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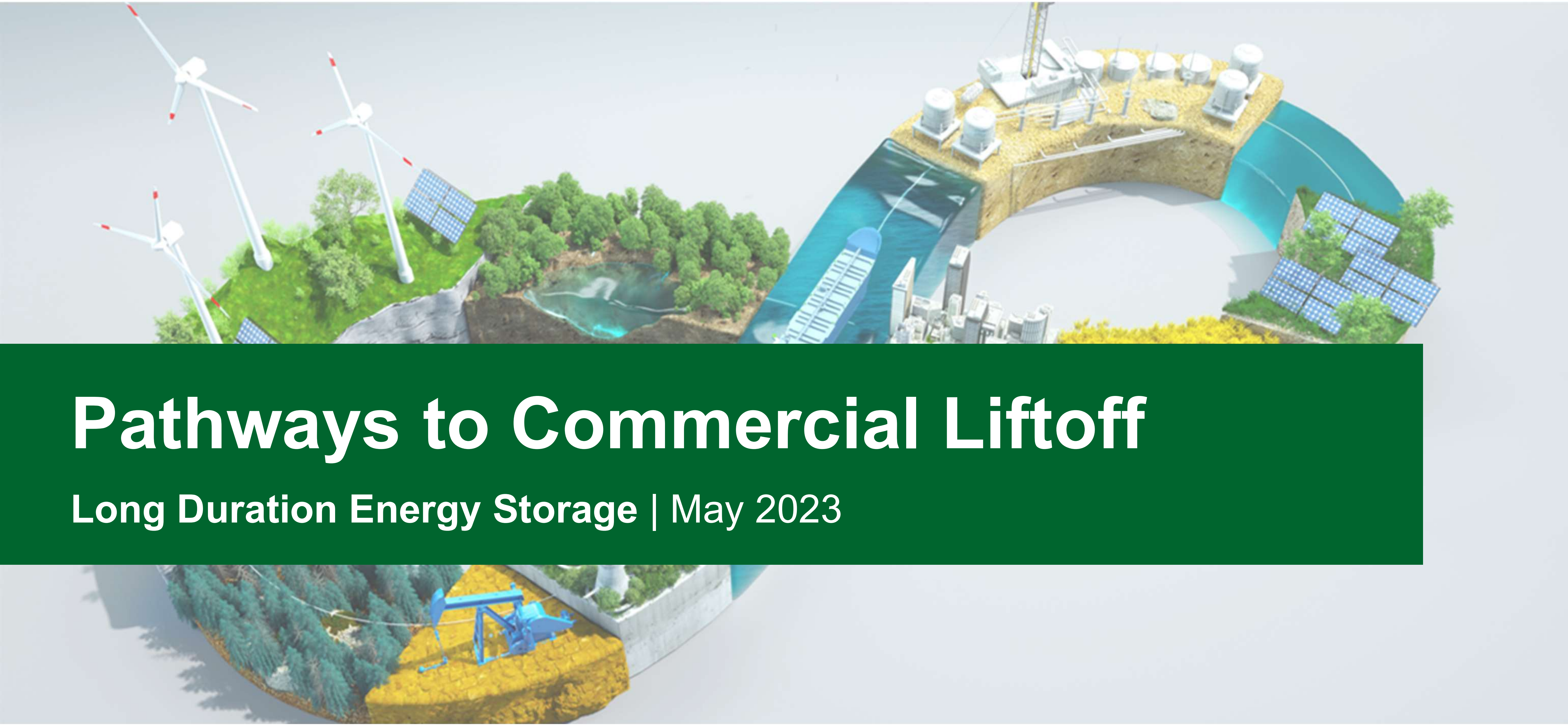


Pathways to Commercial Liftoff

Long Duration Energy Storage | May 2023

Executive summary

1. Long Duration Energy Storage covers the set of technologies which can provide **~10 to ~160 hours of duration of dispatch** in a power context. The report defines and focuses on **two market segments: Inter-day LDES (10-36 hours) and Multi-day LDES (36-160+ hours)**

2. The availability of **cost-effective LDES technologies is an option to enable high renewable pathways and grid resilience**, **reduce the need for new natural gas** buildout for reliability, and **enhance energy independence** by diversifying domestic energy storage supply chains.

   – As a result, a net-zero US power grid could include **~460 GW of LDES by 2050**. However, there are multiple technologies competing with LDES, so **LDES will need market interventions to win and scale, but pathways that leverage LDES are projected to deliver ~$10-20B in annual savings by 2050**.

