Reliability in a Decarbonizing Electricity Grid

Massachusetts Institute of Technology
Center for Energy and Environmental Policy Research

Fall 2022 Research Workshop

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Energy+Environmental Economics

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Agenda

- A changing grid creates new reliability challenges
- Resource adequacy modeling for a changing grid
- Applications and future challenges

Resource adequacy, not operations, is the biggest reliability challenge on decarbonizing grids

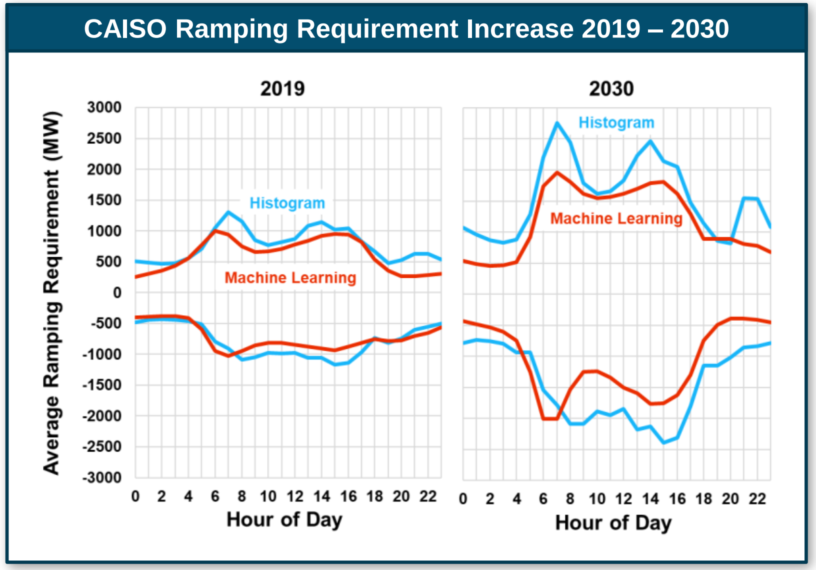
- Operational reliability will require increased ramping, flexibility, fast starts, etc.
- However, wind and solar can be dispatched very precisely
- Energy storage technologies can provide flexibility services at low cost

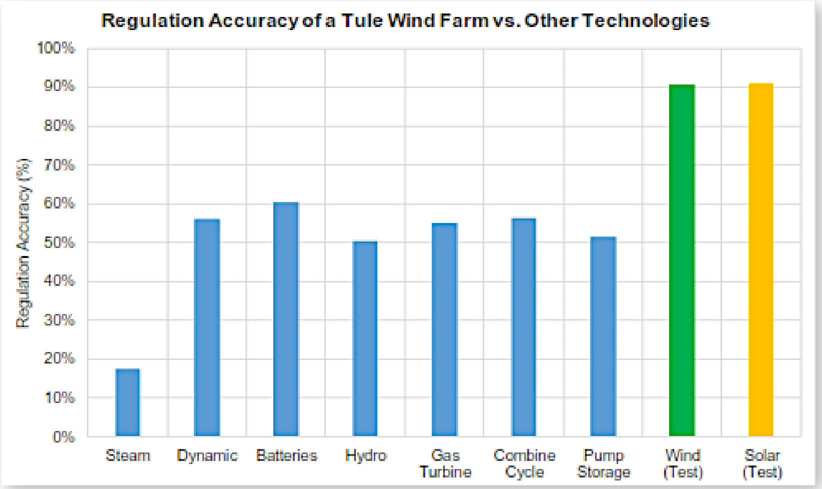
References:
https://www.nrel.gov/workingwithus/partners/partnerships-caiso-first-solar.html

https://www.energy.gov/eere/success-stories/articles/eere-success-story-beyond-power-wind-plants-can-provide-full-suite

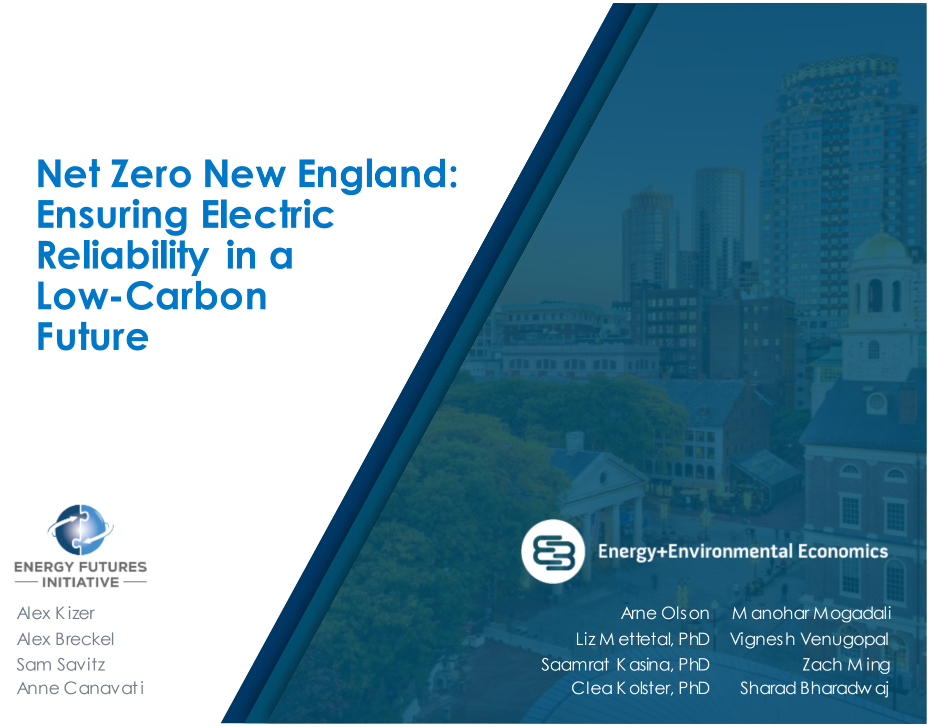
https://www.ethree.com/wp-content/uploads/2018/10/Investigating-the-Economic-Value-of-Flexible-Solar-Power-Plant-Operation.pdf

The remainder of this presentation focuses on the challenges related to resource adequacy


CAISO Ramping Requirement Increase 2019 – 2030


Regulation Accuracy of a Tule Wind Farm vs. Other Technologies

A changing grid creates new reliability challenges



Net Zero New England: Ensuring Electric Reliability in a Low-Carbon Future

ENERGY FUTURES INITIATIVE

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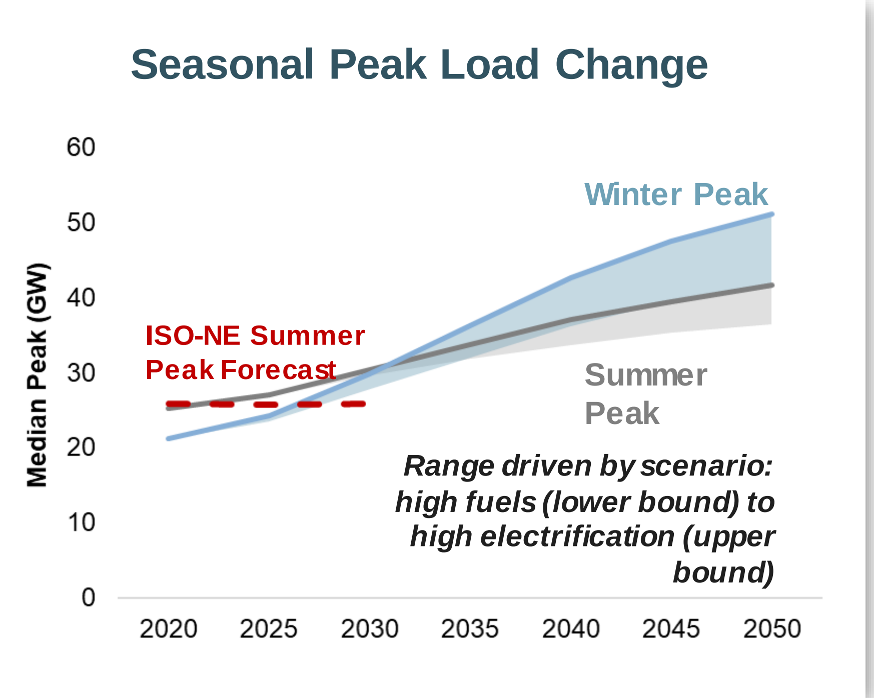
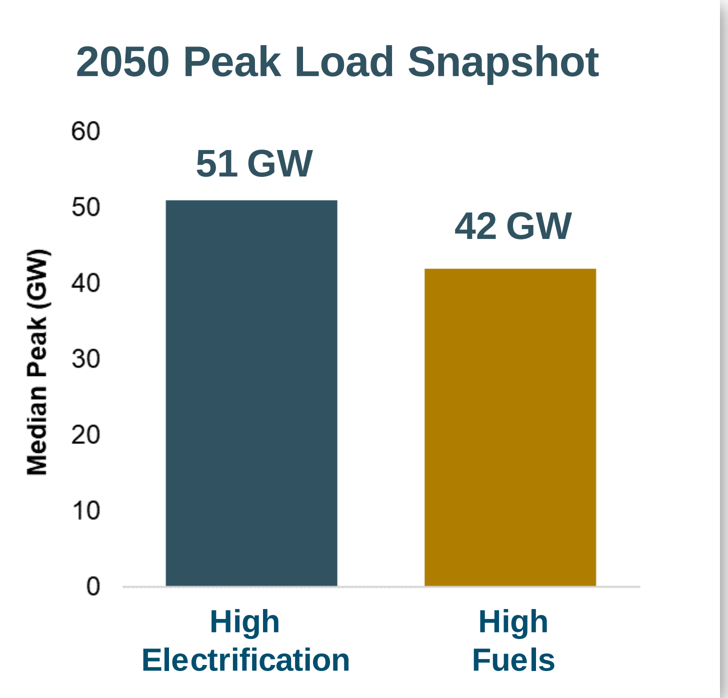
Case study derived from E3 and Energy Futures Initiative, *Net Zero New England: Ensuring Electric Reliability in a Low-Carbon Future*, November 2020 https://www.ethree.com/new-study-evaluates-deep-decarbonization-pathways-in-new-england/

Funding provided by Calpine Corporation

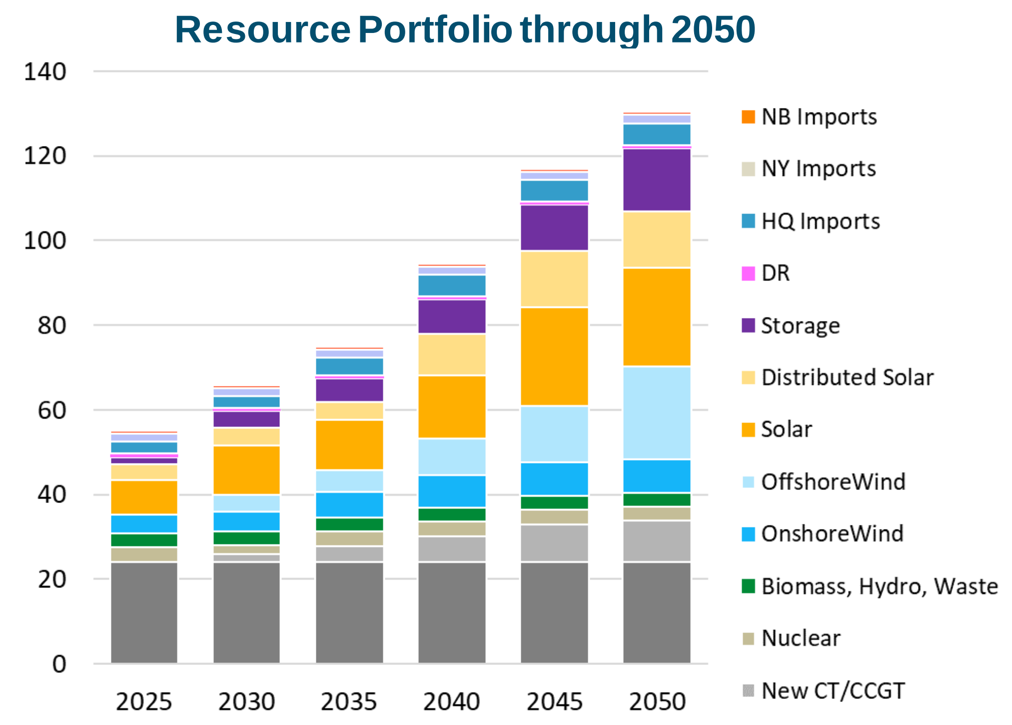
Under deep decarbonization, New England electricity system doubles in size and becomes winter-peaking

