Utility and Grid Operator Resources for Future Power Systems Webinar Series

Fundamentals of Resource Adequacy for Modern Power Systems

Paul Denholm, National Renewable Energy Laboratory (NREL)

NREL Webinar Series

June 26, 2025

Agenda

Ongoing Concerns About Resource Adequacy (RA)

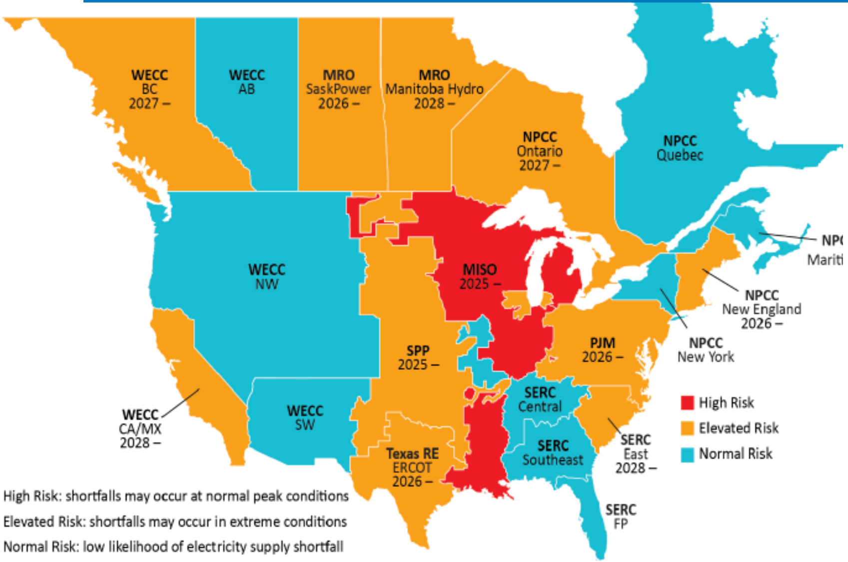
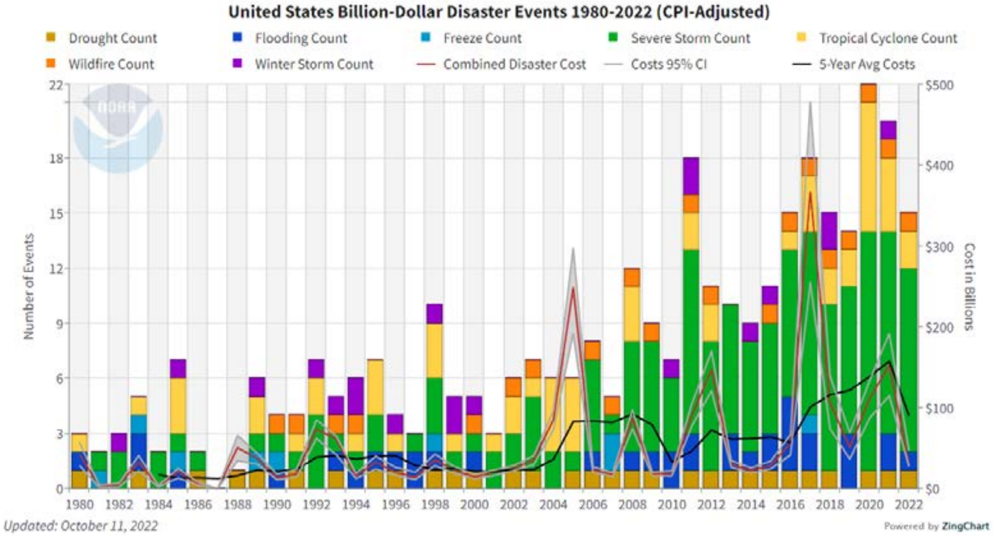


Figure 1: Risk Area Summary 2025–2029



North American Electric Reliability Corporation (NERC) Long Term Reliability Assessment

- Elevated or high risk in many regions
- Winter fuel supply a major challenge
- Capacity reserves a challenges in some regions

Source: NERC Long Term Reliability Assessment (link)

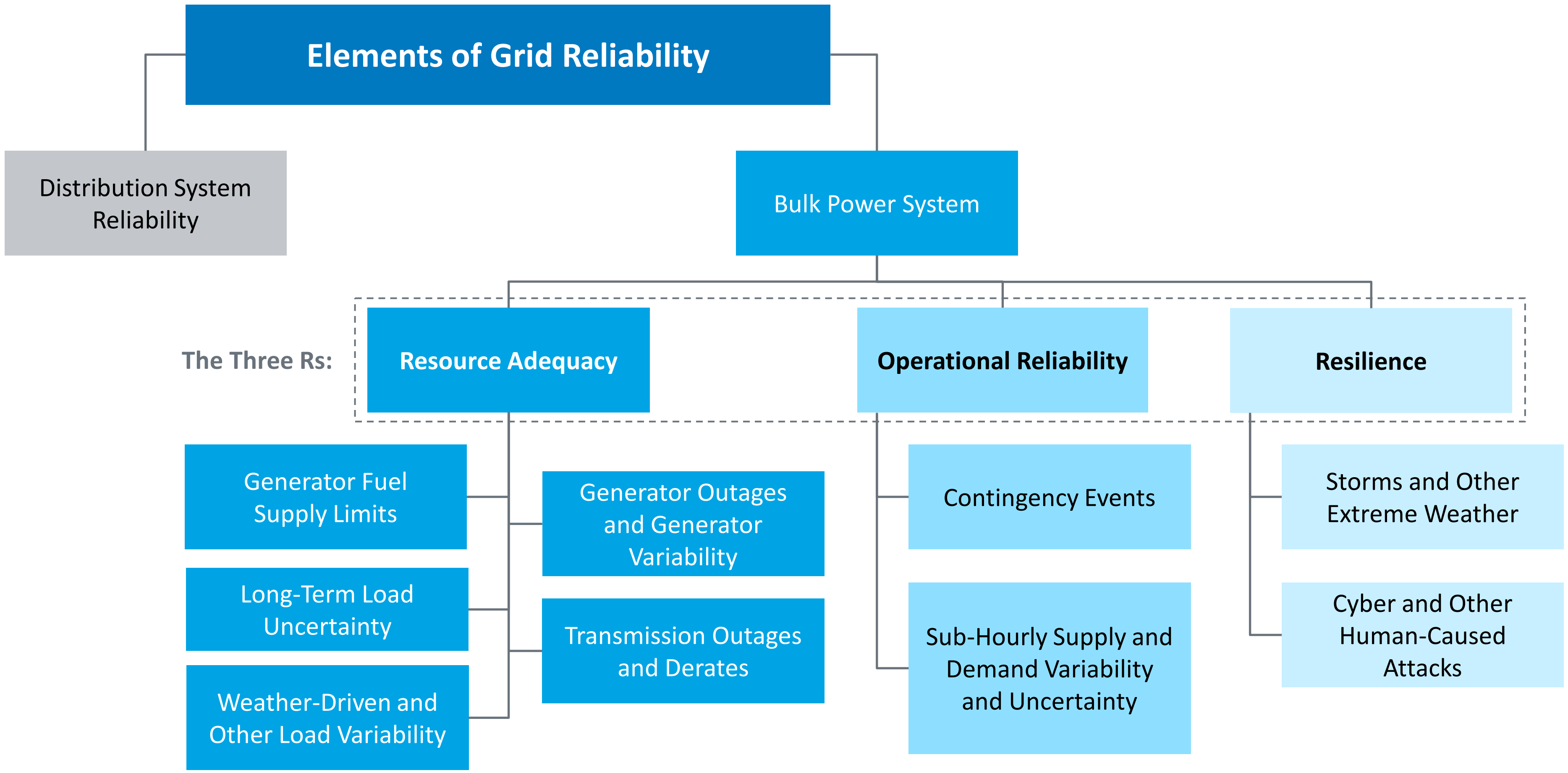
Recent Events

- Winter storm Elliott (end 2022)
- Winter storm Uri (early 2021)
- Alberta (early 2024)

Source: NERC-FERC Winter Storm Elliott Report: Inquiry into Bulk-Power System Operations During December 2022 (link)

Additional discussion: https://www.esig.energy/event/g-pst-esig-webinar-advances-in-the-use-of-probabilistic-resource-adequacy-methods/

Definitions


Elements of Grid Reliability
Distribution System Reliability
Bulk Power System
The Three Rs:
Resource Adequacy
Operational Reliability
Resilience
Generator Fuel Supply Limits
Long-Term Load Uncertainty
Weather-Driven and Other Load Variability
Generator Outages and Generator Variability
Transmission Outages and Derates
Contingency Events
Sub-Hourly Supply and Demand Variability and Uncertainty
Storms and Other Extreme Weather
Cyber and Other Human-Caused Attacks

Reliability

BASIC DEFINITION*

A measure of the ability of a power system to deliver electricity to all points of consumption and receive electricity from all points of supply within accepted standards and in the amount desired.

Source: CIGRE, "The Future of Reliability," Tech. Brochure No 715, 2018.

* Note that these definitions are currently being debated and subject to evolution.

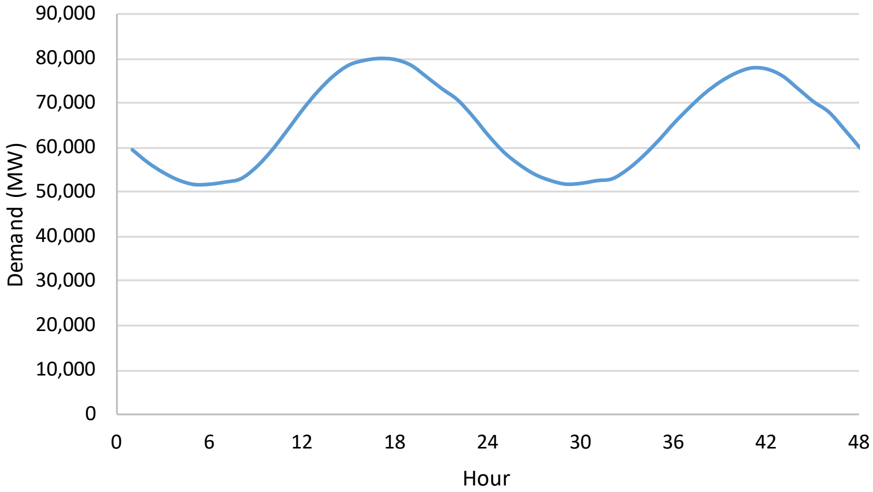
Resource Adequacy

Basic Definition*

A measure of the ability of a power system to meet the electric power and energy requirements of its customers within acceptable technical limits, taking into account scheduled and unscheduled outages of system components.