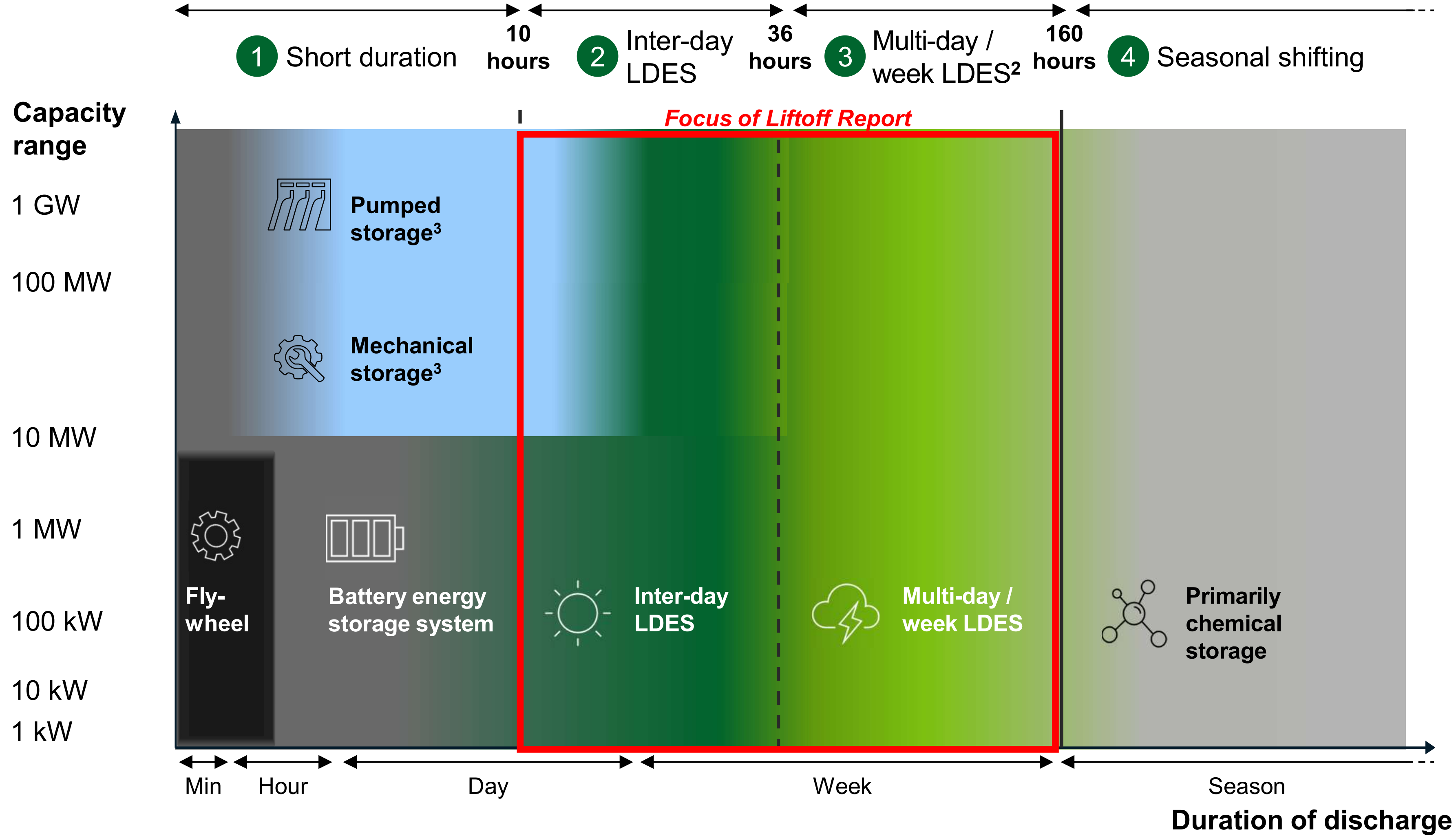
3. LDES technologies **require public and private investment** to drive down cost and market intervention to compensate differentiated performance for the technology to scale to an industrial level in a net-zero world – this liftoff requires three key areas of action:

   A. **Technology cost / performance improvement** via grid-scale demonstration projects, starting immediately with the most near-term applications, to achieve competitive cost and operational performance (**45-55% capital cost reduction** and **7-15% RTE improvement** from today).

   B. **Market and regulatory evolution** to provide **market compensation for LDES services of at least $75 / KW-year** is required to enable LDES deployments, at both the state-level (e.g., longer IRP horizons, LDES procurement carveouts) and ISO-level (e.g., expanded capacity / resource adequacy markets).

   C. **Flexible and rapid supply chain formation** (expanding to **$330B by 2050** and **10-15 GW of annual deployment by 2035**) will be needed in collaboration with industry and local players to avoid deployment bottlenecks ahead of a potential surge in demand

① Storage technologies can be segmented based on their duration of dispatch with LDES filling the Inter-day to Multi-day / week role



Codifying the technology

0-10 hours	1	**Short duration:** Durations up to 10 hours
10-36 hours[2]	2	**Inter-day LDES:** Sometimes called "diurnal"
36-160 hours[1]	3	**Multi-day / week LDES:** Commonly called "seasonal"
160+ hours	4	**Seasonal shifting:** Generally included in "seasonal", but distinct in that this does function as a conventional, storable fuel

1 Technologies & market use cases may span across duration categories (e.g., technology's duration may encompass both Multi-day / week and Seasonal shifting
2 LDES systems with 36+ hours of duration are considered Multi-day / week as they can discharge to cover 2+ full days of peak demand (e.g., 8a to 8p)
3 Pumped storage and Mechanical storage can operate effectively as both short-duration and inter-day LDES systems

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1 There are numerous technologies within Long Duration Storage

NON-EXHAUSTIVE – HYDROGEN AND HYBRID LONG DURATION STORAGE EXCLUDED

Less Desirable → More Desirable

Faces geologic constraints[1] | Not enough public datapoints to obtain a reliable value | Inter-day | Can function as both | Multi-day / week

Duration	Energy storage form	Technology	Nominal 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	70–170	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 CO2 [1]	4–24	50–60	10–500	70–80	4-6
Multi-day / week	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	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

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

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

② LDES complements renewables, reduces the need for new natural gas, and diversifies storage supply chains

Enabling high renewable development and enhancing resilience

LDES **reduces the cost and risk associated with high renewable pathways** by balancing intermittent renewables and reducing the costs and risks around grid expansion. LDES also **enhances local resiliency** to respond to increasingly extreme weather events.

Reducing the need for new natural gas capacity

Having available and cost-effective LDES **reduces the need for 200 GW+ of new natural gas capacity** in a net-zero world.

