LDES Scoping Report

C2ES LDES WORKING GROUP MEETING

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Brattle

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Overview

1. LDES Technology, Costs, and Operations
2. Value of LDES in the Power Sector
3. Identified Barriers to LDES Deployment

Executive Summary

Growing need for energy shifting and low-carbon capacity creates opportunity for an array of **Inter-day LDES** (10-36 hrs) technologies, however they will need to compete with lithium-ion for shorter duration applications (less than 12 hours)

- Emerging needs for winter reliability present an immediate opportunity, subject to ongoing reforms.

Anticipated grid needs under deep decarbonization present major grid challenges that **Multi-day LDES** (36+ hrs) technologies could address with their distinct cost structure

Key barriers to LDES deployment include:

- Technical challenges
- Reaching economies of scale in deployment (while pacing with emerging grid needs)
- Failure to recognize the value of LDES in utility and RTO planning processes and government incentive structures

Brattle Review of Developing Literature on LDES

We reviewed 50+ studies from LDES developers, states, ISO/RTOs, and academic research on LDES value and barriers for power system applications

Key takeaways summarized in the following slides

Selection of key LDES studies we reviewed:

- US Department of Energy, Pathways to Commercial Lift-off: LDES, 2023
- LDES Council, Driving to Net Zero Industry Through LDES, 2023
- The Brattle Group, New England Energy Storage Duration Study, 2023
- EPRI, Net Zero 2050: US Economy-Wide Deep Decarbonization Scenario Analysis, 2023
- E3, Charging Forward: Energy Storage in a Net Zero Commonwealth, 2023
- E3/Form Energy, California CEC: Assessing the Value of Long Duration Energy Storage, 2023
- Form Energy, Clean, Reliable, Affordable: The Value of Multi-Day Storage in New England, 2023
- Form Energy, Modelling Multi-Day Energy Storage in New York, 2023
- NREL, Storage Futures Study: The Challenge of Defining Long-Duration Energy Storage, 2022
- LDES Council, The Journey to Net-Zero: An Action Plan to Unlock A Secure, Net-Zero Power System, 2022
- LDES Council, Net-zero power: Long Duration Energy Storage for a Renewable Grid, 2021

1. LDES Technology, Costs, and Operations

Takeaways on LDES Technology, Costs, and Operations

LDES Technology: "LDES" includes a wide range of technologies and storage durations

- **Inter-day (10-36 hr) LDES:** several in development at lower end of range (10-18 hr duration) that will need to outcompete shorter-duration and lower cost Li-ion storage to meet emerging inter-day grid needs
- **Multi-day (36-160 hr) LDES:** fewer in development capable of multi-day output; under deep decarbonization will compete with dispatchable resources (gas, CCS, H2, RNG) to provide reliable output during extended RE droughts

Operations: LDES operations highly dependent on duration, resource mix, and weather variability

- **Inter-day LDES** serves intra- and inter-day shifting needs throughout the year, but cycling less frequently than 4-hr
- **Multi-day LDES** fully cycles 2-3 times per year during extended tight market conditions; limited short-term cycling
- Longer duration storage needs increase with RE penetration and frequency of extended winter reliability events

LDES Costs: Wide variation in LDES costs and uncertain future cost evolutions

- Power (MW) vs energy (MWh) capital costs indicate potential role in the power system
- Round-trip efficiency (i.e. charging cost) tends to be significantly lower for long-duration technologies

Successful LDES technologies will need to combine cost reductions, grid benefits, siting viability or other advantages, and manufacturing feasibility to scale up

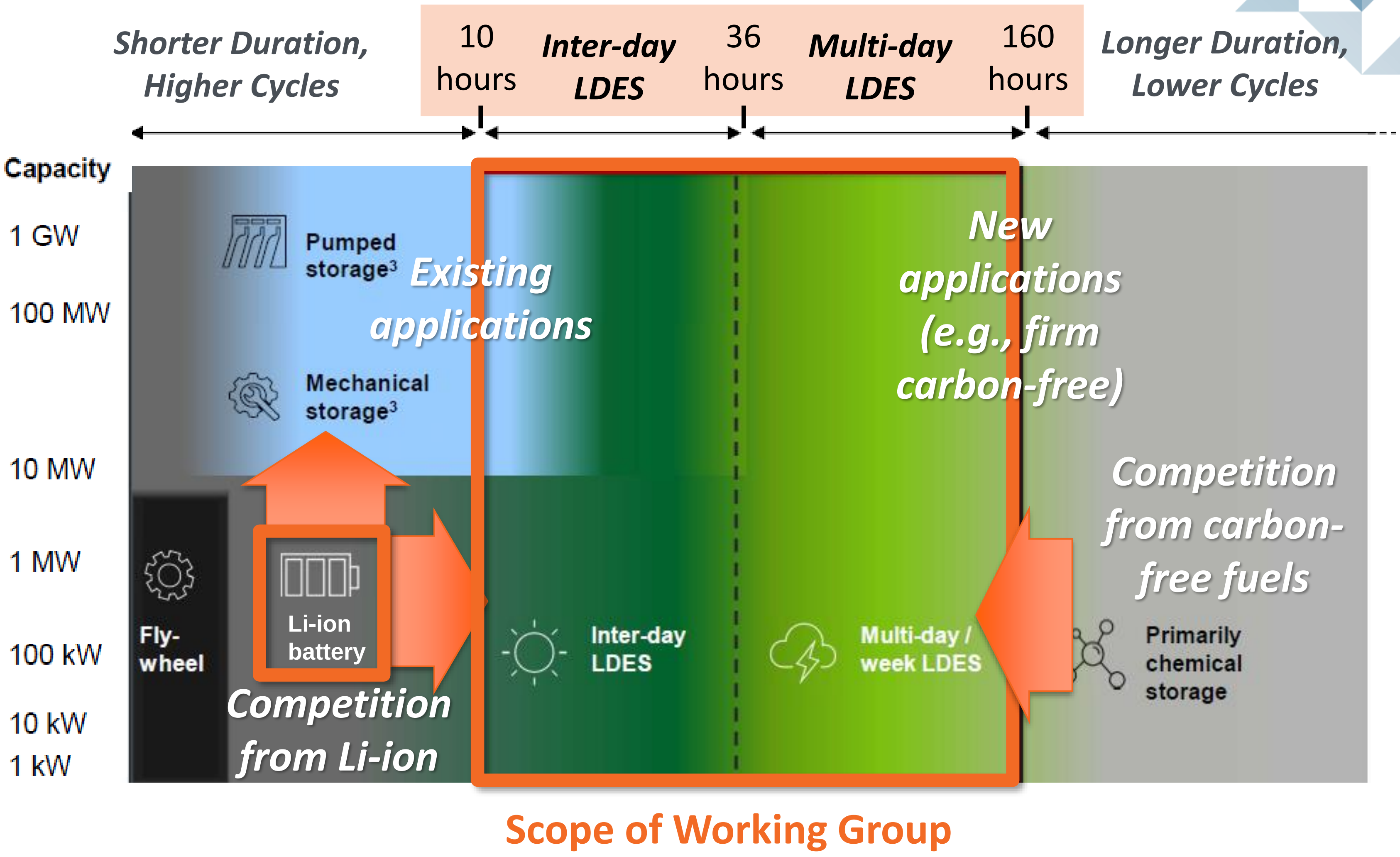
LDES includes a range of durations to meet future system needs

LDES encompasses a wide range of durations that can be split into two buckets:

- **Inter-day LDES: 10-36 hrs**
- **Multi-day LDES: 36-160 hrs**

LDES faces competition from other clean energy technologies to meet future system needs at least cost

- **Inter-day LDES will compete with shorter duration Li-ion**
- **Multi-day LDES will compete with dispatchable clean resources**



Source: Adapted from U.S. Department of Energy, Pathways to Commercial Liftoff: Long Duration Energy Storage, 2023.

LDES Technologies Overview

Development underway of multiple LDES technologies, primarily for **Inter-day LDES (10-36 hrs)** with few developers at commercial operations for **Multi-day LDES (36+ hrs)**

Duration	Energy storage form	Technology	Nominal duration, hrs
Multi-day / week	~~Thermal~~	Sensible heat (e.g., molten salts, rock material, concrete)[2]	10-200[2]
		Latent heat (e.g., aluminum alloy)	25–100
		Thermochemical heat (e.g., zeolites, silica gel)	XX
	Electrochemical	Aqueous electrolyte flow batteries	25–100
		Metal anode batteries	50–200
		Hybrid flow battery, with liquid electrolyte and metal anode (some are Inter-day)	8–50[2]
Inter-day	Mechanical	Traditional pumped hydro (PSH) △	0–15
		Novel pumped hydro (PSH)	0–15
		Gravity-based △	0–15
		Compressed air (CAES) △	6–24
		Liquid air (LAES)	10–25
		Liquid CO2	4–24

Scope of LDES Working Group

△ Faces geologic constraints | Inter-day | Can function as both | Multi-day/week

Representative LDES OEMs

Other Electrochemical:

- Energy Vault: hybrid H_2 fuel cell + Li-ion BESS **(12-96 hrs)**
- NAS Batteries: sodium sulphur **(6+ hrs)**

- Invinity Energy Systems: redox flow battery **(2-12 hrs)**

- Ambri: liquid metal battery **(4-24 hrs)**
- EnerVenue: metal-hydrogen battery **(2-12 hrs)**
- Form Energy: iron-air battery, **(100+ hrs)**

- ESS Inc.: iron flow battery **(6-12 hrs)**
- EOS Energy: zinc-hybrid battery **(3-12 hrs)**
- NextEra Energy Resources: aqueous zinc battery **(10 hrs)**
- Redflow: zinc bromide flow battery, **(1-12 hrs)**

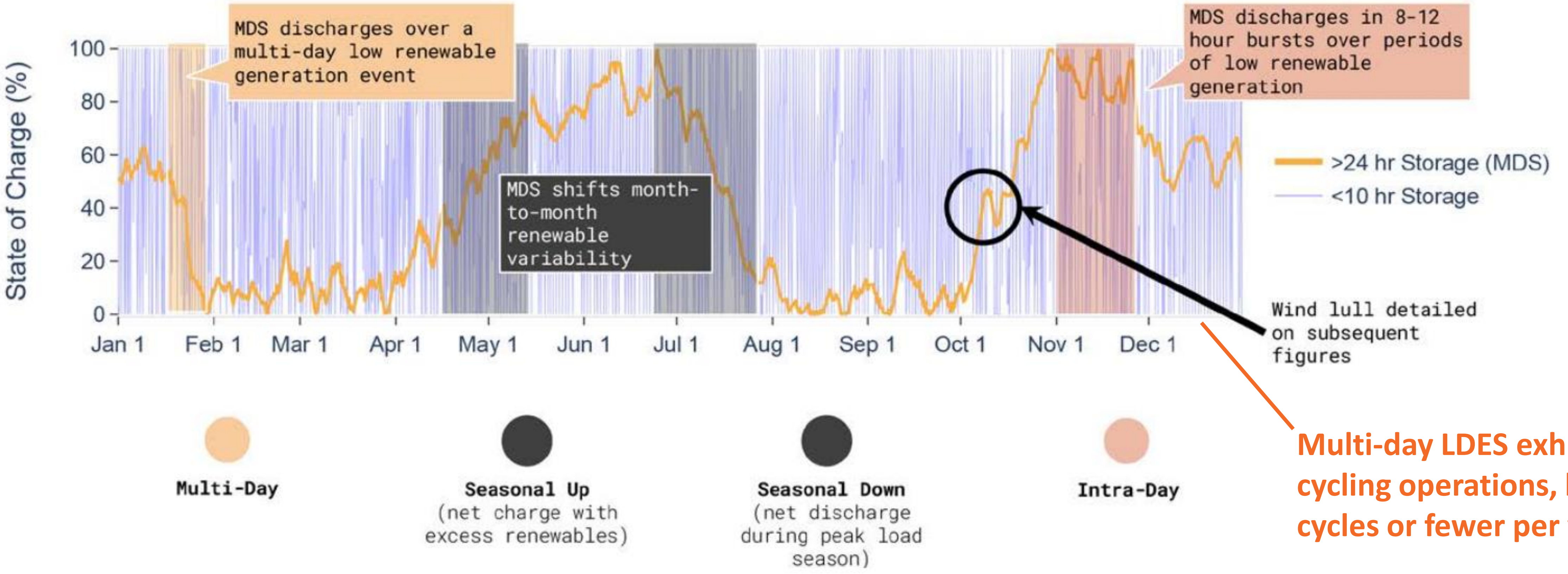
- Quidnet Energy geomechanical pumped hydro storage **(10+ hrs)**
- Energy Vault: gravity storage **(2-18 hrs)**
- Hydrostor: advanced compressed air energy storage **(8+ hrs)**
- Highview Power: liquid air **(6+ hrs)**
- Energy Dome: liquid CO_2 storage **(8-24 hrs)**

Source: Adapted from U.S. Department of Energy, Pathways to Commercial Liftoff: Long Duration Energy Storage, 2023.