Source: NERC

Resource Adequacy – Meeting the Constantly Varying Demand in All Time Periods



Resource adequacy aims to assess whether a system has the mix of resources to meet projected demand at various timeframes

- Includes both supply side and demand side resources
- Assessed for different timeframes: seasonal, annual, X years out

Elements of Resource Adequacy Analysis

What is being assessed?

What is the anticipated demand?

- Economic/population growth
- Load portfolio shifts
- Operating reserve requirement

What resources will be available?

- Conventional generation
- Renewables
- Demand side measures
- Imports
- Storage

What are the resource supply and weather risks?

- Hydro levels
- Weather uncertainty (including load)
- Generator and transmission failure

Resilience

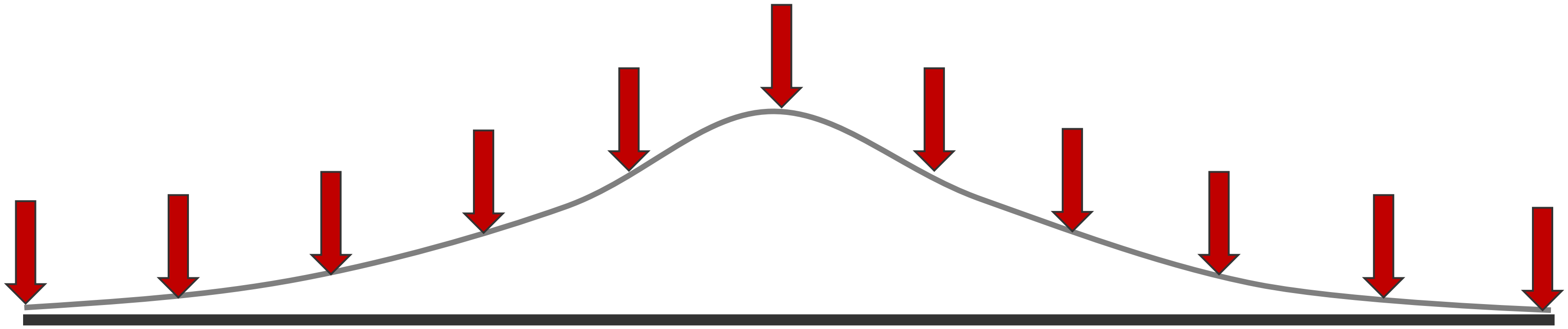
BASIC DEFINITION*

A measure of the ability of a power system to anticipate, prepare for, respond to, and recover from potentially disruptive events, ideally while maintaining an adequate level of system function and with minimum damage or adverse impact.

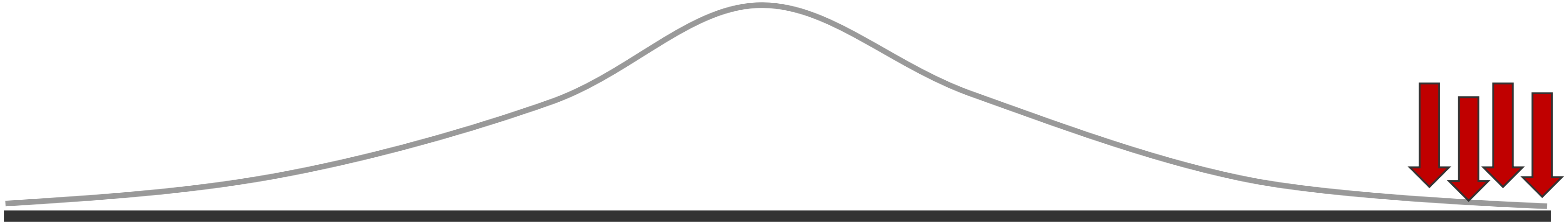
* Note that these definitions are currently being debated and subject to evolution.

Adequate Versus Resilient

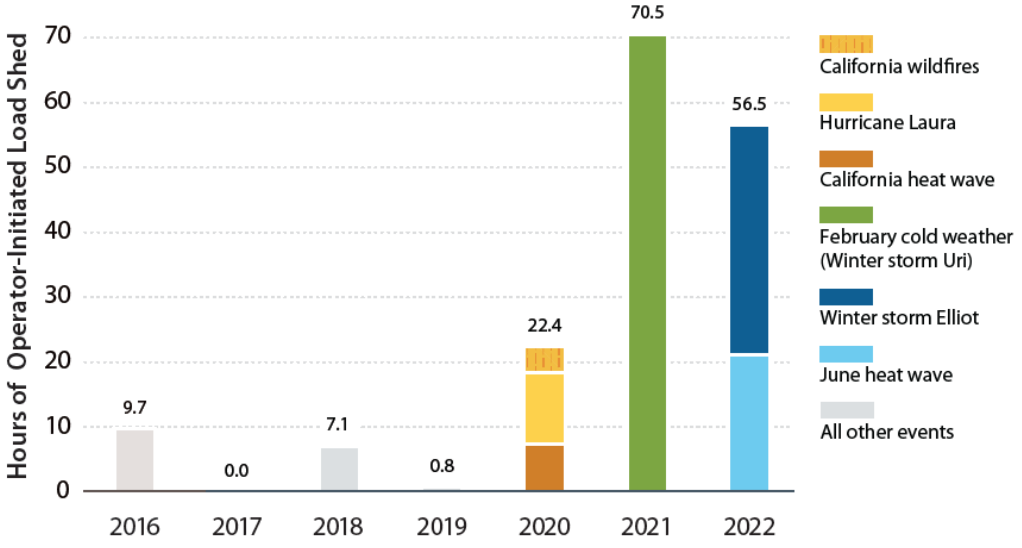
Adequacy: How well does the system perform across all potential conditions?



Resiliency: In extreme situations, how extensive is the damage?



Extreme Weather Blurs the Line Between Resource Adequacy and Resilience



- Extreme weather drives outages
- Need **long data sets** to understand the ability to contribute to adequacy – often a challenge with tail events
- Need to also have data sets that capture **operational forecasting** of the resource in week to day- to hour-ahead timeframes
- **"Extreme" events** may include long periods of low wind or reduced irradiance over large areas at periods of relatively high load

Resource Adequacy Metrics

Probabilistic Resource Adequacy Metrics

Metric	Name [common units]	Definition
LOLE	Loss of Load Expectation [days/year]	Number of days during which there is some unserved energy (at some point within that day)
LOLH	Loss of Load Hours [hours/year]	Number of hours during which there is some unserved energy
EENS or EUE	Expected Energy Not Supplied or Expected Unserved Energy [GWh/year]. Can also be normalized (NEUE) to express in terms of parts per million	Total unserved energy over a period of time (typically one year)
LOLEv	Loss of Load Events [number/year]	Number of contiguous periods during which there is some unserved energy

For more information about the LOLE metric, see: Stephen, Gord, Simon Tindemans, John Fazio, Chris Dent, Armando Figueroa Acevedo, Bagen Bagen, Alex Crawford, Andreas Klaube, Douglas Logan, and Daniel Burke. 2022. "Clarifying the Interpretation and Use of the LOLE Resource Adequacy Metric.“ Presented at: 2022 17th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS). IEEE Resource Adequacy Working Group. https://doi.org/10.1109/PMAPS53380.2022.9810615.

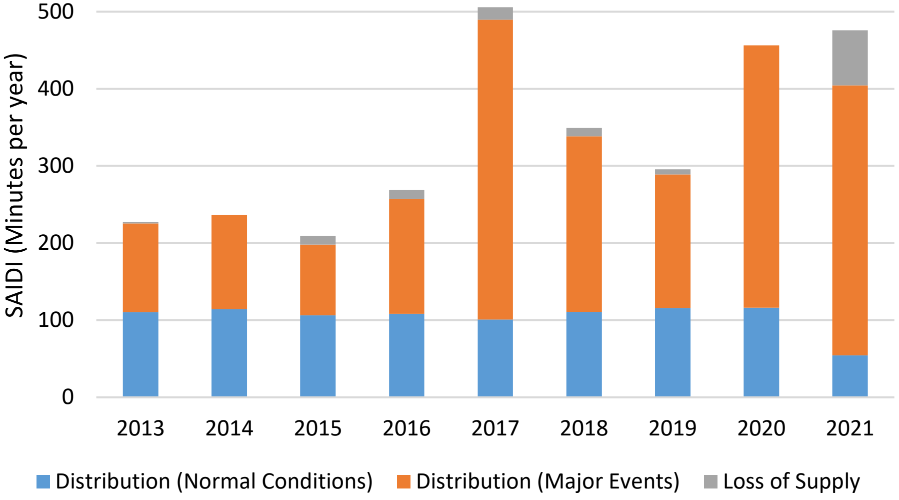
Resource Adequacy Metrics and Criteria in North America

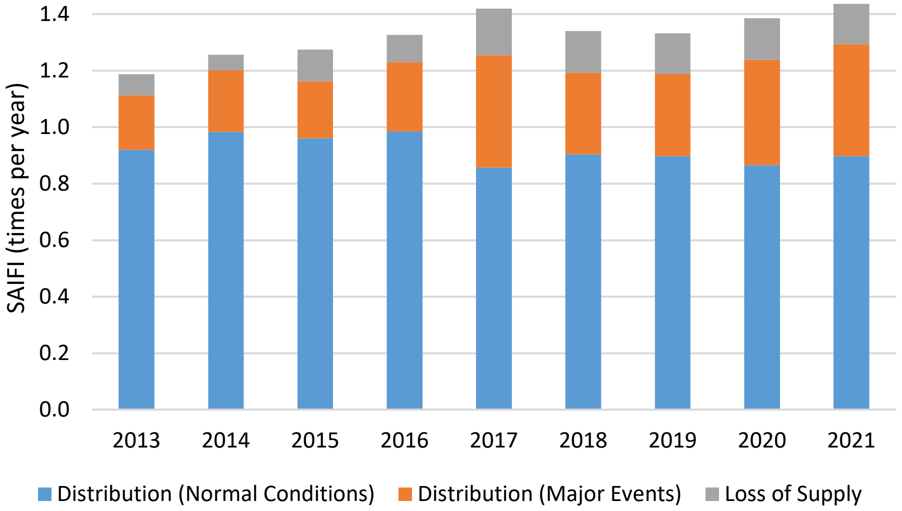
Region	Metrics/Criteria	Responsible Entity
MISO	LOLE ≤ 0.1 days/year	MISO
MRO-Manitoba Hydro	LOLE ≤ 0.1 days/year	Manitoba Public Utilities Board
NPCC-Maritimes	LOLE ≤ 0.1 days/year	Maritimes Sub-areas and NPCC
NPCC-New England	LOLE ≤ 0.1 days/year	ISO-NE and NPCC
NPCC-New York	LOLE ≤ 0.1 days/year	NYSRC and NPCC
NPCC-Ontario	LOLE ≤ 0.1 days/year	IESO and NPCC
NPCC-Québec	LOLE ≤ 0.1 days/year	Hydro-Québec and NPCC
PJM	LOLE ≤ 0.1 days/year	PJM Board of Managers
SERC-C	LOLE ≤ 0.1 days/year	Member Utilities
SERC-E	LOLE ≤ 0.1 days/year	Member Utilities
SERC-FP	LOLE ≤ 0.1 days/year	Florida Public Service Commission
SERC-SE	LOLE ≤ 0.1 days/year	Member Utilities
SPP	LOLE ≤ 0.1 days/year	SPP RTO Staff and Stakeholders
TRE-ERCOT[1]	LOLE ≤ 0.1 days/year	Electric Reliability Council of Texas (ERCOT) Board of Directors
WECC-AB	LOLP[2] ≤ 0.02%	WECC
WECC-BC	LOLP[2] ≤ 0.02%	WECC
WECC-NWPP-US & RMRG	LOLE ≤ 0.1 days/year	WECC
WECC-SRSG	LOLP[2] ≤ 0.02%	WECC
WECC-CAMX	PRM ≥ 15% Additional local and flexible RA requirements	WECC
Hawaii	ERM ≥ 30% (3 islands), 60% (2 islands)	HECO

The "one day in 10 years" criterion, initially just used as an example in reliability calculations, has since been accepted as the de facto reliability standard.

