U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

The Role of Long-Duration Energy Storage in the Grid of the Future

California Energy Storage Alliance (CESA) 14th Annual Market Development Forum

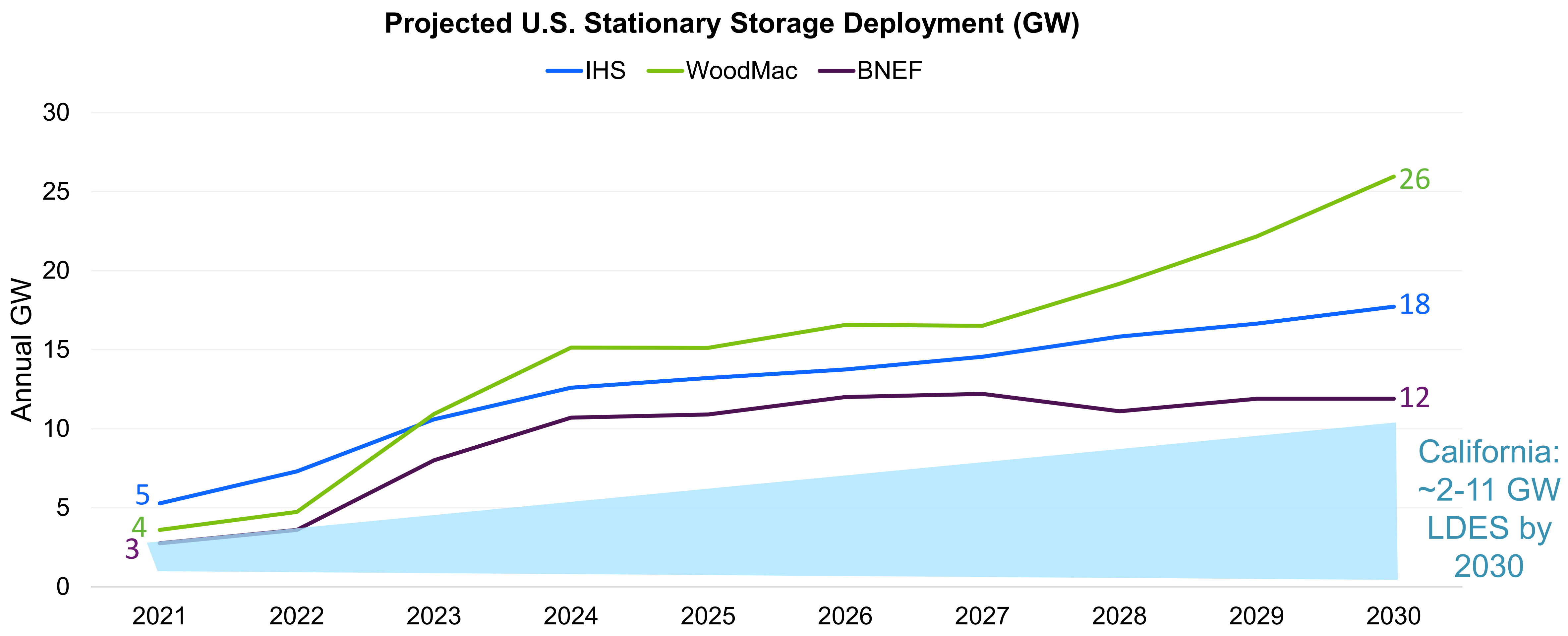
October 2023

Nyla Khan

Outline

- Storage landscape and path to 2030
- DOE and Office of Electricity’s (OE’s) actions to advance long duration energy storage (LDES)
- Opportunities for engagement

Grid storage deployment is projected to rapidly grow



Diverse technology options means improving the resiliency of grid storage supply chains

Lithium-ion Battery Supply Chain Risk Assessment

Product/ Components	Are U.S. suppliers competitive in the global market?	Is the supply chain secure because the material is NOT on the proposed or current Critical Materials List? OR because the U.S. does NOT import > 50%?
Lithium	No	No
Cobalt	No	No
Nickel	No	No
Manganese	No	No
Iron	Yes	Yes
Natural Graphite	No	No
Silicon	Yes	Yes
Refined LiOH/ Li2CO3	No	No
Refined CoSO4	No	No
Refined NiSO4/ C1 Ni	No	No
Refined Manganese	No	No
Synthetic Graphite Anode Materials	No	No
Natural Graphite Anode Materials	No	No
CAM/ p-CAM	No	No
LIB Cathodes	No	No
Graphite Anodes	No	No
Silicon-based anodes	Maybe	No
Separators	No	No
Electrolytes	No	No
Cells	No	No
Modules/Packs/ Racks	Yes	No
Energy Storage System Packages	Maybe	No
Cells/ Packs	Yes	No
Metals	No	No

Flow Battery Supply Chain Risk Assessment

Product/ Components	Are U.S. suppliers competitive in the global market?	Is the supply chain secure because the material is NOT on the proposed or current Critical Materials List? OR because the U.S. does NOT import > 50%?
Iron	Yes	Yes
Vanadium	No	Yes
Zinc	Yes	Yes
Manganese	No	No
Sulfuric Acid	Yes	Yes
Refined Iron	Yes	Yes
Refined Vanadium	No	Yes
Refined Zinc	Yes	Yes
Hydrochloric Acid	Yes	Yes
Graphite	No	Maybe
Sulfuric Acid	Yes	Yes
Polyethylene	Yes	Yes
Separator - Polyethylene	No	No
Pumps	Yes	Yes
Heat exchangers	Yes	Yes
Electrolytes	Maybe	Maybe
Iron Flow Batteries/ Systems	Yes	Yes
Vanadium Flow Batteries/ Systems	No	Maybe
Zinc Flow Batteries/ Systems	No	Maybe