Simulated LDES Operations

Inter-day LDES serves intra- and inter-day needs throughout the year and cycles nearly every day

Multi-day LDES cycles on a seasonal basis while providing limited shorter-term cycling capabilities



Multi-day LDES exhibits low cycling operations, likely 2 cycles or fewer per year

Source: Form Energy, Modeling Multi-Day Energy Storage in New York: Storage Portfolios that Can Enable a Reliable, Zero Carbon Grid, 2023.

Need for Multi-day LDES will depend on resource mix

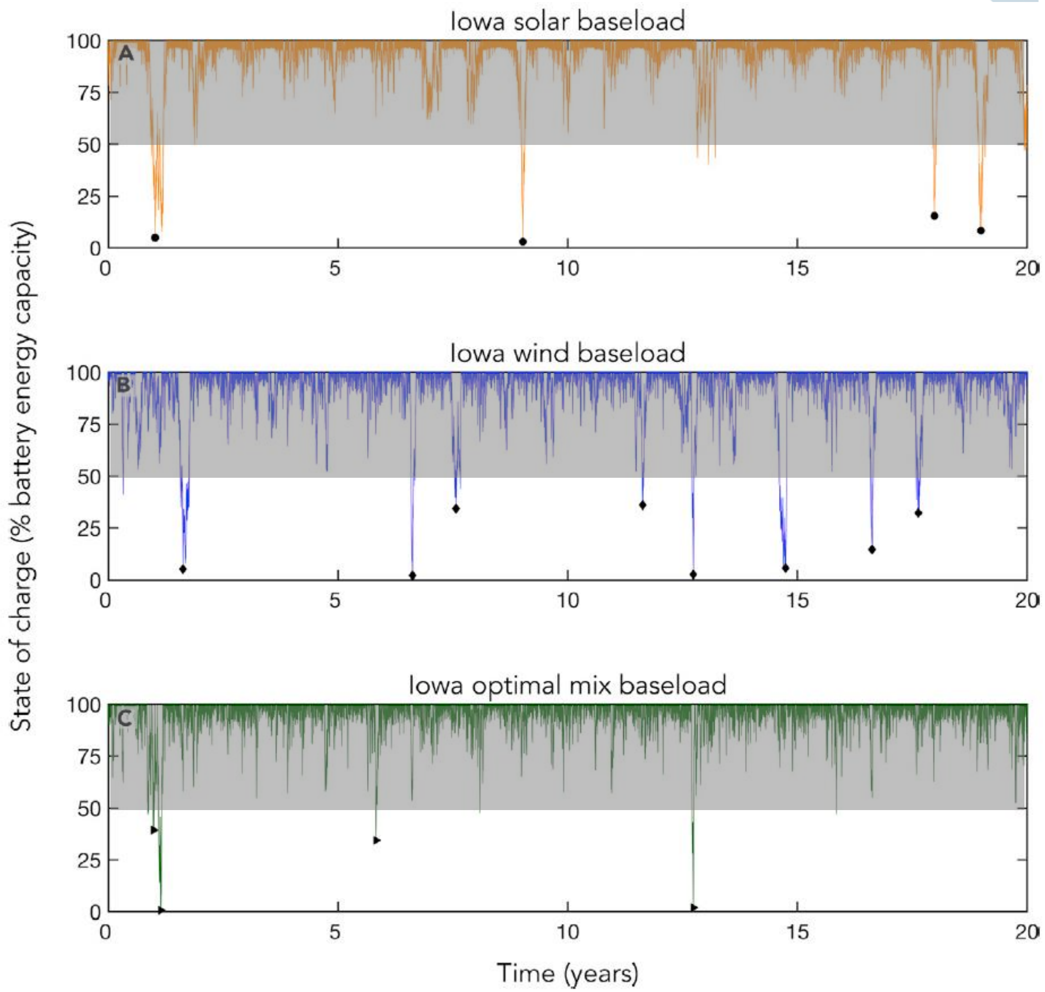
Multi-day LDES operations differ depending on the weather-dependent supply variability of the resource mix and climate conditions

- Multi-day LDES deep cycles most frequently in high wind system
- RE diversification reduces need for frequent deep LDES discharges

Longer timeframes reveal impact of weather patterns on how multi-day LDES operates

Cycling pattern demonstrates that most storage needs are for short-duration with occasional deep discharge periods, indicating the key role for Multi-day LDES

20 Year Multi-Day LDES Simulated Operations



Source: MIT, Storage Requirements and Costs of Shaping Renewable Energy Toward Grid Decarbonization, 2019.

LDES Costs Overview

Ratio of power (MW) to energy (MWh) capital costs indicate potential role in the power system:

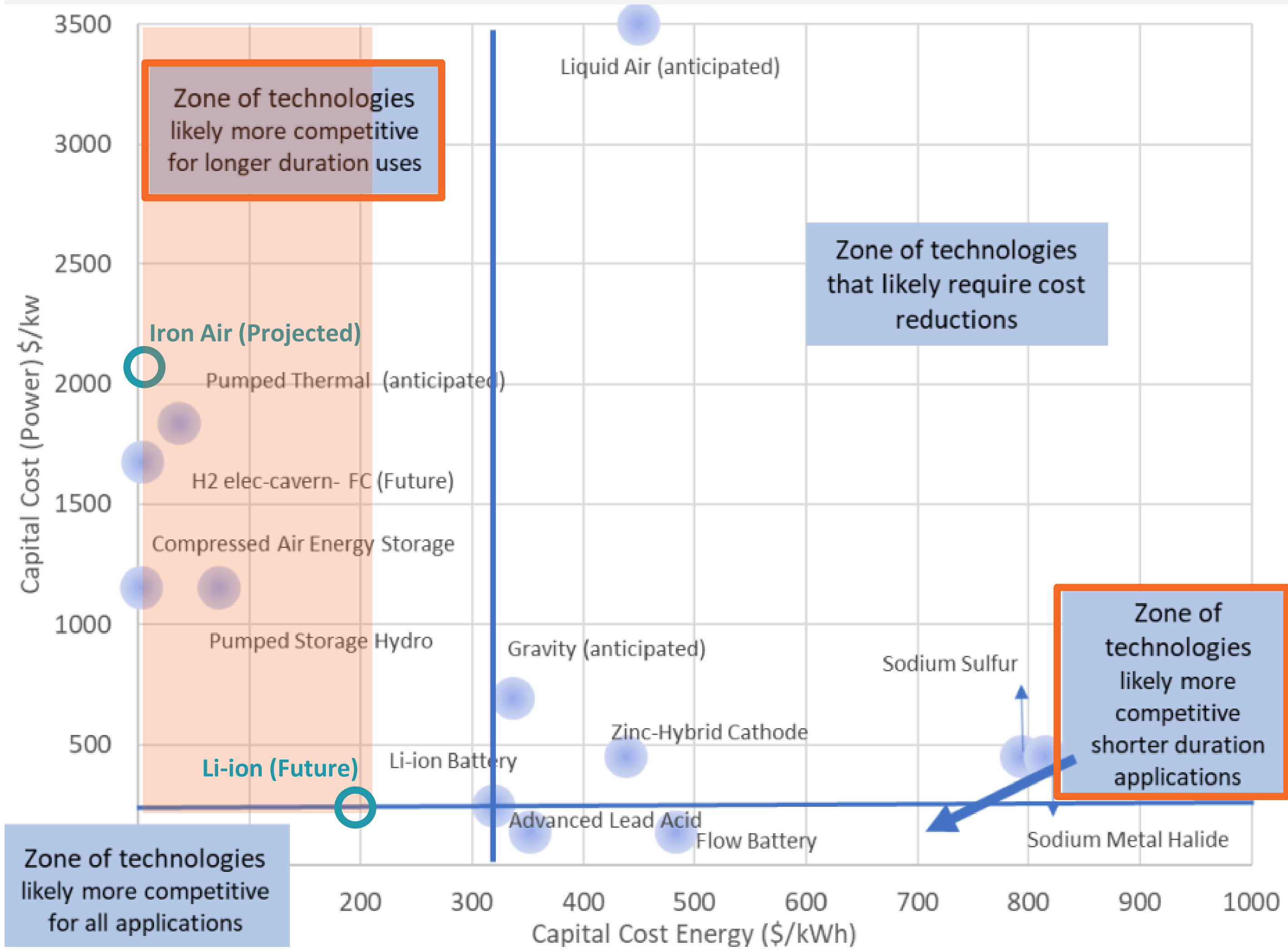
- Low energy, high power -> long duration needs
- High energy, low power -> short duration needs

Li-ion costs likely the basis against which **Inter-day LDES** technologies will compete:

- Li-ion is mature with established industries (electric vehicles and consumer electronics) driving development and cost reductions
- Widely deployable vs. pumped hydro which has geological and permitting constraints

Projected costs for LDES technologies demonstrate opportunity to provide lower cost long-duration storage

Power vs Energy Capital Costs for Storage Technologies (2021 data)

