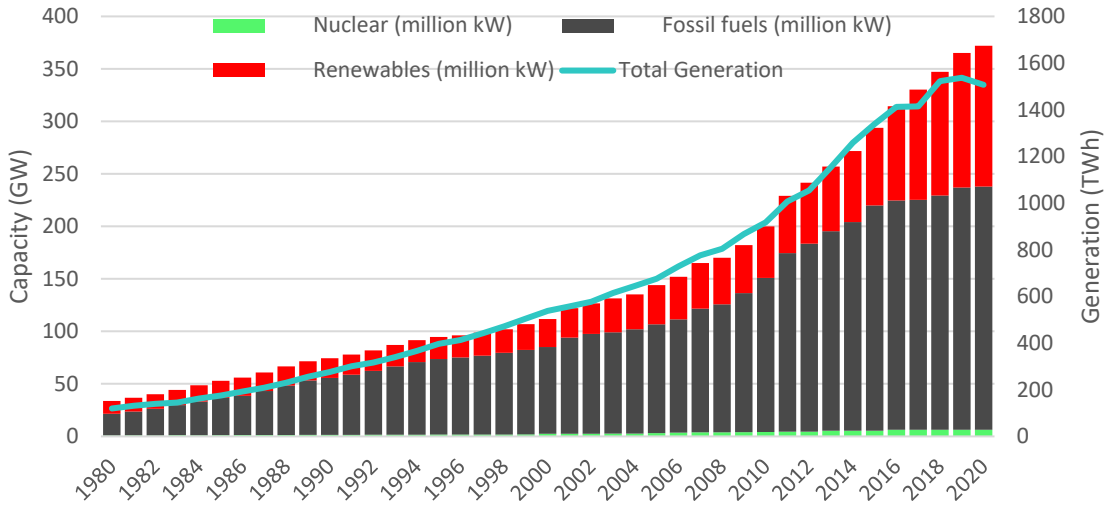
China Detail: Capacity (GW) and Generation (TWh)

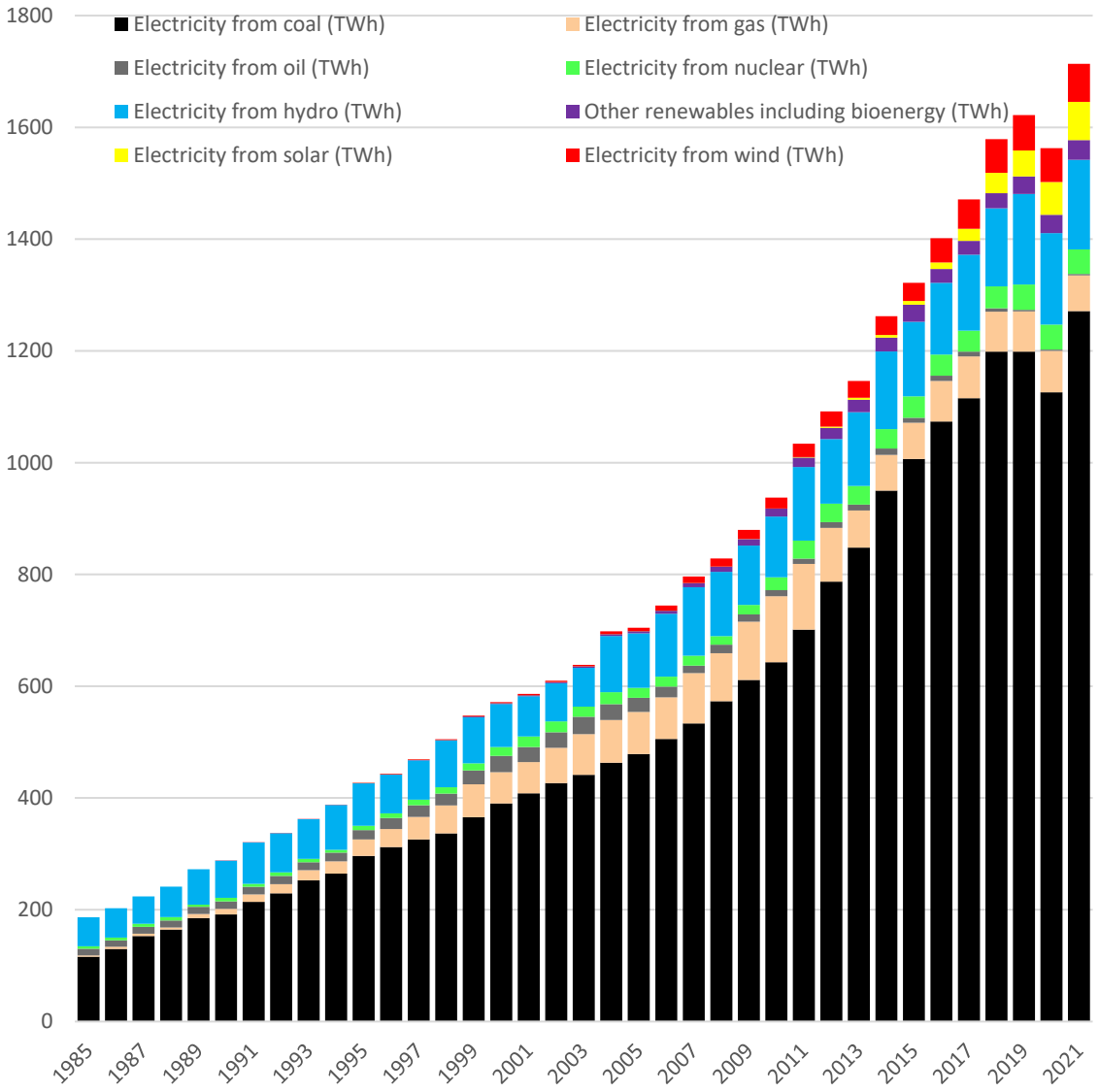




India

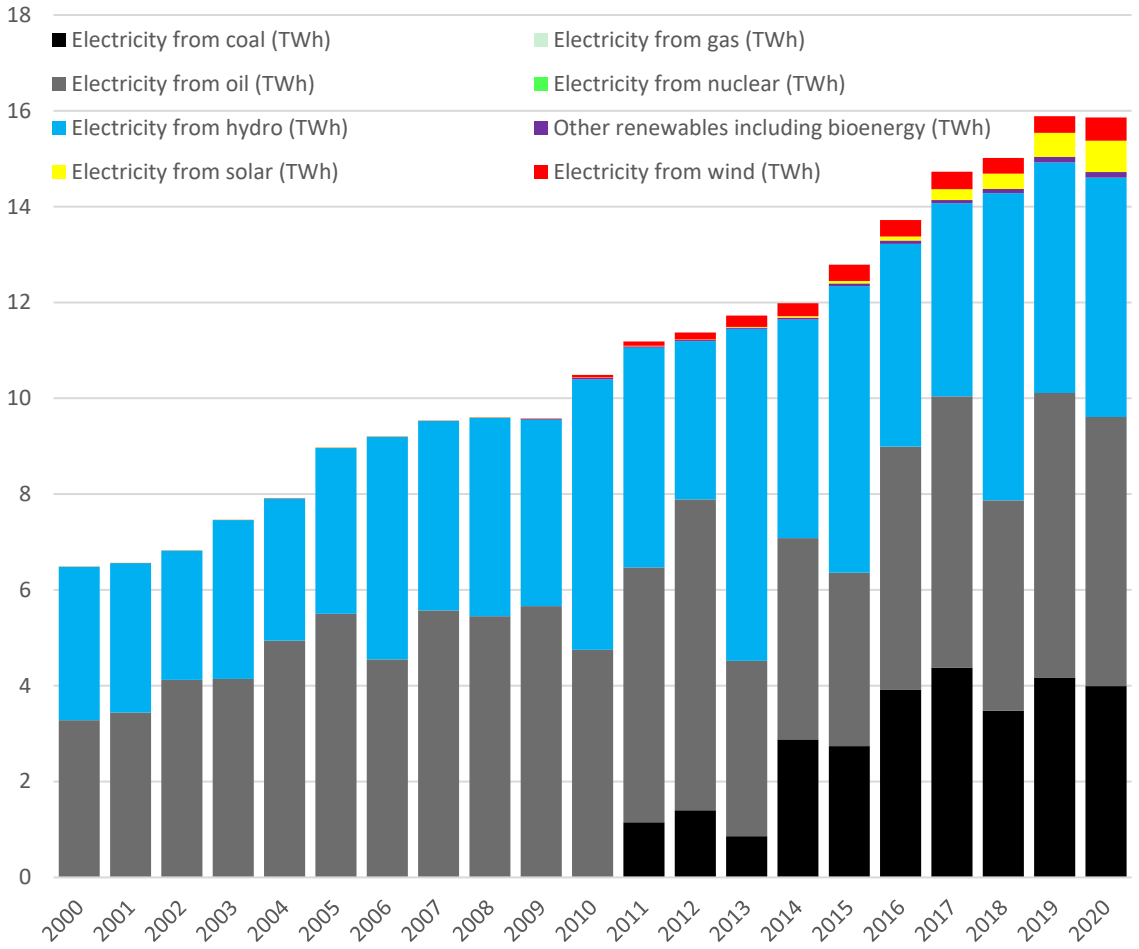
- **India Is Braced for Months of Power Outages Amid a Blistering Heatwave**
  - May 2, 2022.
- A power crisis in India that's delivering hours-long blackouts, halting manufacturing lines and triggering street protests is forecast to continue for months, adding pressure on the nation's economic rebound.



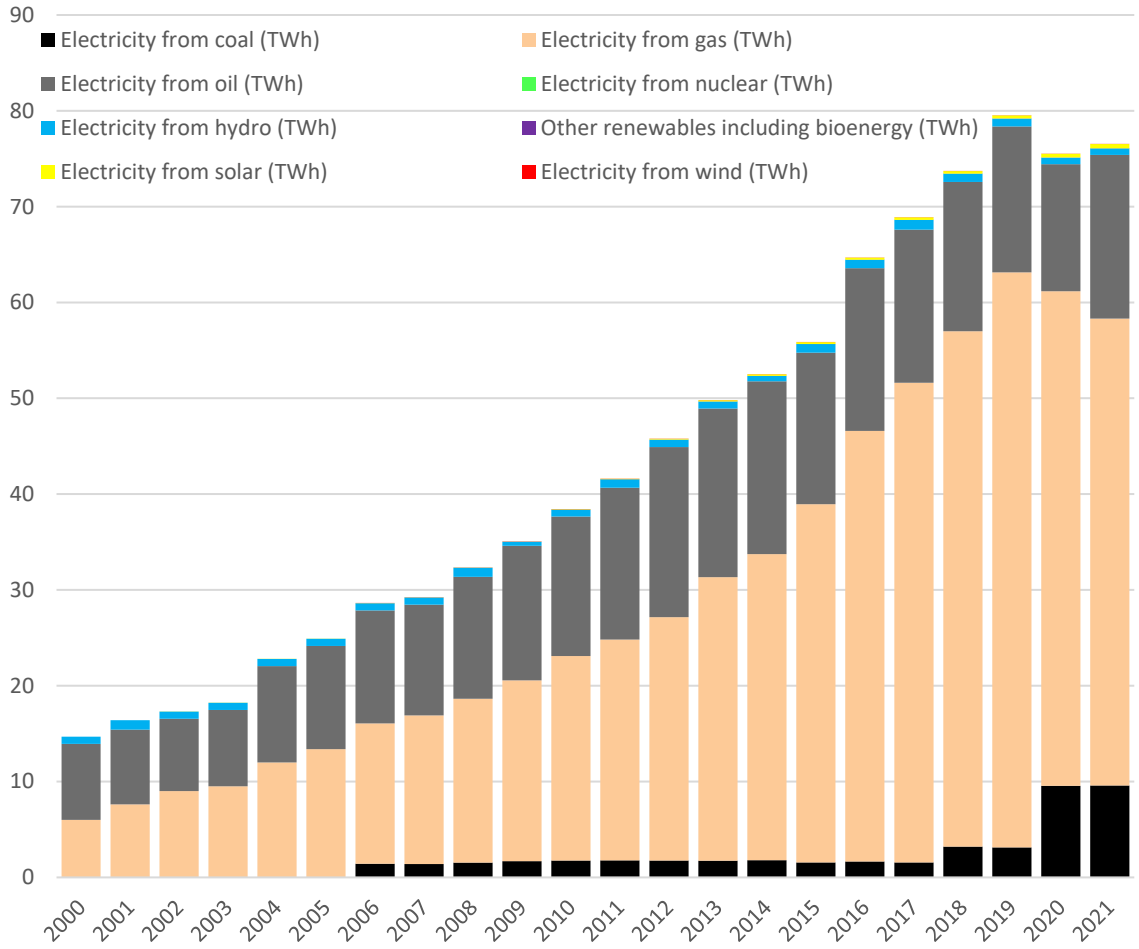


Sri Lanka and Bangladesh

Sri Lanka



Bangladesh



Diesel and Natural Gas Price Driven Load Shedding – Bangladesh Blackout October 4th, 2022
Pakistan Blackout January 23rd, 2023