Lead-acid Battery Supply Chain Risk Assessment

Product/ Components	Are U.S. suppliers competitive in the global market?	Is the supply chain secure because the material is NOT on the proposed or current Critical Materials List? OR because the U.S. does NOT import > 50%?
Lead	Yes	Yes
Sulfur	Yes	Yes
Refined Lead	Yes	Yes
Sulfuric Acid	Yes	Yes
Polyolefin	Yes	Yes
Separator	Yes	Yes
Electrolyte	Yes	Yes
Electrolyte Salts	Yes	Yes
Electrolyte Solvents	Yes	Yes
Lead Acid Batteries	Yes	Yes
Lead Acid ESS	Maybe	Yes
Lead	Yes	Yes

DOE Grid Energy Storage Supply Chain Deep Dive Assessment

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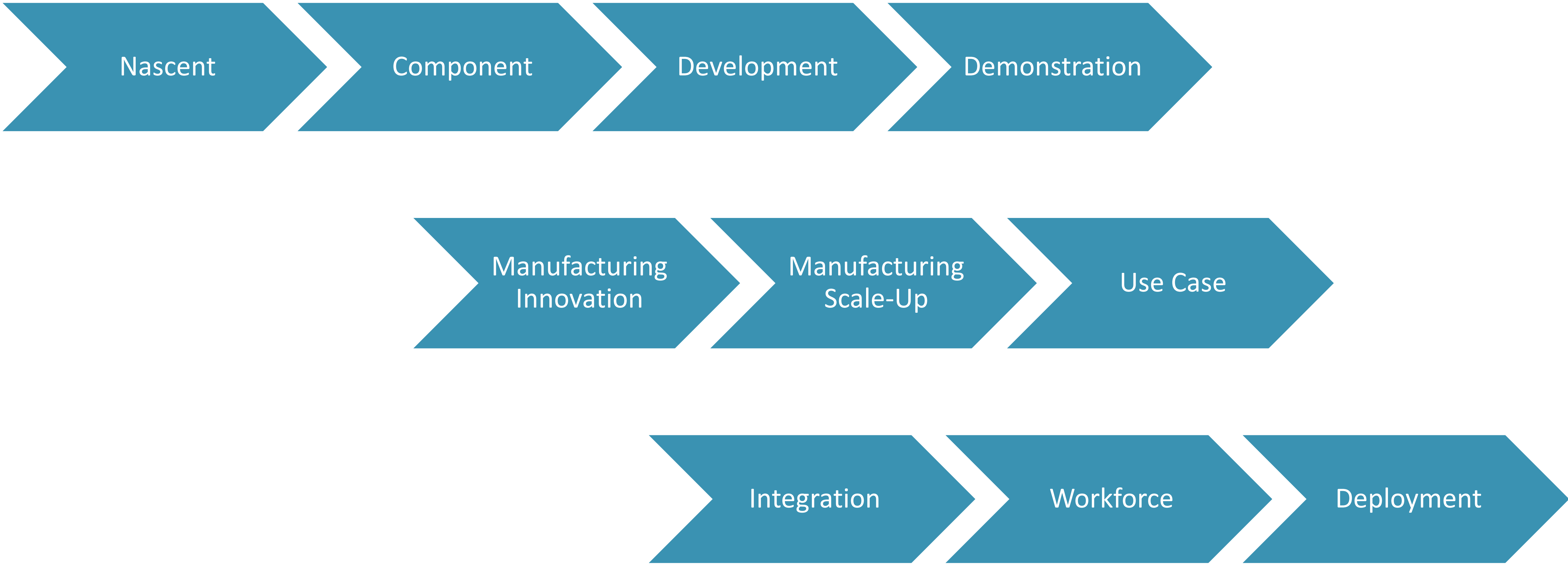
The road to deployment has many steps



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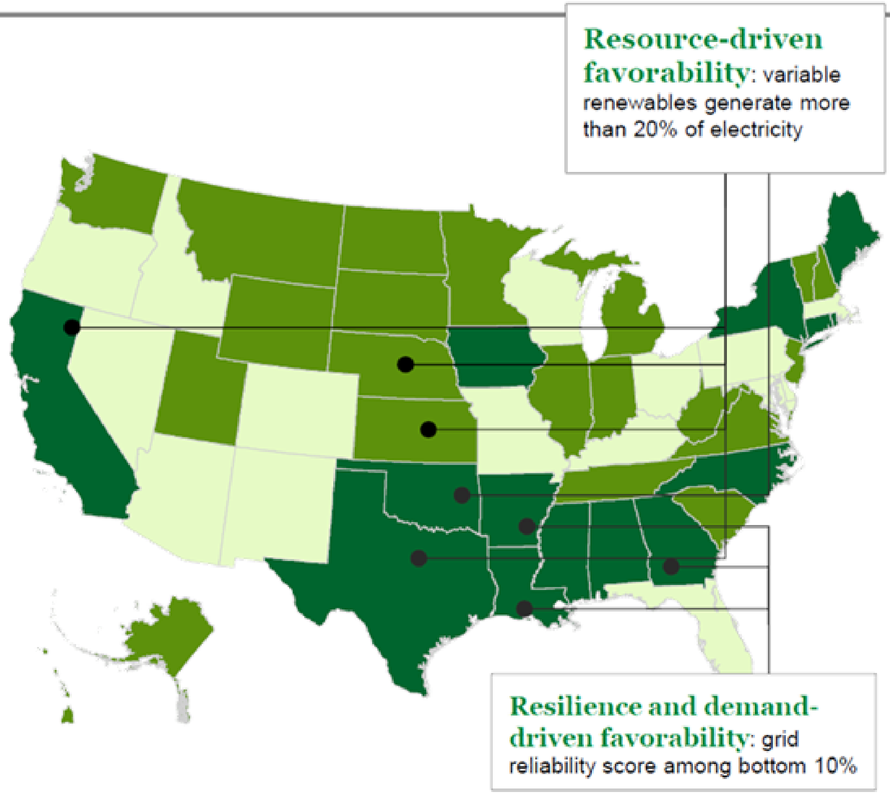
LDES adoption readiness varies across states