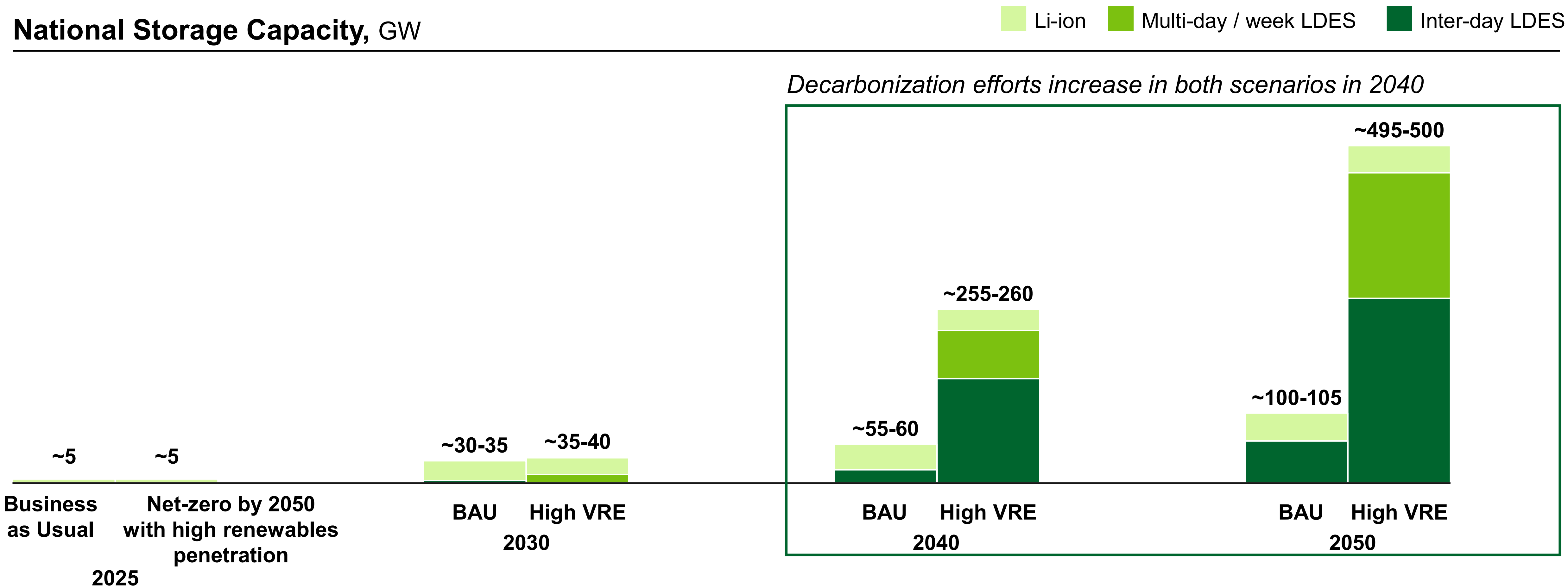
As a result, pathways that leverage LDES are projected to **deliver ~$10-20B in annual savings by 2050.**

Diversifying domestic energy storage supply chain

A diversified set of storage **technologies reduces the risk of net-zero goals being contingent upon lithium-ion manufacturing** buildout, and acknowledges the **durable role of LDES** even in scenarios with aggressive Li-ion cost improvements.

② High renewables scenario drives LDES market growth with additional LDES required in scenarios with net-zero goals

National Storage Capacity, GW



Source: Pathways to Commercial Liftoff modelling efforts

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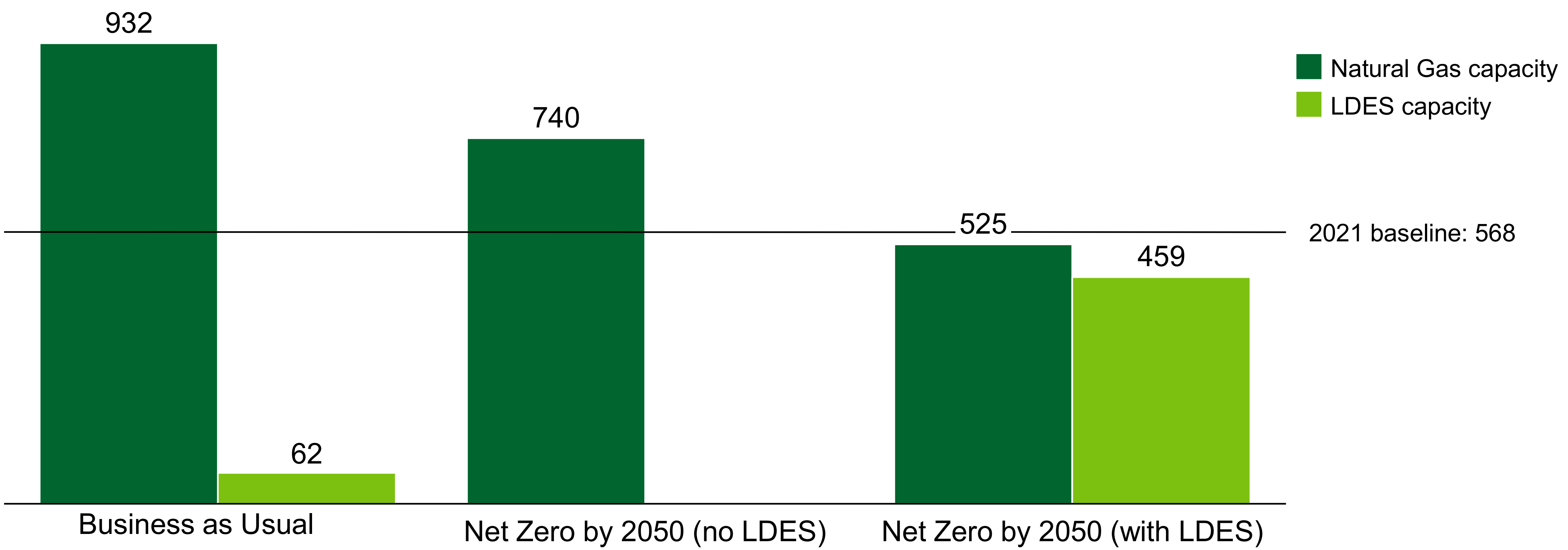
2 Net zero scenarios all include Natural Gas with CCS; however, LDES removes the need for 200GW+ of Natural Gas capacity

Total Installed Capacity in 2050, GW



1. Includes both Diurnal and Seasonal LDES; Does not include Li-Ion

Scenarios that include competitive LDES are projected to deliver **~$10-20B in annual savings** in operating costs and avoided capital expenditures by 2050.