[1] LOLE is reported as a guideline metric, not a requirement in the ERCOT system, which relies on energy only and scarcity pricing to meet resource adequacy needs.
[2] The LOLP metric represents an event-period of one day and a horizon of 10 years.

Resource Adequacy is generally not the problem - Most outages occur on the distribution system



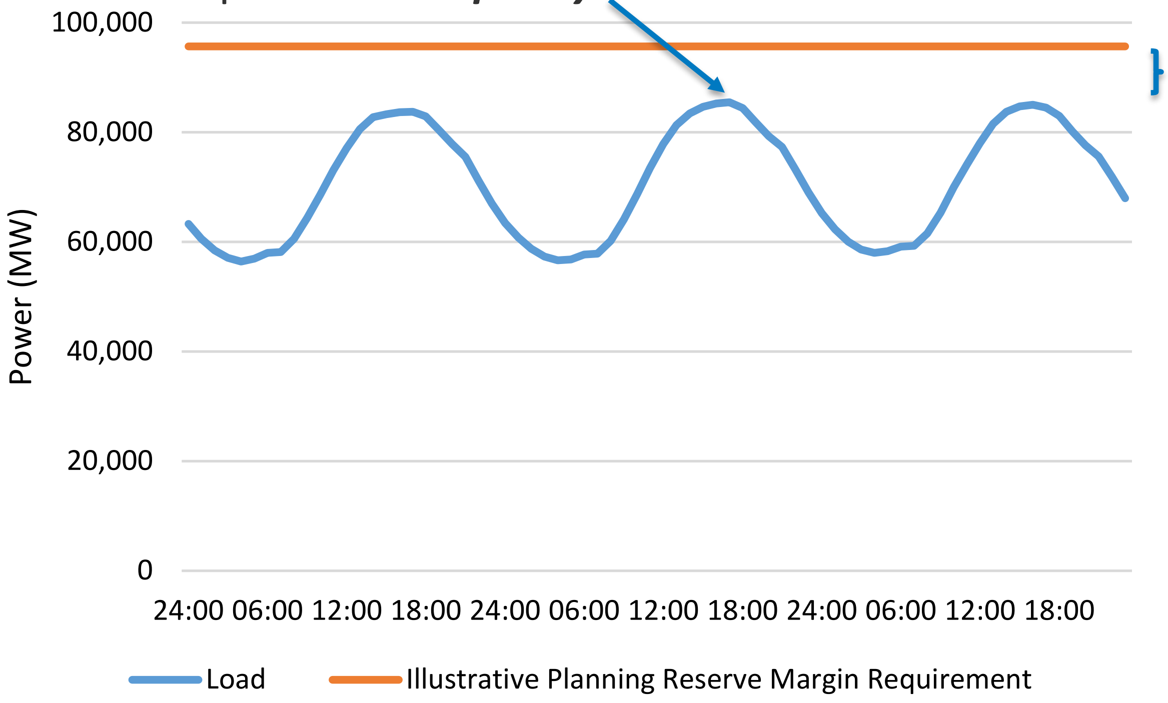


Source: U.S. Energy Information Agency Electric Power Annual

Probabilistic Measurement of Resource Adequacy

Planning Reserve Margin (PRM)

At the point of peak demand, the system must have at least 85 GW of operational ***capacity.***

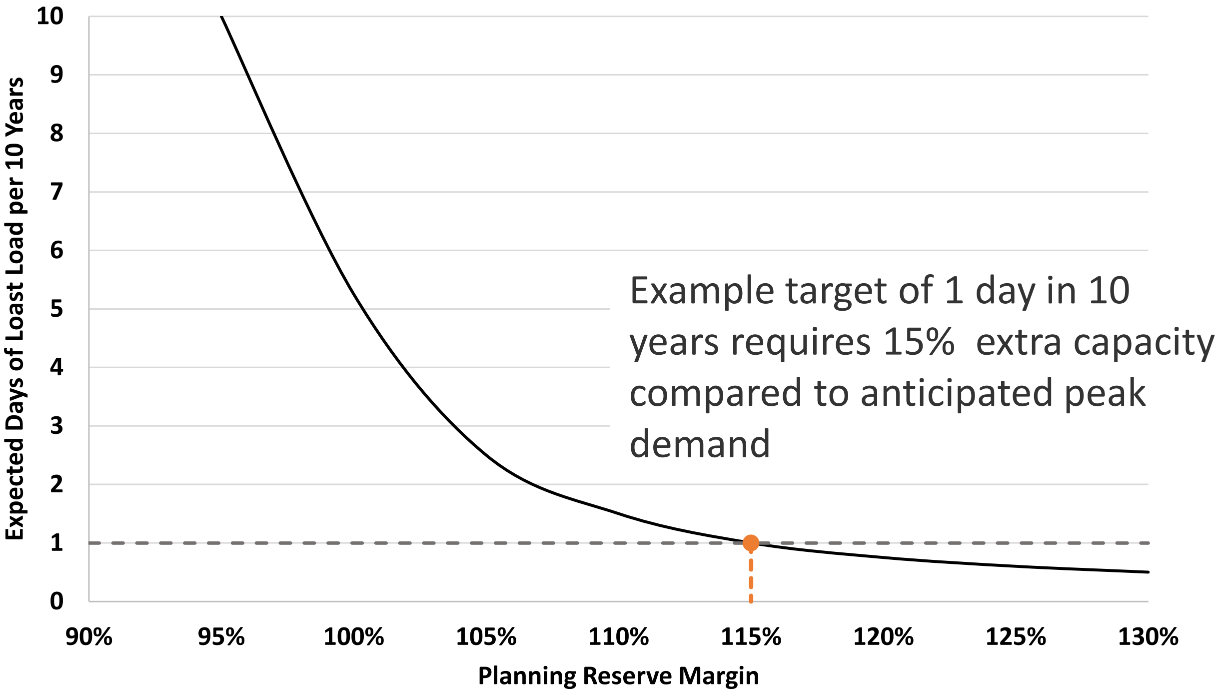


To ensure 85 GW of operational capacity, an additional PRM is required: in this example, about 15% or about 13 GW.

But What Is the Right Planning Reserve Margin? - Cost-Based Adequacy Standards

Loss of Load Expectation Versus Planning Reserve Margin

Possible reliability standards considered

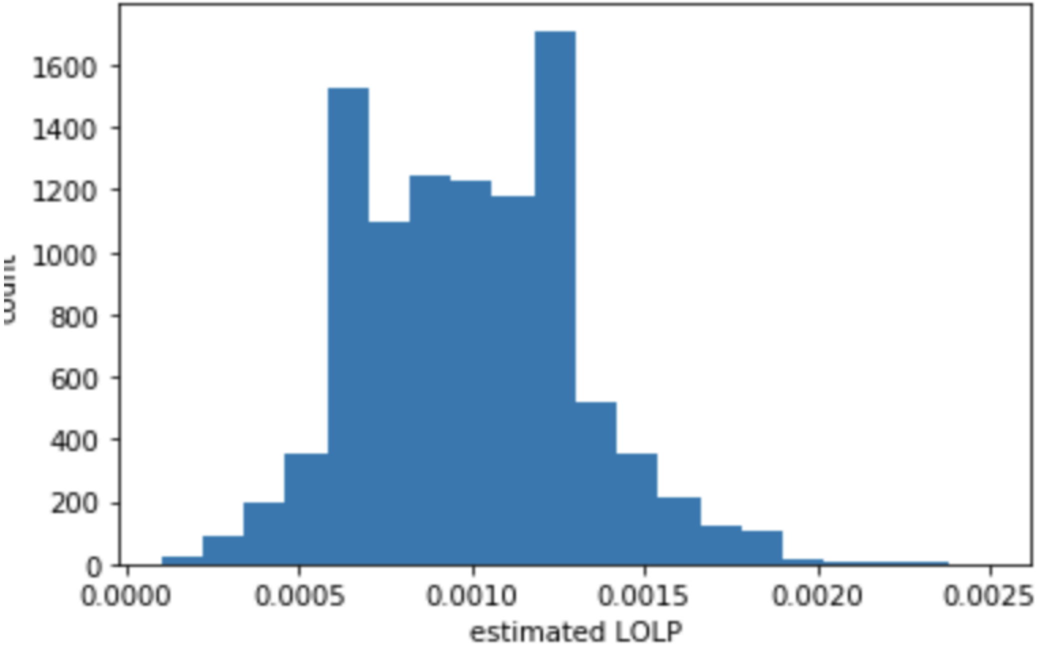


Elements of Resource Adequacy Analysis

Power system element	Process
Generator (thermal)	Forced outages
	Maintenance
Variable renewable generation	Resource availability
Demand	Inflexible demand
	Flexible demand
Transmission	Forced outages
Storage	Scheduling
Hydropower	Inflow
	Outflow and pumping

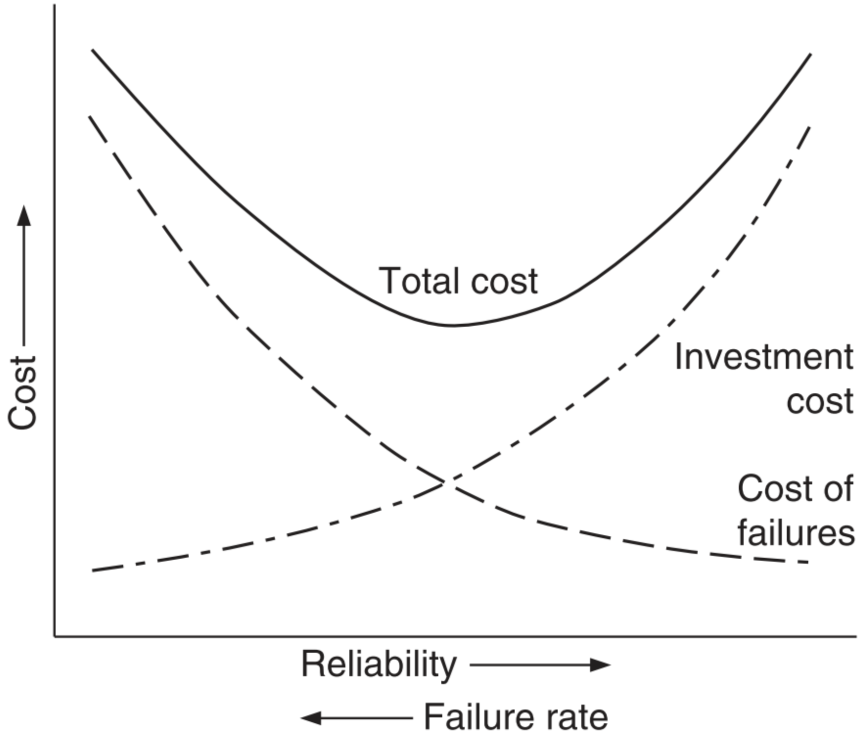
Monte Carlo Analysis

Results of 10,000 independent runs of 10,000 samples each



Loss of Load Probability (LOLP)

Value-Based Reliability Planning



Questions

- What is the cost of failures (i.e., lack of reliability)?
- What is an optimal balance – and how can we find it?