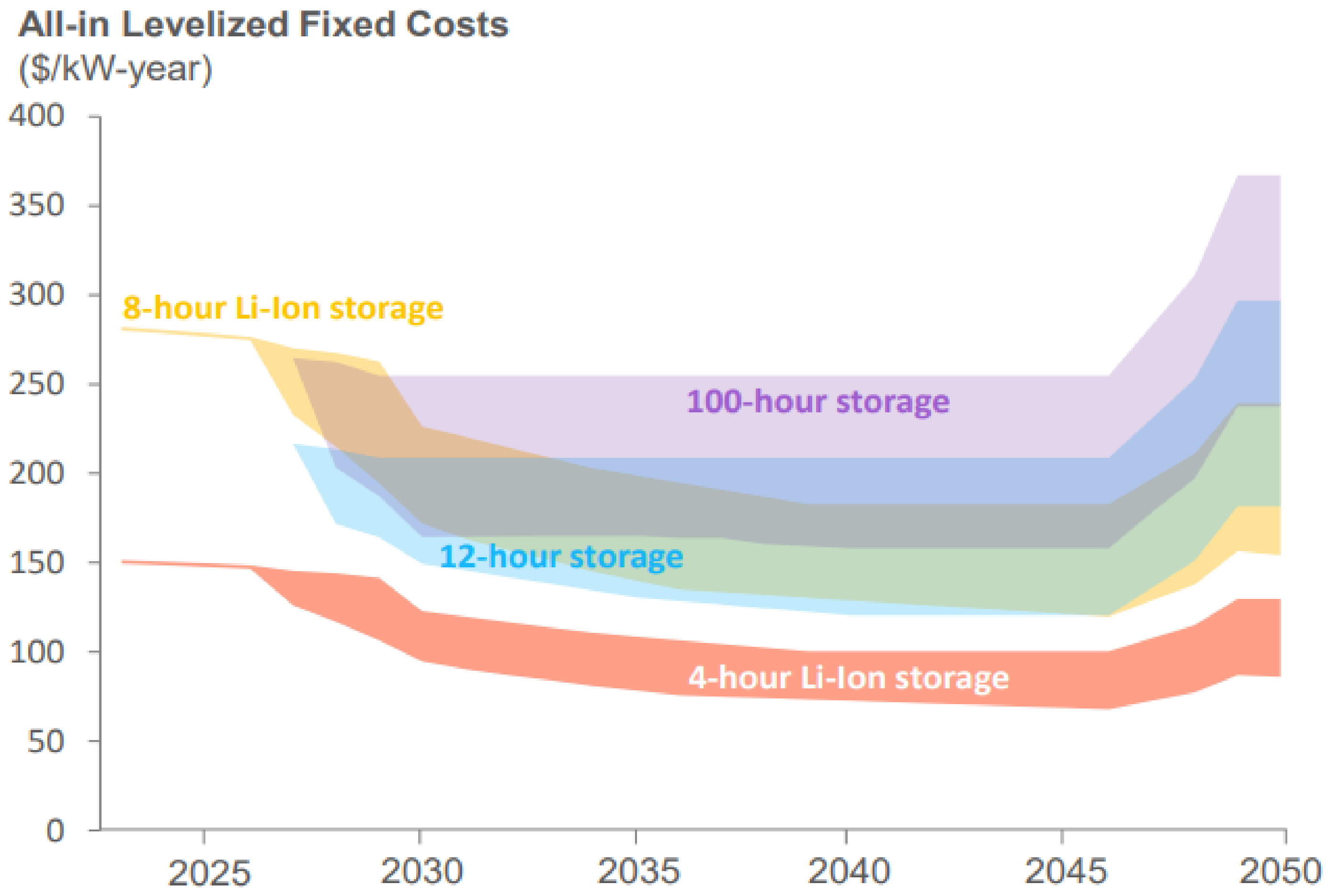


Source: NREL, Storage Futures Study: Key Learnings for the Coming Decades, 2022.
Note: Cost data for Iron Air from Form Energy, Modelling Multi-Day Energy Storage in New York, 2023; Future Li-ion data from NREL, Annual Technology Baseline 2023, Moderate Scenario.

LDES cost evolution widely uncertain and currently greatly dependent on tax incentives

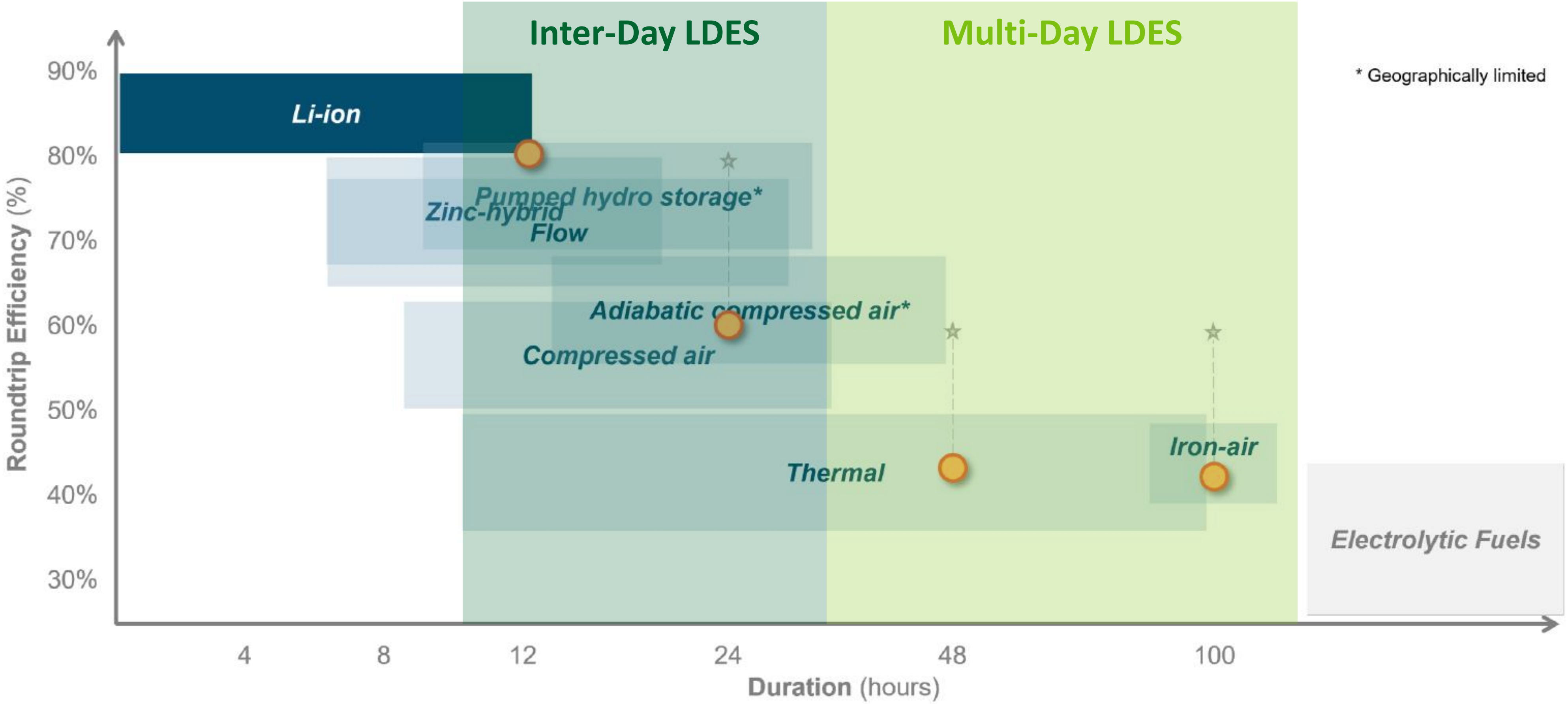
Future LDES costs are subject to substantial uncertainty and could even be flat in real terms if manufacturing is unable to scale up

Currently planned expiration of IRA tax incentives beyond 2045 have large impact on future costs



Source: E3, Charging Forward: Energy Storage in a Net Zero Commonwealth: Prepared for MassCEC and DOER, 2023.

Longer duration LDES technologies have lower efficiency



Source: Adapted from E3/Form Energy, California CEC: Assessing the Value of Long Duration Energy Storage, 2023.

Additional considerations that affect LDES competitiveness

- Varying degrees of technology readiness and scale: research → pilots → scale-up → mature
- Some storage technologies face fundamental material constraints which could affect mass scalability and limit cost reductions such as vanadium redox flow and cobalt-rich Li-ion chemistries
- Others face geological constraints which limit deployment and could mean some areas of the country are not suitable such as CAES, pumped hydro, and gravity
- Many LDES technologies can offer safer alternatives to Li-ion for operating in dense urban areas, factories with volatile chemicals, and other locations which require high levels of safety

2. Value of LDES in the Power Sector

Takeaways on Value of LDES in the Power Sector

- Largest value drivers of LDES in the power sector are in resource adequacy (capacity value), energy shifting, and increasing grid utilization or deferring transmission/distribution buildout in some areas (“wires optimization”)
  - **Inter-Day LDES** can address nearer- and mid-term applications
  - **Multi-Day LDES** can be especially effective at addressing the longer-term challenges of decarbonization, potentially offering significant system-cost savings
- Resource adequacy value includes “lowest hanging fruit” in addressing winter reliability risks, a higher-value near-term need that LDES can fulfill
  - However, current reliability modeling needs reforms to better assess LDES winter reliability value, moving from “capacity adequacy” to “energy adequacy” modeling focus

Estimate of LDES Value Drivers for the Power Sector

Capacity provision includes "lowest hanging fruit" for LDES now: long-duration winter & local reliability needs

Legend: xx T&D optimization value; xx Value/spend measures

2040

Value created by LDES	Cumulative LDES: Installed power capacity (GW)	Cumulative LDES: Installed energy capacity (TWh)	Cumulative value creation (USD bn)	Annual LDES capex spend (USD bn)
Energy shifting, capacity provision, and T&D optimization	~1,300–2,300	~80–135	~470[1]; ~300–650[2]	~175–215
Optimization of energy for industry with remote or unreliable grids	~110	4	~120	~4–5
Isolated island grids	~90–100	3	~30–35	~10
Firming for PPAs	~40	2	~5–10	<1
Stability services provision (inertia)	0	0	~5–10[3]	na[4]
Total	~1,500–2,500	~85–140	~950–1,300	~190–230

Greater $/MW value create potential near-term use cases, despite lower overall need

Source: LDES Council, Net-zero power: Long Duration Energy Storage for a Renewable Grid, 2021.

Taxonomy of LDES Value Drivers for the Power Sector

Resource Adequacy

- **Winter reliability risks:** LDES can discharge during reliability events that are long duration or when limited recharging opportunities exist for short term storage
- **Local reliability needs:** LDES can address local reliability needs and relieve congestion on the grid

Energy Shifting: LDES can charge during periods of high renewable output to later discharge when renewable output is low and prices are high

Ancillary Services/Resilience/Stability

- **Black start capability:** many LDES technologies can provide critical capability to recover from a total or partial regional grid shutdown
- **Operating reserves**: since LDES have fast ramping capabilities paired, they can provide operating reserves
- **Active and reactive power services**: like all storage technologies, LDES can provide ancillary services necessary for maintaining grid stability and balancing (frequency response, inertial service, uncertainty/ramp reserve)

Renewables Integration

- **Reduced curtailments**: excess renewable generation can be better utilized to lower emissions
- **Profile shaping**: LDES can enable 24/7 clean energy consumption profiles (e.g. 24/7 clean PPAs)
- **Reduced land use**: LDES enables less build out of solar/wind to achieve same clean energy target at same reliability

Resource adequacy value of storage is dependent on resource mix and demand patterns

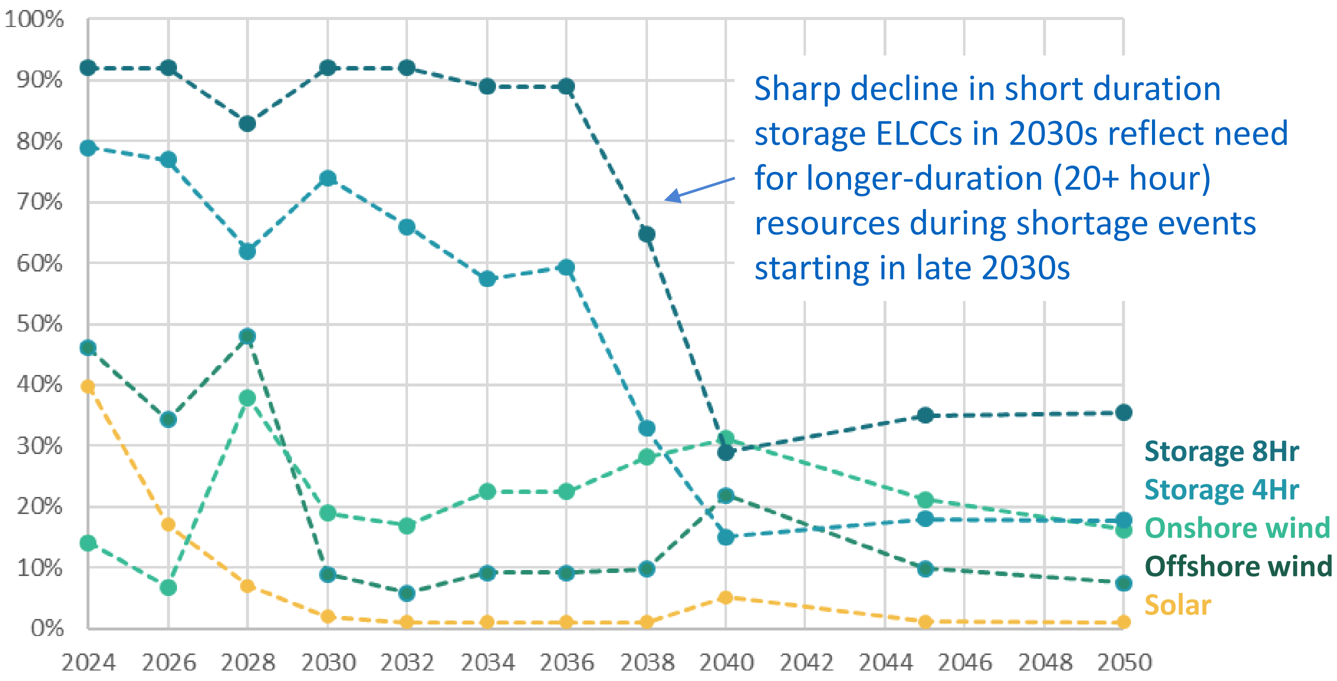
Resource adequacy value of a resource is often calculated through Effective Load Carrying Capability "ELCC" analysis