- Electrification is a key strategy to decarbonize transportation and building heat
- New England peak load increases from 25 GW in 2019 to 42-51 GW by 2050

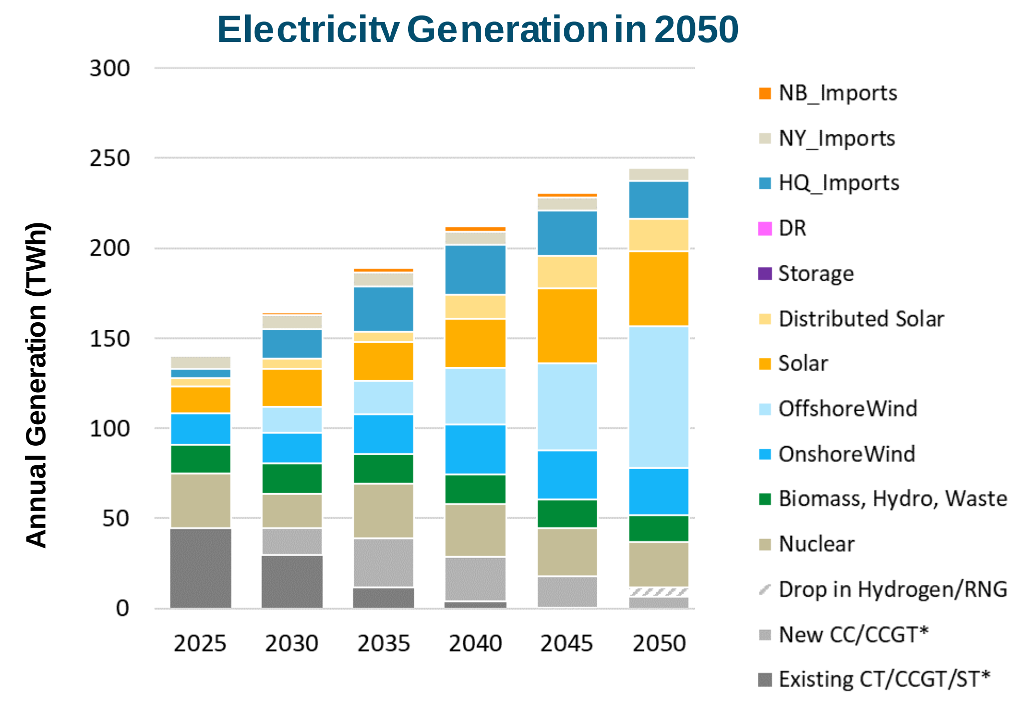




New England resource mix: variable renewables backed by thermal

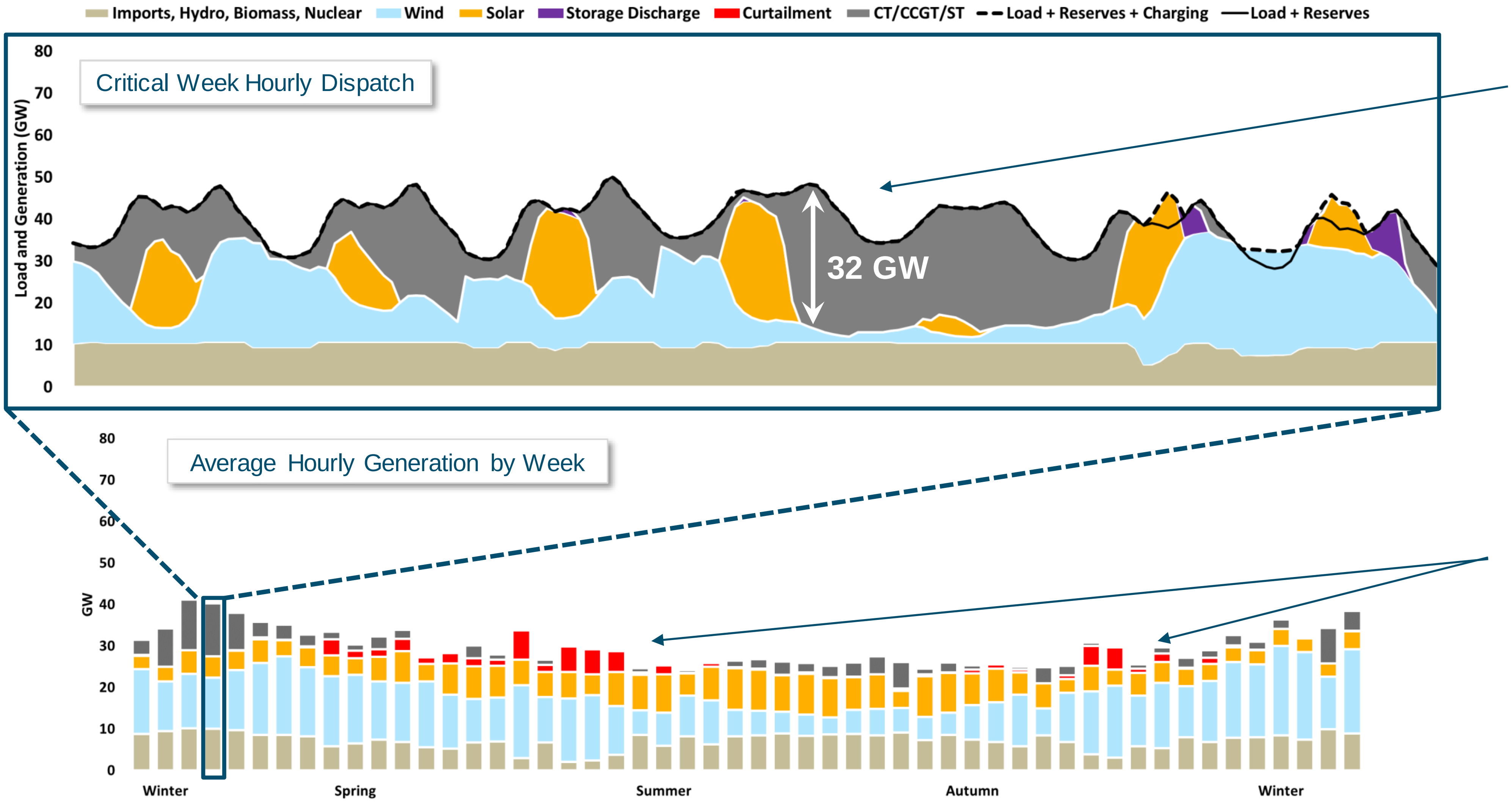

Resource Portfolio through 2050

**CT/CCGT (new or existing) can burn natural gas and/or a zero-carbon fuel*


Electricity Generation in 2050

- **Additions by 2050 include 35 GW of solar, 29 GW of wind, 13 GW of battery storage, 10 GW of thermal peakers, 4 GW hydro imports**
- **CO2 emissions reduced by 93% to 2.5 MMT, variable renewables provide ~70% of generation by 2050**

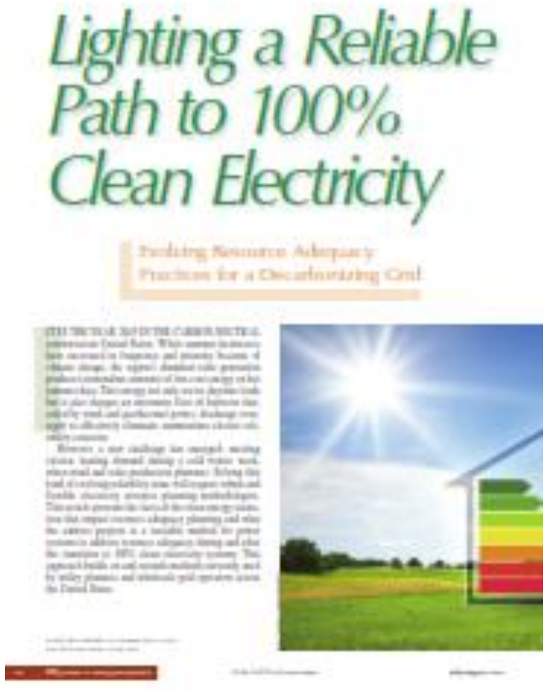
Critical week dispatch in High Electrification case



During low renewable conditions, 32 GW of thermal peaking generation is dispatched for reliability

During favorable conditions, clean generation is more than sufficient to meet load

Resource Adequacy Modeling for a Changing Grid



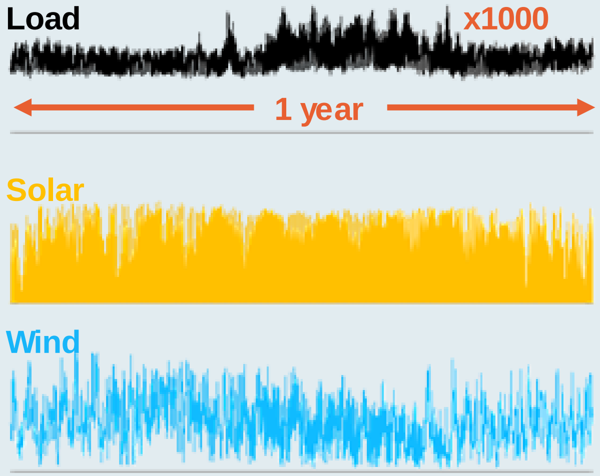
Lighting a Reliable Path to 100% Clean Electricity

Burdick, et al., “Lighting a Reliable Path to 100% Clean Electricity: Resource Adequacy Practices for a Decarbonizing Grid”, IEEE Power and Energy Systems Magazine, July/August 2022

Overview of best practices in resource adequacy analysis

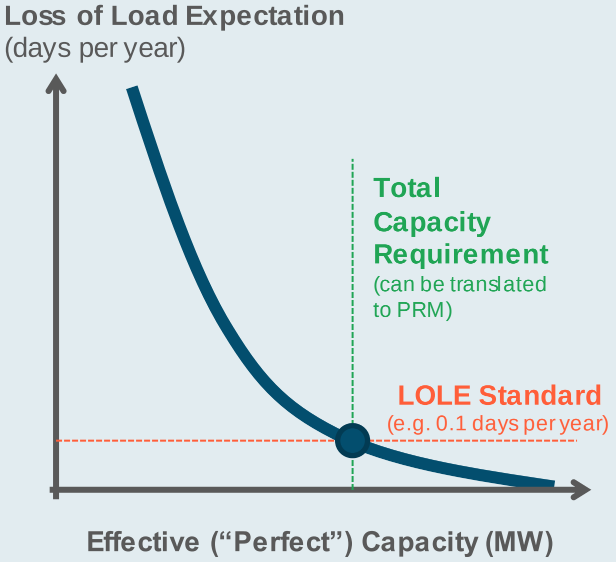
Develop a representation of the loads and resources of an electric system in a loss of load probability model

LOLP modeling allows a utility to evaluate resource adequacy across all hours of the year under a broad range of weather conditions, producing statistical measures of the risk of loss of load



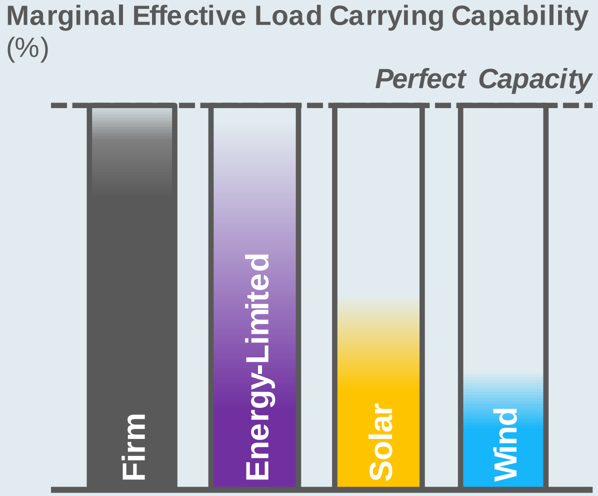
Identify the amount of perfect capacity needed to achieve the desired level of reliability

Factors that impact the amount of perfect capacity needed include load & weather variability, operating reserve needs