Singh, Chanan, Panida Jirutitijaroen, and Joydeep Mitra. 2018. *Electric Power Grid Reliability Evaluation*. Wiley.

Valuing Reliability - Determining Customer Interruption Costs

- There are large differences in Customer Interruption Costs, depending on
  - Customer type (residential, small-medium enterprise, industrial)
  - Time of interruption
  - Duration of interruption
  - Frequency of interruption

- Results are condensed into **Customer Damage Functions**. These may be:
  - A single **Value of Lost Load**, expressed in $/MWh (or equivalent)
  - A function of frequency, load type, and duration

Customer Damage Functions

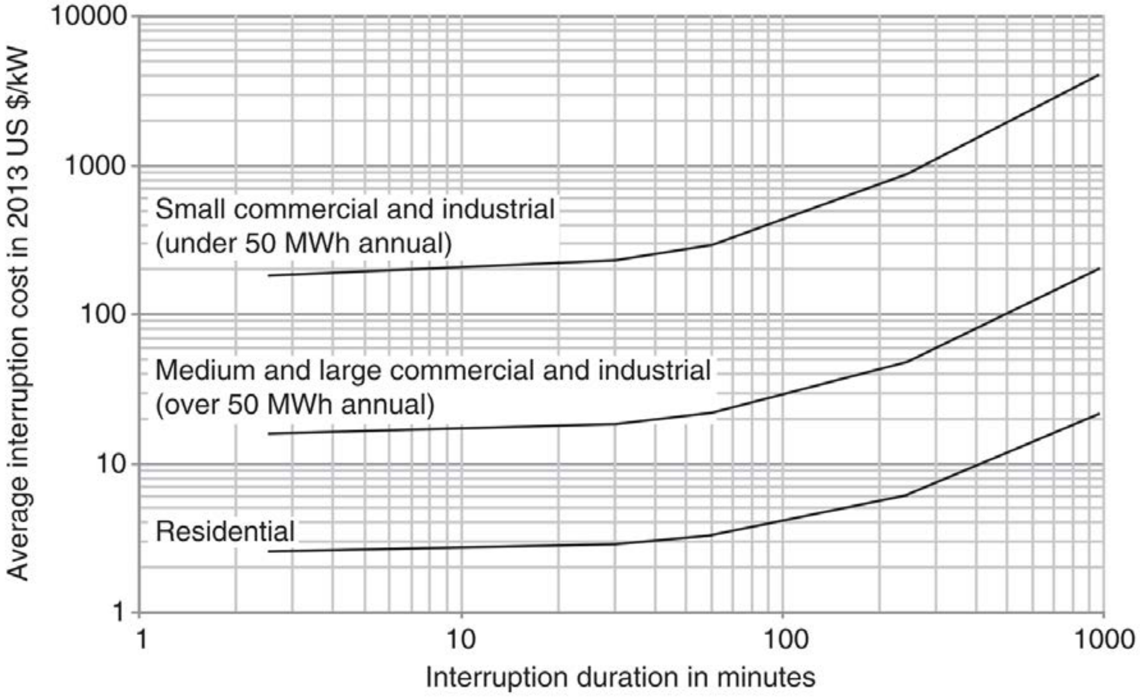


Figure 1.2 Customer damage function (compiled from data in [1]).

Singh, Chanan, Panida Jirutitijaroen, and Joydeep Mitra. 2018. *Electric Power Grid Reliability Evaluation*. Wiley.

Cost-Based Adequacy Standards

- **Ingredients**
  - VOLL (value of lost load; $/MWh)
  - CONE (cost of new entry; $/MW/year) of peaking generator
  - FC (fuel cost; $/MWh)
  - Calculated LOLH (loss of load hours; hours/year)

- Consider: if $LOLH \times VOLL > CONE + FC \times LOLH$ (i.e., cost of first 1MW of outage exceeds cost of new plant), then it is worth building more peaking capacity *for adequacy alone.*

- **Reliability standard**: $LOLH^* = \frac{CONE}{VOLL - FC}$

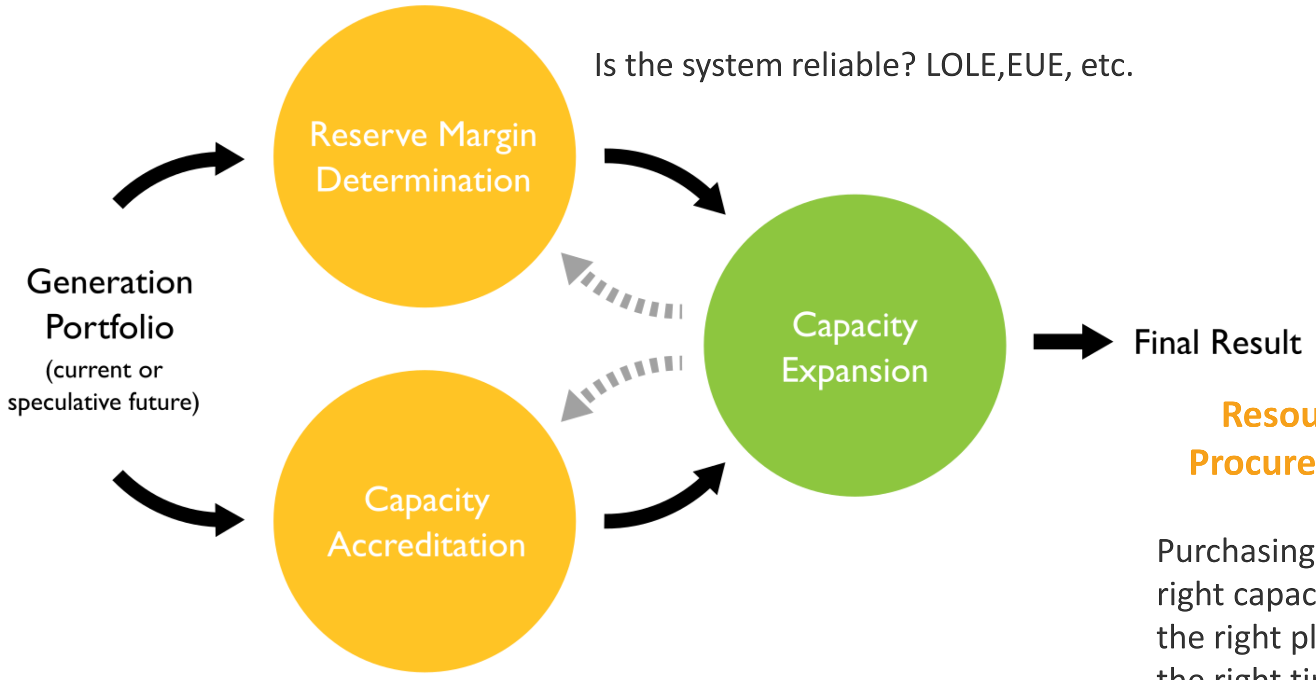
- ***Note****: there are important caveats, especially considering storage and interconnection!*

Investment Incentives and Capacity Accreditation

Traditional Adequacy Constraints: From Planning to Implementation…

Resource Adequacy

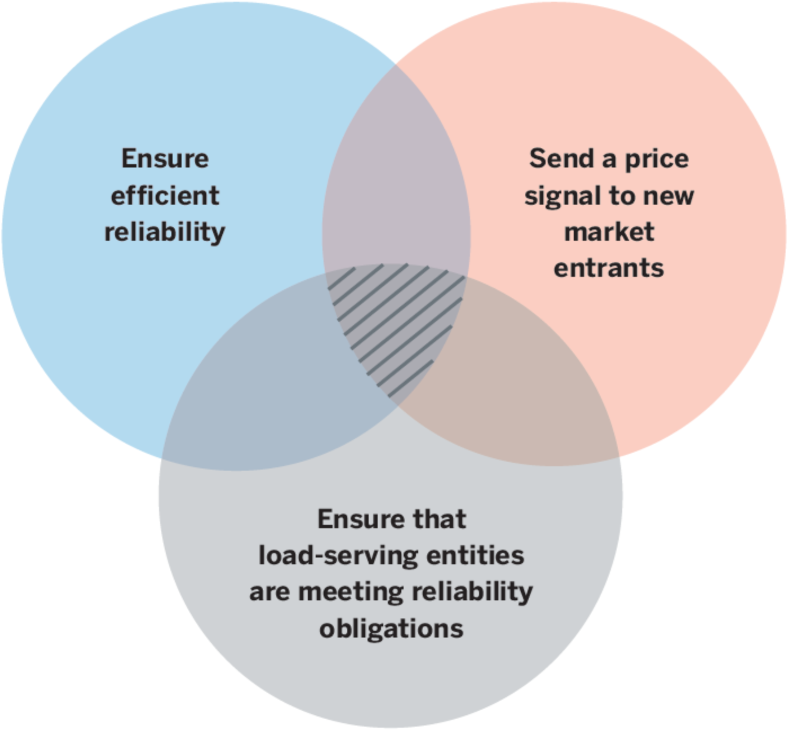
Is the system reliable? LOLE,EUE, etc.



Resource Procurement

Purchasing the right capacity, in the right places, at the right time

Role of Capacity Accreditation



Source: Energy Systems Integration Group.