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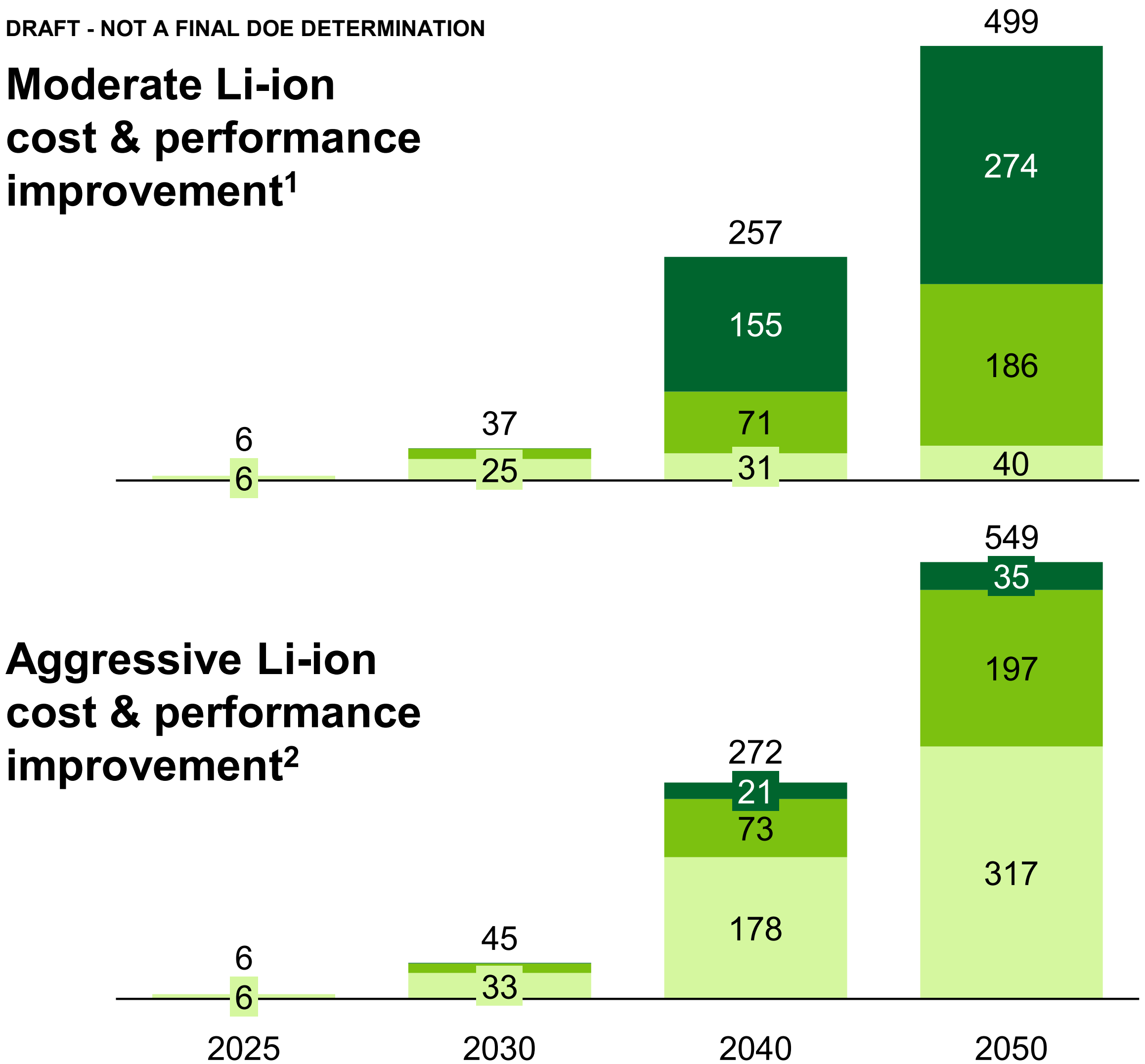
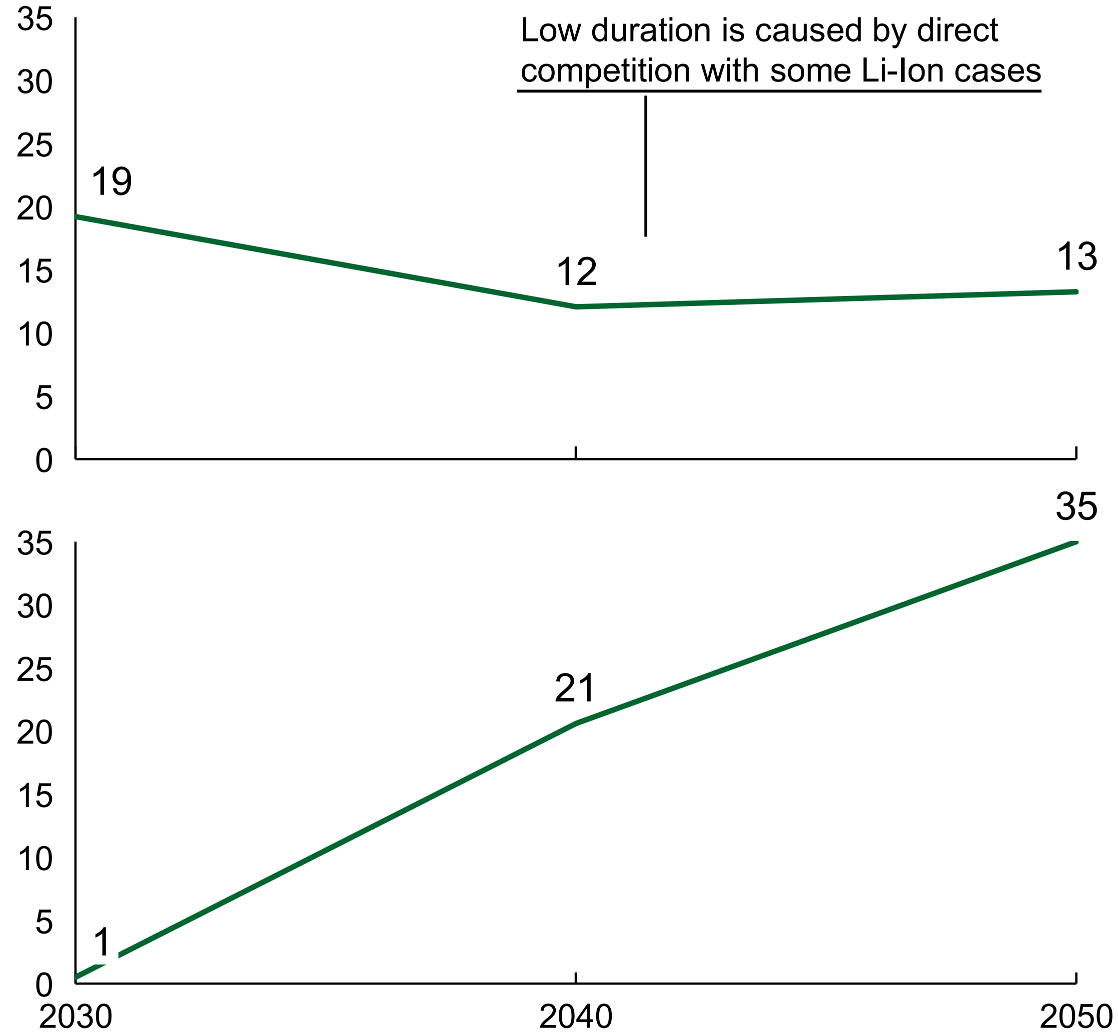
② Moderate and aggressive Li-ion cost & performance improvement scenarios demonstrate durable Multi-day LDES market need