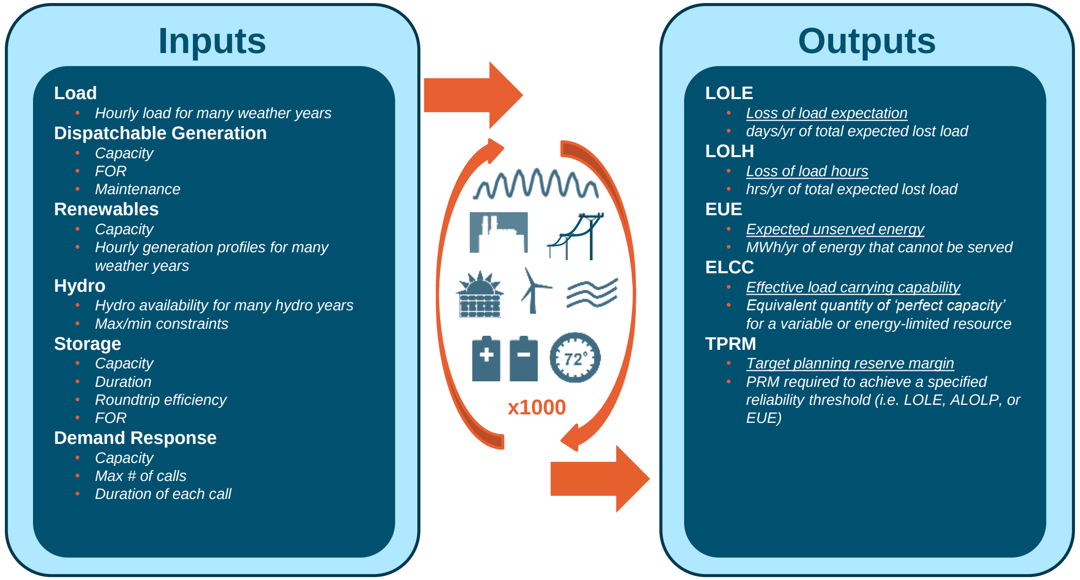
Calculate capacity contributions of different resources using effective load carrying capability

ELCC measures a resource's contribution to the system's needs relative to perfect capacity, accounting for its limitations and constraints



Loss of load probability modeling is the foundation for understanding resource adequacy needs

- **LOLP modeling can be thought of as an organized way to analyze the potential for extreme weather and other events to cause a supply shortfall**
- **LOLP can capture factors that matter for reliability such as:**
  - High loads due to extreme weather
  - Correlations between load and renewable conditions
  - Energy and capacity limitations
  - Dispatch behavior of energy-limited resources such as energy storage, demand response and hydro



Inputs

Load
- *Hourly load for many weather years*

Dispatchable Generation
- *Capacity*
- *FOR*
- *Maintenance*

Renewables
- *Capacity*
- *Hourly generation profiles for many weather years*

Hydro
- *Hydro availability for many hydro years*
- *Max/min constraints*

Storage
- *Capacity*
- *Duration*
- *Roundtrip efficiency*
- *FOR*

Demand Response
- *Capacity*
- *Max # of calls*
- *Duration of each call*

Outputs

LOLE
- *Loss of load expectation*
- *days/yr of total expected lost load*

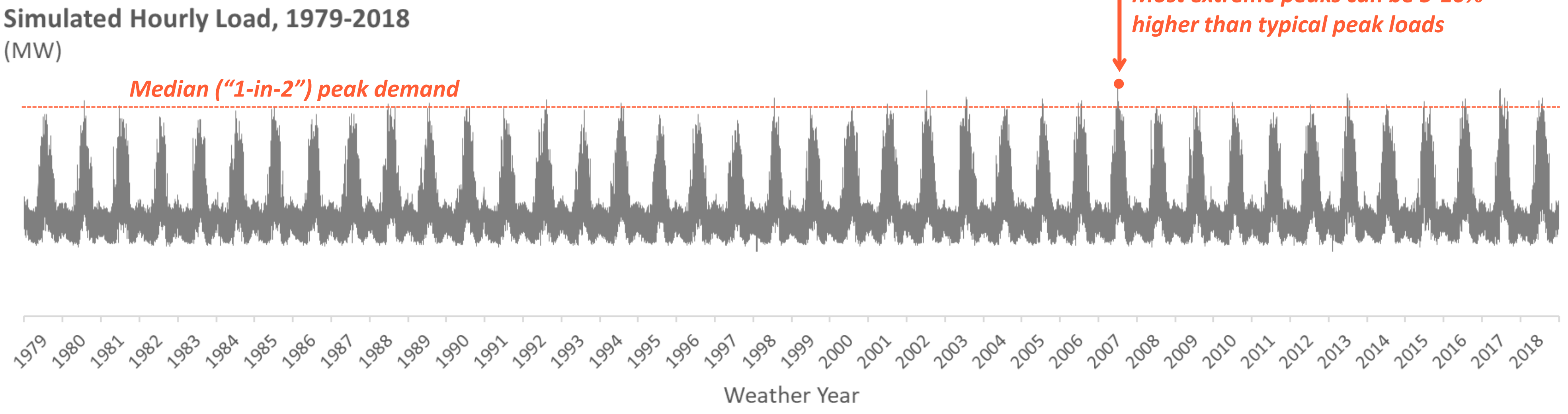
LOLH
- *Loss of load hours*
- *hrs/yr of total expected lost load*

EUE
- *Expected unserved energy*
- *MWh/yr of energy that cannot be served*

ELCC
- *Effective load carrying capability*
- *Equivalent quantity of 'perfect capacity' for a variable or energy-limited resource*

TPRM
- *Target planning reserve margin*
- *PRM required to achieve a specified reliability threshold (i.e. LOLE, ALOLP, or EUE)*

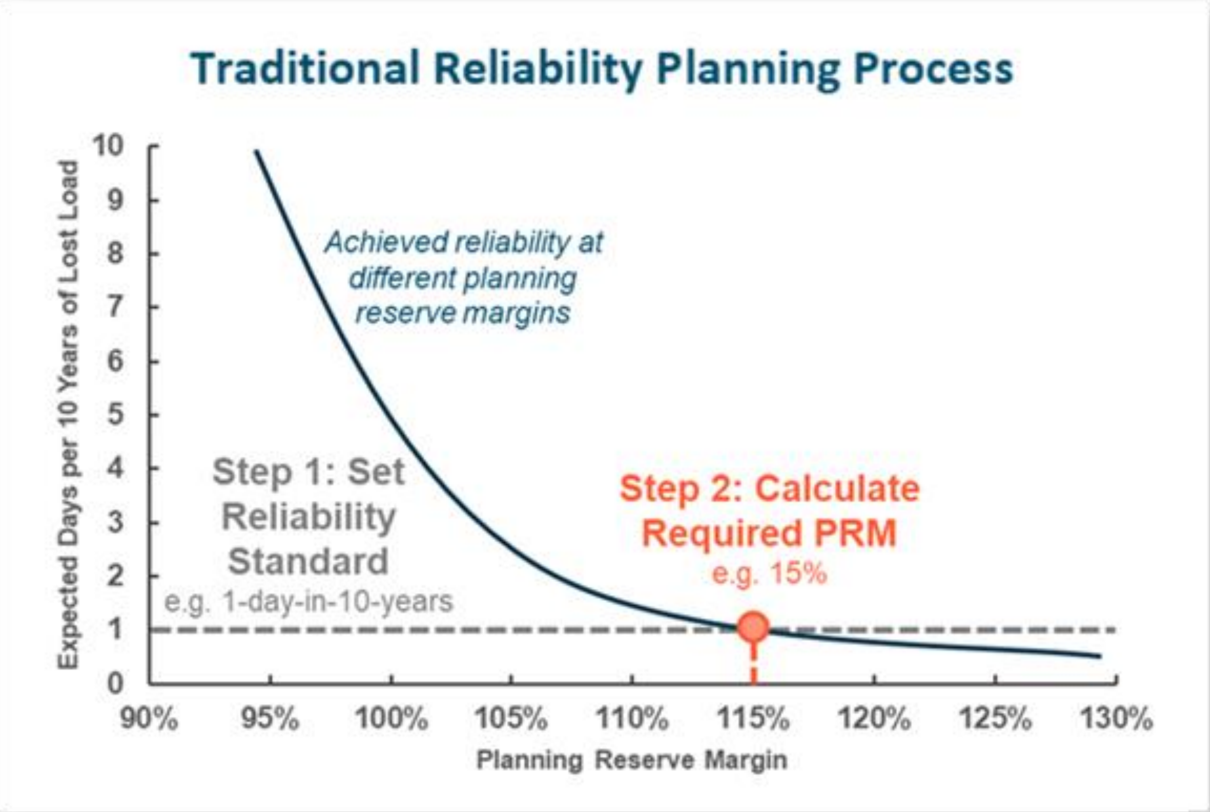
Most extreme peaks can be 5-10% higher than typical peak loads



Simulated Hourly Load, 1979-2018
(MW)

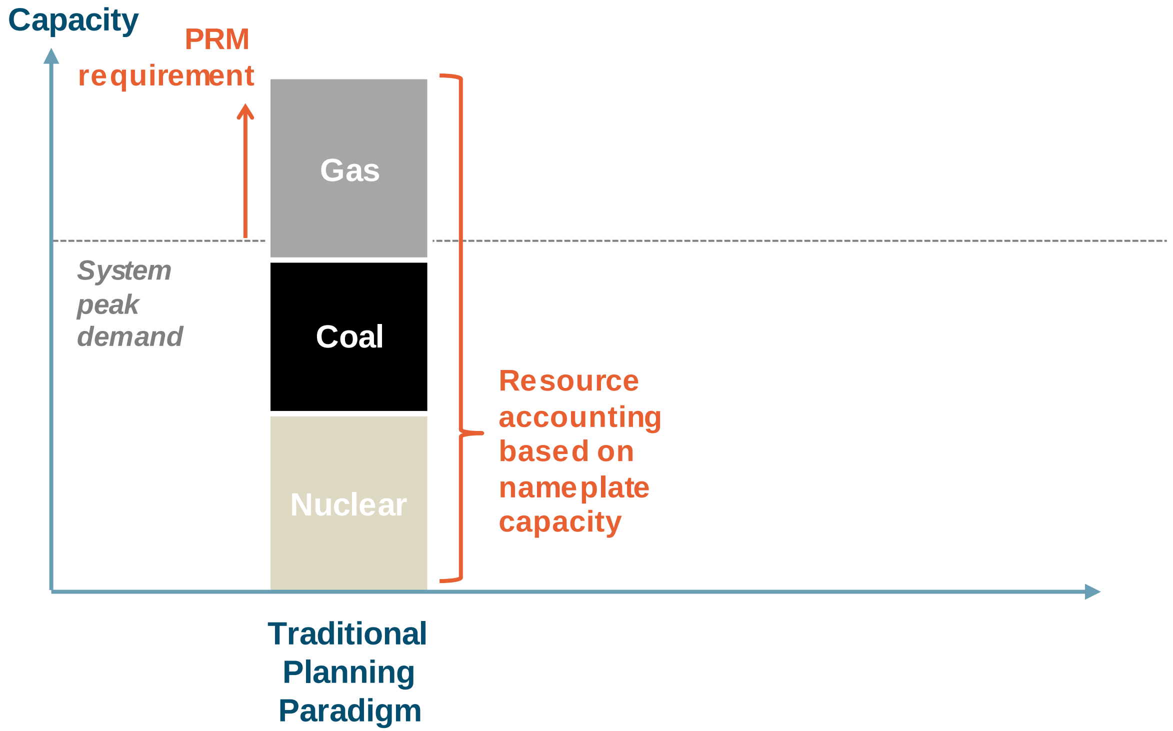
Total Resource Need (TRN) and Planning Reserve Margin (PRM)

- **Total Resource Need is the quantity of effective capacity needed to meet a defined reliability standard**
  - ❑ Typically defined as “1 day in 10 years” or 0.1 LOLE but other definitions are equally valid
- **PRM is measured as the quantity of capacity needed above the median year peak load to meet the LOLE standard**
  - ❑ Calculated as (TRN – Median Peak)/Median Peak
  - ❑ Serves as a simple and intuitive metric that can be utilized broadly in power system planning
  - ❑ Based on robust LOLP modeling
- **The integration of increasing levels of renewables and storage requires thoughtful adaptation of TRN/PRM framework**