"The goal of capacity accreditation is to measure effective capacity contributions, in a technology-agnostic manner, and create a reliability-neutral way to allow for exchanging capacity between resources types while meeting resource adequacy needs."

-Energy Systems Integration Group, *Ensuring Efficient Reliability, New Design Principles for Capacity Accreditation*, 2023

Approaches to Capacity Accreditation

Phase 1

- To determine whether a given system would meet its resource adequacy target, the sum of **installed capacity (ICAP)** of all existing and planned resources was compared to the target **PRM**.

Phase 2

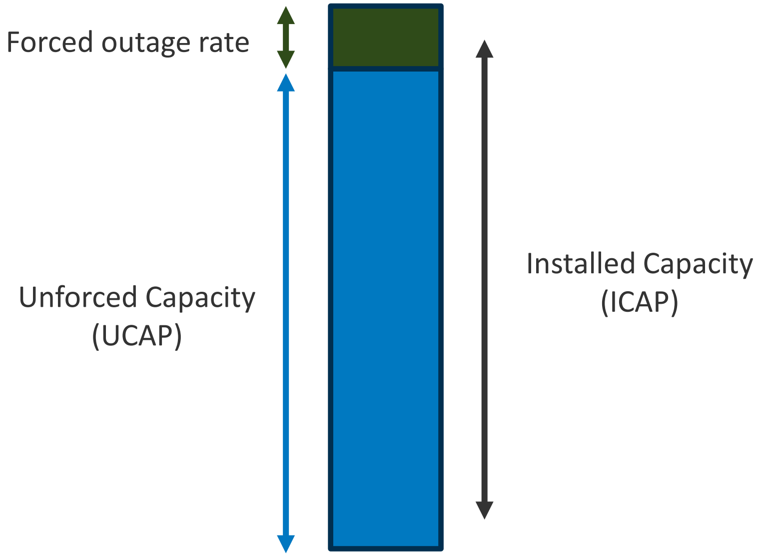
- Entities transitioned from using ICAP to **UCAP (unforced capacity)** to capture some individual characteristics of a resource availability. The UCAP is a separate deterministic accreditation value that derates the ICAP value by an amount equal to the resource's equivalent forced outage rate on demand.
- For wind and solar, a deterministic accreditation value was used based on a time-based assessment where historical output during time windows of highest load were averaged.

Phase 3

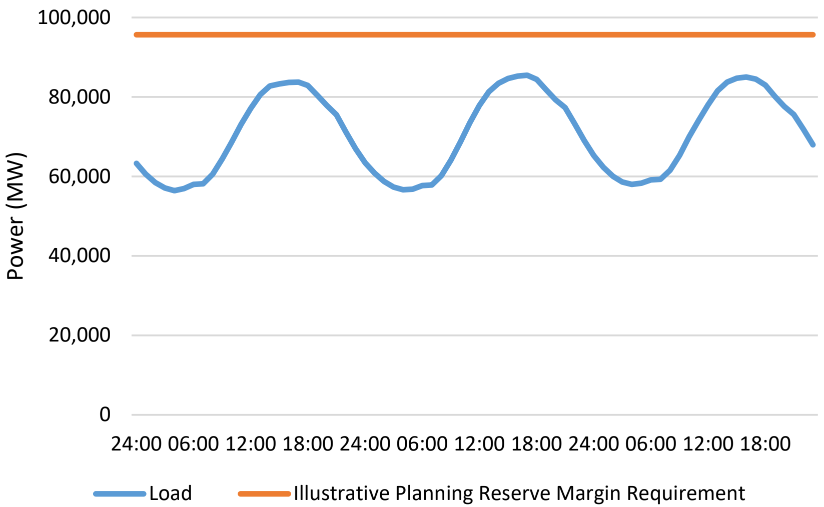
- **Emergence of probabilistic methods**:
  - Increased use of Effective Load Carrying Capability (ELCC)

Key Resource Accreditation Metrics

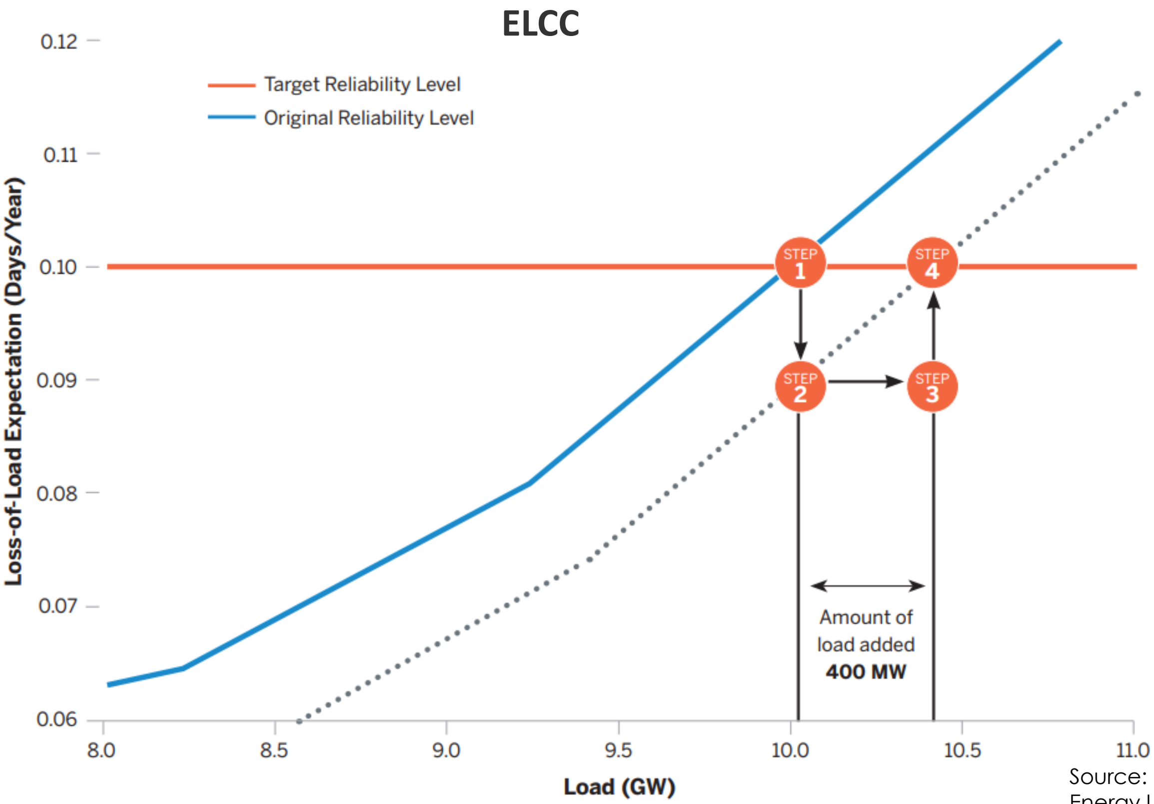
ICAP versus UCAP



PRM



ELCC



ELCC measures the contribution of a resource to reducing loss of load, compared to a constantly available generator (or load).

ELCC can be applied to ***all resource types***

Source: Ibanez & Milligan (2014) National Renewable Energy Laboratory. https://docs.nrel.gov/docs/fy14osti/62847.pdf?

Capacity Credit of Wind and Solar

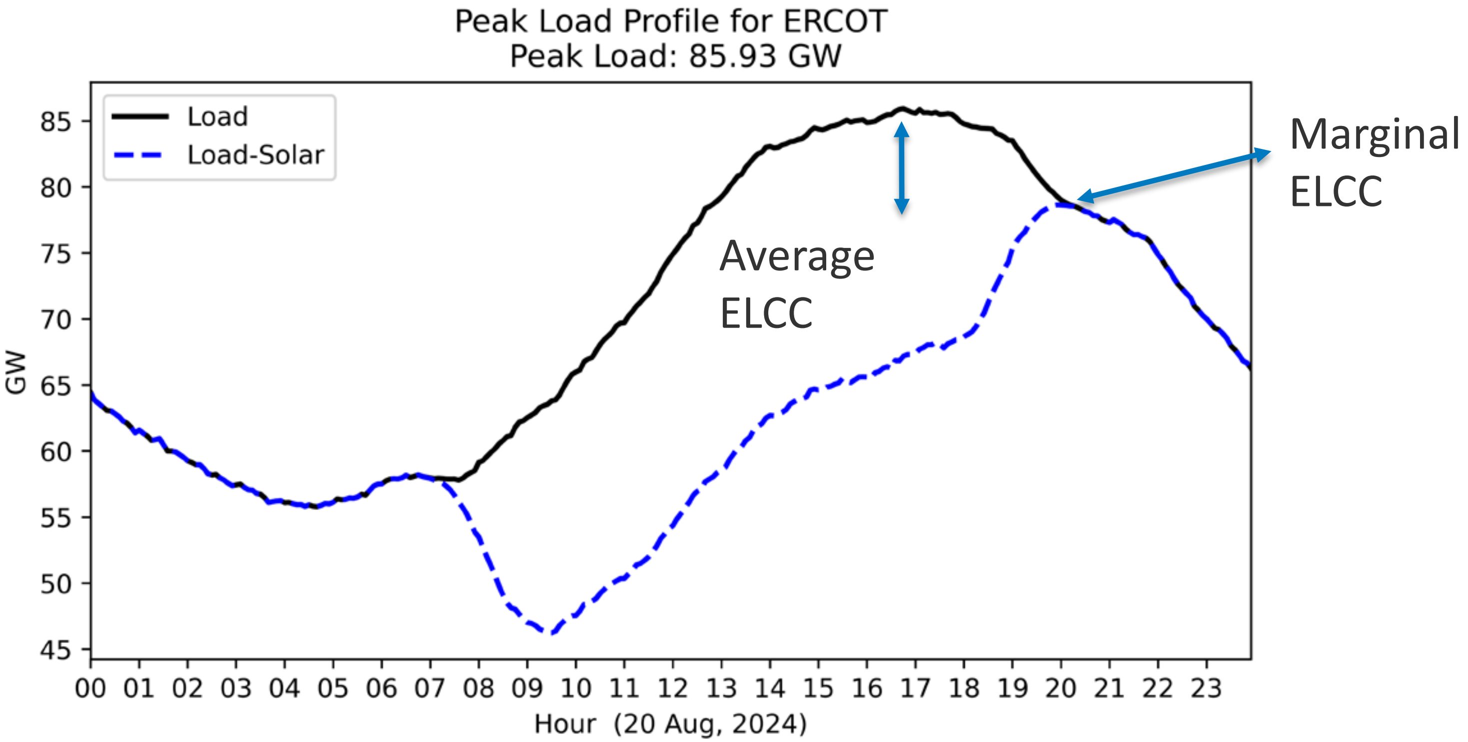
	Wind	Solar
Assessment Area/ Interconnection	Expected % of Nameplate	Expected % of Nameplate
MISO	18%	50%
NPCC-New England	13%	40%
NPCC-New York	12%	47%
PJM	15%	58%
SERC-Central	47%	58%
SERC-East	NA	99%
SERC-Florida Peninsula	NA	59%
SERC-Southeast	NA	88%
SPP	14%	86%
Texas RE-ERCOT	33%	78%
WECC-CA/MX	12%	66%
WECC-SW	20%	40%
WECC-NW	20%	55%
U.S.	17%	61%

NERC-Reported Summer On-Peak Capacity Contribution of Wind and Solar by Reliability Region

These are NOT the values used by the planning authorities in each region!