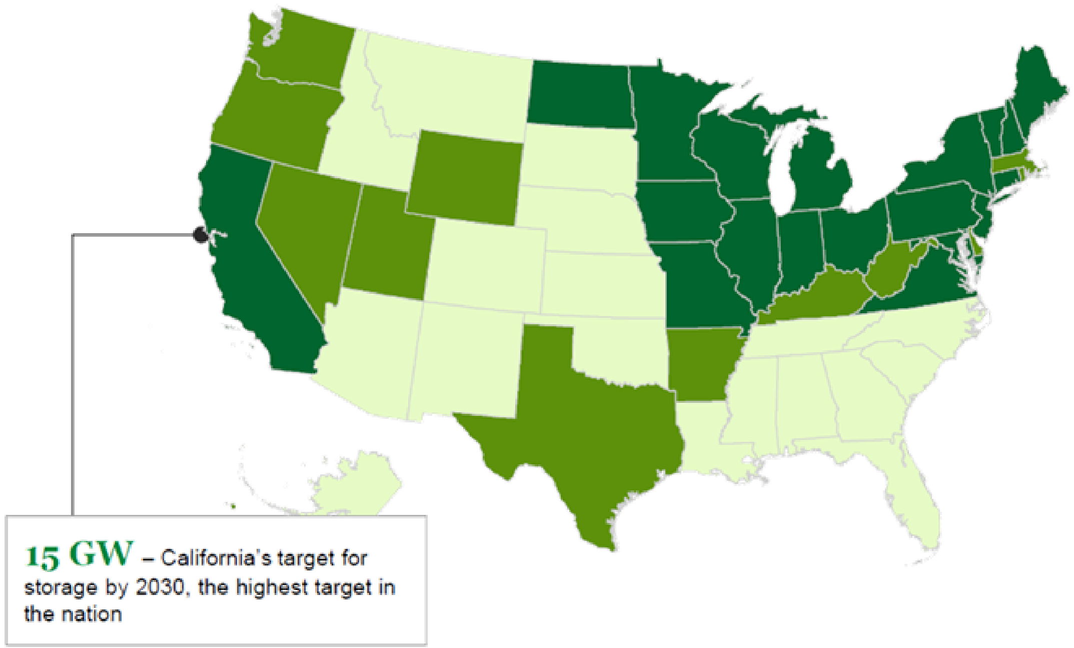
Conditions for LDES deployment are:

Favorable | Emerging | Unfavorable

Grid conditions



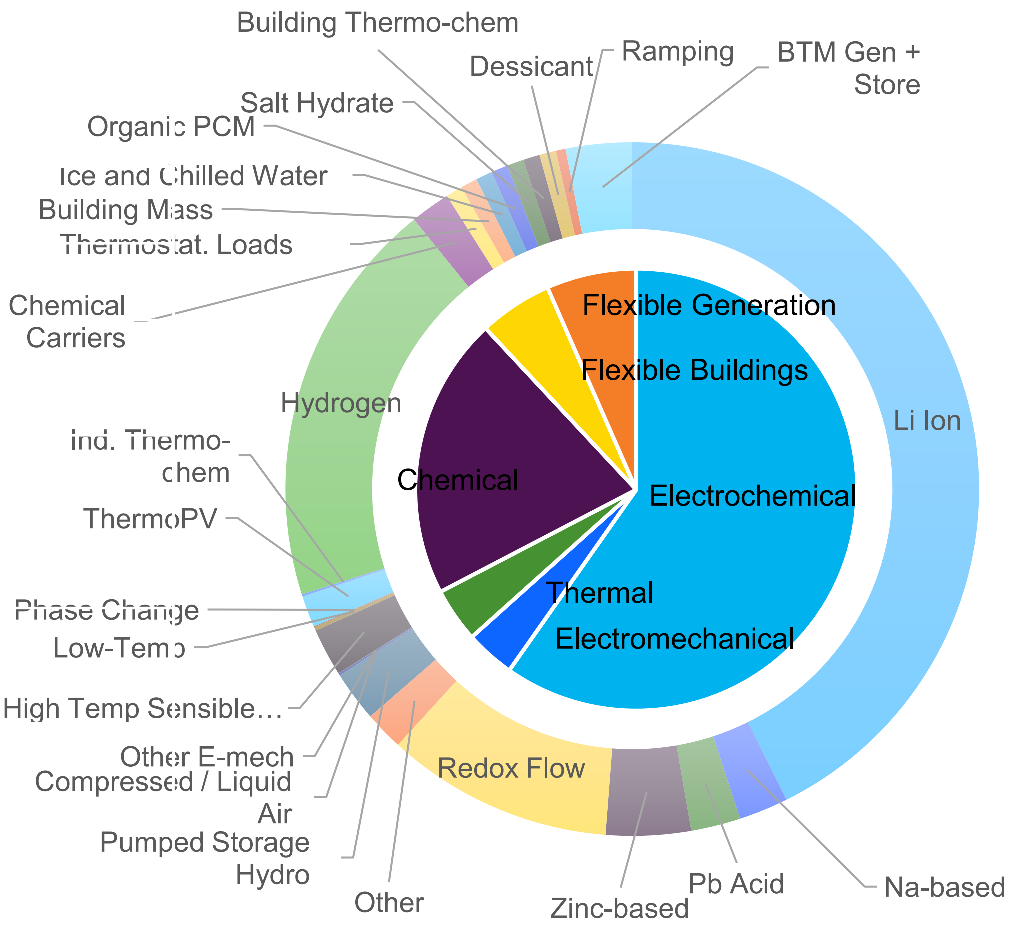
Policy & market construct



DOE has supported 30+ storage technologies

Bidirectional Electric Storage	Electrochemical	Li-Ion & Li-Metal
		Na-Ion
		Na-Metal
		Lead Acid
		Zinc
		Other Metals (Mg, Al)
		Redox Flow
		Reversible Fuel Cells
		Electro-Chemical Capacitors
	Electromechanical	Pumped Storage Hydro
		Compressed Air
		Liquid Air
		Flywheels
		Geomechanical
		Gravitational
Crosscutting	Power Electronics	Power Electronic Systems
Thermal & Chemical	Thermal	High-Temperature Sensible Heat
		Phase Change
		Low-Temperature Storage
		Thermo-Photovoltaic
		Thermochemical
	Chemical	Chemical Carriers (e.g., Ammonia)
		Hydrogen
Flexible Generation & Loads	Flexible Buildings	Thermostatically Controlled Loads
		Building Mass
		Ice & Chilled Water
		Organic Phase Change Material
		Salt Hydrate
		Thermochemical
		Desiccant
	Flexible Generation	Ramping
		Behind-the-Meter Generation + Storage

DOE Funding Shares by Technology



Recent federal legislation galvanizes support for energy storage at DOE

- Bipartisan Infrastructure Law (BIL)
  - 60 new DOE programs (48 demonstration & deployment)
  - Expands funding for 12 existing programs
  - $505 million for LDES demo program (OCED)
  - $10 billion for grid infrastructure programs (GDO)
- Inflation Reduction Act (IRA)
  - Funds investments and incentives totaling $370 billion
  - US to remain global leader in clean energy technology, manufacturing, and innovation
  - Includes investment tax credits (ITCs) and production tax credits (PTCs) for energy storage and new loan authorities given to DOE

Through the Energy Storage Grand Challenge, OE Leads Grid Storage Efforts Across DOE

ESGC

	Materials	Components & Devices	System Design	Grid & System Integration	Supply Chain & Manuf.	Operations	End of Life	Investment & Finance	Markets & Value	Workforce
Electro-chemical	VTO, ARPA-E, SC-BES	AMO, VTO, ARPA-E **OE**	VTO, ARPA-E, SETO	AMMTO, VTO	AMMTO, MESC	OCED **OE**	VTO	LPO, OTT, OCED, AMMTO, LPO, SETO	OTT, EERE-SA, GTO, WPTO, SETO, IEDO, BTO	AMMTO, VTO, OP, OTT
Electro-mechanical	ARPA-E, WPTO	ARPA-E, WPTO	ARPA-E, WPTO	WPTO **OE**	WPTO, AMMTO	OCED				
Thermal	ARPA-E, SETO, SC-BES, BTO	SETO, BTO	SETO, BTO	SETO, BTO	AMMTO, BTO	OCED, SETO	SETO	**OE**		**OE**
Chemical	HFTO, SC-BES, ARPA-E	HFTO	HFTO	HFTO	AMMTO	OCED				
Power Electronics	SC-BES, ARPA-E	ARPA-E, AMMTO, VTO **OE**	AMO, VTO, CESER	VTO, CESER	AMMTO	**OE**				

ARPA-E: Advanced Research Projects Agency–Energy, AMMTO: Advanced Materials and Manufacturing Technologies Office, BTO: Building Technologies Office, FE: Office of Fossil Energy, GTO: Geothermal Technologies Office, HFTO: Hydrogen and Fuel Cell Technologies Office, IEDO: Industrial Efficiency and Decarbonization Office, OE: Office of Electricity, OP: Office of Policy, SETO: Solar Energy Technologies Office, LPO: Loan Programs Office, SC-BES: Office of Science Basic Energy Sciences, VTO: Vehicle Technologies Office, WETO: Wind Energy Technologies Office, WPTO: Water Power Technologies Office