Resource accreditation is simple in the traditional planning paradigm

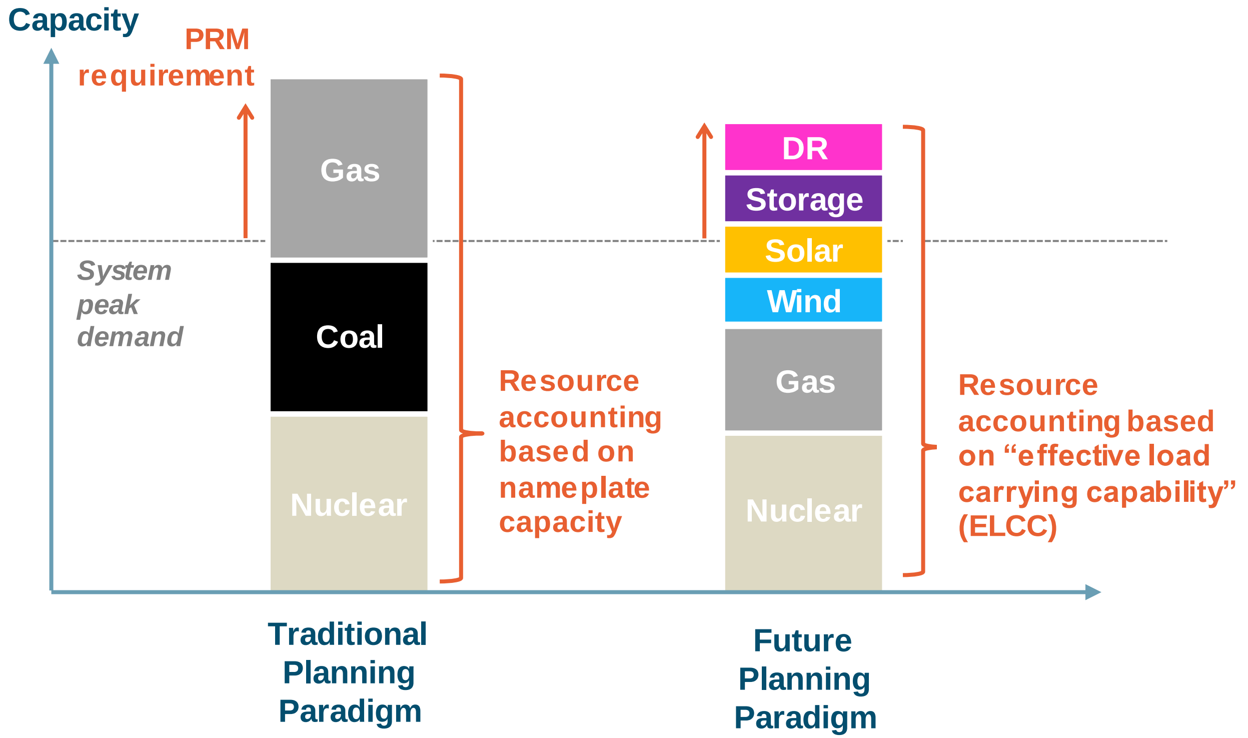
- **PRM defined based on Installed Capacity method (ICAP)**
  - ❑ Covers annual peak load variation, operating reserve requirements, and thermal resource forced outages
- **Individual resources accredited based on nameplate capacity**
  - ❑ Small differences in forced outage rates
  - ❑ No interactions among resources
  - ❑ Forced outages also incorporated through performance penalties



$$Installed\ Capacity = \sum_{i=1}^{n} G_i$$

Adapting the PRM framework for a high renewable future

- **PRM defined based on need for Perfect Capacity (PCAP)**
  - ☐ Covers annual peak load variation and operating reserves only; forced outages addressed in resource accreditation
- **Individual resources accredited based on ELCC**
  - ☐ Large differences in availability during peak
  - ☐ Significant interactions among resources
  - ☐ ELCC values are dynamic based on resource mix



$$Portfolio\ ELCC = f(G_1, G_2, \ldots, G_n)$$

ELCC is calculated using loss-of-load-probability modeling

- **Effective Load Carrying Capability (ELCC) represents the equivalent "perfect" capacity that a resource provides in meeting the target reliability metric (e.g., 0.1 day/year LOLE)**
  - **Derived from LOLP modeling**, building on foundation for resource adequacy analysis
  - Captures **complex interactive effects**, e.g., saturation effects and diversity benefits
  - **Agnostic to technology** and can be applied to all resources

Calculate existing system reliability and tune the system to the target

Add desired resource to portfolio

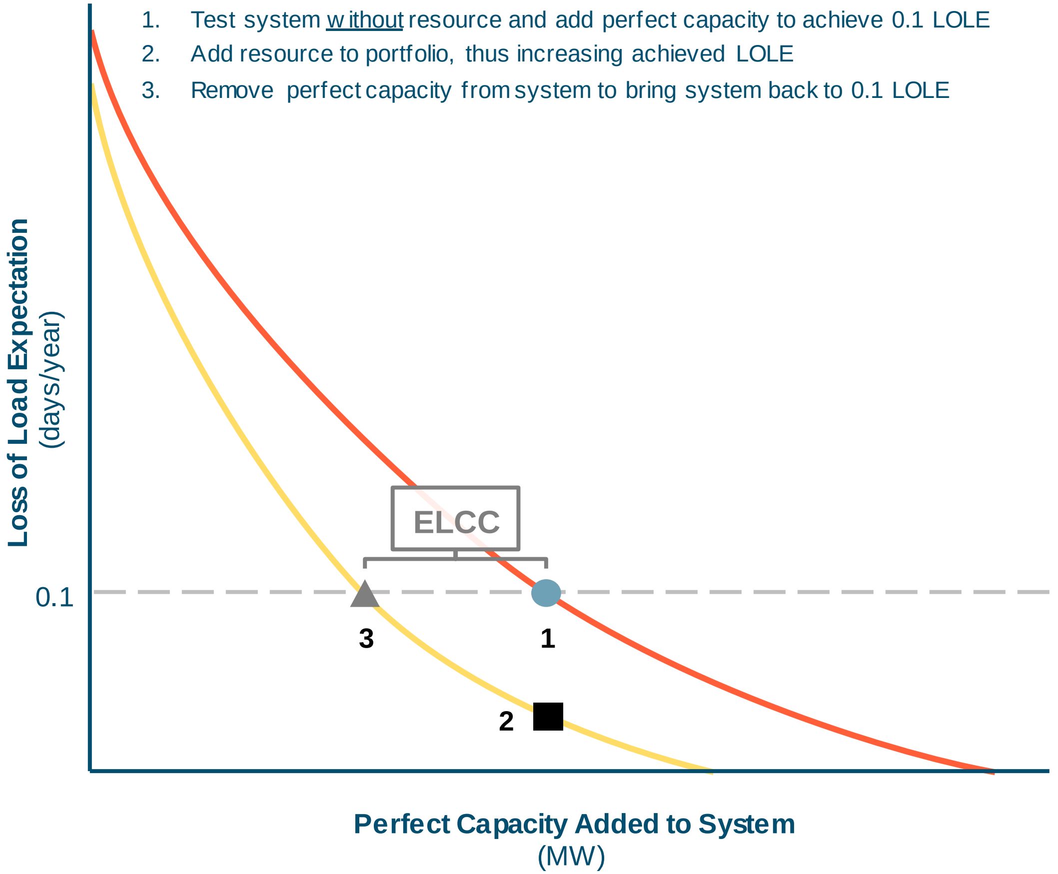
Addition of new source of generation will increase reliability relative to measurement in Step 1

Remove perfect capacity until target reliability is restored

Removal of perfect capacity results in decrease in reliability until original target is met

A resource's ELCC is equal to the amount of perfect capacity removed from the system in Step 3

Illustration of ELCC Calculation Approach



1. Test system without resource and add perfect capacity to achieve 0.1 LOLE
2. Add resource to portfolio, thus increasing achieved LOLE
3. Remove perfect capacity from system to bring system back to 0.1 LOLE

Measuring ELCC of a portfolio and individual resources

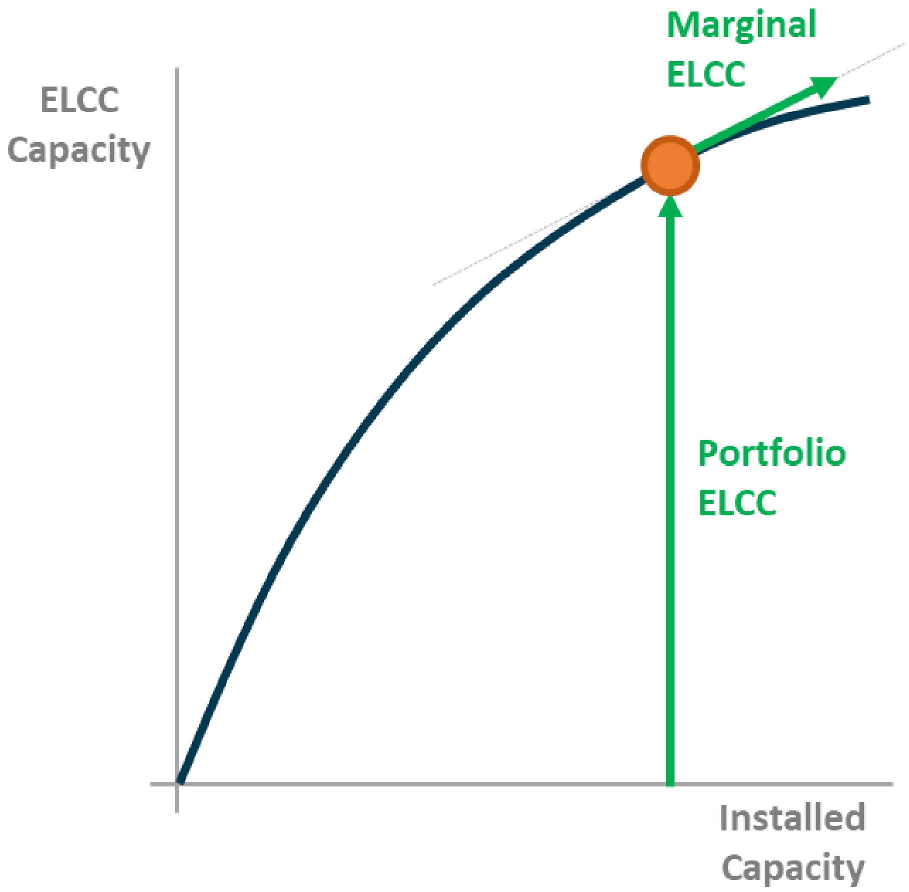
- **ELCC is a function of the portfolio of resources**
    - The function is a surface in multiple dimensions
    - The Portfolio ELCC is the height of the surface at the point representing the total portfolio

$$Portfolio\ ELCC = f(G_1, G_2, \ldots, G_n)\ (MW)$$

- The Marginal ELCC of any individual resource is the gradient (or slope) of the surface along a single dimension – mathematically, the partial derivative of the surface with respect to that resource

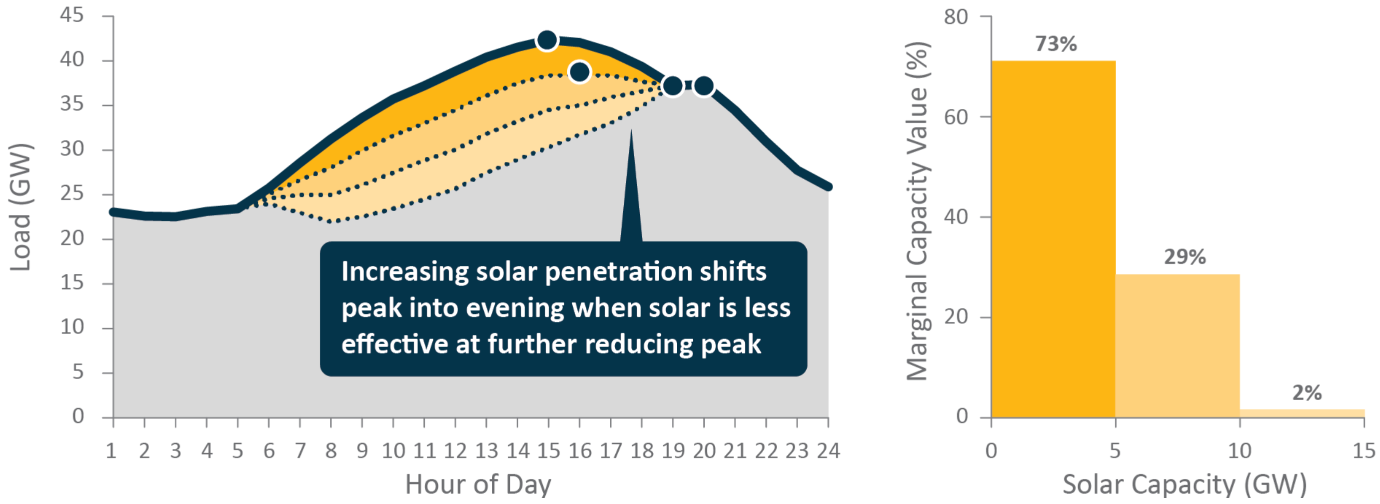
$$Marginal\ ELCC_{G_1} = \frac{\partial f}{\partial G_1}(G_1,\ ,G_2,\ \ldots\ G_n)\ (\%)$$

- **The functional form of the surface is unknowable**
    - Marginal ELCC calculations give us measurements of the contours of the surface at specific points
    - It is impractical to map out the entire surface



The capacity contribution of variable and dispatch-limited resources diminishes at higher penetrations