Let's talk about this one

Marginal Versus Average



Deterministic Versus Probabilistic

Deterministic Approaches ⟷ **Probabilistic Approaches**

Deterministic Approaches

Variations

- Capacity factor during pre-defined number of peak load hours or static risk window (i.e., afternon hours during summer months)
- Exceedance (i.e., capacity available more than 70% of the time)

Advantages

- Simple, transparent, and easy to understand
- Does not require modeling to calculate
- Provides certainty for generation owners

Challenges

- May not align with scarcity periods
- Requires regular updates to the pre-defined risk windows to stay relevant, especially with high penetrations of renewables and storage

Probabilistic Approaches

Variations

- Effective load-carrying capability (ELCC)
- Equivalent firm capacity (EFC)
- Marginal reliability improvement (MRI)

Advantages

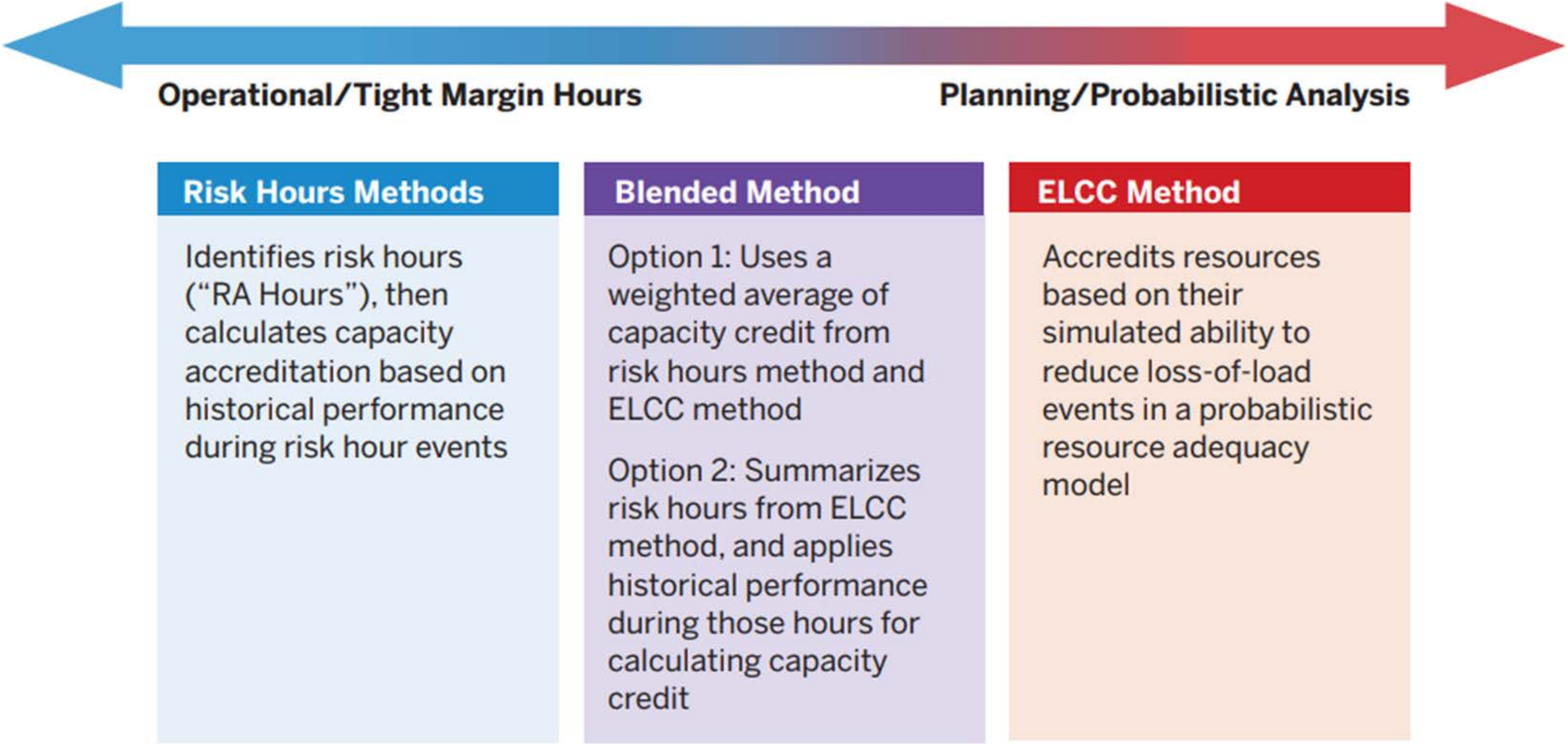
- Evaluates resource performance during periods of scarcity, not just peak demand
- Considers correlation of resources and load
- Accounts for weather-driven resource performance

Challenges

- Computationally intensive
- Sensitive to inputs and assumptions
- Opaque for market participants
- Difficult to apply to all resources and capture plant-specific configurations

Source: Energy Systems Integration Group

Prospective Versus Retrospective



Source: Energy Systems Integration Group, adapted from Midcontinent Independent System Operator (2022b).

Investment Incentives and Mechanisms to Ensure Sufficient Capacity

Integrated Resource Planning

Bilateral capacity contracts

Capacity Market

Energy-Only Market

Independent System Operator (ISO) Capacity RA Mechanisms (as of early 2024)

System Operator	Mechanism
New England (ISO-NE)	Mandatory Forward Annual Capacity Market with Pay for Performance Construct
New York (NYISO)	Mandatory Short-term Seasonal Capacity Market
Independent Electric System Operator (IESO)	Incremental Auction
PJM Interconnection	Mandatory Forward Annual Capacity Market with Pay for Performance Construct
Midcontinent (MISO)	Voluntary Seasonal Capacity Market and Load Serving Entities (LSE) targets
Southwest Power Pool (SPP)	Resource Adequacy Target by LSE, no capacity market
Electric Reliability Council of Texas (ERCOT)	Energy only market, $5000/MWh price cap and operating reserve demand curve price adder
Alberta Electric System Operator (AESO)	Energy only market
California Independent System Operator (CAISO)	Resource adequacy requirement for system, local, and flexible capacity, no capacity market

Source: EPRI

Storage and Flexible Loads

How to Actually Plan for Storage? Storage Modelling Options

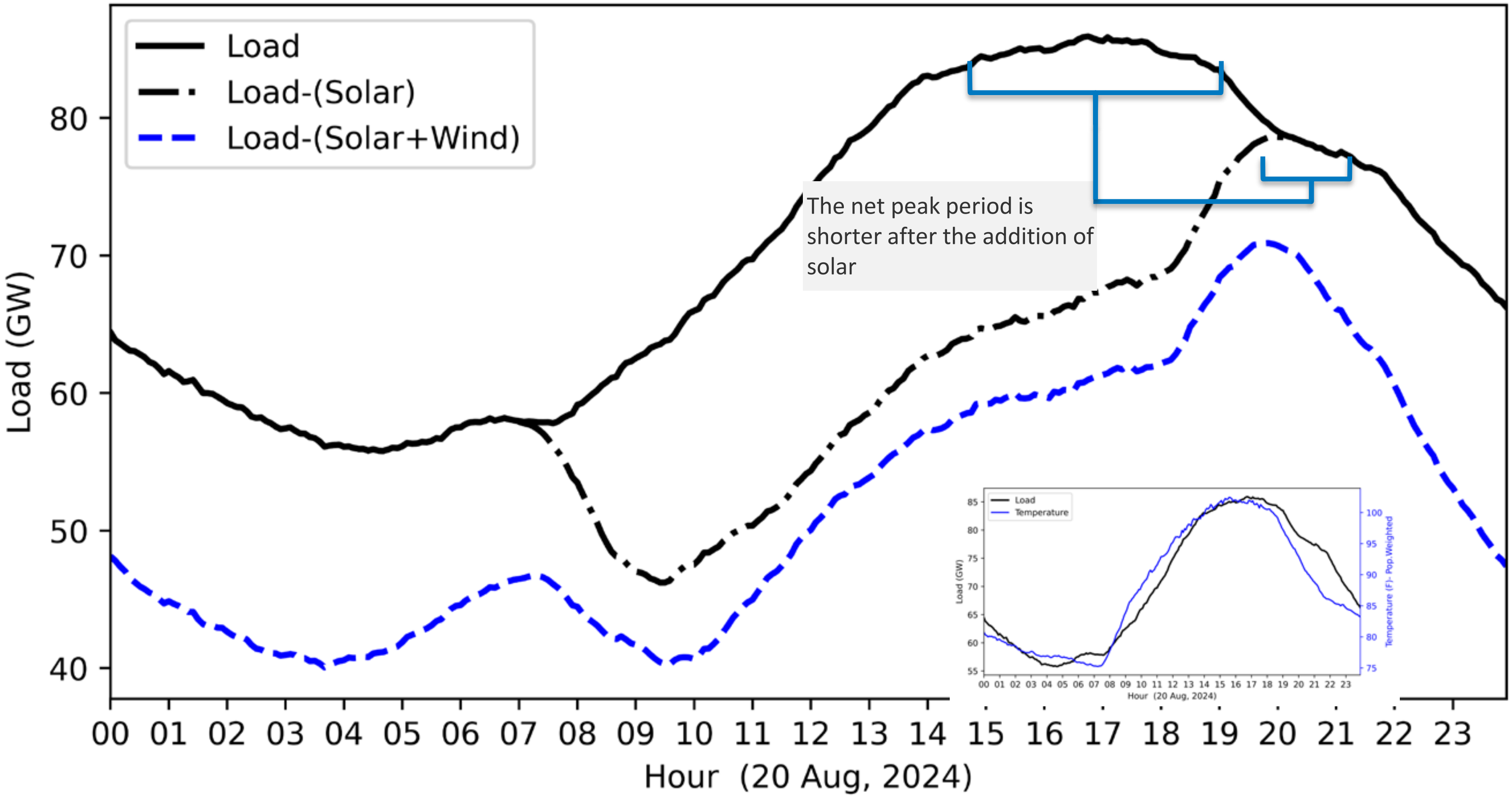
A huge range of options – which way to go?