Energy Earthshots U.S. Department of Energy | Storage™

LONG DURATION STORAGE SHOT TARGET

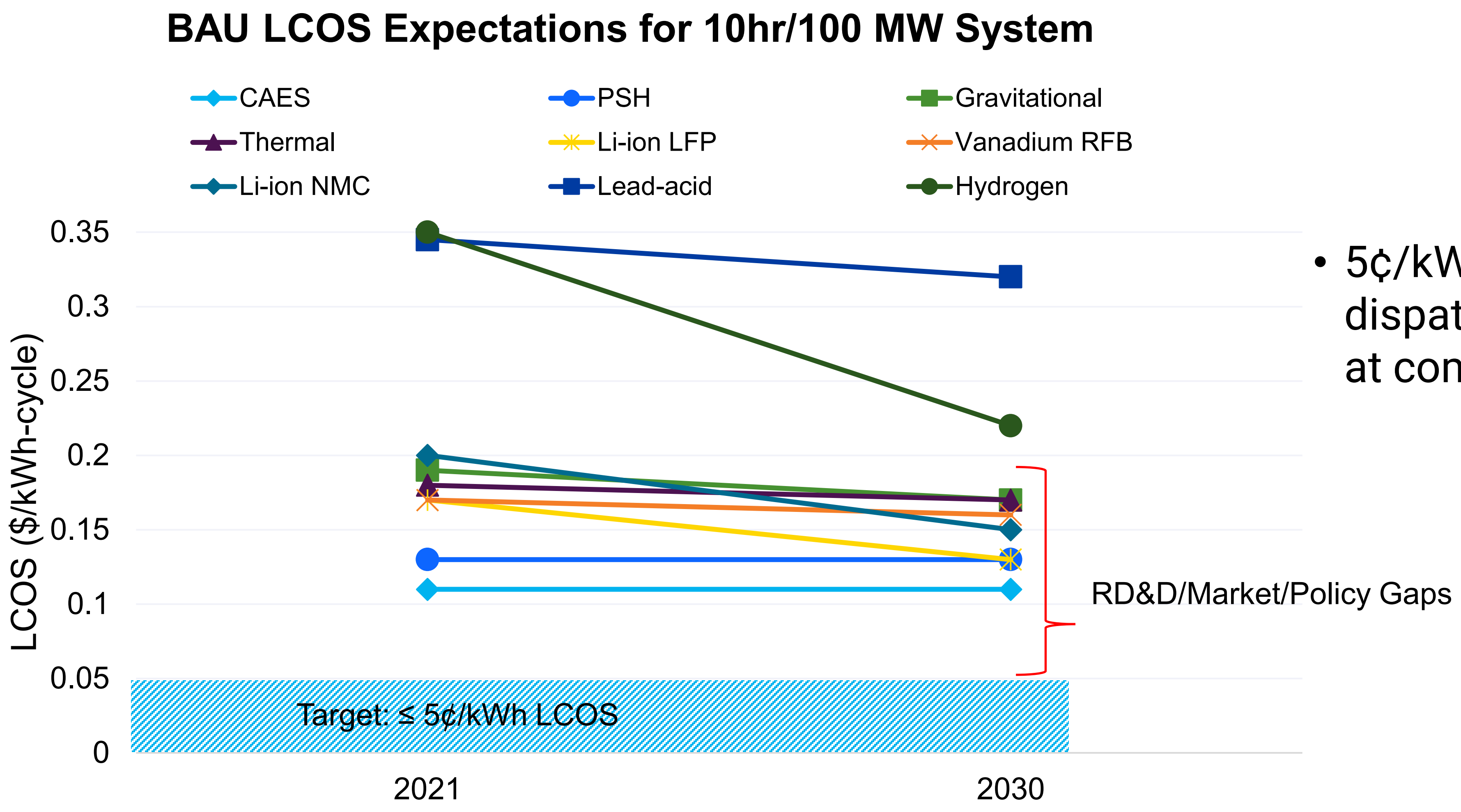
Reduce storage costs by **90%** from a 2020 Li-ion baseline...

...in storage systems that deliver **10+** hours of duration

...in **1** decade

Affordable grid storage for clean power – any time, anywhere

Business-as-usual conditions alone won't achieve $0.05/kWh Levelized Cost of Storage (LCOS)



- 5¢/kWh LCOS enables dispatchable clean energy at competitive costs

We're beginning to understand potential LDES use case scenarios

Inter-day (up to 24hr)
Multi-day / week (up to 100hr)

Low
Med
High

Likely deployment: 2022 → 2030+

Potential Market: High RES[1], GW	Potential Market: Aggressive LIB[2], GW	Use case	Application	Key stakeholders (non-exhaustive)	Competitive with LIB today[5]
28; 28[3]	30; 30[4]	**Load management services**	Large energy consumers (e.g., distribution centers, industrials) could use LDES to manage demand changes (e.g., freight charging purposes during peak season)	• Large peaking power consumers • Energy services players	High
10; 10[3]	1; 1[4]	**Firming for PPAs**	Renewable PPAs can use LDES to ensure that businesses can procure 24/7 renewable electricity	• Leading ESG customers	High
24; 24[3]	26; 26[4]	**Microgrid resiliency**	LDES can ensure reliable power in isolated areas or where the grid has shown to be unreliable / insufficient	• Local power authorities • Microgrid developers or integrators	High
157; 85; 242	17; 77; 94	**Utility resource planning**	Utilities or CCAs can include LDES in integrated long-term energy planning to meet VRE balancing needs	• Vertically integrated & T&D utilities	High
Highly dependent on state regulatory decisions – will be most applicable for multi-day / week LDES		**Transmission and Distribution Deferral**	LDES can offset the need for new transmission and distribution capacity by installing storage in constrained areas	• Utilities • T&D developers • Equity infra investors	Med
117; 101; 217	18; 119; 137	**Energy market participation**	LDES can play a role in shifting electricity from times of high supply to times of high demand, meet system peaks, and provide grid stability (e.g., inertia, frequency regulation)	• RES / T&D developers • Asset owners (IPPs) • Debt investors	Low

DOE Pathways to Commercial Liftoff – Long Duration Energy Storage

1 Based on demand potential from High Renewables Net-zero 2050 scenario
2 Based on net-zero 2050 scenario with a significant drop in Li-ion CAPEX according to NREL 'optimistic' projections
3 Based on the LDES Council Report use case opportunity sizing and adjusted to meet expected ISO demand
4 Maintains ratio of demand potential relative to sum of Utility resource planning & Energy shifting, capacity provision, and power system stability used in High-RES scenario and applies to Aggressive Li-ion scenario
5 Economic (e.g., IRR for customer) and strategic (e.g., resiliency needs, ESG goals) competitiveness for LDES compared to lithium-ion batteries

Source: NREL (Storage Futures Study: Key Learnings for the Coming Decades), LDES Flagship Report (Net-zero power: Long duration energy storge for a renewable grid)

A variety of LDES technologies hold promise

Faces geologic constraints[1]

Inter-day (up to 24hr)

Multi-day / week (up to 100hr)