- Depends on supply mix, temporal patterns in demand and weather, and storage dispatch
- Results are highly sensitive to modeling approach

Reliability modeling should accurately capture synergies between resources and the impact of changing electricity load patterns over time

For example, in ISO New England **longer duration (20+ hour) resource need could emerge in the late 2030s** to ensure reliability in a decarbonizing system

Marginal ELCC Capacity Value of Renewables and Storage *(UCAP %)*



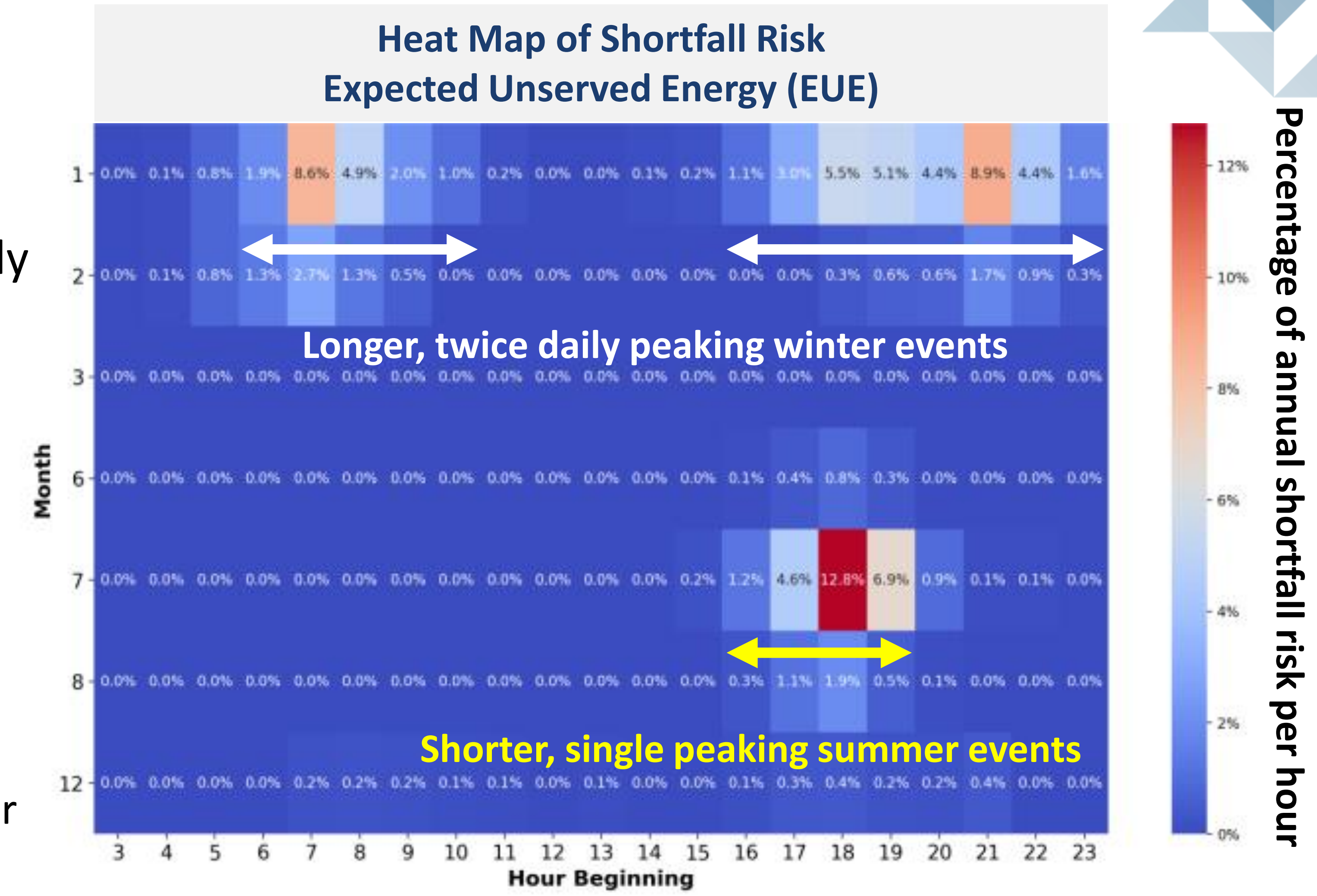
Source: Hagerty, et. al, New England Energy Storage Duration Study, prepared for Cypress Creek Renewables, December 18, 2023.

Winter events create longer duration needs today

Many regions (including warm ones like Mississippi and Florida) exhibit significant winter reliability risk

Winter reliability events are inherently longer duration than summer, and dramatically so in some cases

- 2 daily peaks, one before sunrise and another after sunset
- Mid-day and inter-day recharge opportunities can be limited, so short duration storage may not be able to serve need
- Widespread weather-caused generator outages tend to occur for many hours or days



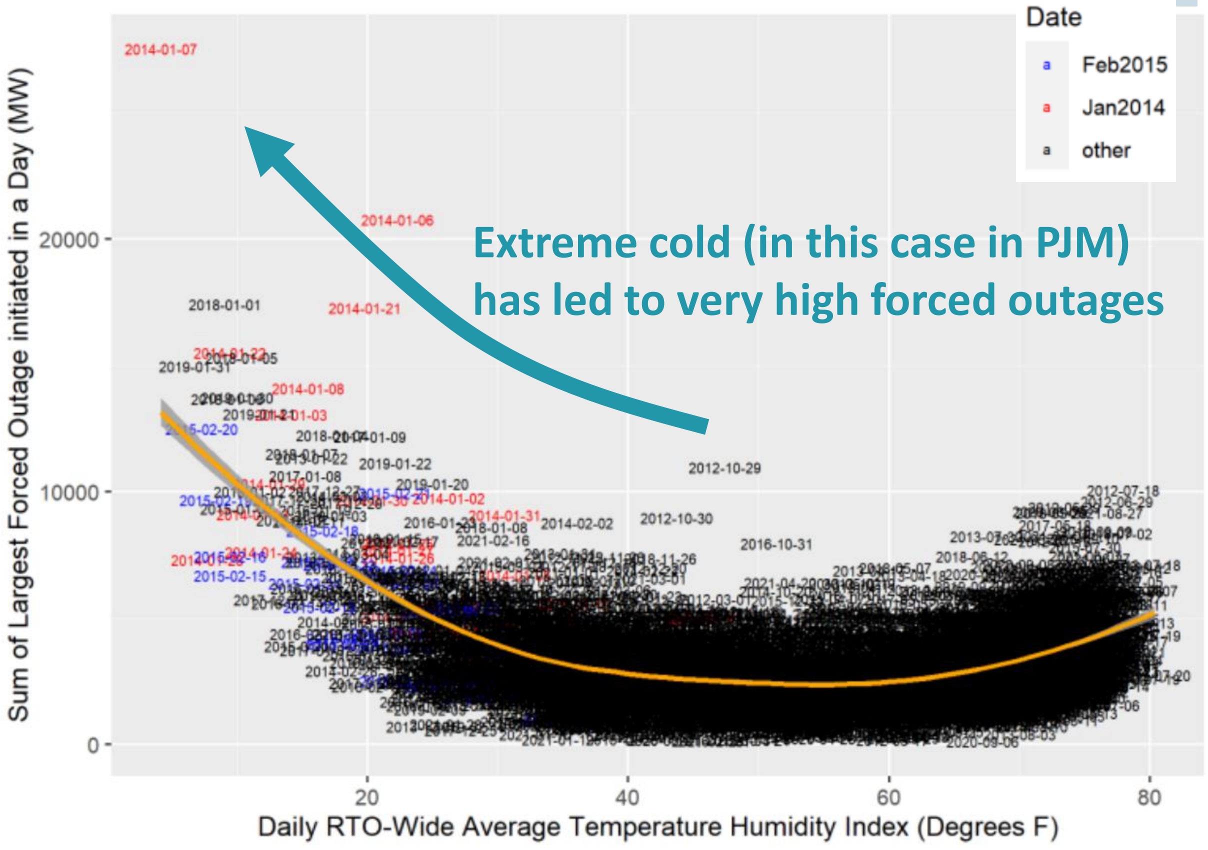
Source: PJM, Capacity Market Reform: PJM Proposal, 2023.

Capacity value models fail to capture winter reliability value of LDES

Shortcomings in current capacity value models (often based on ELCC) do not capture the degree of winter reliability risk, not the ability of LDES to address it:

- Do not capture potential or impact of many conventional generators failing simultaneously due to extreme weather
- Models use short weather histories that omit extreme weather events (esp. cold)
- Use of binary shortfall event flag ("LOLE") vs. shortfall extent metric ("EUE")
- Simple storage dispatch that does not capture LDES capabilities

Forced Outages are Higher at Lower Temperatures



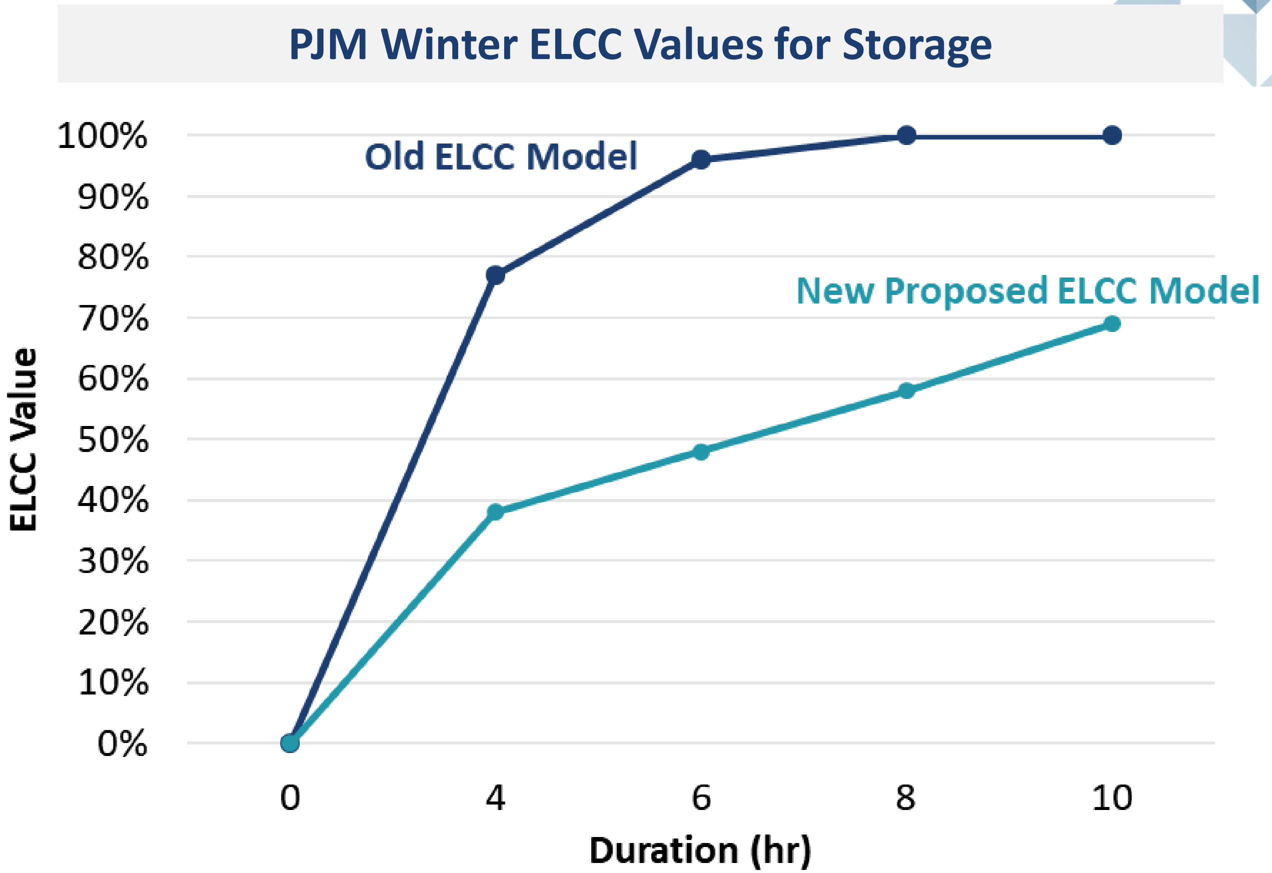
Source: PJM, Update on Conceptual Design for Capacity Market Reforms, 2023.