Li ion | Multi-day / week LDES | Inter-day LDES

National Storage Capacity, GW



Average duration of deployed Inter-day LDES systems, hrs.



1 Assumes Li-ion batteries improve costs and performance at a moderate rate based on current Li-Ion cost curve (54% cost improvement through 2030 and 65% total improvement through 2050 relative to 2021 prices)
2 Assumes capex costs associated with energy component (e.g., battery cell) are 50% lower than in moderate scenario

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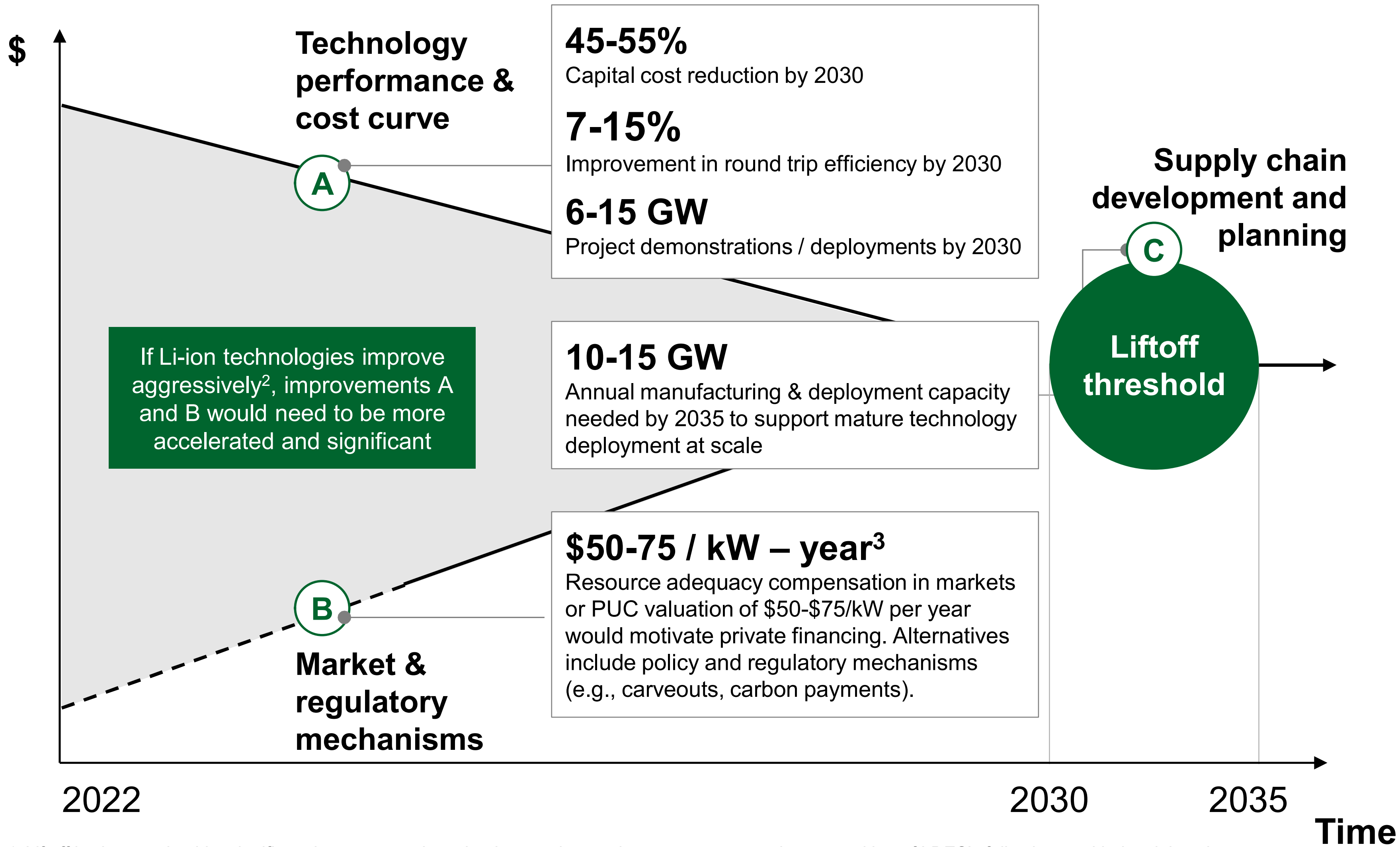
3 Achieving liftoff[1] requires improvements in technology, market compensation, and supply chain development