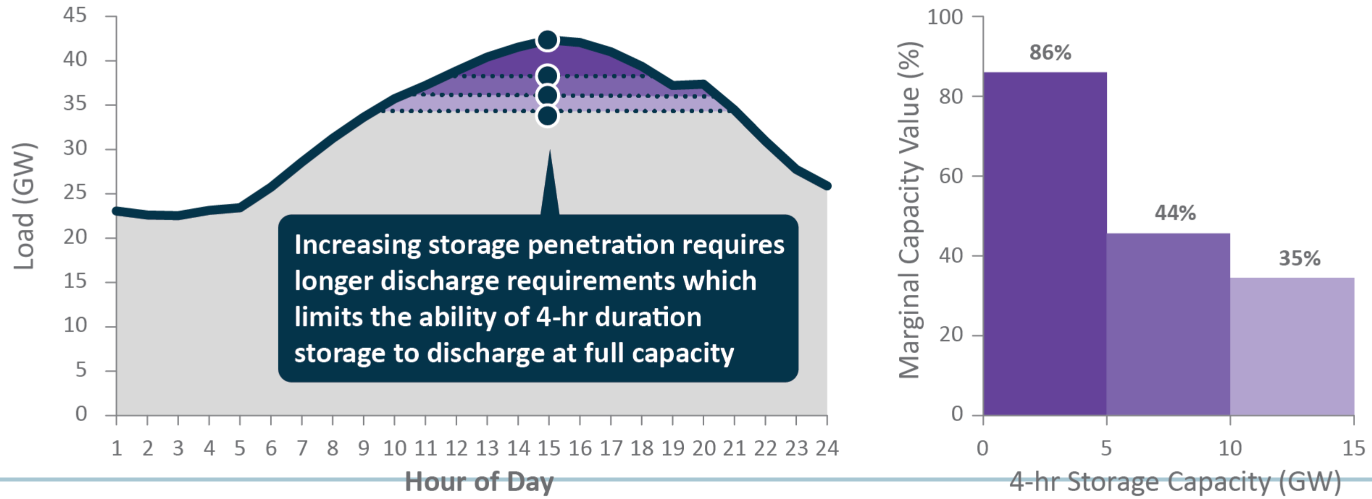
Diminishing Capacity Value of Solar



Increasing solar penetration shifts peak into evening when solar is less effective at further reducing peak

Solar and other **variable resources** (e.g. wind) exhibit declining value due to variability of production profiles

Diminishing Value of 4-hr Storage ELCC

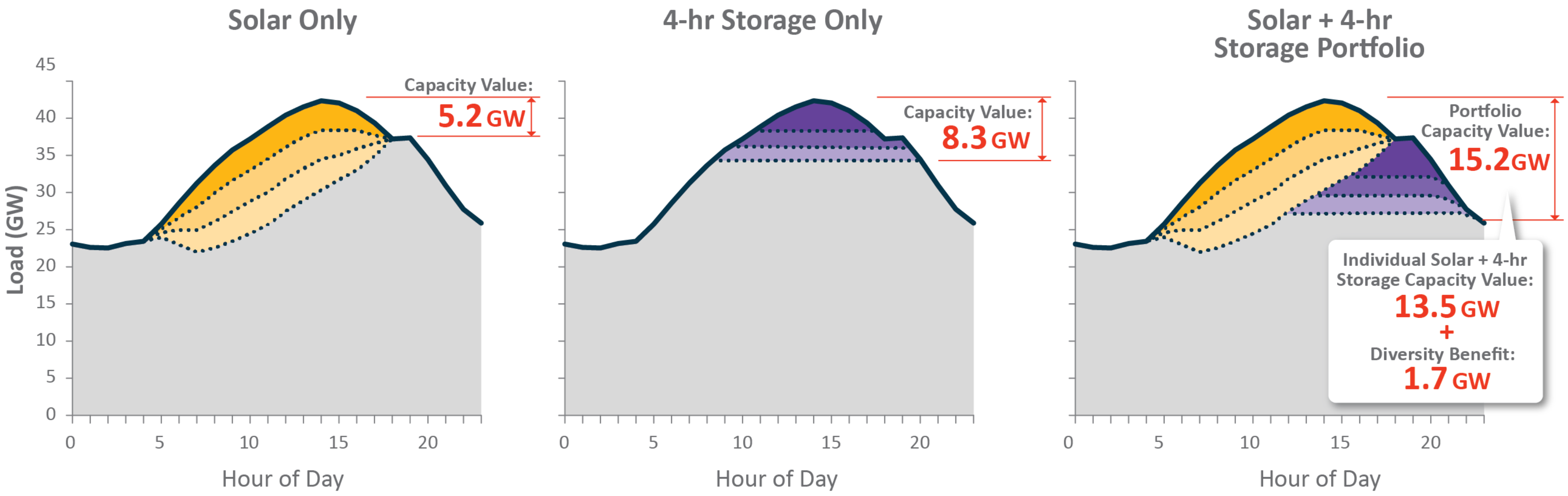


Increasing storage penetration requires longer discharge requirements which limits the ability of 4-hr duration storage to discharge at full capacity

Storage and other **energy-limited resources** (e.g. DR, hydro) exhibit declining value due to limited ability to generate over sustained periods

The capacity contribution of a dispatch-limited resource depends in part on the other resources in the portfolio

- Resources with complementary characteristics produce the opposite effect, synergistic interactions (also described as a “diversity benefit”)
- As penetrations of intermittent and energy-limited resource grow, the magnitude of these interactive effects will increase and become non-negligible



Resource interactions: synergistic or antagonistic pairings

Common Examples of Synergistic Pairings

⊕ **Solar + Wind**

The profiles for many wind resources produce more energy during evening and nighttime hours when solar is not available

⊕ **Solar + Storage**

Solar and storage each provide what the other lacks – energy (in the case of storage) and the ability to dispatch energy in the evening and nighttime (in the case of solar)

⊕ **Solar/Wind + Hydro**

Hydro is an energy-limited resource so increasing penetrations of solar or wind allows hydro to save its limited production for the most resource constrained hours

Common Examples of Antagonistic Pairings

⊖ **Storage + Hydro**

Energy limitations on both storage and hydro require longer and longer durations after initial penetrations

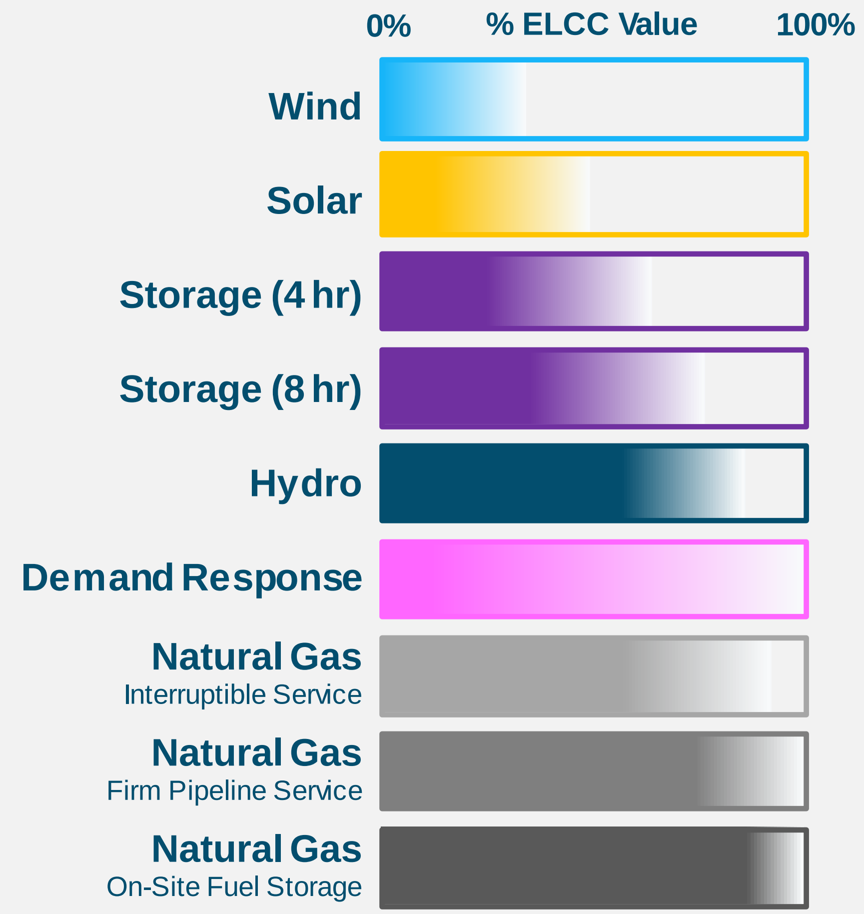
⊖ **Storage + Demand Response**

Energy limitations on both storage and hydro require longer and longer durations after initial penetrations

No resource is "perfect" – ELCC can and should be applied to all resources

- **ELCC creates level playing field by measuring all resources against perfect capacity**
- **Can account for all factors that can limit availability:**
  - Hourly variability in output
  - Duration and/or use limitations
  - Seasonal temperature derates
  - Temperature-related outage rates
  - Forced outages
  - Energy availability
  - Fuel availability
  - Correlated outage risk, *especially under extreme conditions*
- **Use Perfect Capacity (PCAP) accounting as opposed to ICAP or UCAP**

Illustrative ELCC Values Across Technologies



Applications and Future Challenges

Applications of advanced resource adequacy techniques

- **Vertically-integrated utilities:**
  1. Develop LOLP model and calculate Total Reliability Need based on defined reliability standard
  2. Map out surface of marginal ELCCs in one or more dimensions, e.g., solar + storage (can assume other dimensions are independent)
  3. Apply marginal ELCCs to assess the reliability contribution of *new* resources in bid evaluation

- **Organized markets:**
  1. Develop LOLP model and calculate Total Reliability Need based on defined reliability standard
  2. Calculate Marginal Reliability Need as TRN minus portfolio effects
  3. Allocate net MRN to individual LSEs based on load during hours of highest reliability need
  4. Map out surface of marginal ELCCs in one or more dimensions
  5. Apply marginal ELCCs to assess the reliability contribution of *existing and new* resources in centrally-cleared capacity auction

Current and future challenges in resource adequacy

+ Defining appropriate reliability standard

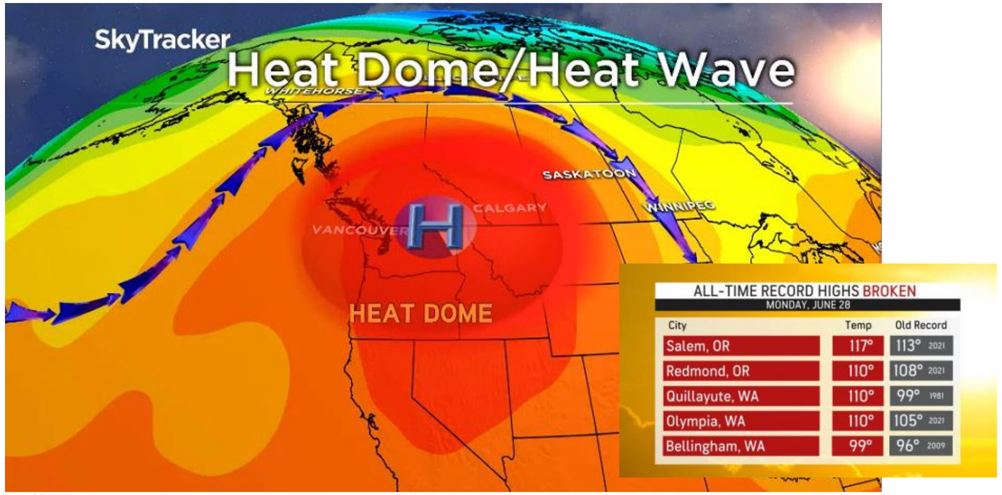
- ☐ No solid analytical foundation for 1-day-in-10-years
- ☐ What is the value of lost load?
- ☐ Bending the demand curve with price responsive demand

+ Adapting weather data for climate change

- ☐ Past performance is not indicative of future results

+ Addressing fuel limitations in thermal accreditation

- ☐ Thermal resources without firm fuel supplies should get lower ELCC accreditation, but it is difficult to develop appropriate statistical information
- ☐ “Common mode failure” such as pipeline disruption or temperature driven fuel supply interruptions



ALL-TIME RECORD HIGHS BROKEN
MONDAY, JUNE 28

City	Temp	Old Record
Salem, OR	117°	113° 2021
Redmond, OR	110°	108° 2021
Quillayute, WA	110°	99° 1981
Olympia, WA	110°	105° 2021
Bellingham, WA	99°	96° 2009

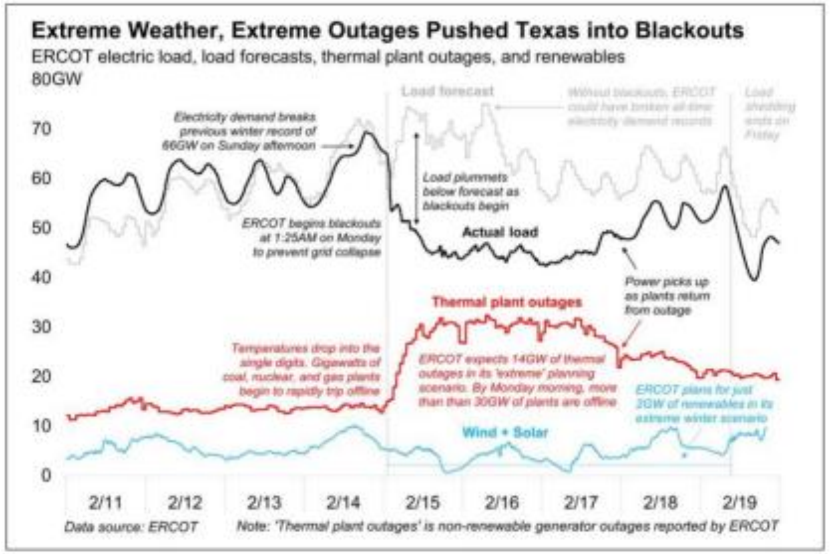


Figure 1. ERCOT data posted to Twitter by Brian Bartholomew (@BPBartholomew)

Thank you!