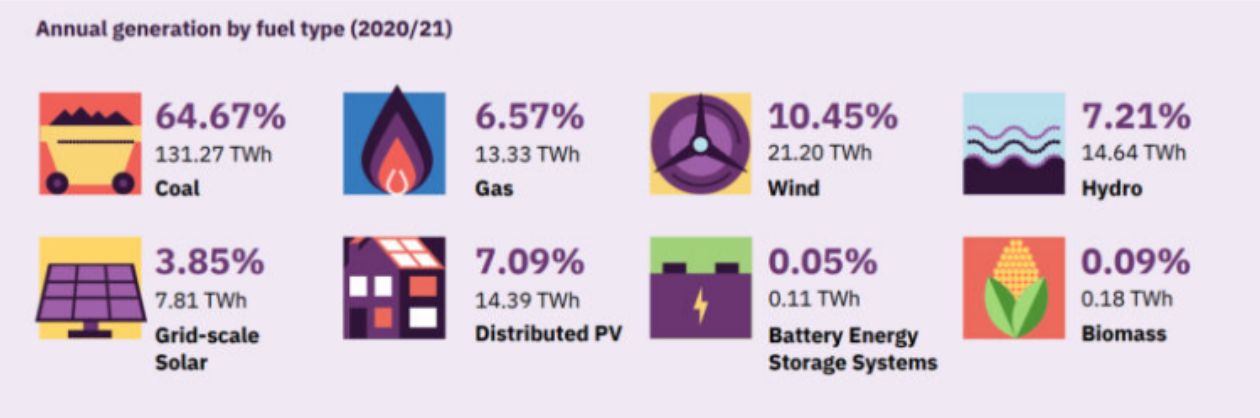
Australia

Administered Price Caps – Electricity

Not all market mechanisms work as planned – Reliability Implications

- Electricity spot prices in Queensland reached a cumulative high price threshold of $1,359,100 (accumulated over seven days) on 12 June 2022, triggering an administered price cap of $300/MWh in accordance with the National Electricity Rules.

https://www.reuters.com/business/energy/australian-energy-market-operator-lift-market-suspension-this-week-2022-06-22/



Australian Energy Market Operator's (AEMO) National Electricity Market (NEM) had a total generating capacity of 65,252 MW as of December 2021. At the end of 2021, coal produced the majority of its generated power. Courtesy: AEMO

A key issue is that the price cap has not been updated in more than 20 years, McNamara noted. "It was originally designed to reflect the maximum price a gas peaker would need to recover its costs. But with gas prices currently at A$40/GJ (which is also an artificial cap, so we know that's as high as it can go), this ceiling would need to be around A$500/MWh to ensure all generators can cover their costs," she said.

Is the NEM Broken? No, Says Power and Gas Trade Group

https://www.powermag.com/australian-energy-crisis-prompts-suspension-of-national-electricity-market/

Charting the Future …

Resource Adequacy

Flexibility | Managing Cost and Risk

Scenario Generation to Include High-Stress Periods

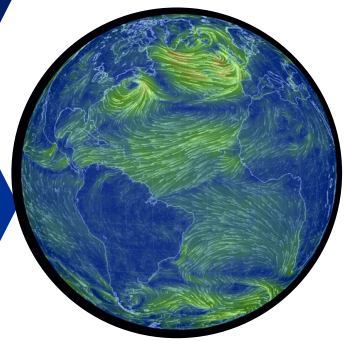
Process developed through ISO-NE Extreme Weather Risk study and RAI

Power System Information
e.g. generators, demand

Weather Data
Historical & Climate Model

Asset Risk Profiles
e.g. normal operating ranges

Project Future Weather
Historical weather overlaid on climate model projections



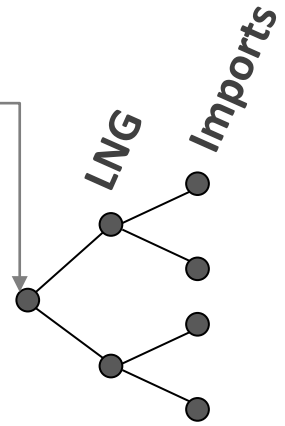
Identify High Risk Events
Screen weather for periods of potential high risk

Cold Snap

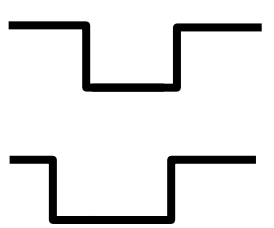
Severe Storm

Heatwave

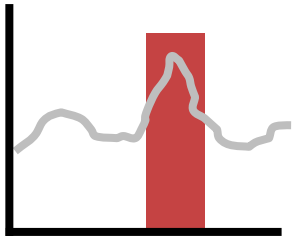
Event Scenarios
Identify potential non-weather scenarios



Weather Dependent Outages
Simulate outages of thermal plant



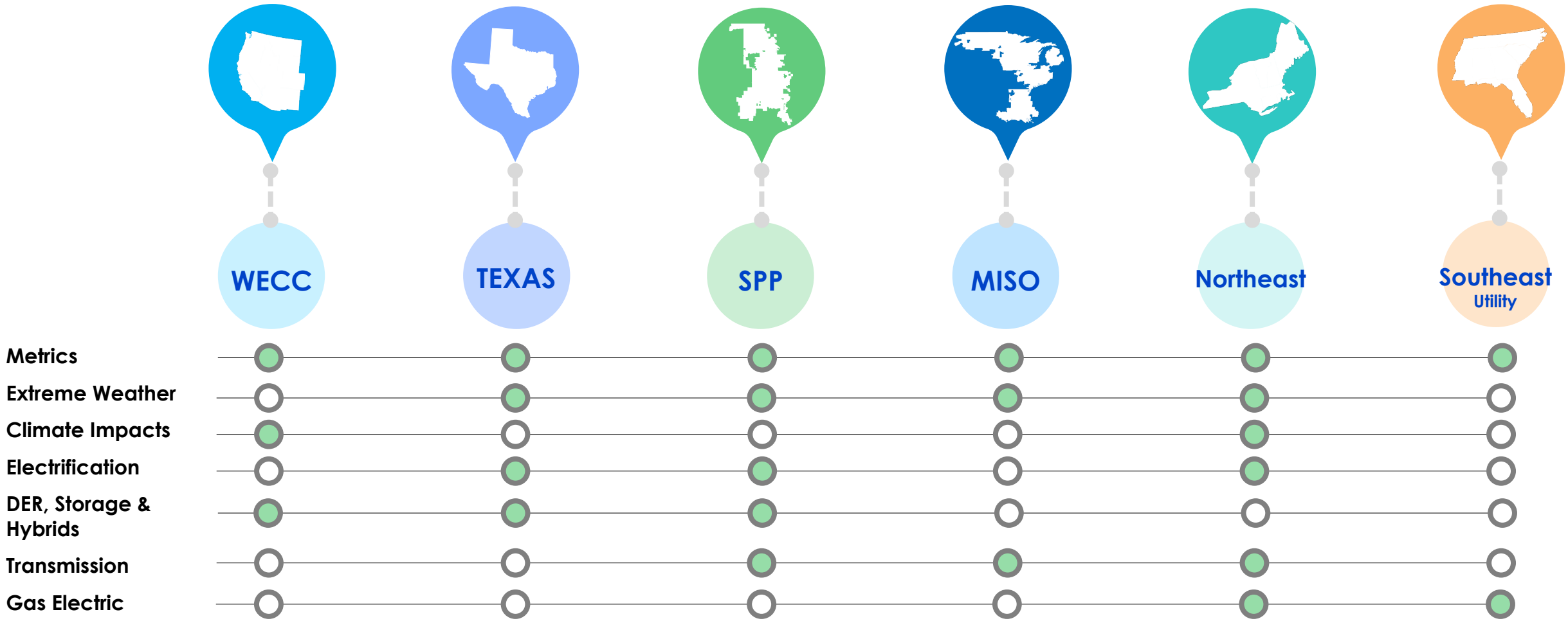
Operational Simulation
Simulate how the system operates through events



Structured process to ID highest risk scenarios to expose true risk

EPRI RA Initiative and Climate READi providing guidance and Scenario Generation tool

RA Initiative: Foundational Case Studies



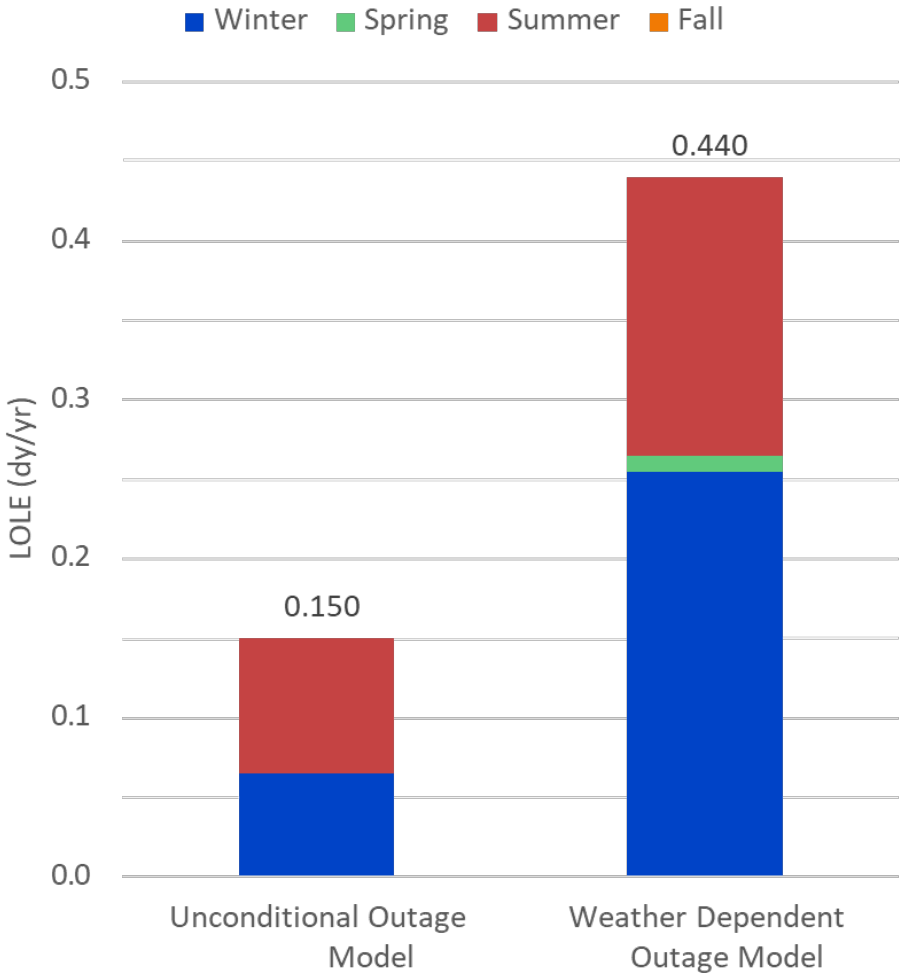
Six case studies of future systems, in different climate and electrification contexts, used to assess a range of key questions and study tool capabilities.