“Energy adequacy” models can reveal LDES value

Energy-adequacy models for ELCC:

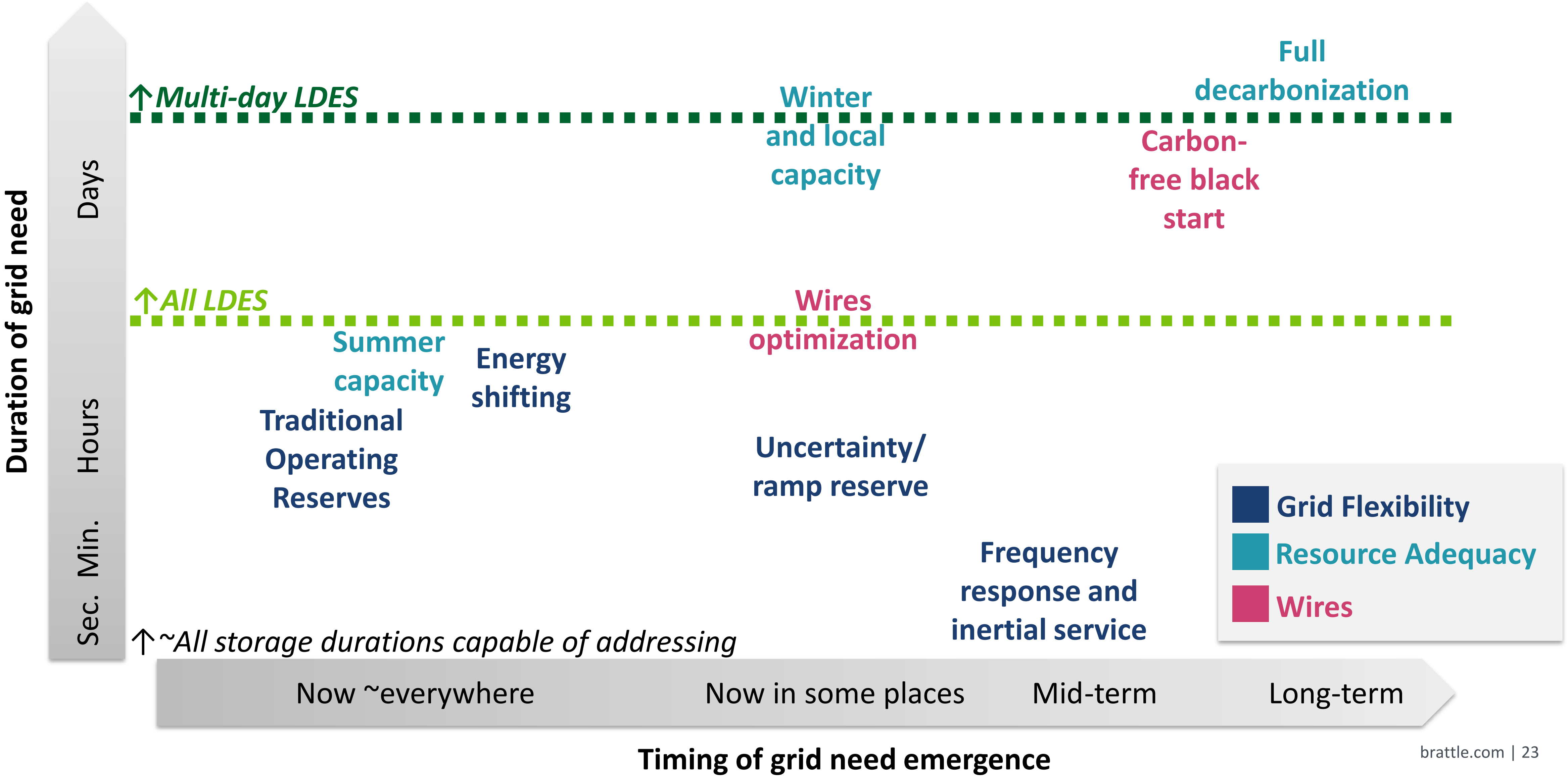
- Instead of fewer peak hours in summer, focus on annual (8760 hr) assessment of capability
- Account for supply limitations in detail to capture shortage from both high demand and low supply availability
- Capacity values are based on the expected ability to meet demand during the most challenging system conditions

Energy adequacy approach with seasonal differentiation of ELCCs better captures winter risks and would reveal greater LDES winter capacity value compared to short duration storage (e.g., 2.5x higher in PJM)

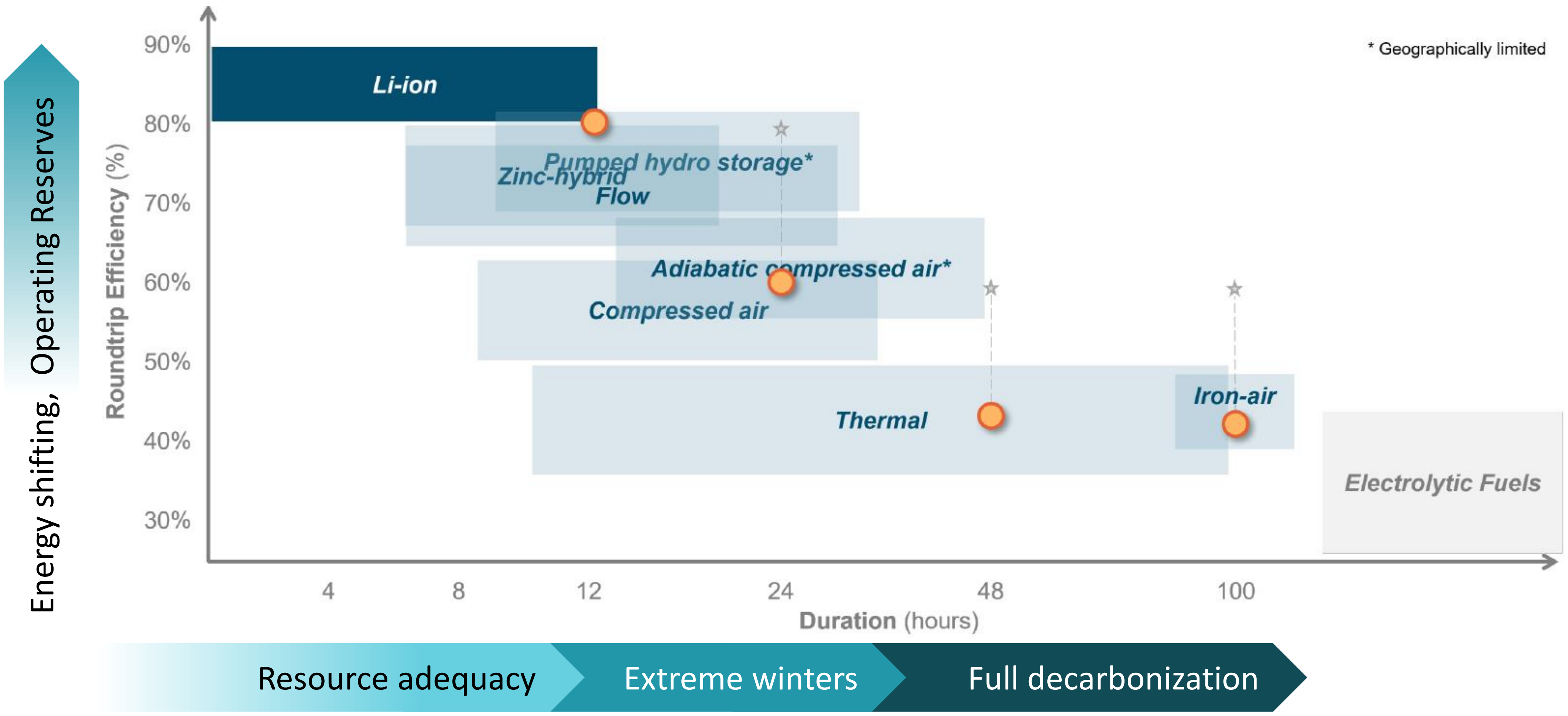


Notes and Sources: PJM only models 4 to 10 hour storage, lines below 4-hrs are for graphical purposes and not indicative of ELCC value. See PJM, Updated ELCC Class Ratings for the 2025/26 BRA, 2023 and PJM, Capacity Market Reform: PJM Proposal, 2023.

Value of LDES is emerging over the mid- and long-term



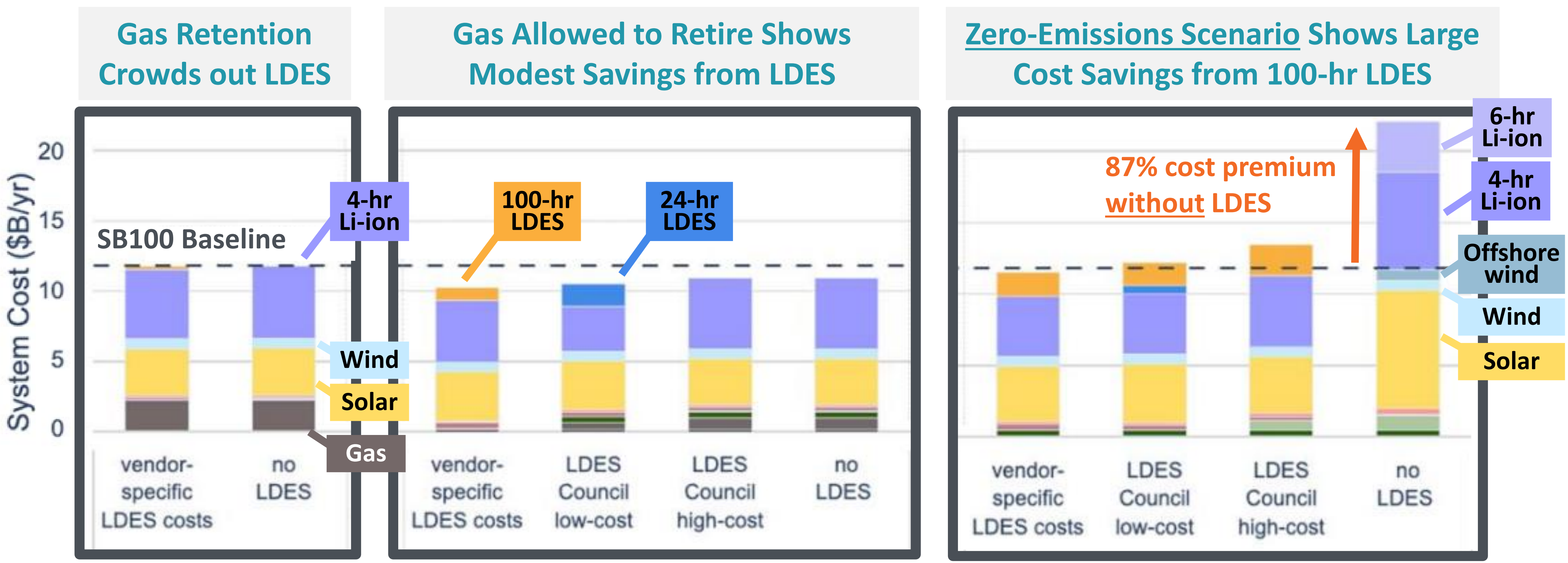
Round trip efficiency can be less in longer duration storage technologies since they fulfill different grid needs



Source: Adapted from E3/Form Energy, California CEC: Assessing the Value of Long Duration Energy Storage, 2023.