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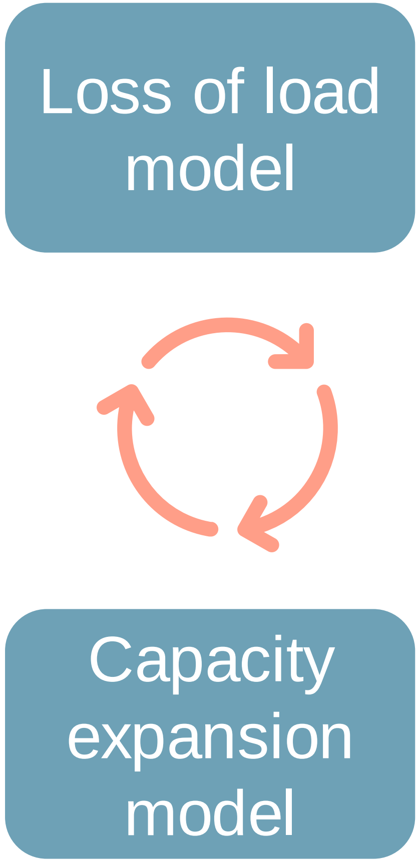
Energy+Environmental Economics

Appendix: Application of ELCC Surfaces in Capacity Expansion Modeling

Planning models need resource adequacy contributions

- **Capacity expansion models enforce resource adequacy constraints when planning power systems**
- **To ensure reliability at minimum cost, the marginal *and* total resource adequacy contribution of energy-limited resources needs to be accurately reflected**
  - But declining marginal capacity values and interactive effects between resources require <u>constant re-calibration</u> of energy-limited resource adequacy contributions
- **Not feasible to embed a detailed loss-of-load model within a capacity expansion model**


Loss of load model

Capacity expansion model

How does it end???

Workflow for using ELCC "surface" in planning

1. LOLE model

   Calculate ELCC of combinations of energy-limited resources over a wide range of installed capacities

2. Linear equations

   Convert portfolio ELCC values at a range of penetrations into linear equations for marginal and total ELCC

3. Capacity Expansion

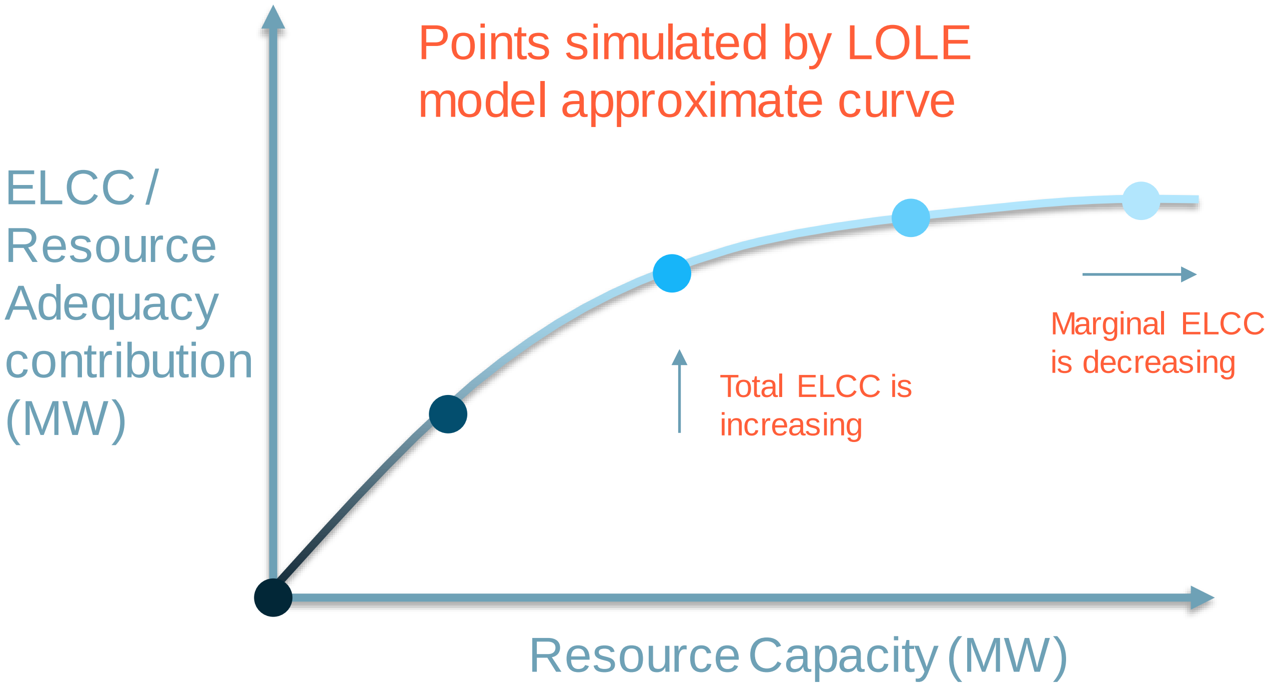
   Implement "surface" equations in capacity expansion model, create least-cost portfolios

4. Reliability Check

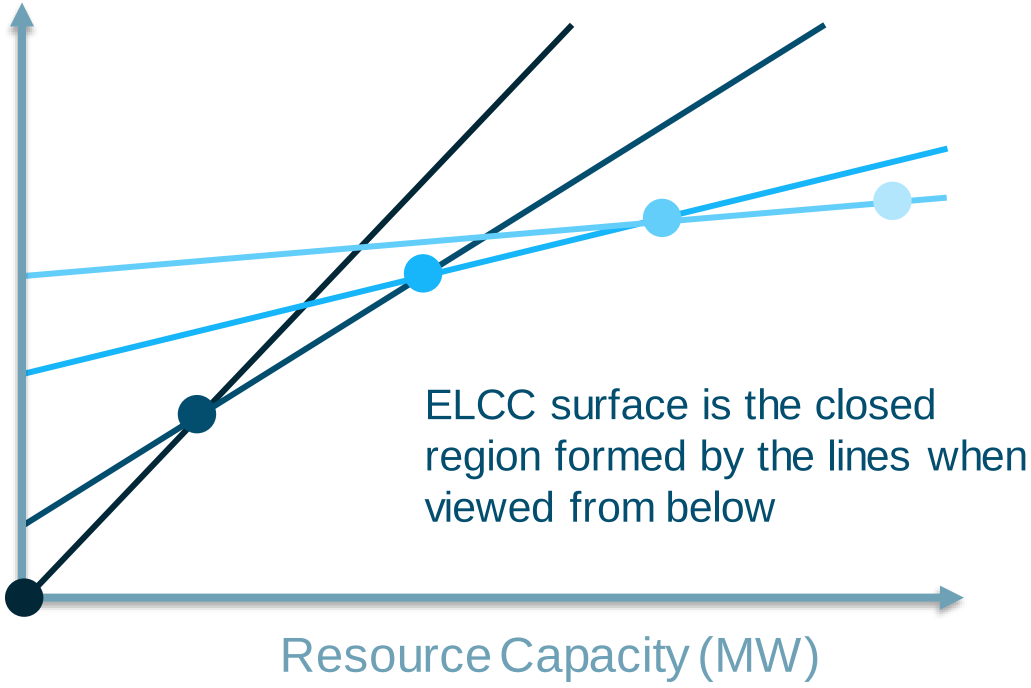
   Check reliability using LOLE model, adjusting if any issues are found

Building an ELCC surface in one dimension

Calculate ELCC at Different Levels of Penetration



Linear equations to approximate ELCC curve

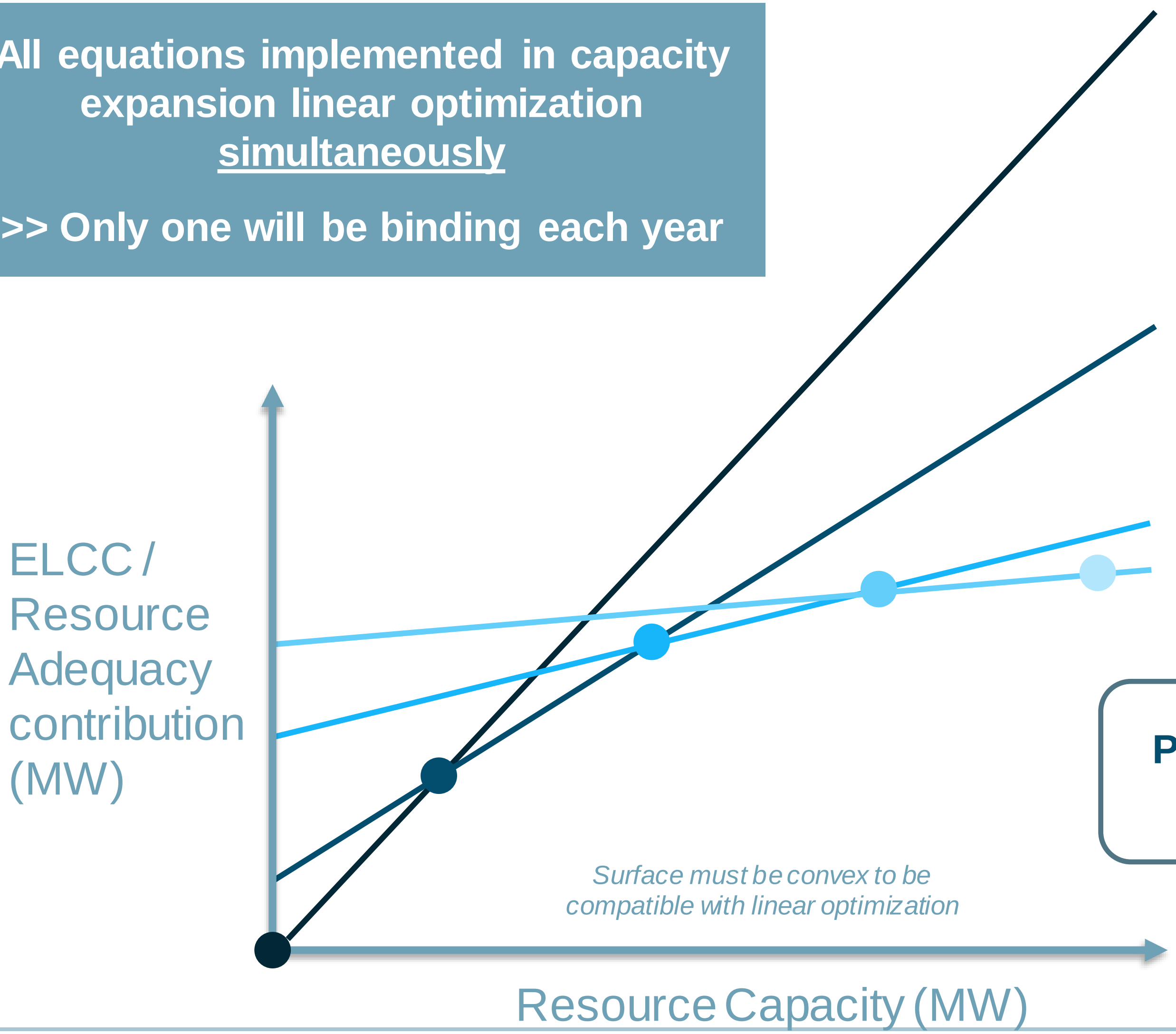


ELCC surface is the closed region formed by the lines when viewed from below

Implementing in capacity expansion model

All equations implemented in capacity expansion linear optimization simultaneously