Major Resource Adequacy Improvements

Transitions

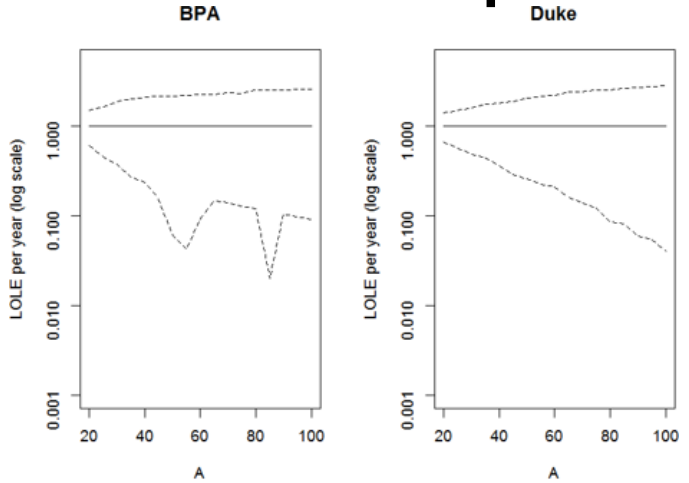
New Assets are more Variable existing assets are aging

Weather Dependent Outages



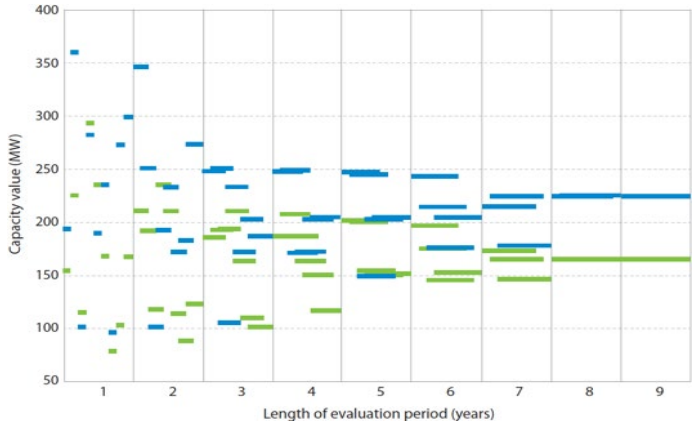
Wind and solar output is weather dependent

- **Long datasets** needed
- 'Extreme' events may include long periods of low wind or reduced irradiance over large areas at periods of relatively high load – how do they look in the future?



Capacity Adequacy and Variable Generation: Improved Probabilistic Methods for Representing Variable Generation in Resource Adequacy Assessment, 2016

Equivalent Load Carrying Contribution varies with penetration



Metrics and Criteria

LOLE is frequency metric and typically evaluated as average

Metrics that include impact of magnitude and duration expose additional risk

Very different customer impacts for same LOLE level

LOLE = Loss of Load Expectation
EUE = Expected Unserved Energy

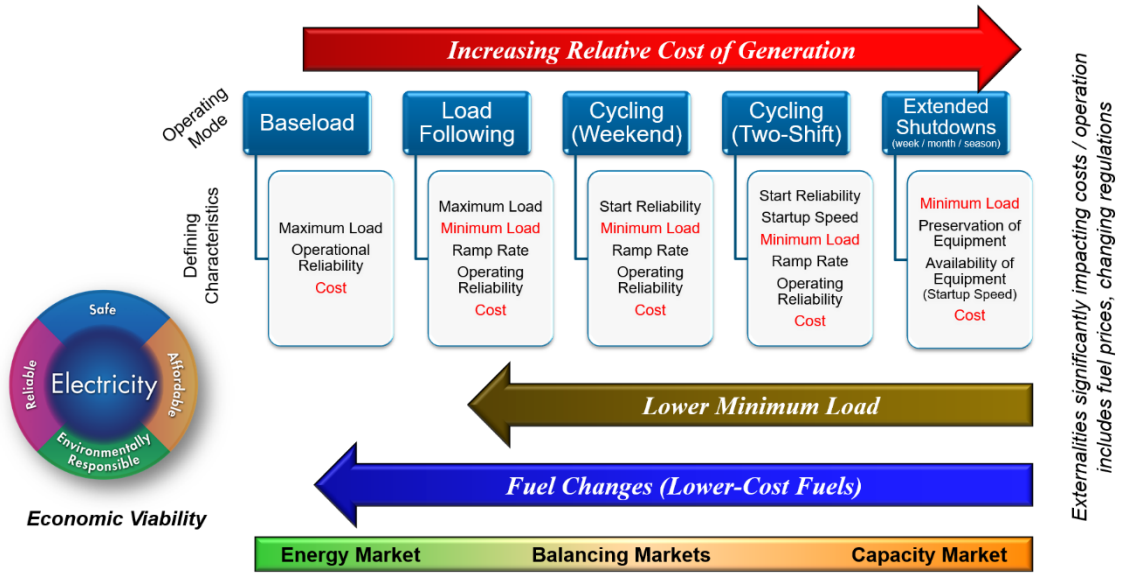
NPCC Case Study: Risk exposed by various metrics

Region	scenario	Daily LOLE	Hourly LOLE	EUE	Million MWh EUE/MWh load
A	Base avg	0.10	0.16	83.81	0.43
	Future avg	0.10	0.15	72.22	0.35
	VRE avg	0.10	0.15	77.27	0.37
B	Base avg	0.10	0.43	25.71	0.90
	Future avg	0.10	0.31	21.17	0.72
	VRE avg	0.10	0.34	29.24	0.99
C	Base avg	0.10	0.44	494.62	3.70
	Future avg	0.10	0.37	390.02	2.79
	VRE avg	0.10	0.39	471.74	3.37
D	Base avg	0.10	0.34	262.94	1.75
	Future avg	0.10	0.25	144.10	0.99
	VRE avg	0.10	0.25	145.27	1.00
E	Base avg	0.10	0.55	444.74	3.39
	Future avg	0.10	0.47	285.91	2.04
	VRE avg	0.10	0.48	354.57	2.54
F	Base avg	0.10	0.33	662.03	0.83
	Future avg	0.10	0.29	298.75	0.37
	VRE avg	0.10	0.28	278.64	0.34

EPRI RAI provides RA Metric Viewer tool and guidance to ID metrics that expose true risk

Actions to Enable Energy Supply Transition

Be More Flexible



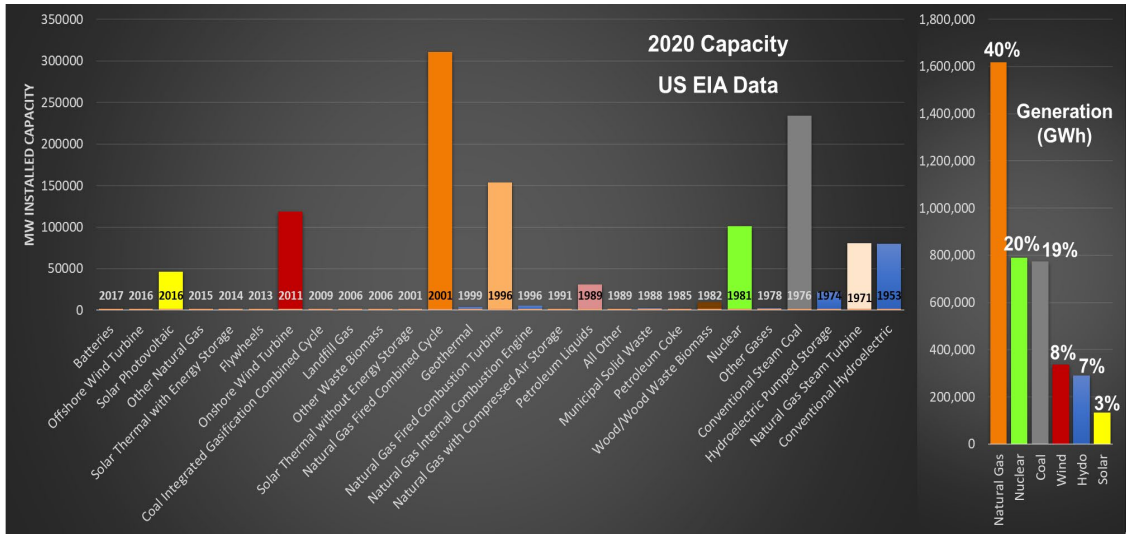
Drive Down Cost* and Risk

- Integrated Life Management
- Maintenance Management & Technology
- On-line Equipment Health Monitoring
- Inspection & Testing Technology
- Risk Management Tools
- Asset Integrity

**Fixed Costs are critical*

"You can't wipe out society and make a whole new society. You have to deal with the society that exists. But you have to figure out how you're going to change it to something that's better."

Chauncey Starr, EPRI Founder

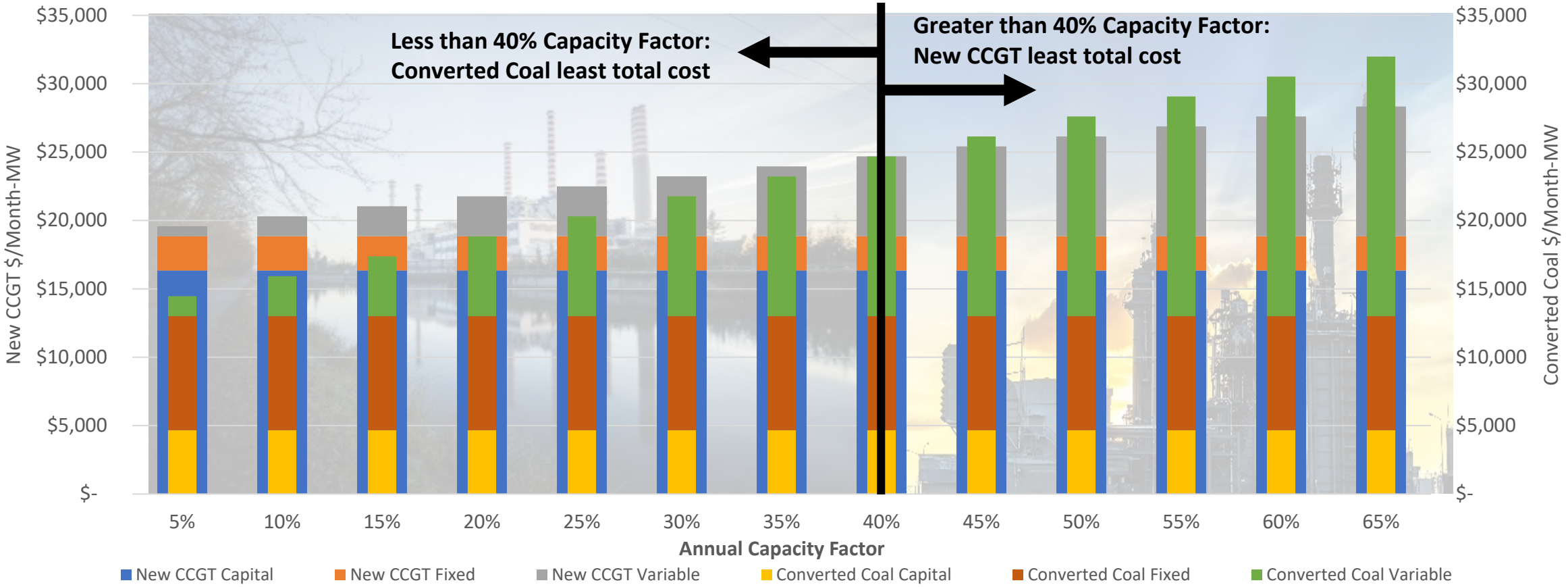


Affordable Backup Power

Back of the Envelop – Gas CCGT or Converted Coal?