Value of LDES in California: Senate Bill (SB) 100

Models of reliable zero emissions systems with LDES show cost savings vs. comparable "No LDES" systems; however, retention of gas capacity limits potential LDES cost savings



Source: Adapted from E3/Form Energy, California CEC: Assessing the Value of Long Duration Energy Storage, 2023.

3. Identified Barriers to LDES Deployment

Identified barriers to LDES deployment

Technical

- Need for improvements in performance and efficiency
- Supply chains and large-scale manufacturing need to be established
- Materials, geographic constraints of some LDES technologies
- Limited information available on technology feasibility and performance capabilities

Economic

- High cost of LDES and limited information on projected costs at full-scale deployment
- Skilled "green collar" workforce needs to be developed and potentially faces scarcity due to competition from other green industries

Market/ Remuneration

- Resource adequacy mechanisms do not fully capture value of LDES, need reform (better modeling)
- Some centralized planning (utility IRPs) do not look out far enough to adequately assess LDES portfolio value relative to other pathways

Policy

- Storage procurement mandates and subsidies (where they exist) currently make no distinction between short and long duration storage
- Utilities need to gain experience with LDES assets through pilot projects or credible third-party evaluations

Appendix

LDES ECOSYSTEM

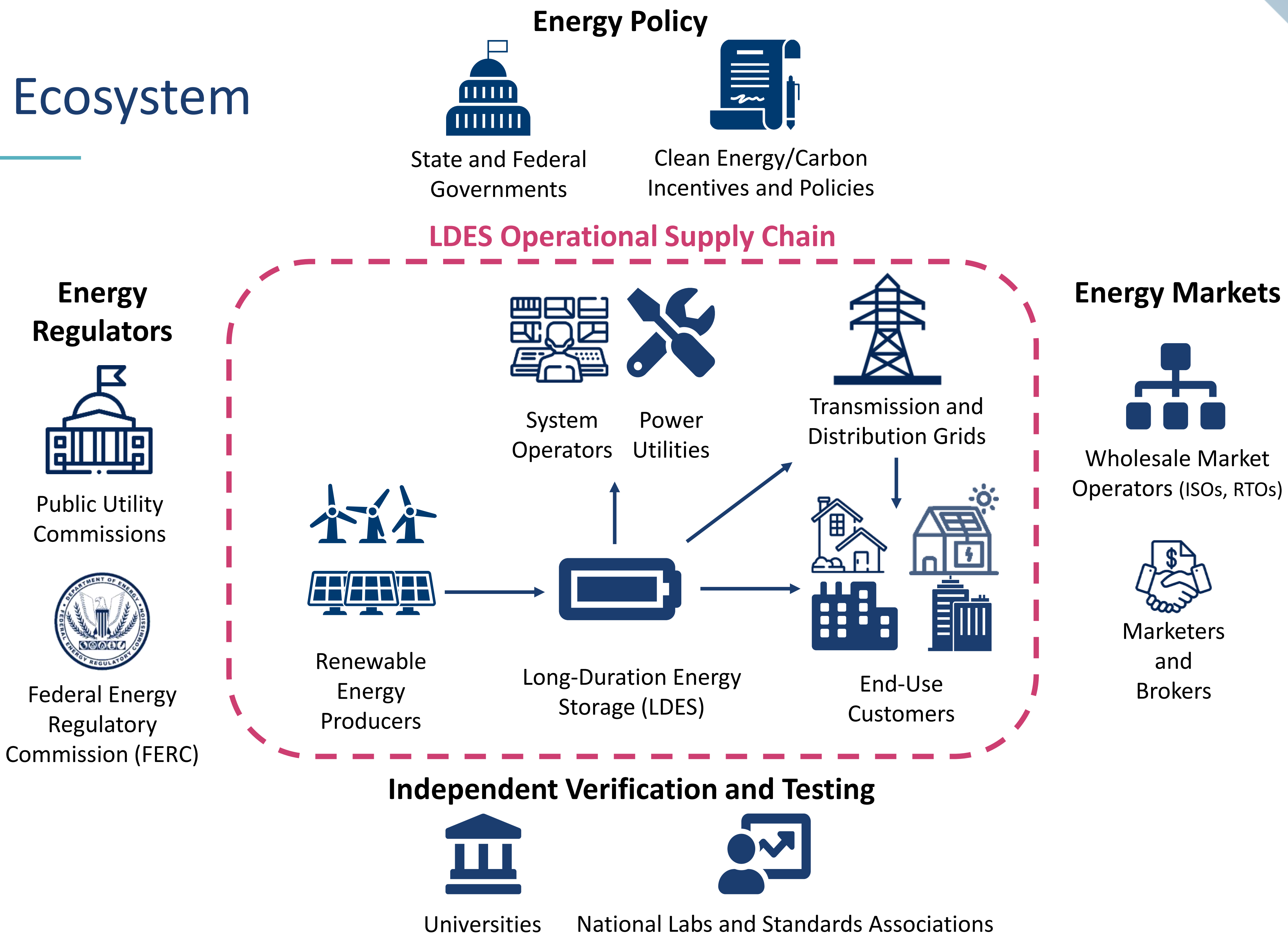
LDES COSTS

WINTER RELIABILITY RISKS

LDES PILOT PROJECTS AND OEMS

BIBLIOGRAPHY

LDES Ecosystem



LDES Costs

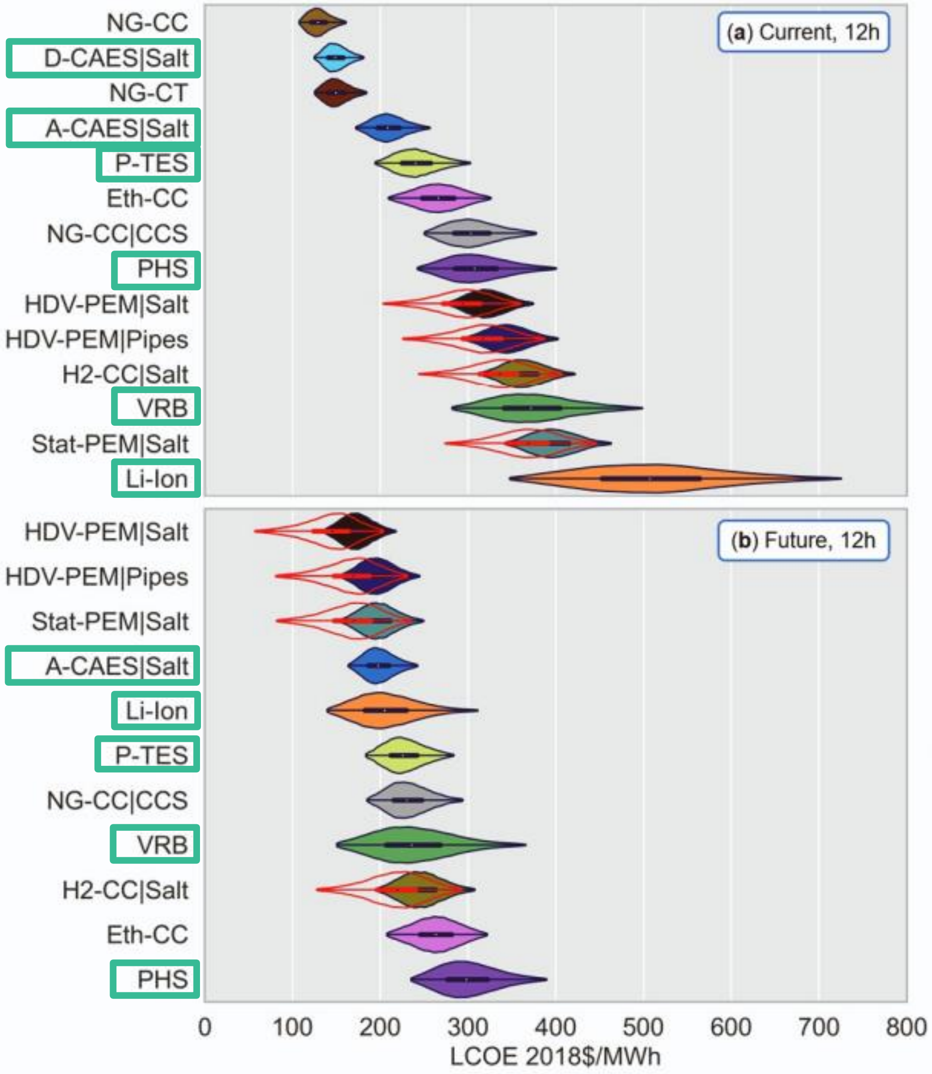
Potential Inter-day LDES Costs vs Competing Technologies

For inter-day LDES (12 hour baseline), current compressed air energy storage (CAES) costs are among the most competitive on an *unsubsidized* basis (LDES resources highlighted in green boxes).

In the future, Li-ion batteries could become cost competitive at higher durations potentially competing with CAES and other inter-day LDES

(not all LDES technologies were envisioned in this study)

Unsubsidized Levelized Cost Distributions for Inter-day Dispatchable Technologies



Source: Hunter et.al, Techno-economic analysis of long-duration energy storage and flexible power generation technologies to support high-variable renewable energy grids, 2021.

Acronyms: Natural Gas Combustion Turbine (NG-CC); Carbon Capture and Storage (CCS); Diabatic/Adiabatic Compressed Air Energy Storage (D-CAES or A-CAES); Heavy-duty Vehicle H2 Fuel Cell with PEM electrolysis (HDV-PEM); Hydrogen-fired Combined Cycle turbine (H2-CC); Stationary H2 Fuel Cell with PEM electrolysis (Stat-PEM); Pumped Hydro Storage (PHS); Natural Gas Combustion Turbine (NG-CT); Pumped Thermal Energy Storage (P-TES); Ethanol-fired Combined Cycle (Eth-CC); Vanadium Redox-flow Battery (VRB); Lithium Ion Battery (Li-ion); H2 storage in geological salt caverns (Salt); H2 storage in underground pipes (Pipes).

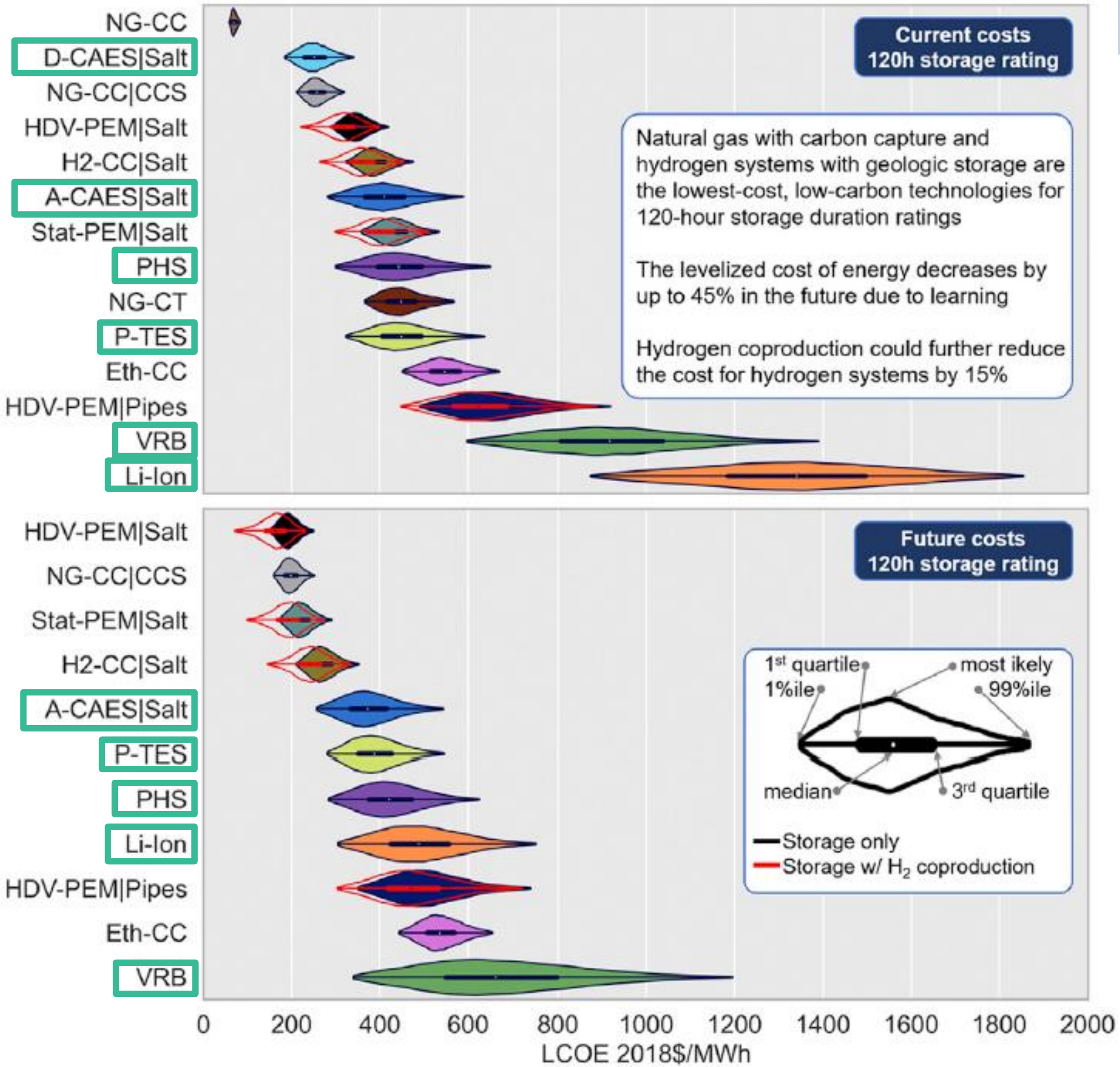
Potential Multi-day LDES Costs vs Competing Technologies