Can function as both

Less Desirable — More Desirable

Duration	Energy storage form	Nominal Technology	Duration, hrs	LCOS[5], $/MWh	Min. deployment size, MW	Average RTE[1], %	TRL
Inter-day	Mechanical	Traditional pumped hydro (PSH) (faces geologic constraints)	0–15		200 – 400	70–80	9
		Novel pumped hydro (PSH)	0–15	70–170	10–100	50–80	5-8
		Gravity-based (faces geologic constraints)	0–15	90–120	20–1,000	70–90	6-8
		Compressed air (CAES) (faces geologic constraints)	6–24	80–150	200–500	40–70	7-9
		Liquid air (LAES) [1]	10–25	175–300	50–100	40–70	6-9
		Liquid CO_2 [1]	4–24	50–60	10–500	70–80	4-6
	Thermal	Sensible heat (e.g., molten salts, rock material, concrete) [2]	10-200[2]	300	10–500	55–90	6-9
		Latent heat (e.g., aluminum alloy)	25–100	300	10–100	20–50	3-5
		Thermochemical heat (e.g., zeolites, silica gel)	XX	XX	XX		XX
	Electrochemical	Aqueous electrolyte flow batteries	25–100	100-140	10–100	50–80	4-9
		Metal anode batteries	50–200	100	10–100	40–70	4-9
		Hybrid flow battery, with liquid electrolyte and metal anode (some are Inter-day) [2,3]	8–50[2]	XX	>100	55–75	4-9

DOE Pathways to Commercial Liftoff – Long Duration Energy Storage

Source: Adapted from LDES Council Net-Zero Power Report 2021, Wood Mackenzie Long Duration Energy Storage Report 2022, Company websites, Academic research

1 Demand potential / market size is limited by the requirement for specific geological formations
2 Codified based on primary technology type
3 Can function as inter-day, but organized based on longest duration potential
4 Some flow batteries under development will not work for multi-day, but it is categorized here as such given the technology's maximum duration

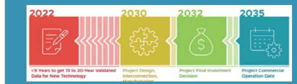
OE announced $30 million to help enable the Long Duration Storage Shot (LDSS)

ESGC

Driving down LCOS

10 Long Duration Storage Shot Technology Strategy Assessment reports

$15 million Storage Innovations Technology Liftoff FOA



Validating ES performance

Rapid Operational Validation Initiative (ROVI)

$15 million Demonstration and Validation FOA

LONG DURATION STORAGE SHOT TARGET

$0.05/ kWh Levelized Cost of Storage

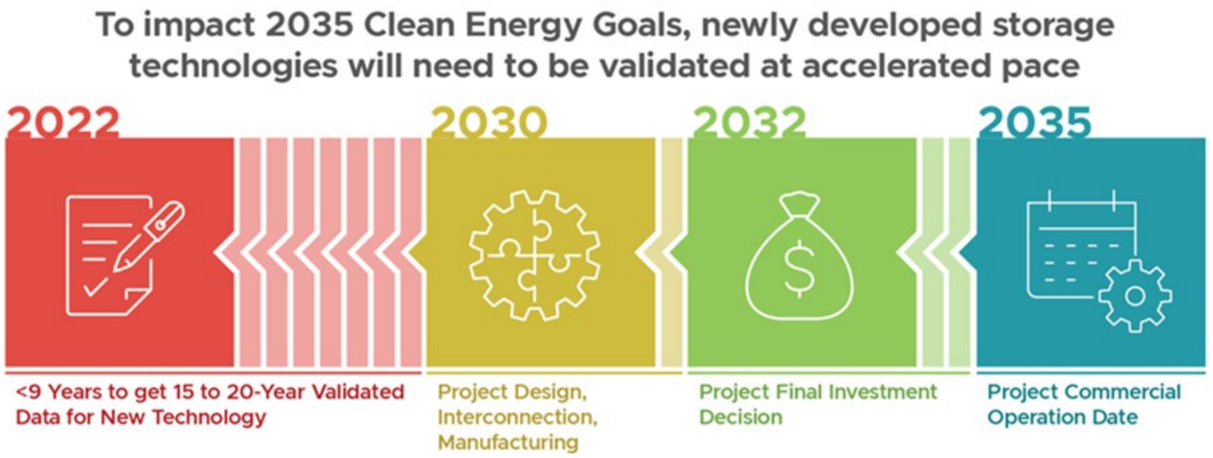
Driving down LCOS: OE engaged with stakeholders to model the impact of innovation on cost for 10 LDES technologies

- Access to capital and financing
- Limited market opportunities
- Technology validation for industry acceptance
- Interconnection queues and permitting
- Integrating technologies
- Manufacturing supply chain
- Workforce development
- Standards and codes