Least Cost Option

Capital Cost, Rate of Return, Capacity Factor, Efficiency



Assumptions Used*	Capital*	Annual Fixed O&M	VOM	Term
New CCGT	$700/kW	$30/kW	$20/MWh	20 year
Converted Coal	$200/kW	$100/kW	$40/MWh	20 years

***dollar values are generic – actual costs will vary**

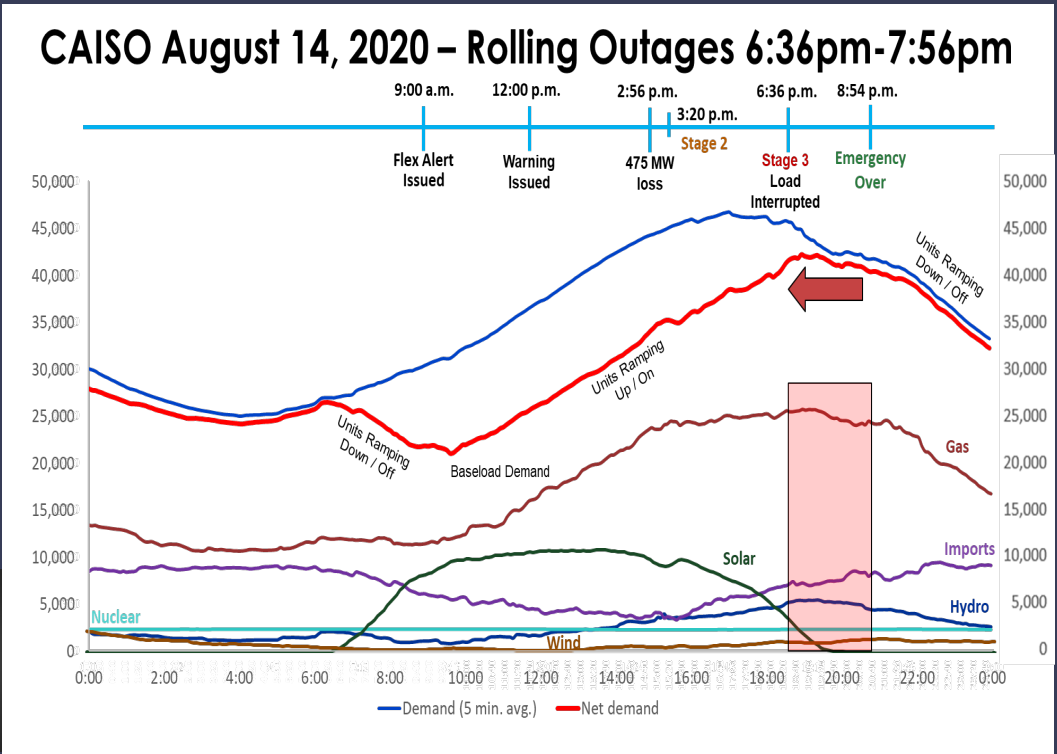
****9% rate of return**

Key Days for Dispatchable Generation (Flexible Thermal)

Increasingly defined by Variable Renewable Energy

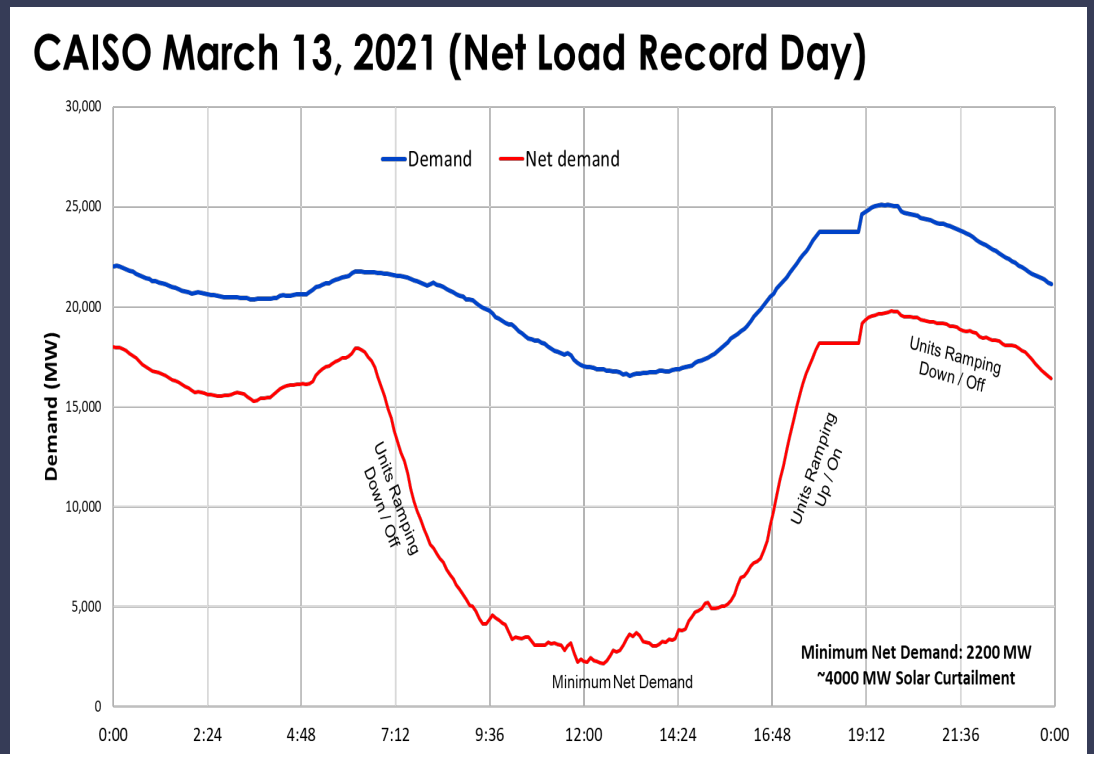
Net Load Peak Days

- All units required to meet the peak
- Hottest or coldest days
  - Hot days limit output and efficiency
  - Cold days reliability concerns



Net Load Minimum Days

- Units needed to turn down or shut down but prepared to respond
  - Can be offline for days before being required



Key Days for Dispatchable Generation (Flexible Thermal)

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Net Load Peak Days

- All
- Ho
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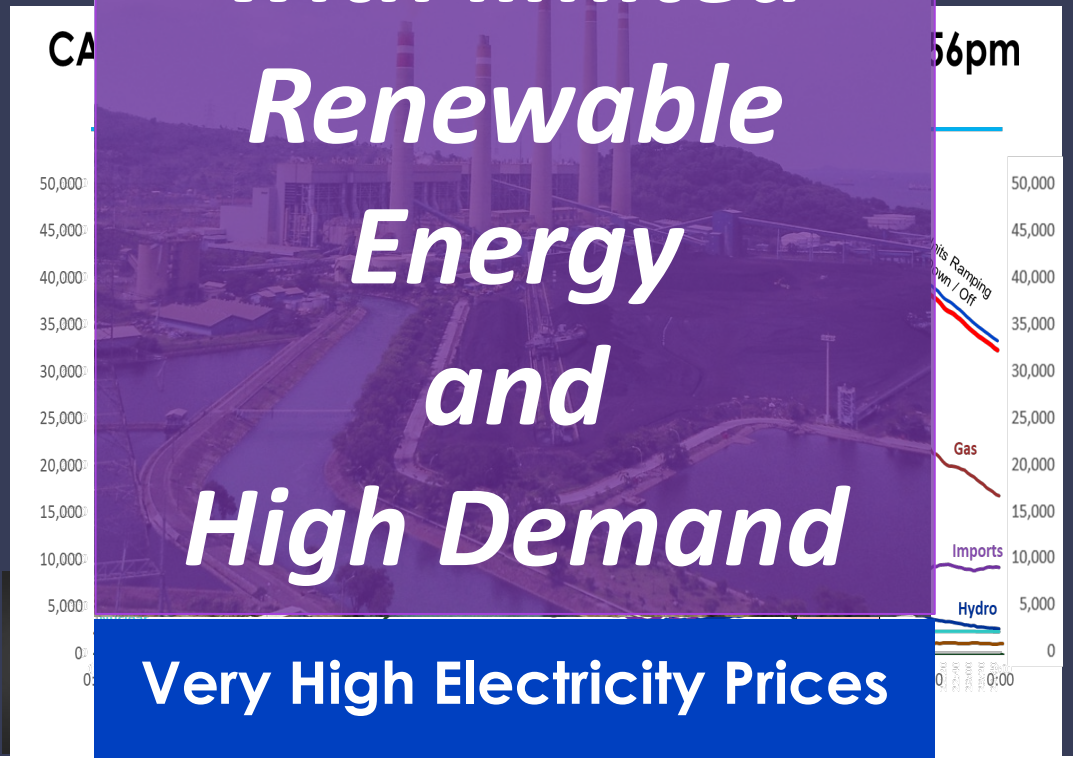
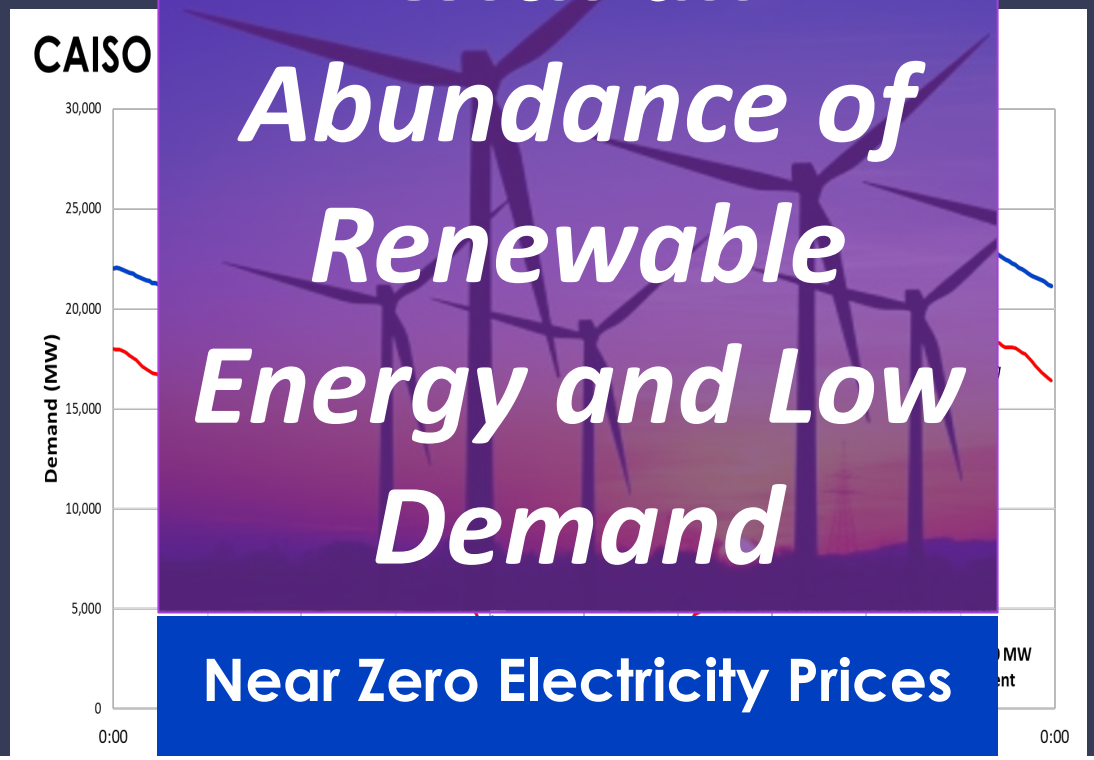