For multi-day LDES (120 hour baseline), current compressed air energy storage (CAES) and pumped hydro storage (PHS) costs are among the most competitive on an *unsubsidized* basis (LDES resources highlighted in green boxes).

In the future, potential of hydrogen or natural gas (NGCCS) to become cost competitive option for low-carbon dispatchable needs

(not all LDES technologies were envisioned in this study)

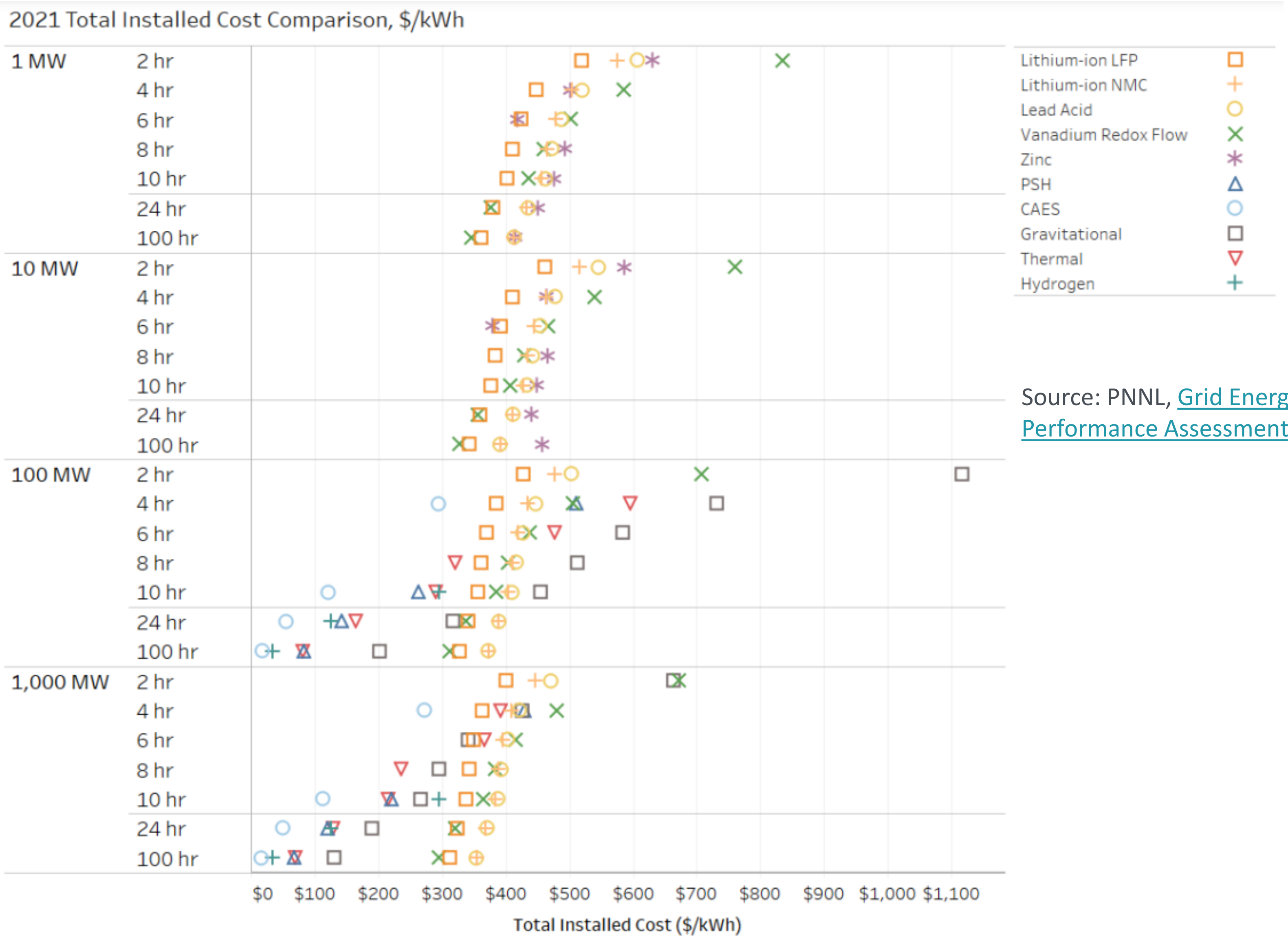
Unsubsidized Levelized Cost Distributions for Multi-day Dispatchable Technologies



Source: Hunter et.al, Techno-economic analysis of long-duration energy storage and flexible power generation technologies to support high-variable renewable energy grids, 2021.

Acronyms: Natural Gas Combustion Turbine (NG-CC); Carbon Capture and Storage (CCS); Diabatic/Adiabatic Compressed Air Energy Storage (D-CAES or A-CAES); Heavy-duty Vehicle H2 Fuel Cell with PEM electrolysis (HDV-PEM); Hydrogen-fired Combined Cycle turbine (H2-CC); Stationary H2 Fuel Cell with PEM electrolysis (Stat-PEM); Pumped Hydro Storage (PHS); Natural Gas Combustion Turbine (NG-CT); Pumped Thermal Energy Storage (P-TES); Ethanol-fired Combined Cycle (Eth-CC); Vanadium Redox-flow Battery (VRB); Lithium Ion Battery (Li-ion); H2 storage in geological salt caverns (Salt); H2 storage in underground pipes (Pipes).

Potential LDES Costs vs Competing Technologies (total capital cost)



Source: PNNL, Grid Energy Storage Technology Cost and Performance Assessment, 2022.

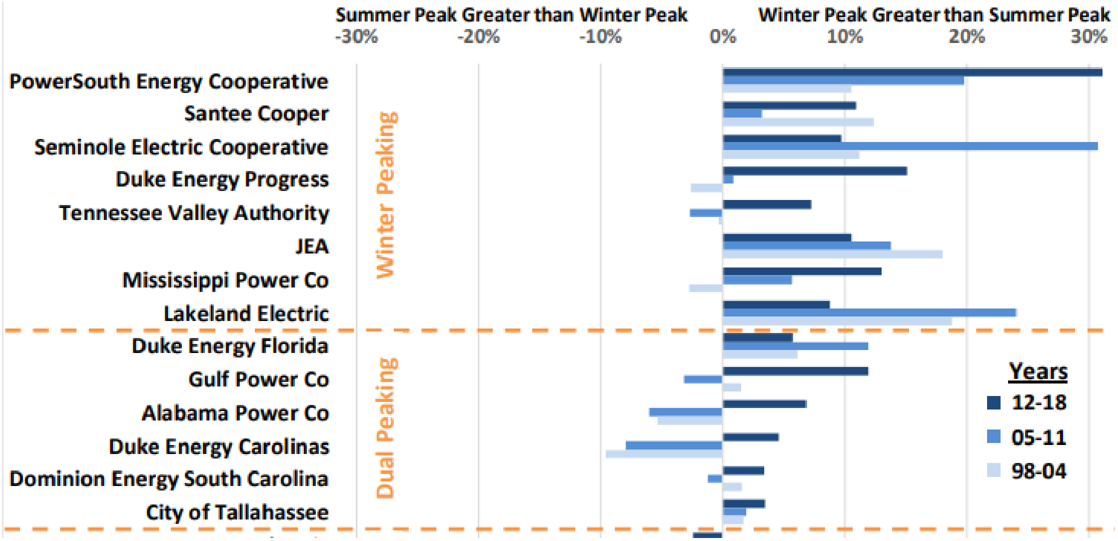
Winter Reliability Risks

Winter Reliability Events Are Widespread Today

Many regions (even warm ones like Mississippi and Florida) exhibit significant winter reliability risk

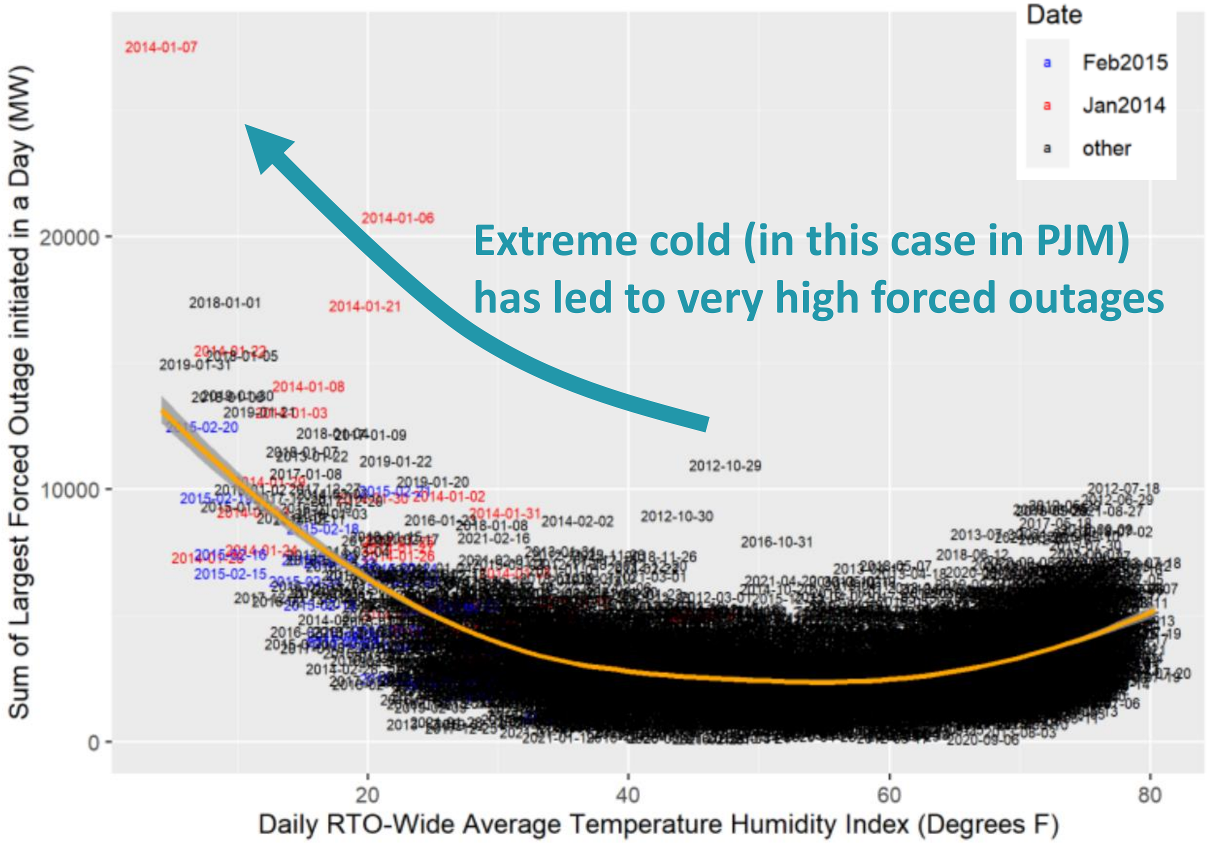
- Widespread electric heat in many warm regions; extreme cold weather every one or two decades can drive demand above summer peaks
- Extreme cold has led to widespread generator failures, except with the most robust winterization
- Limited fuel availability in some regions under extreme cold

Most southeastern utilities are winter or dual peaking



Source: Southern Alliance for Clean Energy, Seasonal Electric Demand in the Southeastern United States, 2017.