Possible objectives
Greedy shortfall reduction
Minimizing depth of shortfall
System cost minimization
Price competition between storage providers

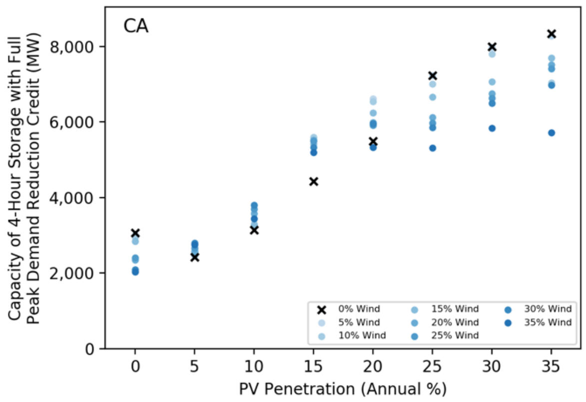
⟺

Possible dispatch
Greedy dispatch (e.g., prioritise storage with long time to go)
Optimal dispatch with perfect foresight
Rolling horizon optimal dispatch
Stochastic programming solution that accounts for uncertainty

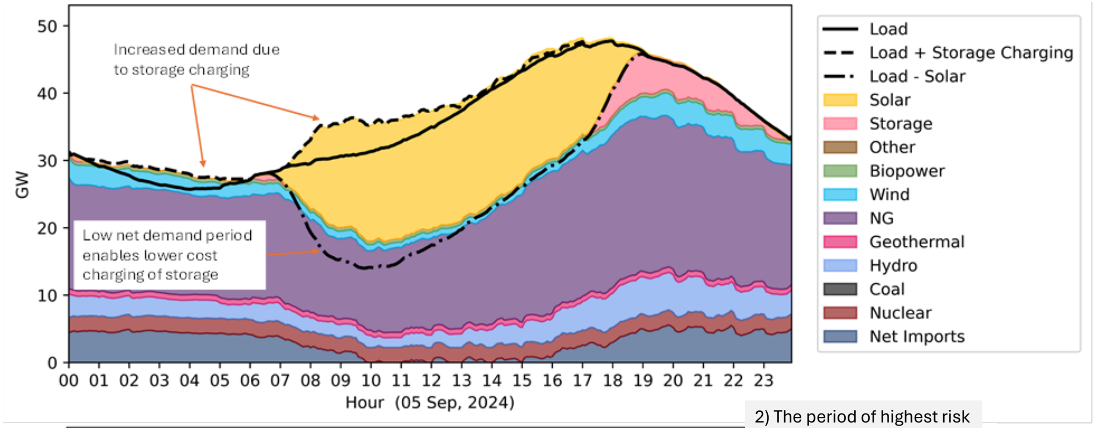
Contribution of Solar and Wind - Example from Summer 2024

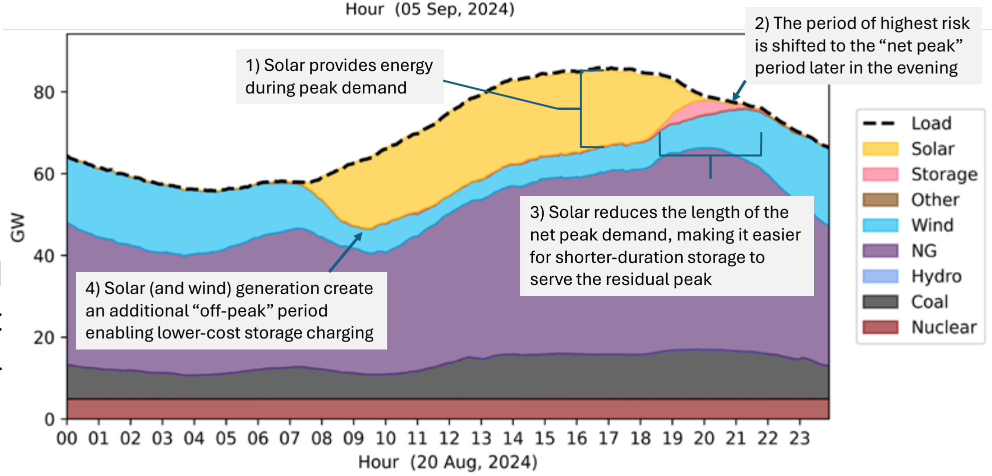


Storage and Resource Adequacy



Synergy between solar and storage in providing resource adequacy





Actual contribution of storage toward resource adequacy in California Independent System Operator and ERCOT in 2024

Demand Flexibility

- Flexible demand can consist of (a combination of)
  - Load change (down or up)
  - Load shifting
- Coordination is often less well integrated into markets
- Modeling
  - All the same issues as for storage, plus…
  - Time constraints (e.g., recovery peaks)
  - Varying availability (day night schedules, etc.)
  - More uncertainty about activation

Evolving Practices for Resource Adequacy Assessment

Why the Need for Updated Practices?

Changing weather patterns

- Climate change
- Increased frequency of extreme weather events

Changing resource mix

- Renewable generation
- Storage
- Sector coupling (natural gas, power to X)

Load evolution

- Load flexibility
- Large loads
- Electrification

Increased coupling of markets

- Interregional assessments and markets

Investment risks

- Assessing reliability contribution of many different resource types

Additional Complexity to Consider

Optimization: more realism in dispatch decisions

Common simplifications in dispatch modelling include:

- Using continuous dispatch decisions, ignoring:
  - Unit commitment
  - Minimum generation levels
- Ignoring genuine uncertainty (using predictable variability instead)
  - No short-term forecast errors
  - Perfect anticipation of faults
- Cost-based dispatch instead of markets
- Transmission network

Modern Developments in Resource Adequacy Research

Better use of adequacy models

- Better input data
- Improved load forecasting
- New metric approaches

New model capabilities

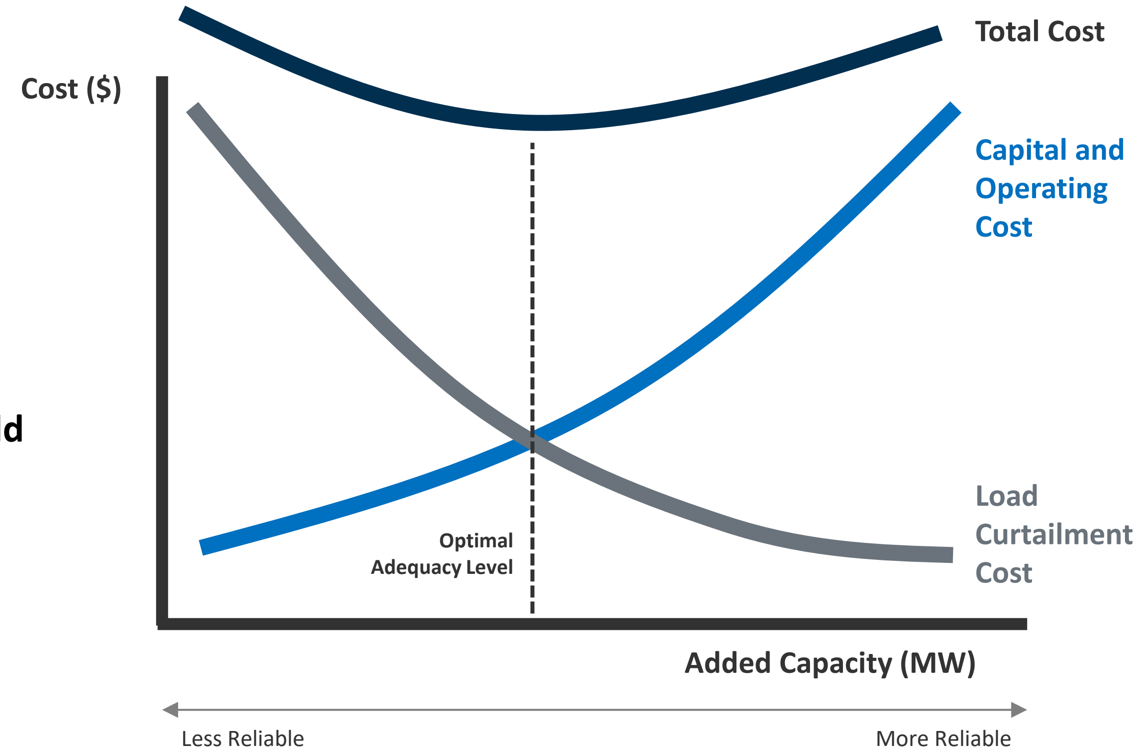
- Correlated outage modeling
- Incorporation of short-term forecast errors
- Storage modeling
- Demand flexibility modeling

Improving analysis methodology

- Monte Carlo sampling strategies
- Resource adequacy and capacity planning

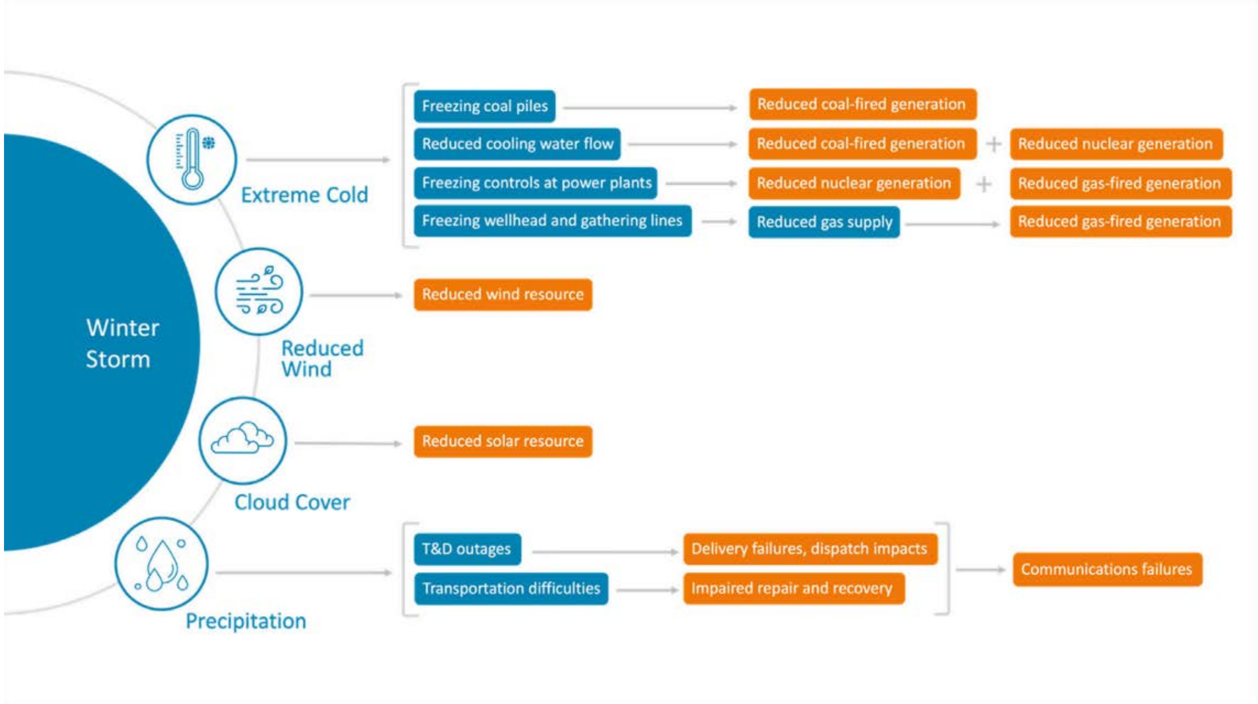
Better Connection Between Reliability and Cost

The resource adequacy criterion should be used to establish the appropriate trade-off between reliability and cost, which are intrinsically linked. This should be transparent.