Days / Hours with limited Renewable Energy and High Demand

Very High Electricity Prices

Net Load Minimum Days

- Units
  - but p
  - – Ca
  - ired



Days / Hours with an Abundance of Renewable Energy and Low Demand

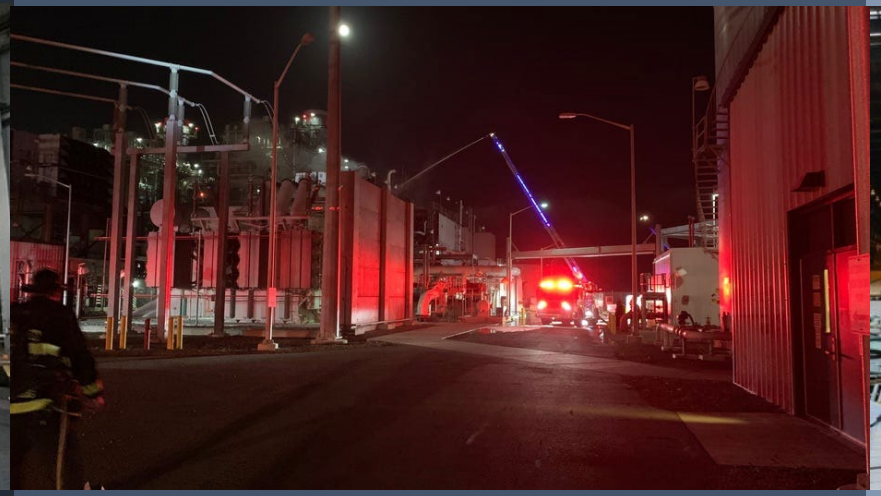
Near Zero Electricity Prices

2021 … Tough Year for Steam Turbine-Generators

May 4th, Australia Coal Fired Unit

https://www.csenergy.com.au/news/cs-energy-releases-photo-of-unit-c4

May 27th, California Combined Cycle



https://www-eastbaytimes-com.cdn.ampproject.org/c/s/www.eastbaytimes.com/2021/06/28/power-plant-explosion-prompts-hayward-officials-to-demand-answers-oppose-restarting/amp/

Aug 8th, South Africa Coal Fired Unit

https://www.dailymaverick.co.za/article/2021-08-09-eskom-confirms-explosion-at-medupi-days-after-station-comes-onstream-investigations-under-way/

Steam Turbine – Generator Wrecks

Concluding Thoughts

Role is Changing

Investment, Operation, and Maintenance Approaches must change

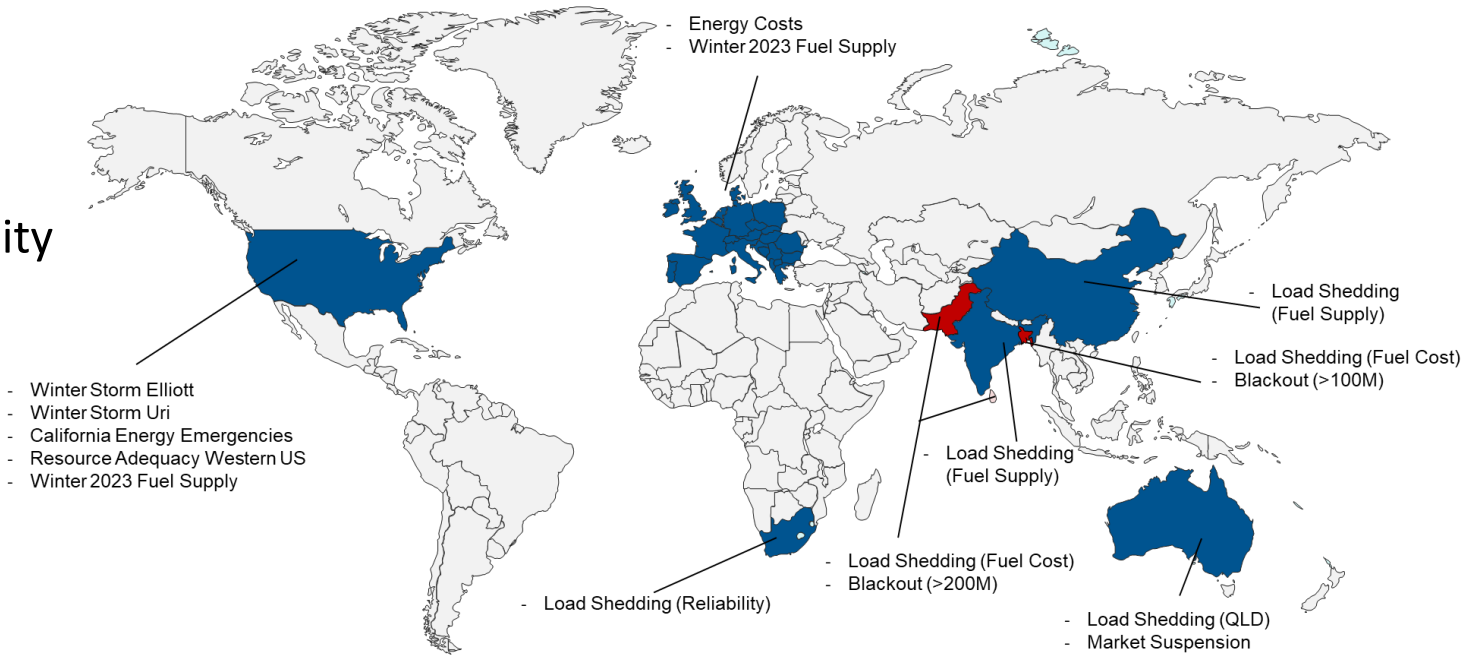
Delivering Reliability is becoming more complex

An Asset that isn't needed today could be tomorrow …

Technology developments will shape the futures possible – the best options are not likely to be clear today – but decisions today effect the possible

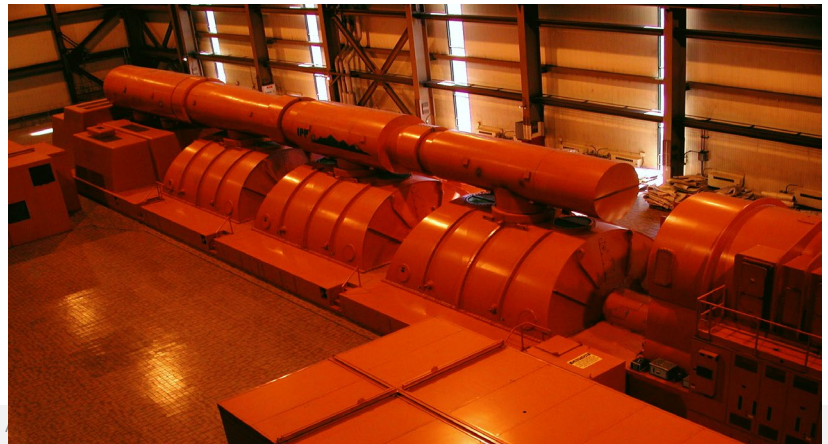
Key Takeaways

- Electricity Supply Reliability at Risk
  - Cost increases typically precede reliability failures
- Latent Risk in Aging Assets
  - New role of dispatchable assets aggravates the risk
- New Assets
  - Limited dispatchability
    - Significant Energy output, not necessarily at peak demand hours
- Interdependencies Risks may not be fully known
  - Winter failures can lead to cascading issues
- System collapses possible on marginal days
  - Low renewable output / high demand



50 or 60 Hz

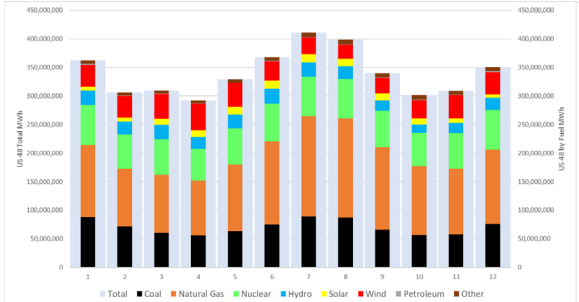
Hz = Cycles per Second



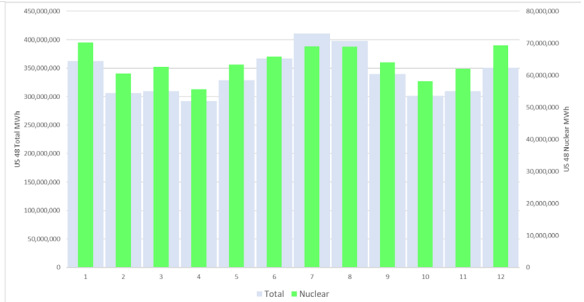
Together...Shaping the Future of Energy™

2022 Generation Shape Fitting – Monthly Energy

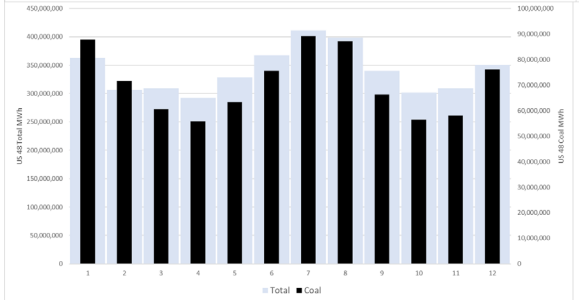
All



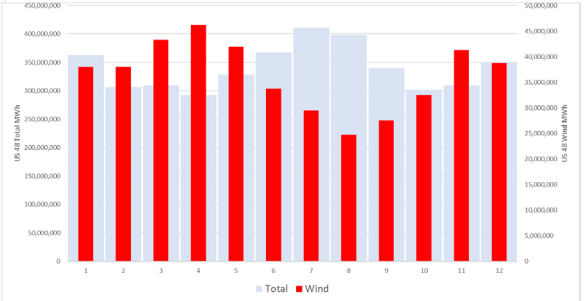
Nuclear



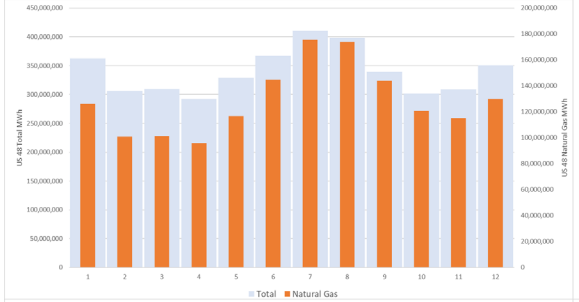
Coal



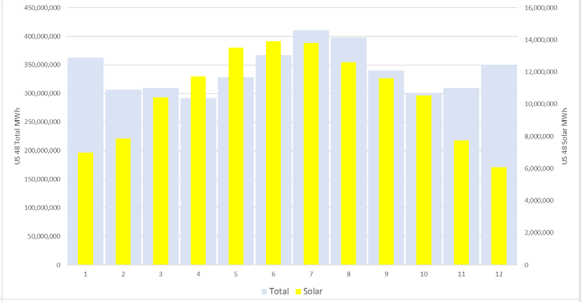
Wind



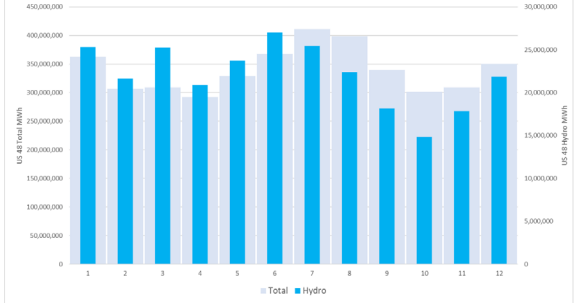
Gas



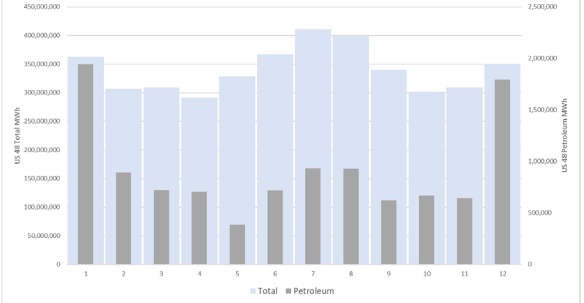
Solar



Hydro



Petrol.