1 Liftoff is characterized by significant improvement in technology and operating parameters, market recognition of LDES's full value, and industrial-scale manufacturing and deployment capacity. These improvements are needed to attract the private capital that is needed to meet LDES deployment targets
2 Need for Multi-day / week technologies remains in both Li-ion scenarios; Aggressive Li-ion will reduce need for supply chain buildout
3 $ / kW - year varies by geography

- Liftoff occurs when **LDES technologies are deployed** (without project-specific intervention) **at scale across the US power grid**
- Within this decade, it is most important that **LDES technologies are demonstrated in-field** and begin to receive adequate **market compensation for the future value** they bring to a net-zero grid
- By 2030, an **industrial scale manufacturing and deployment base** must be forming

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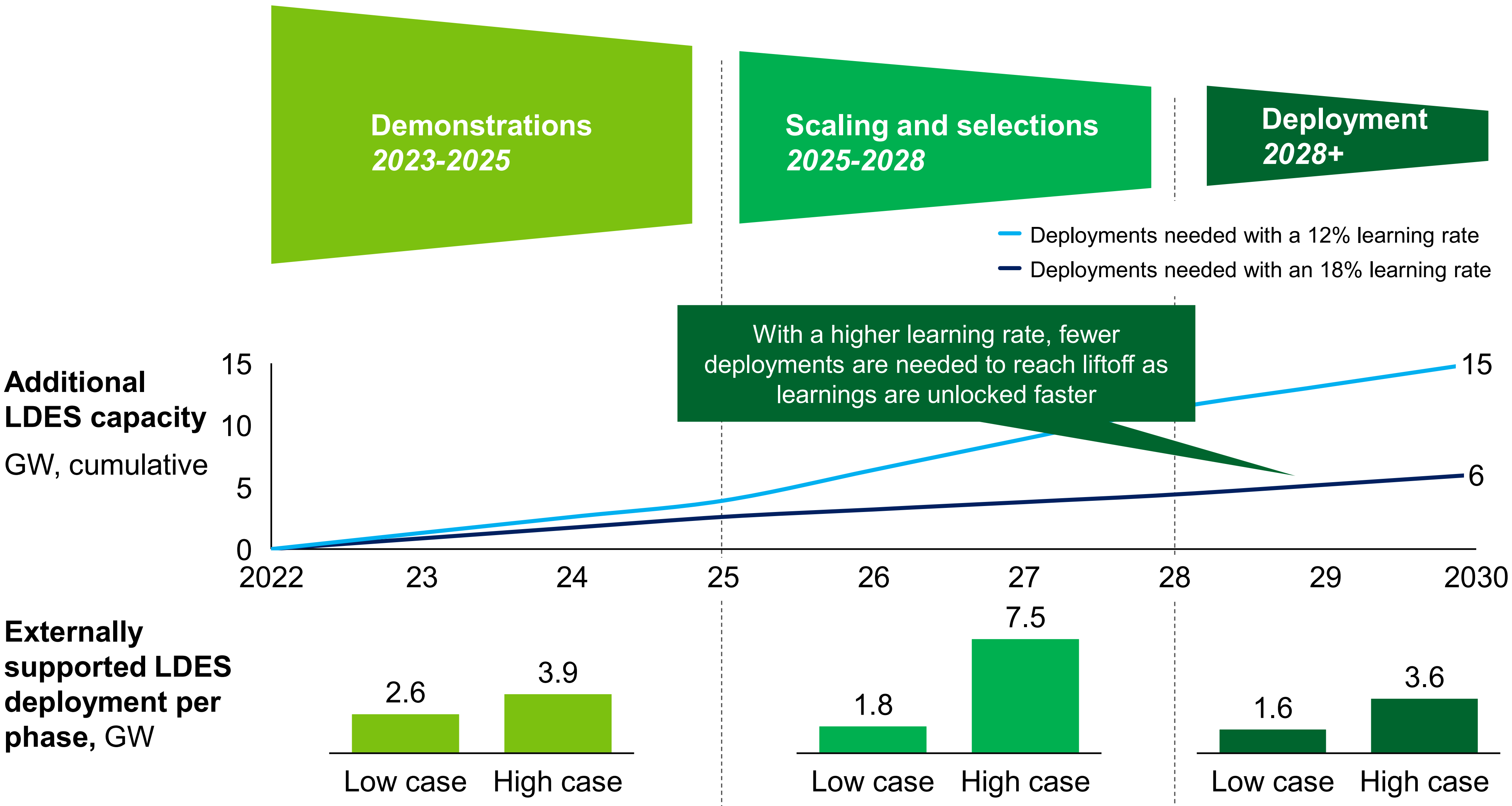
3A External support (e.g., grants or cost share) for projects through scale-up phases assists reaching competitive technology cost / performance

2023 *Average project size will increase while required external support will decrease over time* **2030+**



$9-12B of total US investment will be needed by 2030

- Global investment will **ramp at a faster rate due to desire for energy independence**
- By 2040, **US investment alone would reach $140B**
- Specific external support of these projects could result in **3-9 technologies achieving aggressive learning targets** by 2030