Forced outages are higher at lower temperatures



Source: PJM, Update on Conceptual Design for Capacity Market Reforms, 2023.

LDES "Low Hanging Fruit": Winter Reliability Events

Based on our experience and literature review to date, a key value proposition for LDES would be the ability to meet resource adequacy needs (capacity), especially during winter reliability events.

In the next slides, we provide a summary of winter reliability issues, how LDES is particularly valuable for these events, and the challenges of capturing the value of LDES to support winter reliability.

Reliability Modeling: Initial Barriers to Realizing Full Winter Resource Adequacy Value of LDES Today

Shortcoming	Potential Barrier	Potential Solutions in Reliability/ELCC Models
Weather history well under 20 years, fails to capture extreme cold scenarios	Winter does not appear risky → devalues winter capability	Use a 20+ year weather history
Coincident forced outages are not modeled in the capacity value assessment	Winter does not appear risky → devalues winter capability; duration of winter events is unrealistically short	Simulate the dependence of forced outages on temperature
Capacity value assessment (ELCC) model of storage can only optimize one day at a time	Fails to capture the capabilities of long-duration storage	Ensure the model is simulating storage output by optimizing reliability value over many days simultaneously
Use of binary shortfall event flag ("LOLE") vs. shortfall extent metric ("EUE")	Fails to quantify the greater magnitude of winter shortfalls → devalues winter capability	Use the "expected unserved energy" (EUE) metric instead of the "loss of load expectation" (LOLE) metric

Reliability models are highly sensitive; any one of these changes can make a crucial difference to the value of long-duration storage

Example: PJM's Proposed Capacity Market Reforms

	Initial Reliability Model	New Reliability Model (for June 1, 2025+)
History	Weather history back to June 1, 2012	Weather history back to 1993
Extreme weather outages	Coincident forced outages are not modeled in the capacity value assessment	The model assumes coincident forced outages go up as temperatures are more extreme
Simulated storage output	Capacity value assessment (ELCC) model of storage can only optimize one day at a time	No change
Reliability metric	Loss of Load Expectation (LOLE)	Expected Unserved Energy (EUE)
Result: winter risk share	Winter risk is **~5%** of total annual risk	Winter risk is **~68%** of total annual risk
Result: ELCCs	**4hr storage is 94%** annual ELCC	**4hr storage is 38% winter ELCC and 59% annual ELCC** (10 hour storage is 69% winter and 81% annual)

Further potential reforms: *Model the output of storage resources of greater than 10 hours duration, targeting reliability value across many days*

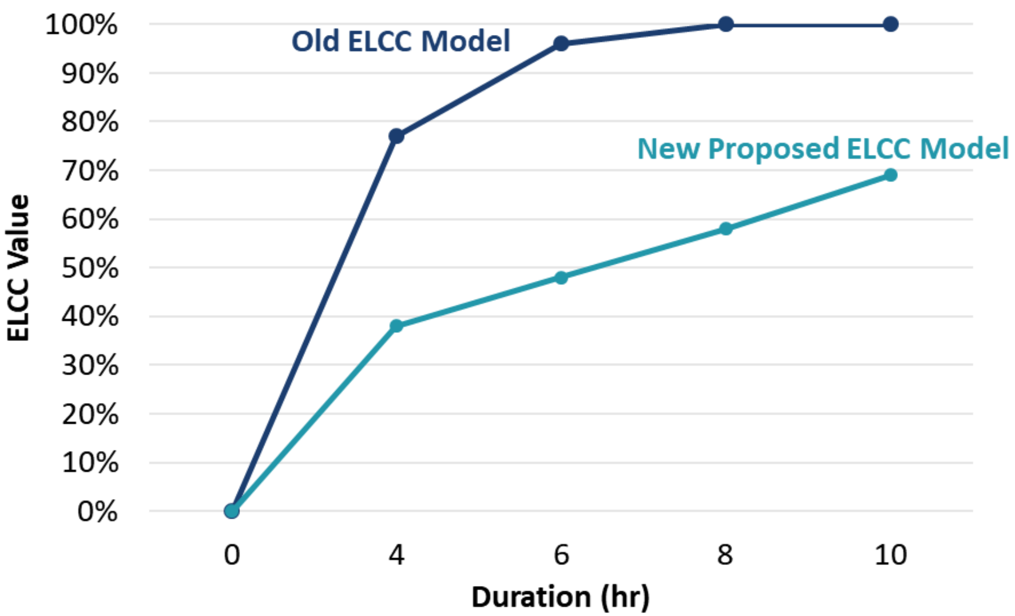
Reliability Models Reveal the Value of Storage and Drive Investment Decisions

Reliability models that properly capture winter risks could give long duration storage more winter capacity value vs. short duration (e.g., 2.5x higher in PJM).

Reliability models assess worst-case scenarios of supply vs. demand based on historical patterns in peak demand, generator failures, renewable output, etc.

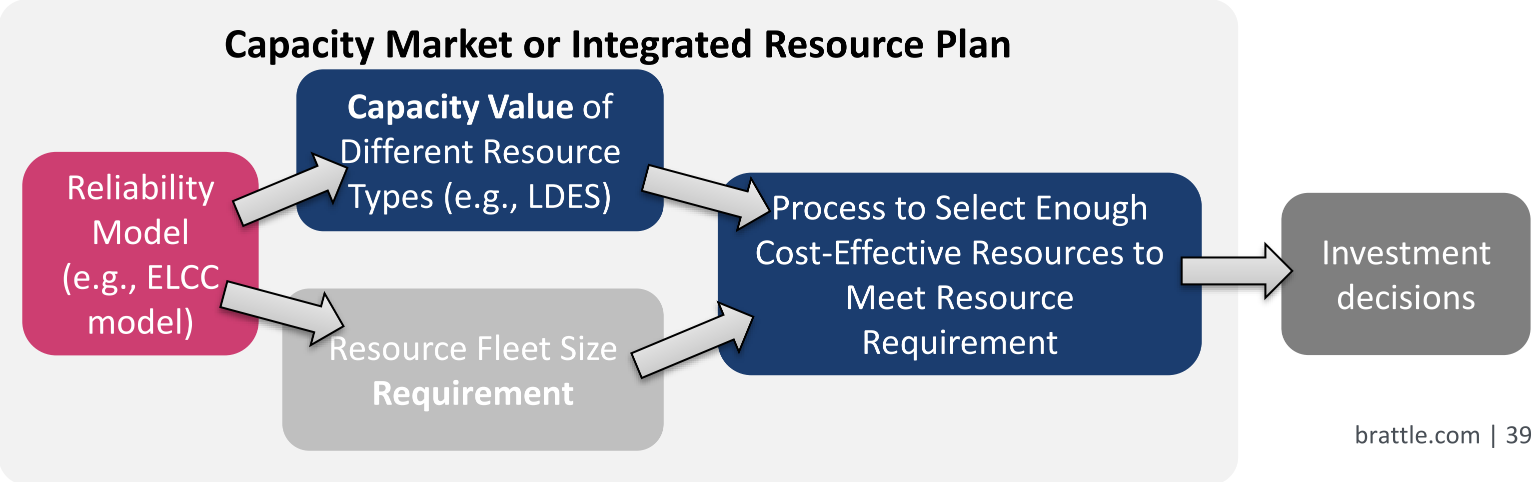
They calculate capacity values based on the expected ability of a resource to meet demand during the most challenging conditions.

PJM Winter ELCC Values for Storage



Notes and Sources: PJM only models 4-10 hour storage, so lines below 4-hrs are for graphical purposes and not indicative of ELCC value.

PJM, Updated ELCC Class Ratings for the 2025/26 BRA, 2023 and PJM, Capacity Market Reform: PJM Proposal, 2023.



LDES Pilot Projects and OEMs

LDES Pilot Projects List (1/2)

DOE/OCED LDES Pilot Projects

Urban Electric Power - STOred Rechargeable Energy Demonstration (STORED), Zinc Manganese Dioxide Battery

Invinity Energy Systems - Rural Energy Viability for Integrated Vital Energy (REVIVE), Vanadium Redox Flow Battery

Redflow - Children's HospitAl Resilient Grid with Energy Storage (CHARGES), Zinc Bromide Flow Battery

NextEra Energy Resources, LLC - Front-of-the-meter Utilization of Zinc bromide Energy Storage (FUZES), Aqueous Zinc Battery

Energy Dome - Columbia Energy Storage Project, Liquid CO2 Storage

Form Energy - Multiday Iron air Demonstration (MIND), Iron-Air Battery

ARPA-E DAYS Program

Antora Energy - Solid State Thermal Battery

Brayton Energy - Improved Laughlin-Brayton Cycle Energy Storage

Columbia University - Minimally Orchestrated Storage Technology for Duration Addition to Electricity Storage

Echogen Power Systems - Low-Cost, Long Duration Electrical Energy Storage Using a CO2-based Pumped Thermal Energy Storage (PTES) System

Form Energy - Aqueous Sulfur Systems for Long-Duration Grid Storage

Michigan State University (MSU) - Scalable Thermochemical Option for Renewable Energy Storage (STORES)

National Renewable Energy Laboratory (NREL) - Economic Long-Duration Electricity Storage by Using Low-Cost Thermal Energy Storage and High-Efficiency Power Cycle

Quidnet Energy - Geomechanical Pumped Storage

RedoxBlox - Scalable Thermochemical Option for Renewable Energy Storage (STORES)

United Technologies Research Center (UTRC) - High-Performance Flow Battery with Inexpensive Inorganic Reactants

University of Tennessee, Knoxville (UT) - Reversible Fuel Cells for Long Duration Storage

LDES Pilot Projects List (2/2)

Utility or OEM Specific Pilot Projects

- Dominion Energy – Form Energy Battery and EOS zinc-hybrid battery
- Dominion Energy/Virginia State University – EnerVenue metal-hydrogen battery
- Great River Energy – Form Energy Battery
- Georgia Power – Form Energy Battery
- PG&E – Energy Vault, Hybrid Battery H2 fuel cell Storage (48hr) Microgrid Project
- Salt River Project – CMBlu Energy, organic solid flow battery

LDES OEMS List

- Ambri: liquid metal battery (4-24 hrs)
- Energy Dome: liquid CO_2 storage (8-24 hrs)
- Energy Vault: gravity storage (2-18 hrs); hybrid hydrogen fuel cell + Li-ion BESS (12-96 hrs)
- EnerVenue: metal-hydrogen battery (2-12 hrs)
- EOS Energy: zinc-hybrid Battery (3-12 hrs)
- ESS Inc.: iron flow battery (6-12 hrs)
- Form Energy: iron-air battery, (100+ hrs)
- Highview Power: liquid air (6 hrs – “several weeks”), primarily UK/Australia
- Hydrostor: advanced compressed air energy storage (8+ hrs)
- Invinity Energy Systems: (Avalon/RedT merger), vanadium redox flow battery (2-12 hrs)
- NAS Batteries: sodium sulphur (6+ hrs)
- NextEra Energy Resources: aqueous zinc battery (10 hrs)
- Redflow: zinc bromide flow battery, (1-12 hrs), primarily Australia

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