>> Only one will be binding each year



Surface must be convex to be compatible with linear optimization

ELCC <= 1 * ResCap + 0

Example values

ELCC <= 0.7 * ResCap + 80

ELCC <= 0.3 * ResCap + 200

ELCC <= 0.1 * ResCap + 300

Portfolio ELCC <= Incremental Capacity Value * Resource Capacity + Line Intercept

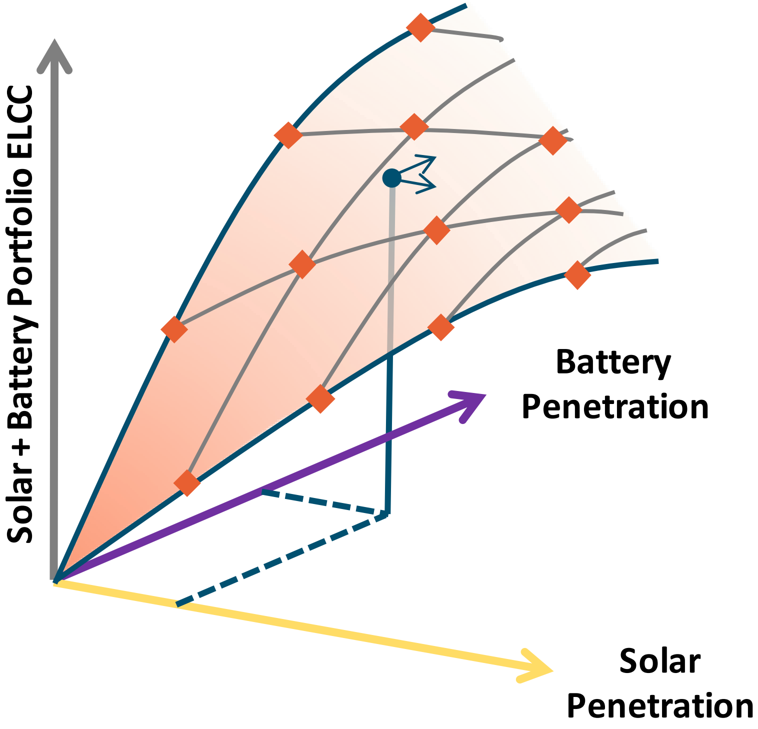
General form of equation

Now in two dimensions….

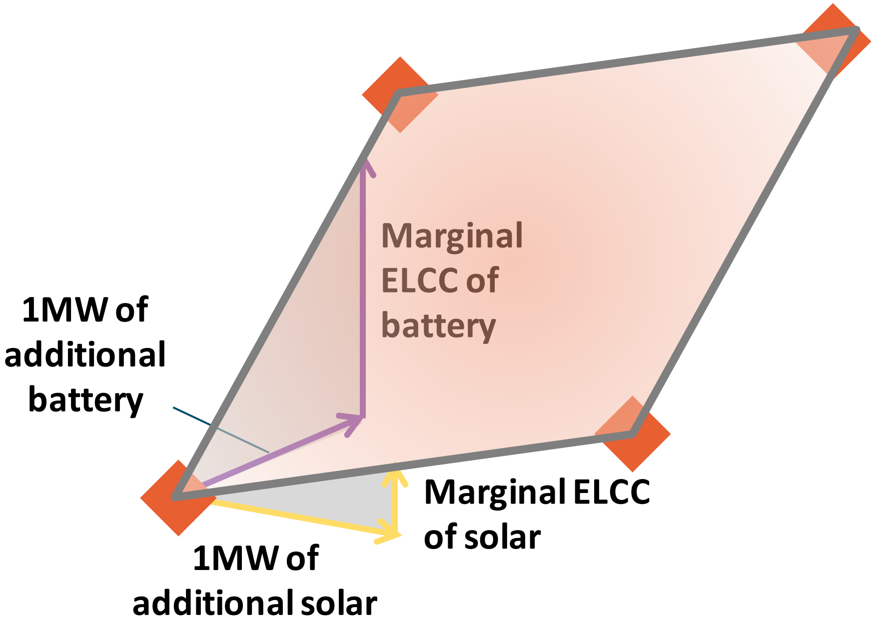
- A two-dimensional ELCC surface can capture both diminishing returns and diversity benefits between resources

◆ *The height of the orange dots gives the total solar + storage portfolio ELCC*

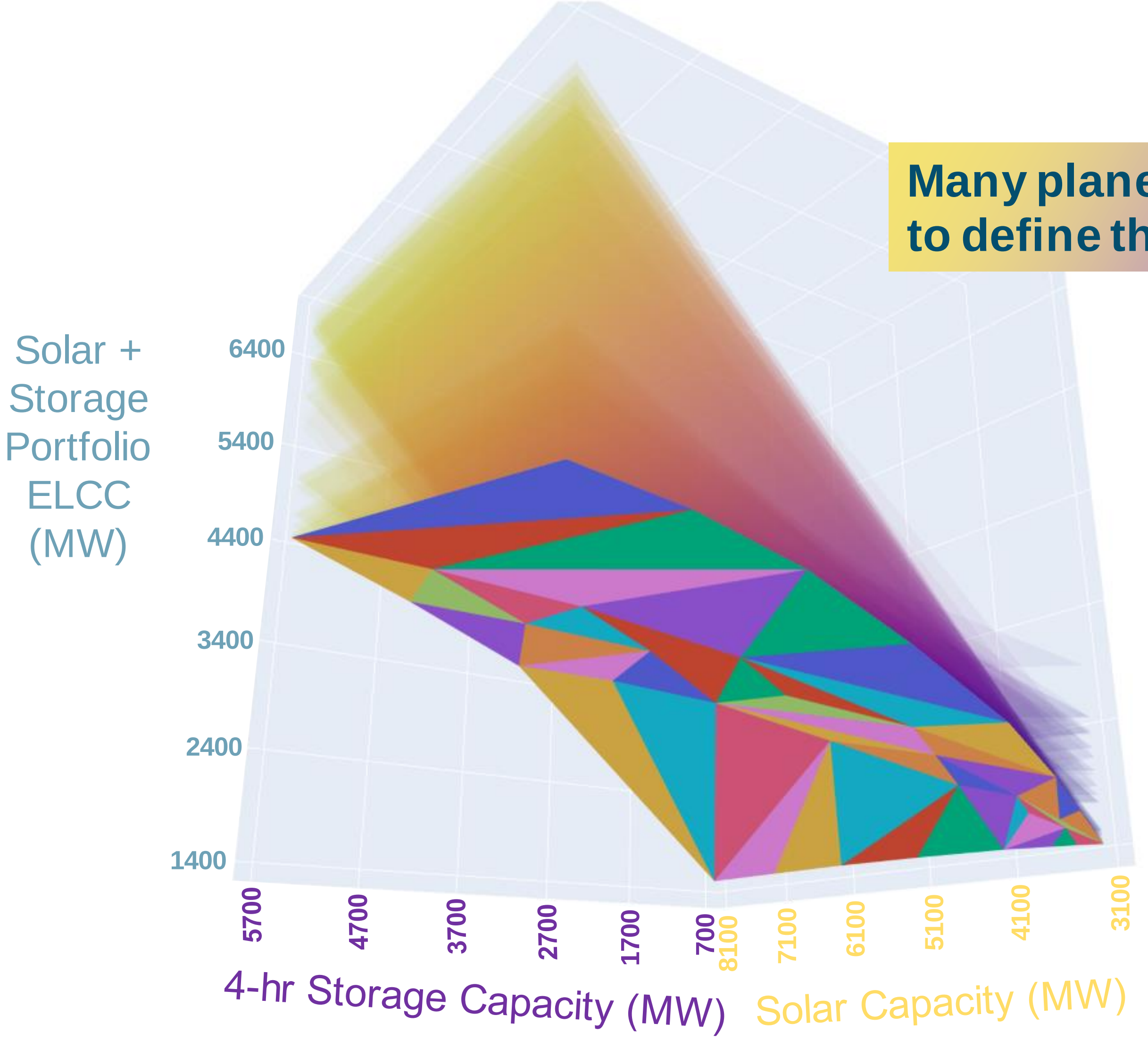
The slope between each point gives the marginal capacity value of solar and storage at a given capacity



For any plane on the surface:



NVE solar + storage surface



Many planes intersect to define the surface

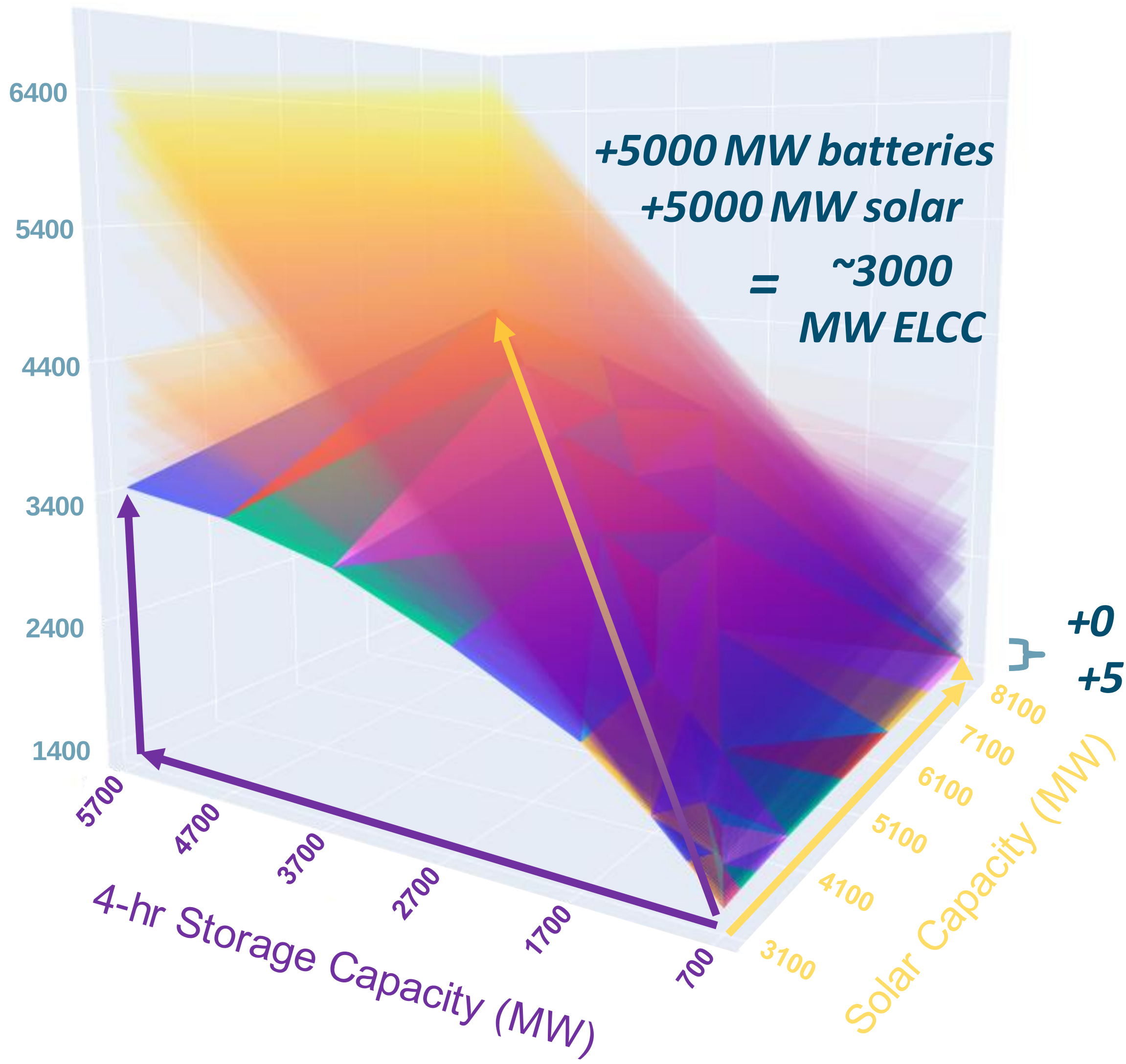
The patchwork "quilt" is a convex surface defined by the planes

Notes

- **NV Energy surface MW values for solar and battery are <u>incremental</u> to a 2030 portfolio simulated by RECAP**
    - ~700 MW batteries, 3100 MW Solar, ~1400 MW portfolio ELCC (axes don't start at zero)
- **Picture at left is for a *near*-final NV Energy surface – final surface was extended past values shown here**