Another look back at 2022. Summing up monthly electricity generation by fuel source. Note the fuel source MWh are on the secondary y-access and for the fuel specific bar charts there is a large difference in the primary y and secondary y axis scale, as well as the secondary y axis scale between the charts. The shape though of each compared to the shape of our total demand (light blue) is important as we transition.

Top left puts it all together, we peak in electricity usage in the US lower 48 in the summer, with low points in the shoulder seasons (spring and fall) and another (lower) peak in the winter.

For coal we relied on our capacity to ramp up in the winter and (less so) in the summer to meet our needs.

For natural gas we really relied heavily on it for the summer peak, it ramps up in winter but not nearly the same increase compared to coal (or petroleum) on a relative scale, in the winter season.

For hydro the early winter and late spring were peak periods (after the snow melt as we get to late summer / early fall there is a drop off).

Nuclear runs baseload and takes outages in the spring and fall so it can be available at nearly full output in the summer and winter and this is well reflected in the 2022 total MWh data.

Wind MWhs peaked in the spring, but was much lower in the summer. There are implications to that. Building MWs of wind capacity to fill a summer MWh demand peak will lead to a lot more MWhs of wind in the spring but not necessarily MWhs of wind in the summer when demand is higher.

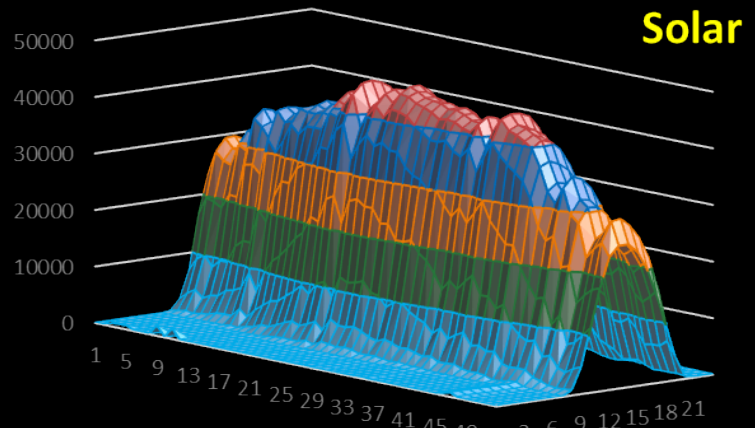
Solar MWhs peak in the early summer, but are also high in later spring and early autumn, but reach an annual low in winter. Building solar to fill a winter MWh demand peak has a similar seasonal challenge to wind.

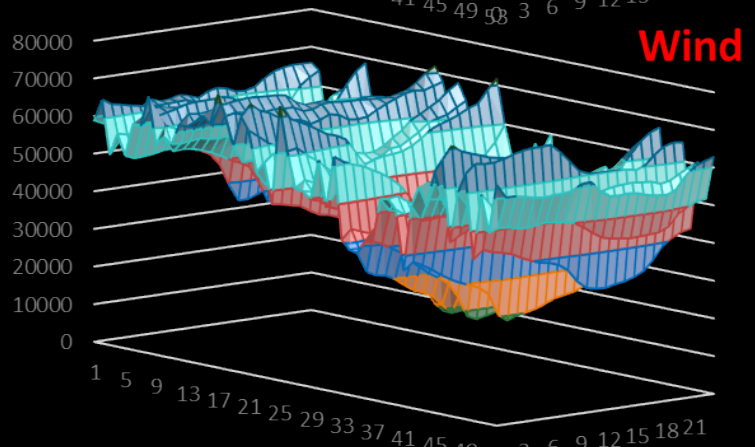
Petroleum MWhs peak in the winter. We often rely on oil as a backup fuel in the winter when gas may get diverted for home heating use.

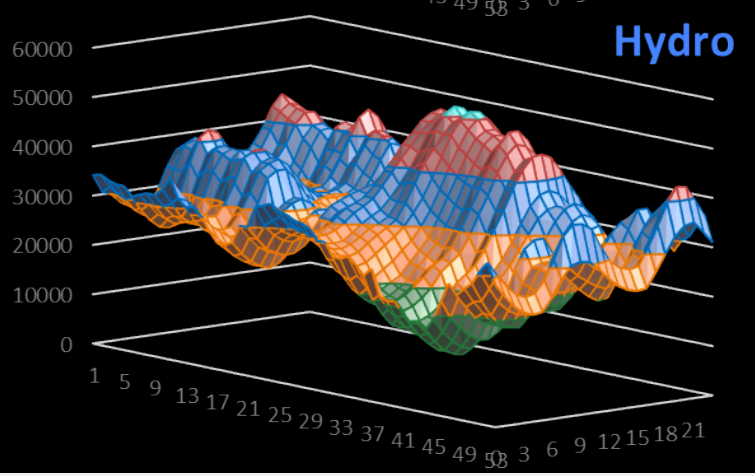
Bearing in mind the seasonality of variable generation sources is really important as we continue the transition.

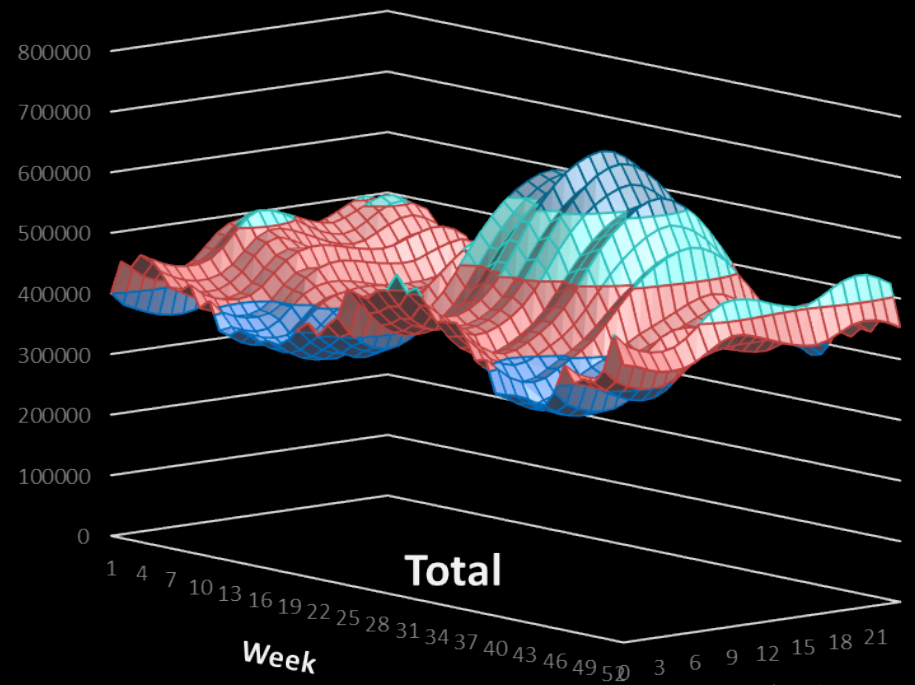
Batteries with 4,8,10 hour capacity are not well suited for redistributing surplus spring energy to the summer or winter.