10 LDSS Technology Strategy Assessment Reports

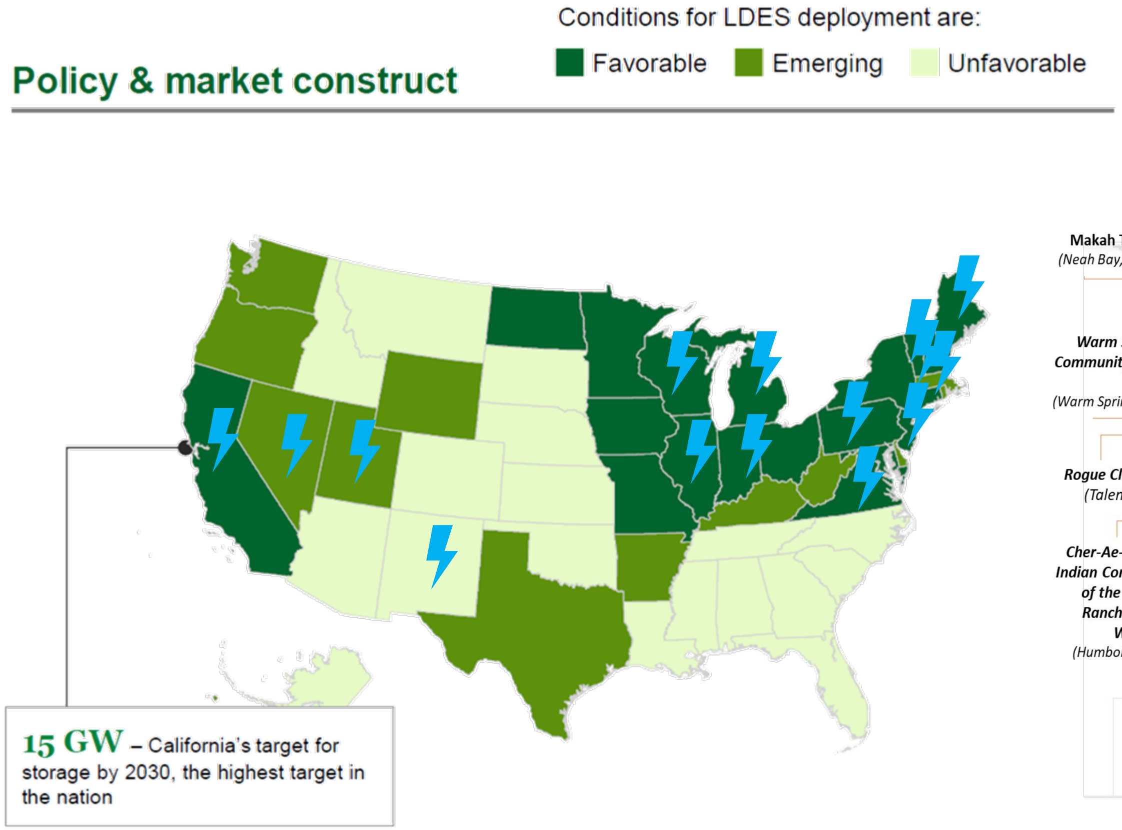
- Lithium-ion
- Lead-acid
- Flow Batteries
- Zinc Batteries
- Sodium Batteries
- Pumped Storage Hydropower
- Compressed-Air Energy Storage
- Thermal Energy Storage
- Supercapacitors
- Hydrogen Storage

Validating ES performance: the Rapid Operational Validation Initiative (ROVI) aims to make storage bankable, faster

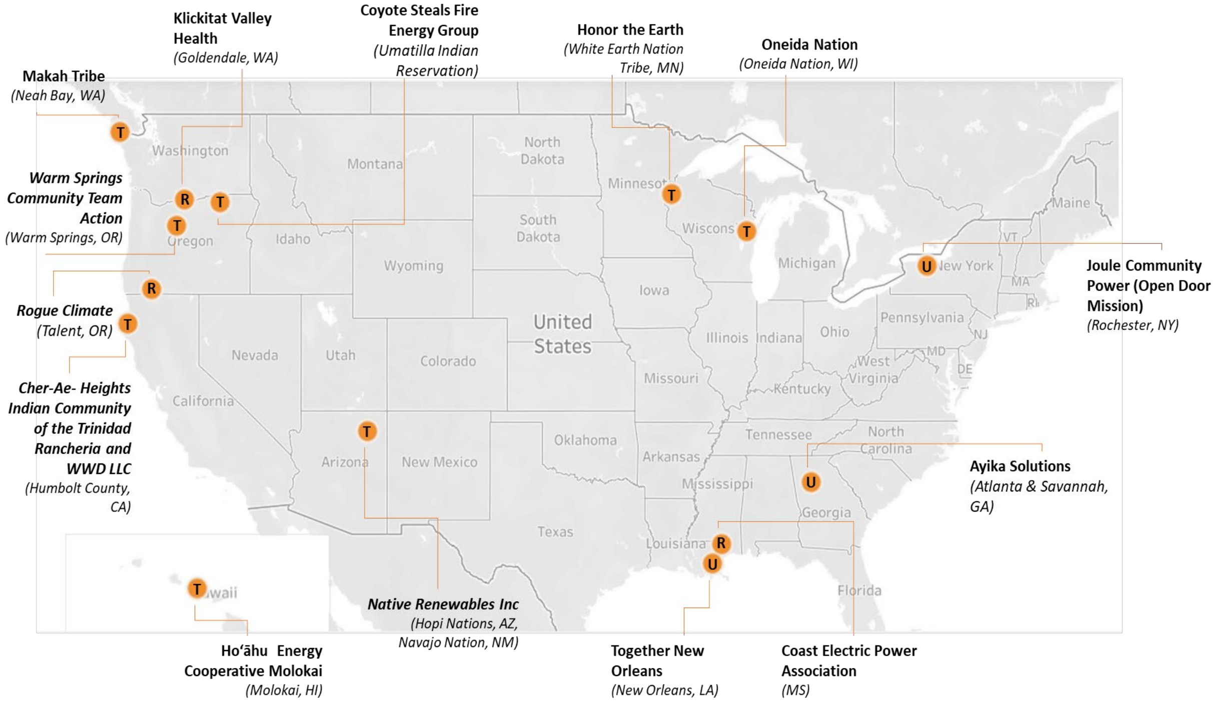


15- to 20-year financial grade performance projections with 1 year of combined testing and validation

Preparing decisionmakers with technical assistance



States participating in DOE Storage-Focused technical assistance



Communities participating in DOE Storage-Focused technical assistance

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DOE’s ES awardees* span the storage pipeline

Nascent/Component (15)

Office of Electricity
Cache Energy (2023)
Cryostone (2023)
Electrified Thermal Solutions (2023)
Gravity Power LLC (2023)
KineticCore Solutions (2023)
NerG Solutions (2023)
RCAM Technologies (2023)
Rondo Energy (2023)
THEMES LLC (2023)
Thermal Battery Corporation (2023)