Surface shows interactive effects of solar and storage

Rotate



+5000 MW batteries
+5000 MW solar
= ~3000 MW ELCC

+5000 MW batteries
+0 MW solar
=
~2000 MW ELCC

+0 MW batteries
+5000 MW solar
= ~100 MW ELCC

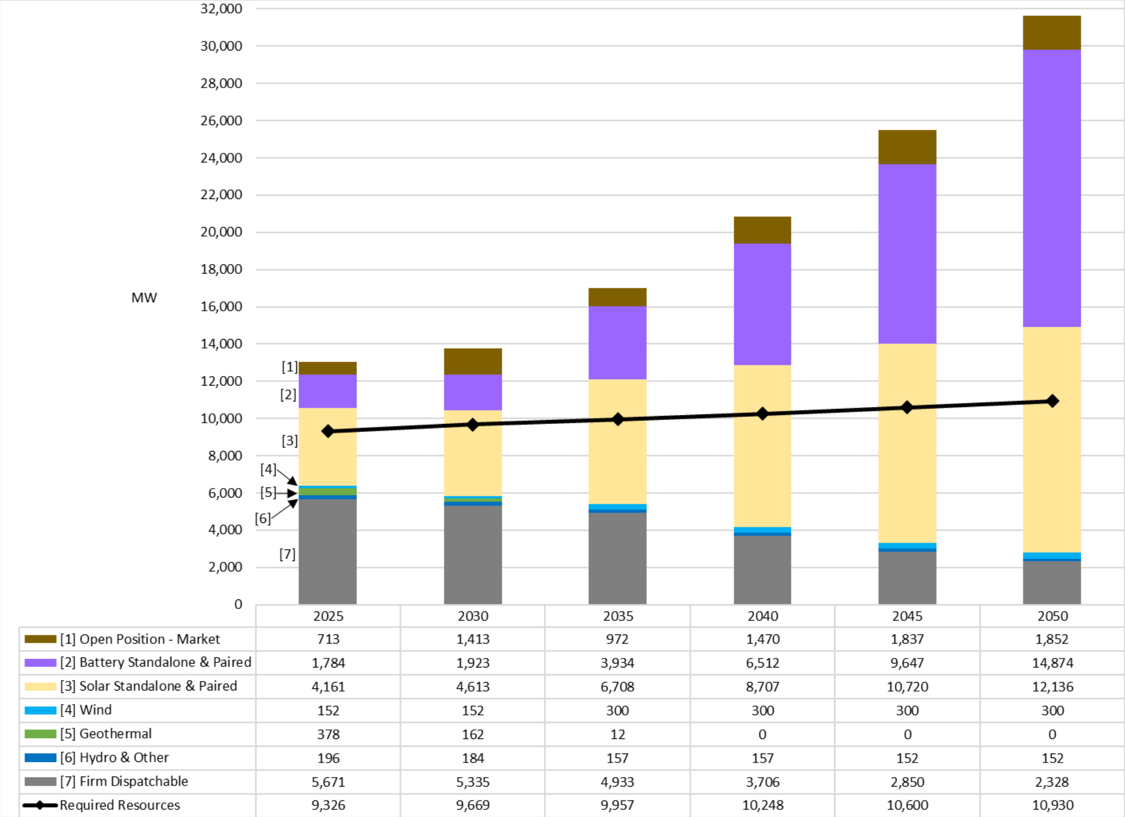
Solar (MW)	Storage (MW)	ELCC (MW)
5000	0	**100**
0	5000	**2000**
5000	5000	**3000**

2100

900 MW ELCC from diversity

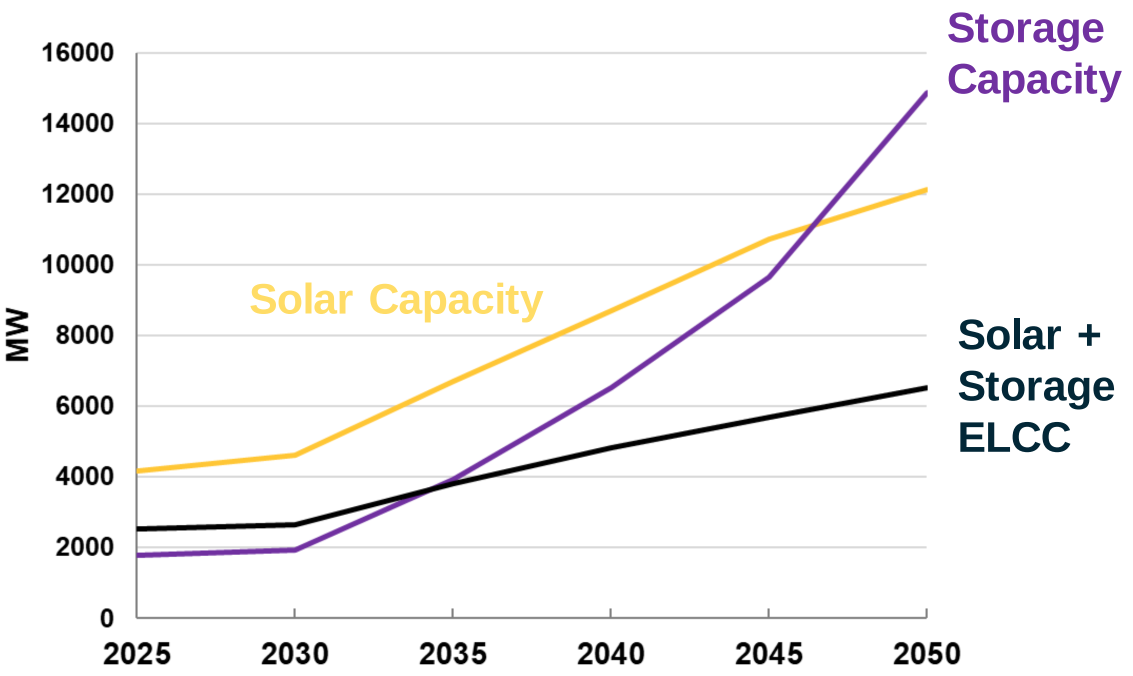
NV Energy solar + storage ELCC results

NV Energy Resource Portfolio (credit NV Energy)



	2025	2030	2035	2040	2045	2050
🟫 [1] Open Position - Market	713	1,413	972	1,470	1,837	1,852
🟪 [2] Battery Standalone & Paired	1,784	1,923	3,934	6,512	9,647	14,874
🟨 [3] Solar Standalone & Paired	4,161	4,613	6,708	8,707	10,720	12,136
🟦 [4] Wind	152	152	300	300	300	300
🟩 [5] Geothermal	378	162	12	0	0	0
🟦 [6] Hydro & Other	196	184	157	157	152	152
⬛ [7] Firm Dispatchable	5,671	5,335	4,933	3,706	2,850	2,328
◆ Required Resources	9,326	9,669	9,957	10,248	10,600	10,930

Solar + Storage ELCC



E3 use cases *to date*

Platforms

- **E3's RESOLVE capacity expansion model**
  - Python + pyomo code for linear equations
- **PLEXOS LT**
  - Custom constraints and decision variables
- **Excel**
  - Lookup tables – for example a load & resource "L&R" table

Configurations

- **1 Dimension**
  - Batteries
  - Wind
- **2 Dimensions**
  - Solar + battery
  - Solar + wind
  - Offshore wind + wind
- **3 Dimensions**
  - No one…yet

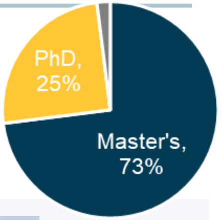
Clients

- NV Energy
- California PUC
- California Energy Commission
- Calpine (Net Zero New England, California)
- El Paso Electric
- Puget Sound Energy
- Sacramento Municipal Utility District
- Nova Scotia Power
- New Brunswick Power
- Xcel Energy
- + more

Who is E3?

Thought Leadership, Fact Based, Trusted.

100+ full-time consultants | 30 years of deep expertise | Engineering, Economics, Mathematics, Public Policy…




San Francisco

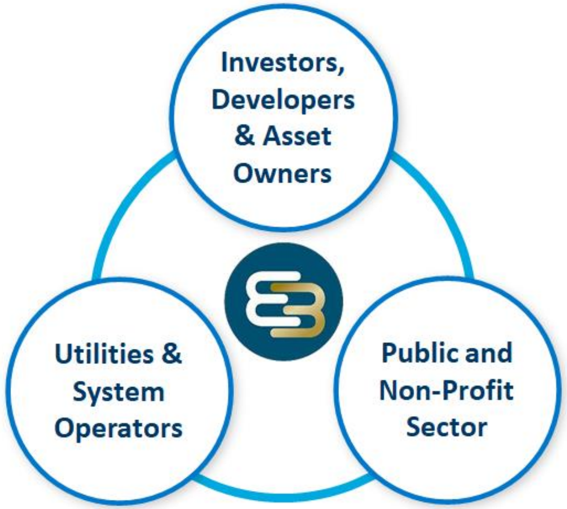

New York


Boston


Calgary

E3 Clients

300+ projects per year across our diverse client base


Investors, Developers & Asset Owners

Utilities & System Operators

Public and Non-Profit Sector

Recent Examples of E3 Projects

Buy-side diligence support on several successful investments in electric utilities (~$10B in total)

Acquisition support for investment in a residential demand response company (~$100M)

Supporting investment in several stand-alone storage platforms and individual assets across North America (10+ GW | ~$1B)

Acquisition support for several portfolios and individual gas-fired and renewable generation assets (20+ GW | ~$2B)

United Nations Deep Decarbonization Pathways Project

California: 100% clean energy planning and carbon market design for California agencies

Net Zero New England study with Energy Futures Initiative

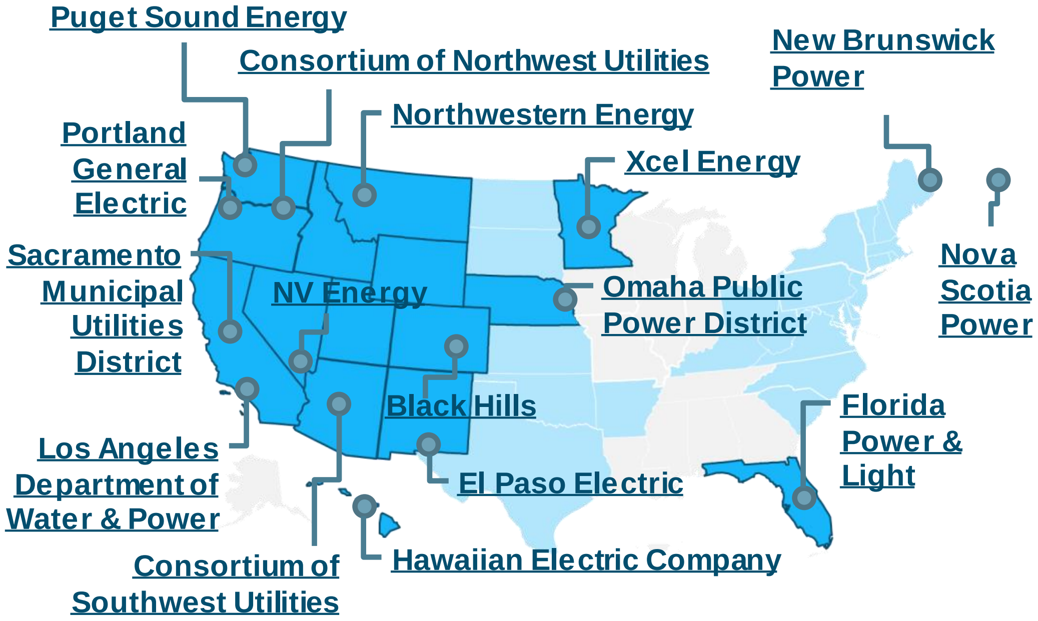
New York: NYSERDA 100% clean energy planning

Pacific Northwest: 100% renewables and resource adequacy studies for multiple utilities

E3 has extensive experience supporting utilities in studying resource adequacy

- **Rapid transformation of electric supply portfolios have led many utilities to revisit their approaches to ensuring resource adequacy**
- **E3 has worked with utilities across North America to design and implement modernized frameworks to meet future resource adequacy needs**
- **Considerations include:**
  - Establishing a planning reserve requirement tied to fundamental loss-of-load-probability modeling
  - Valuing contributions of non-firm resources (renewables and storage) using effective load carrying capability (ELCC)
  - Accounting for changing system needs under deep decarbonization

E3 has worked directly with utilities across North America to study resource adequacy needs



▨ *States where E3 has provided direct support to utilities to develop resource adequacy frameworks*

□ *Areas where E3 has worked with non-utility clients to examine issues related to resource adequacy*

Thank you!

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Energy+Environmental Economics