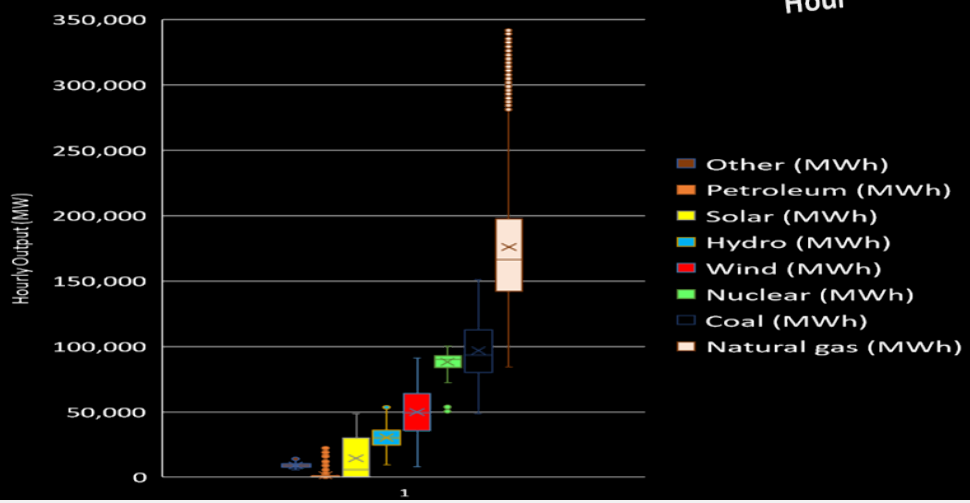
US Lower 48
2022 Shape of Generation

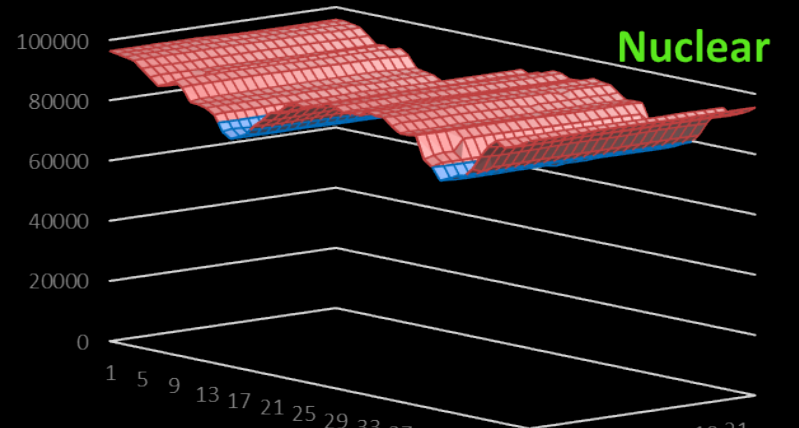


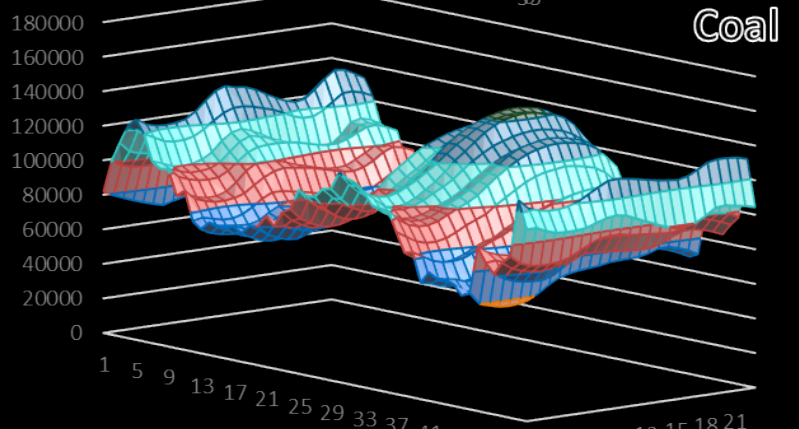


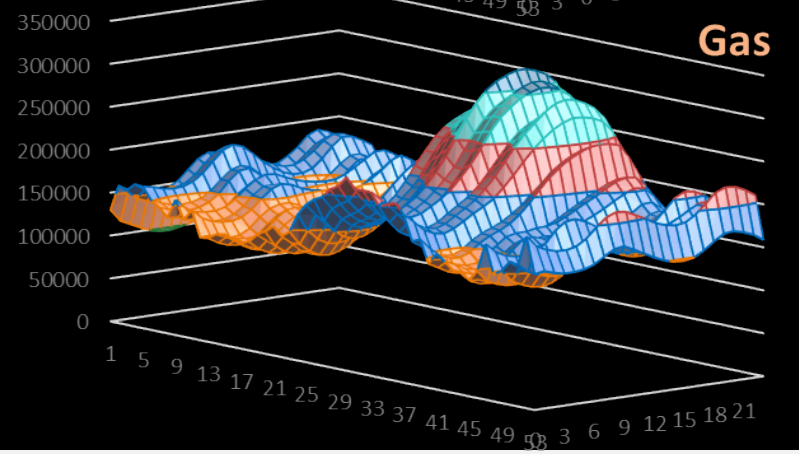






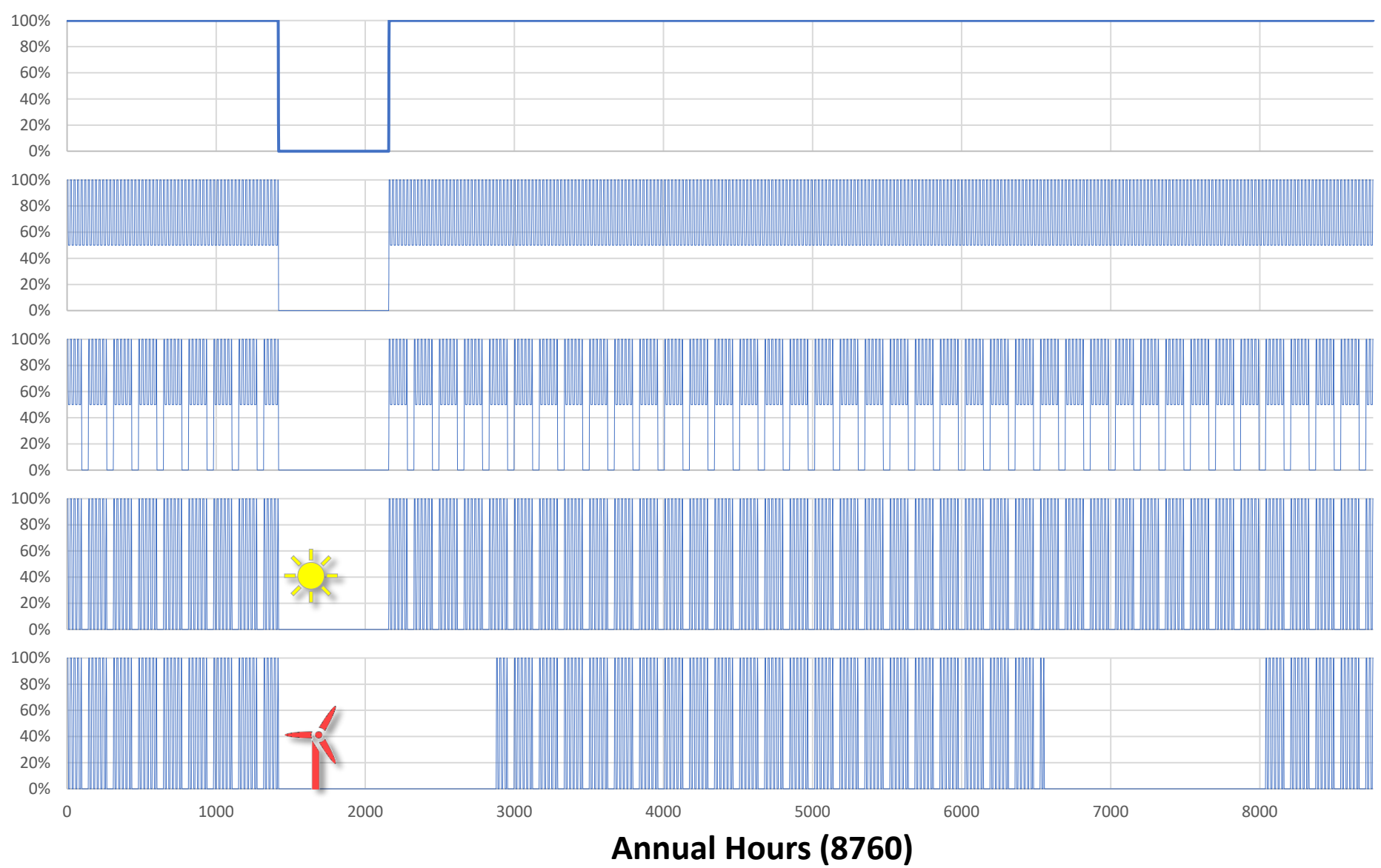






Different Thermal Plant Annual Operation Modes

	Capacity Factor	Service Factor	Starts
Baseload	92%	92%	1
Load Following	66%	92%	1
Weekend Cycling	49%	68%	50
Daily Cycling	35%	43%	250
Extended Shutdown	25%	35%	150



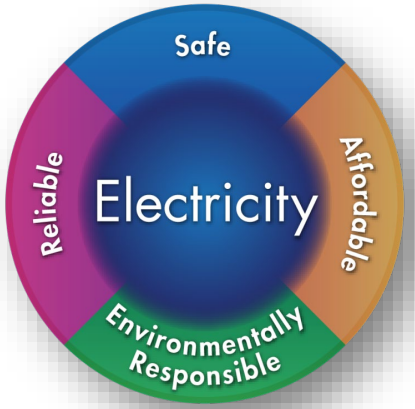
Spectrum of Flexible Operation

Operating Mode

Defining Characteristics

Increasing Relative (Marginal) Cost of Generation

Baseload	Load Following	Cycling (Weekend)	Cycling (Two-Shift)	Extended Shutdowns (week / month / season)
Maximum Load Operational Reliability Cost	Maximum Load Minimum Load Ramp Rate Operating Reliability Cost	Start Reliability Minimum Load Ramp Rate Operating Reliability Cost	Start Reliability Startup Speed Minimum Load Ramp Rate Operating Reliability Cost	Minimum Load Preservation of Equipment Availability of Equipment (Startup Speed) Cost



Economic Viability

Lower Minimum Load

Fuel Changes (Lower-Cost Fuels)

Energy Market — **Balancing Markets** — **Capacity Market**

Externalities significantly impacting costs / operation includes fuel prices, changing regulations

Retrofits for flexibility are possible but economics can be challenging (especially for ramp rate)

Recurring Themes

- Energy Need from Thermal Assets drops off faster than Capacity Need
  - Annual TWh drops faster, than peak demand GW
    - I.e. capacity factors (revenue) drops, but instantaneously still need capacity for marginal hours (low renewable output, high demand)
- Fewer and Fewer new Thermal Assets, increasingly variable sources
  - Variable generation has correlated output across fleet, and has seasonality that may not coincide with seasonal demand
  - Aging thermal assets must operate flexibly, with revenue constraints

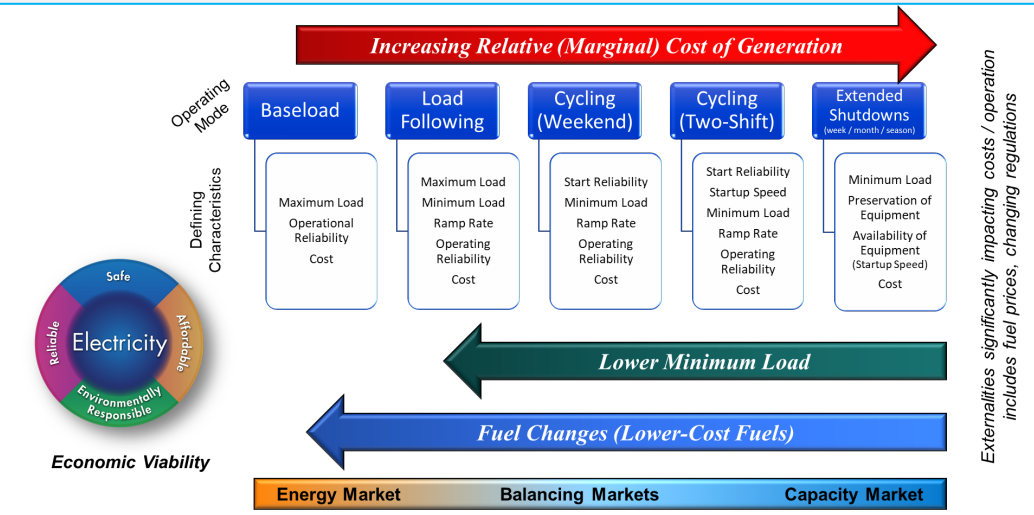
Efficiency versus Flexibility?

Fixed Costs versus Operating Costs?

Build new versus repurpose old?

Optimize hourly output versus annual?

Investment, Operating, and Maintenance Strategies must align with Operating Modes