Office of Science
Form Energy (via MIT) (2017)

ARPA-E
24M Technologies (2021)
Sila Nanotechnologies (2021)
South 8 Technologies (2023)
Tyfast Energy (2023)

Early Development (18)

ARPA-E
24M Technologies (2023)
Ampcera (2023)
Antora Energy (2019)
Brayton Energy (2019)
Columbia University (2021)
Echogen Power Systems (2019)
Energy Storage Systems (2012)
Form Energy (2019)
Michigan State University (2019)
Nat. Renewable Energy Laboratory (2019)
Natron Energy (fmr. Alveo) (2013)
Project K (2023)
Quidnet Energy (2019)
RedoxBlox (2021)
Solid Power Operating (2023)
United Tech. Research Center (2019)
Univ. of Tennessee, Knoxville (2019)
Urban Electric Power (via CUNY) (2010)

Late Development (7)

Office of Electricity
Redflow (2012)

Advanced Manufacturing Office
Antora Energy (2021)

Solar Energy Technologies Office
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Office of Clean Energy Demonstrations
CMBlu (2023)
E-Zinc (2023)
Invinity Energy Systems (2023)

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Demonstration (12)

Office of Electricity
GM Defense (2023)
KORE Power/NOMAD (2023)
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SmartVille (2023)
Urban Electric Power (2023)

Manufacturing Innovations (6)

Advanced Manufacturing Office
Largo Clean Energy (2021)
OTORO Energy (2021)
Quino Energy (2021)
TreadStone Technologies (2021)

ARPA-E
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Zeta Energy (2023)

Use Case/Integration (14)

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Ayika Solutions Incorporated (2023)
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Corvias (2023)
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Native Renewables (2023)

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New York Power Authority (2023)
NextEra (2023)
Solar Bear (2023)
Westinghouse Electric Co. (2023)
Xcel Energy (2023)

Manufacturing Scale Up (22)

Office of Manufacturing and Energy Supply Chains
6k Inc (2022)
Albemarle U.S. (2022)
American Battery Technology Co. (2022)
Amprius (2022)
Anovion (2022)
Applied Materials, Inc. (2022)
Ascend Elements Inc. (2022)
Cirba Solutions (2022)
Group14 Technologies Inc. (2022)
ICL-IP America Inc. (2022)
Koura (2022)
Lilac Solutions (2022)
Membrane Holdings LLC – ENTEK (2022)
Microvast (2022)
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Sila Nanotechnologies (2022)
Solvay Specialty Polymers USA, LLC (2022)
Syrah Technologies LLC (2022)
Talon Nickel (USA) LLC (2022)

Loan Programs Office
EOS Energy Enterprises (2023)
KORE Power (2023)

ARPA-E: Advanced Research Projects Agency–Energy
** Post-ARRA; comprehensiveness not guaranteed*

CESA members who are DOE Awardees*

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Recent Demo/Use Case awardees involve LDES use cases

Use Case	
1	Load management services
2	Firming for PPAs
3	Microgrid resiliency
4	Utility resource planning
5	Transmission & distribution deferral
6	Energy market participation

Demonstration Awardees

	1	2	3	4	5	6
GM Defense	■	■	■			
KORE Power/NOMAD			■	■		■
Echogen Power Systems		■	■			
Energy Dome		■		■		
EOS Energy Enterprises		■			■	
Form Energy			■	■		
Invinity Energy Systems			■			
Redflow			■			
ReJoule	■		■			
SmartVille	■		■			
Urban Electric Power	■		■			

Use Case/Integration Awardees

	1	2	3	4	5	6
Alliant Energy		■		■		
Ayika Solutions Inc.	■		■			
Coast Elec. Power Assoc.	■		■			
Corvias	■	■	■			
Faraday Microgrids			■			
Green Mountain Power			■	■		■
Hoʻāhu Energy Coop. Molokaʻi		■		■		
Nat. Ren. Coop. Org.			■			
Native Renewables	■		■			
New York Power Auth.	■		■			
NextEra		■			■	
Solar Bear	■		■			
Westinghouse Elec. Co.		■	■			
Xcel Energy		■	■	■		

Workforce and Educational Programs

BWI
Battery Workforce Initiative

U.S. DEPARTMENT OF ENERGY | LEEP
Lab-Embedded Entrepreneurship Program

CHAIN REACTION INNOVATIONS
Entrepreneurship at Argonne

INNOVATION CROSSROADS

cyclotronroad

WEST GATE

← More Consortia | More Serial →

The Grid Storage Launchpad (GSL) will be a new signature facility for storage advancement

Validate

Accelerate

Collaborate

- 90,000 sq. ft facility; expected completion early 2024
- Provide systematic and independent validation of new grid storage technologies
- Basic materials and components, through prototyping under grid operating conditions (<100kW)

$75M TOTAL ESTIMATED FACILITYCOST

100 WORKSTATIONS

30+ LAB MODULES

$35M NON-FEDERAL INVESTMENTS

$15M LD RD

$7M

$8M

$5M BATTELLE

Engage with DOE

Opportunities:

[FOA exchange](#)

Office of Electricity | Department of Energy

Events:

Energy Storage Grand Challenge Summit

OE Peer Review

Email lists

Energy Storage Grand Challenge

Webinars

Reach out

Access relevant DOE resources

Meet OE's Energy Storage Division

Eric Hsieh
Deputy Assistant Secretary

Imre Gyuk
Chief Scientist

Caitlin Callaghan
Director, Storage Materials & Systems

Mo Kamaludeen
Director, Storage Validation

Ben Shrager
Storage Analysis

Nyla Khan
Storage Materials & Systems

Vinod Siberry
Storage Validation