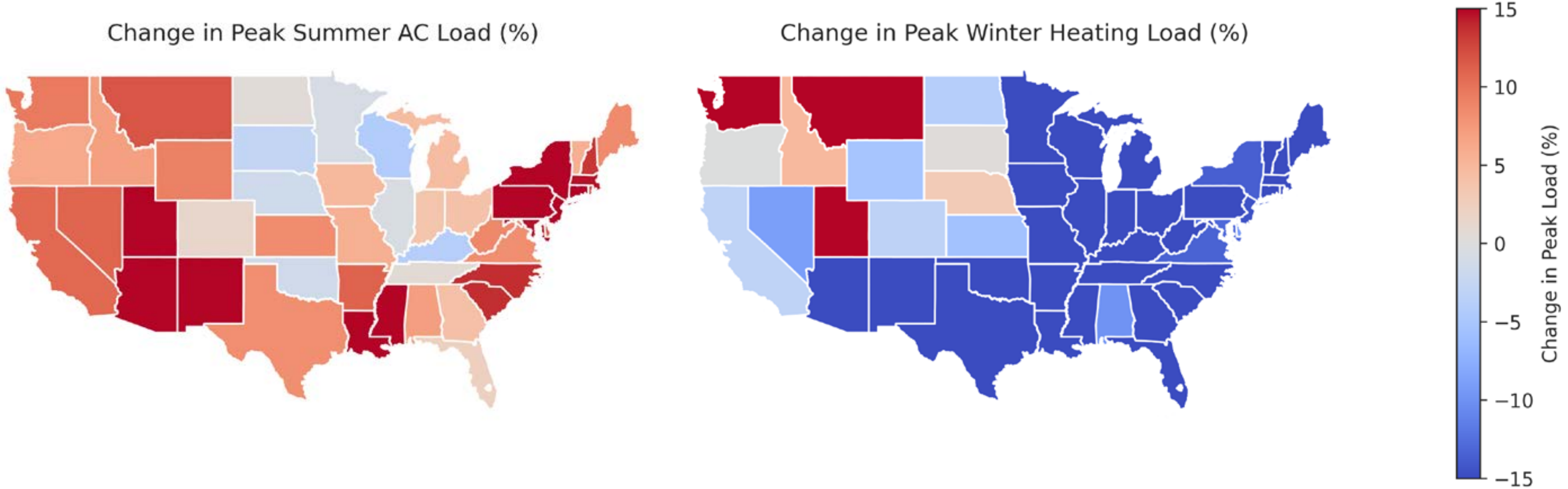
Importance of Correlated Datasets

- **Long data sets** needed to understand ability to contribute to adequacy – typically a challenge as you are looking at tail events
- Need to also understand **operational forecasting** of the resource in week to day to hour ahead time frames
- **‘Extreme’ events** may include long periods of low wind or reduced irradiance over large areas at periods of relatively high load



An extreme event may have multiple dimensions that can begin casual chains that can end in common-mode outages

Change in Seasonal Demand



Widespread increases in summer peak alternating current load and decreases in winter heating load

this only compares historical load to midcentury weather for a single possible climate scenario

AC: Air Conditioning

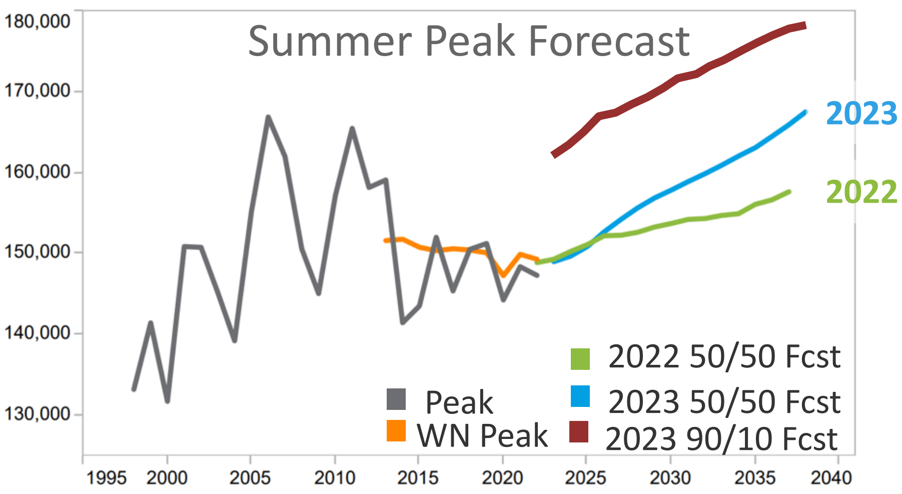
Forecasting Is Getting More Complicated

Drivers Complicating Electric Demand Forecasting

- ⬆ Electrification
- ⬆ Decarbonization (H2, heat)
- ⬆ Weather (extreme temps)
- ⬆ Re-industrialization/On-shoring
- ⬆ Digitalization (data centers, crypto)

- ⬇ End-use efficiency
- ⬇ Customer generation/storage
- ⬇ Customer behaviors/rate structures

Example: PJM Peak Load Forecast 2022 vs 2023



Source: PJM 2023 Load Forecast Report
https://pjm.com/-/media/library/reports-notices/load-forecast/2023-load-report.ashx

Modeling Correlated Outages

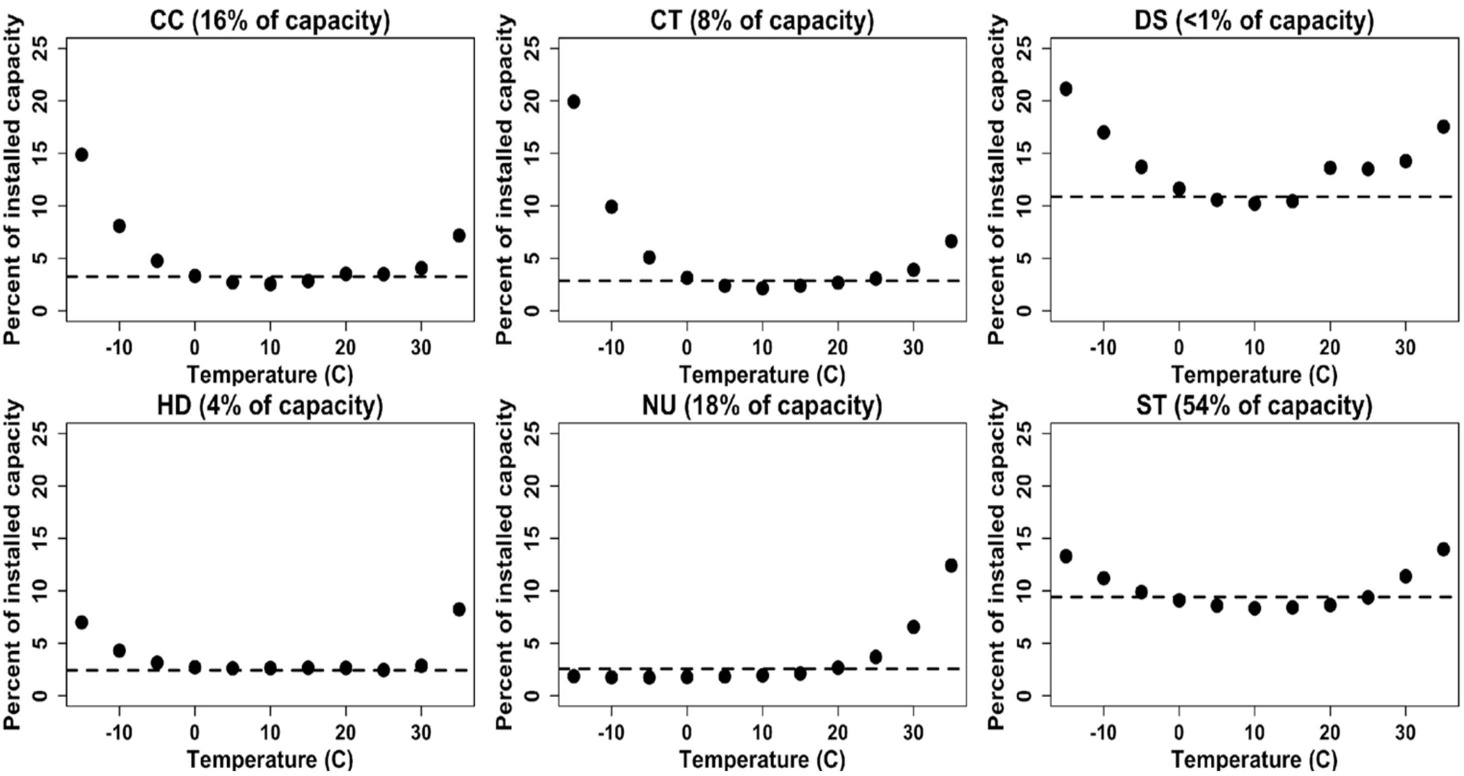


Image credit: PJM

- Allow transition probabilities to vary as a function of temperature
- Recover "stationary distribution" of unavailable capacity for each unit from fitted models
- Data: PJM GADS (1995–2018)

Adapted from Murphy, Sinnott, Fallaw Sowell, and Jay Apt. "A time-dependent model of generator failures and recoveries captures correlated events and quantifies temperature dependence." Applied Energy 253 (2019): 113513.

Research Gaps

Key Gaps

LOW

- Incorporating consistent and correlated weather datasets

MODERATE

- Need for improved and more detailed resource adequacy metrics
- Interregional coordination
- Holistic integration of resource adequacy with other planning activities
- Improved load forecasting… weather impacts, electrification, and climate

SEVERE

- Identification and analysis of outlier, high-impact, low-probability, events
- Winter risk associated with fuel supply and weather dependent outages

Source: Resource Adequacy Gap Assessment: A EPRI Resource Adequacy Assessment Framework Document (3002027833)
https://www.epri.com/research/products/000000003002027833

Thank You

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