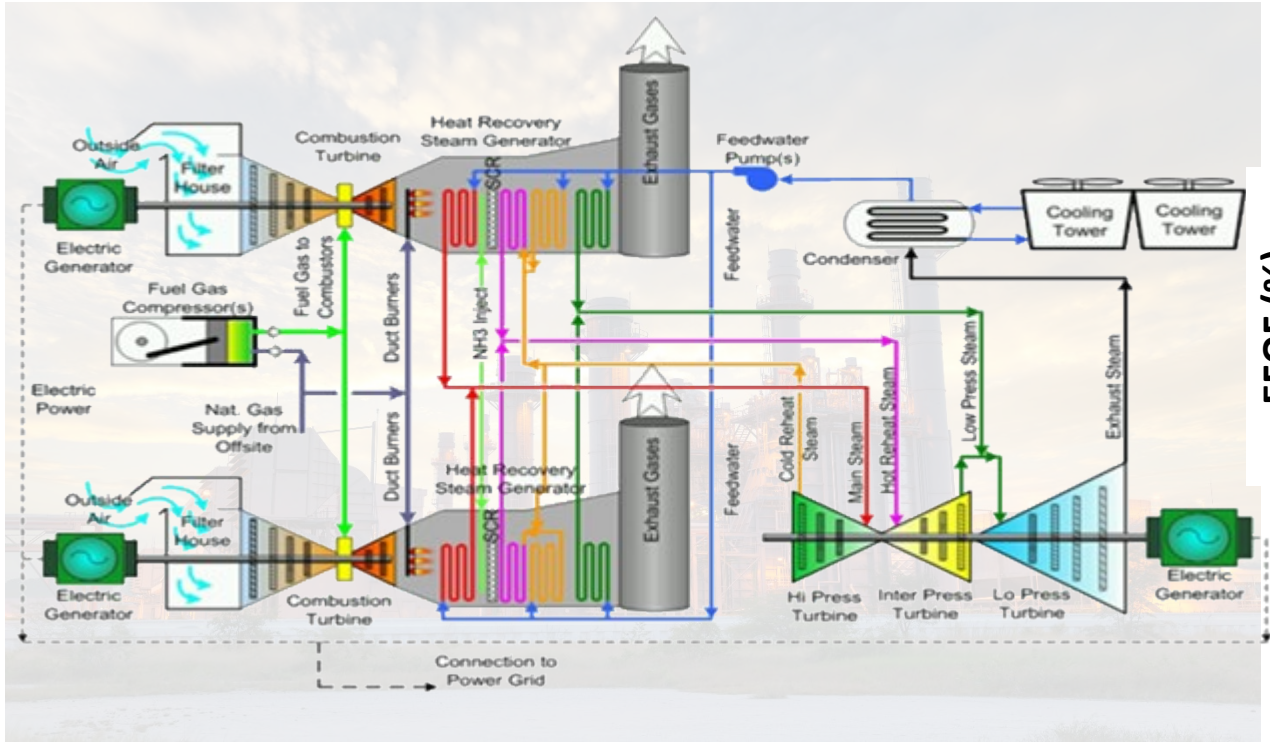


Transition Risk

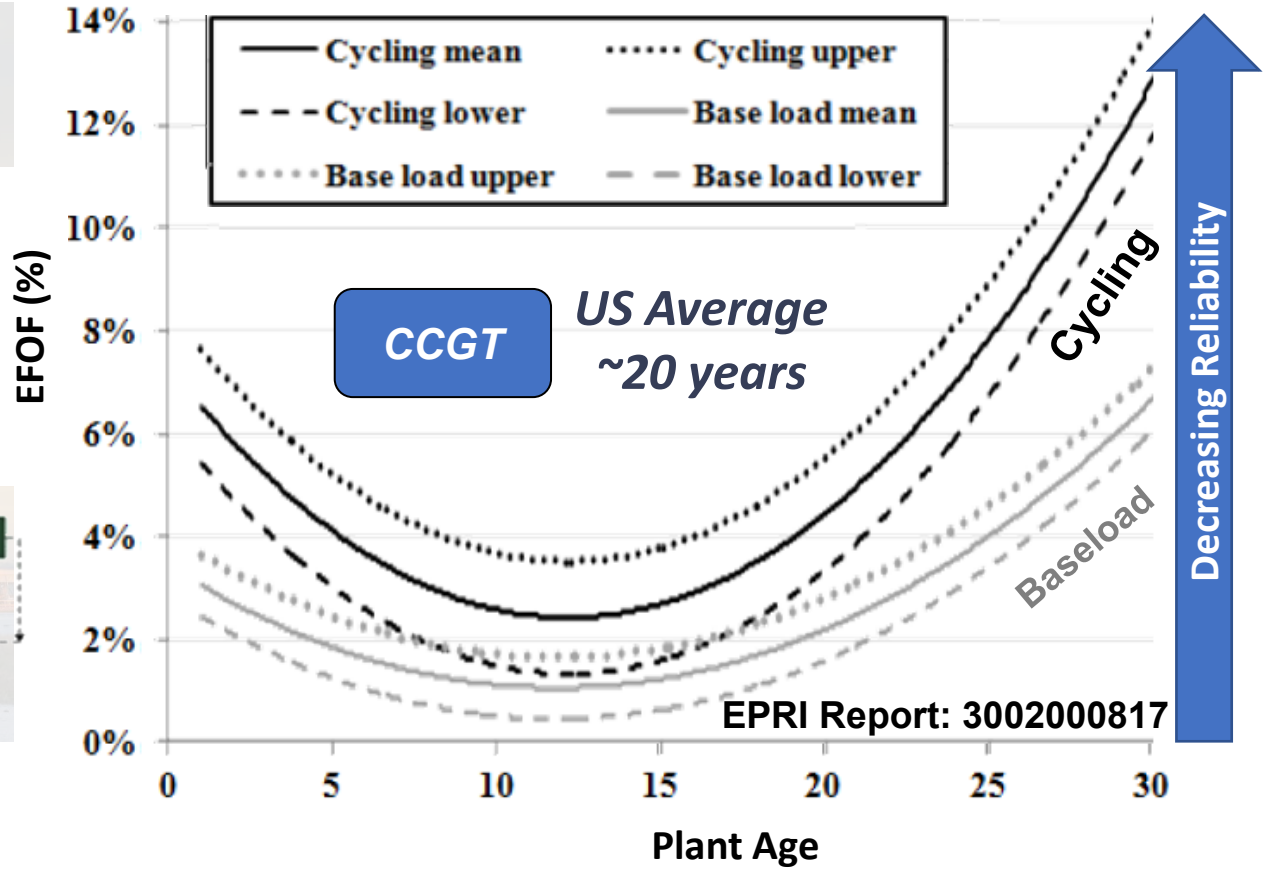
Flexibility and Reliability

Future Reliability Pressure

EFOF = Equivalent Forced Outage Factor



Combined Cycle Gas Turbine (CCGT) Power Plants

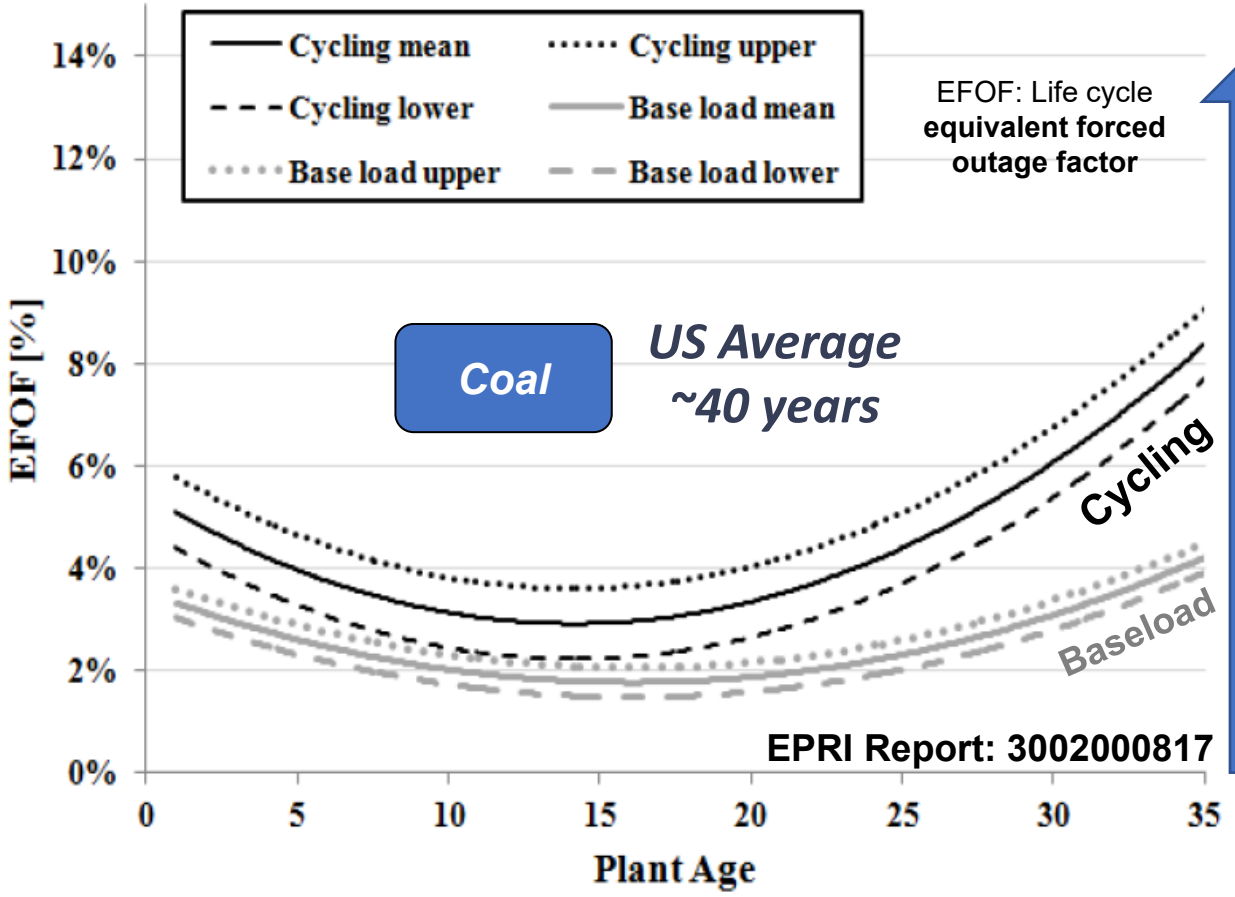


Age and cycling (flexible operation) impacts plant reliability

Flexibility and Reliability

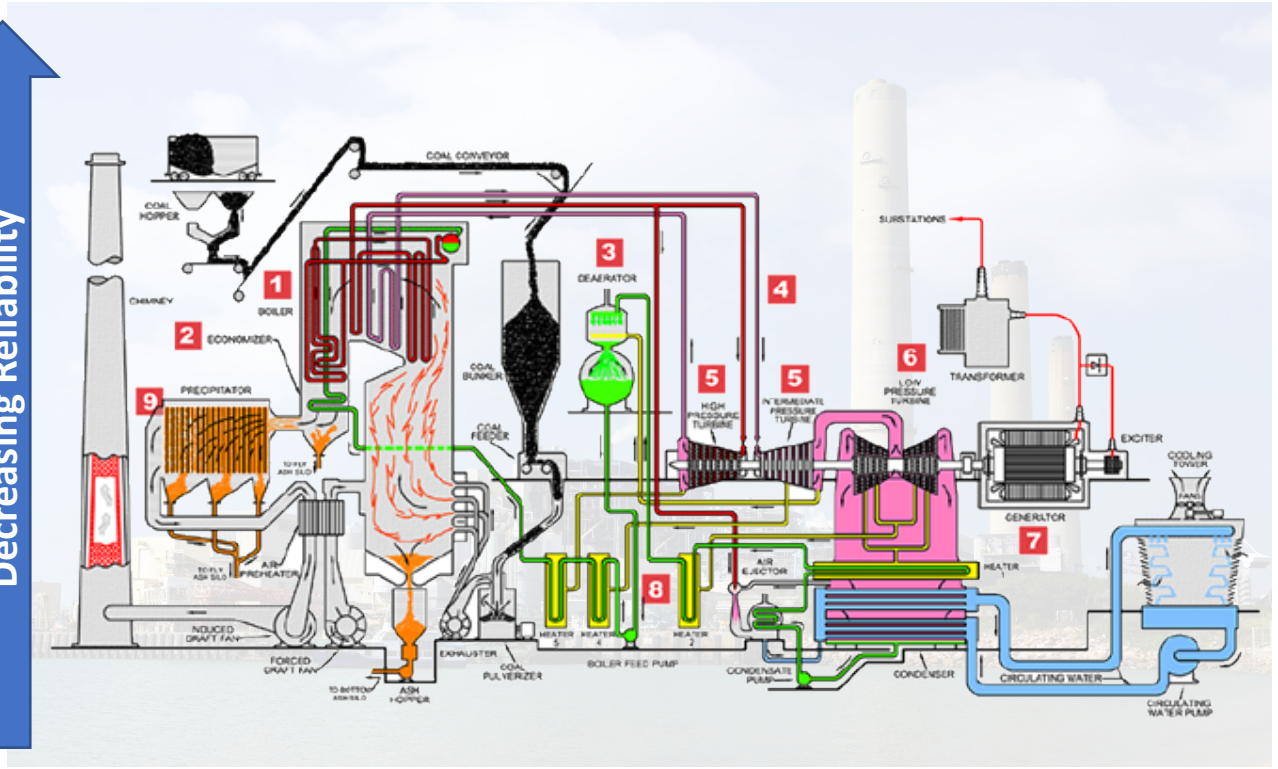
Future Reliability Pressure

EFOF = Equivalent Forced Outage Factor



EFOF: Life cycle **equivalent forced outage factor**

Decreasing Reliability



Conventional Coal Fired Power Plant

Age and cycling (flexible operation) impacts plant reliability