1 Not indicative of total potential market size by this period

3A Demonstrations of near-term applications represent the best path towards necessary cost and performance improvements

Legend: Inter-day LDES | Multi-day / week LDES | Low | Medium | High

Likely year of Deployment	Potential Market Size in High RES[1], GW	Potential Market Size with Aggressive Li-ion[2], GW	Use case	Application	Key stakeholders (non-exhaustive)	Competitive with Lithium-ion today[5]
2022	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
2030+	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	Medium
	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

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)

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3A The key performance criteria for buyers varies across LDES use cases

Critical Criteria / Secondary Criteria

Use case	High VRE demand potential[1], GW	Aggressive Li-ion demand potential[2], GW	Nominal duration, hrs	Ramp rate, %/min	Response time	LCOS, $/MWh	Min. deployment size, MW	Footprint, sq. m
a Load management services	28; 28[3]	30; 30[4]	Critical	Secondary	Secondary		Critical	Critical
b Firming for PPAs	10; 10[3]	1; 1[4]	Critical			Critical		
c Microgrid resiliency	24; 24[3]	26; 26[4]	Critical	Critical	Critical			Secondary
d Utility resource planning	157 + 85 = 242	17 + 77 = 94	Critical	Secondary				
e Transmission and distribution deferral	Highly dependent on state regulatory decisions – will be most applicable for multi-day / week LDES		Secondary			Secondary	Critical	Critical
f Energy market participation	117 + 101 = 217	18 + 119 = 137	Critical	Secondary		Critical		

1 Net-zero by 2050 with high renewable penetration
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 Adjusted following the same ratio between these use cases and Energy shifting and utility resource planning opportunities to adjust for Li-ion improvements

③B Different market conditions could require different types of interventions to prompt LDES deployment

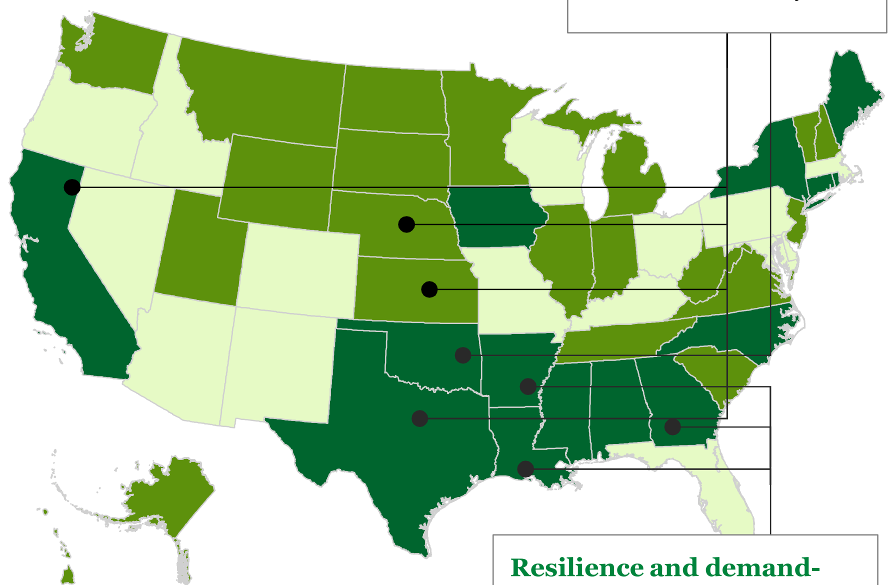
Key

Conditions for LDES deployment are:

Favorable | Emerging | Unfavorable

Grid conditions

Resource-driven favorability: variable renewables generate more than 20% of electricity

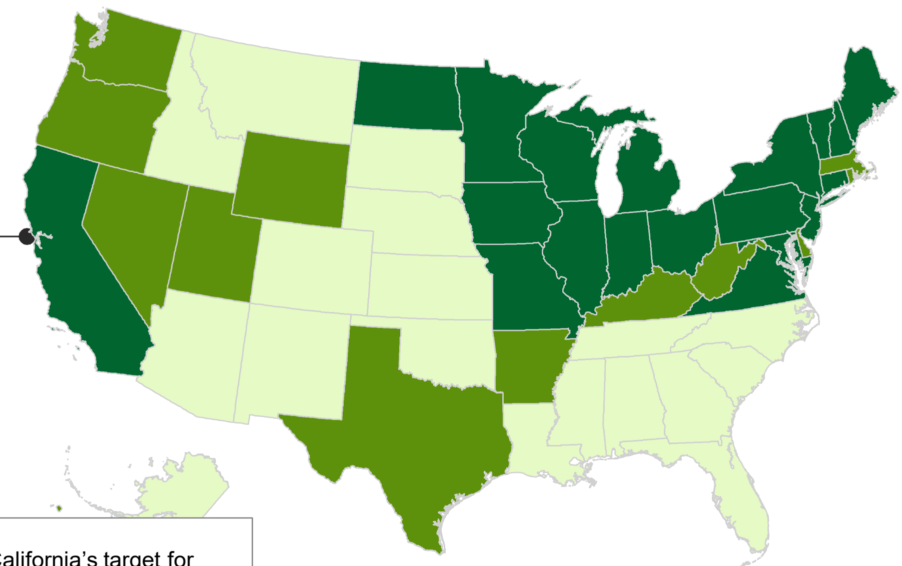


Resilience and demand-driven favorability: grid reliability score among bottom 10%

Potential market mechanisms tied to grid conditions:

- Response to extreme weather events results **in substantial increase of public and private investment in resiliency with recognition of storage infrastructure** for transmission and distribution value
- **LDES incorporated into grid planning** to accelerate renewable interconnection

Policy & market construct



15 GW – California's target for storage by 2030, the highest target in the nation

Potential market mechanisms tied to policy and market construct:

- **LDES procurement targets** matched to RPS targets
- **Capacity market expansion (in ISOs)**
- Longer-term recognition of **resource adequacy provisions** (e.g., 20-year IRPs with third-party integrated planning)

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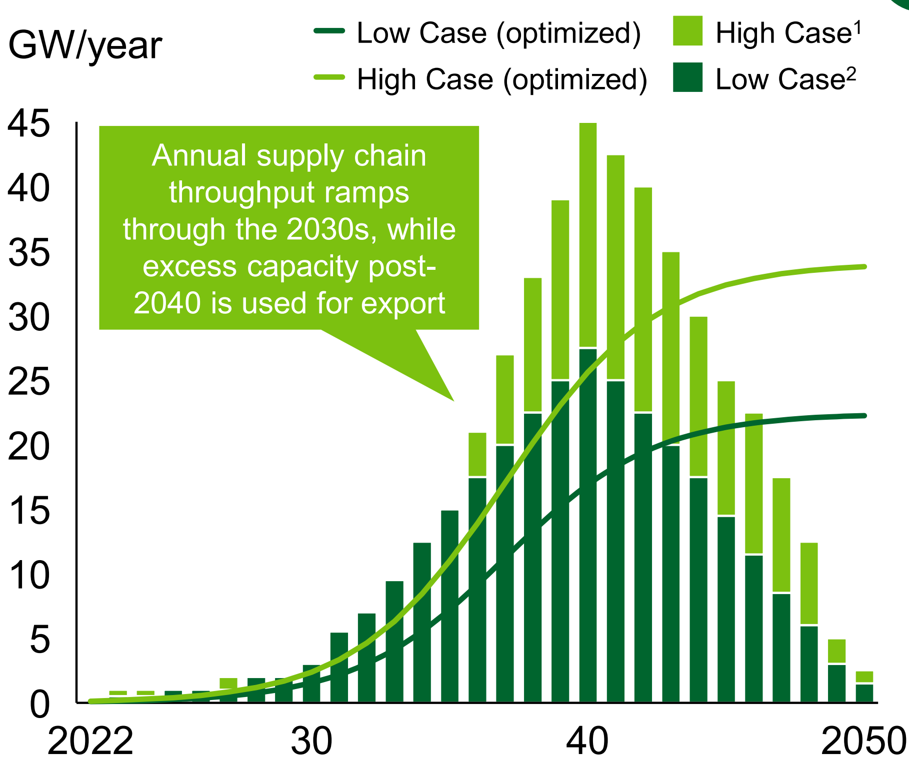
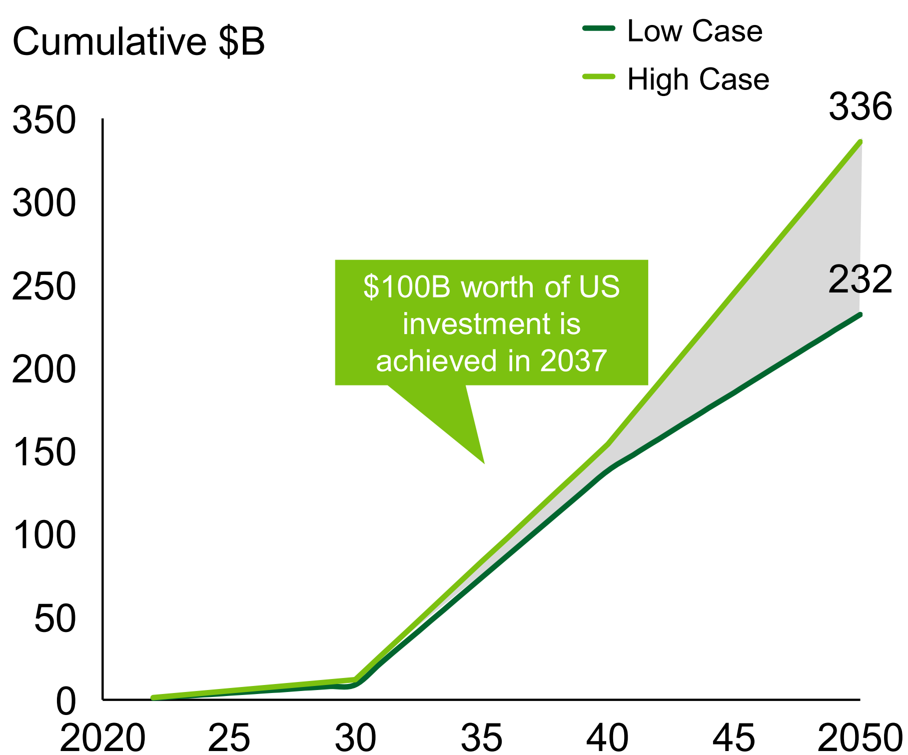
3C An industrial-scale supply chain could require $70-100B in manufacturing investment alone, with up to $330B in total capital formation

Annual deployment need (GW / year)



Total investment need ($B)



Manufacturing needs

- Nearly no at-scale manufacturing facilities exist in the US today
- ~30% of total capital formation needs, or **$70-100B, will be required for manufacturing capacity alone**
- Most technologies can be supplied through domestic or allied supply chains alone, leading to **few areas of vulnerability for large-scale stand-up** (aside from potential labor shortages)
- Annual deployment capacity will be overbuilt by 5 and 10 GW in the low and high cases, respectively, but could be **diverted to exports** post 2040 peak

1 Based on Pathways modeling Unconstrained Renewables Net-zero by 2050 Scenario
2 Based on Pathways modeling Constrained Renewables Net-zero by 2050 Scenario
NOTE: Optimized cases are based on the minimum possible manufacturing buildout by 2050 to meet scenario buildout

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3 Execution will require focus on key leading and lagging indicators

Leading indicators by 2026

$1,000 / kW
Inter-day capex

$1,700 / kW
Multi-day / week capex

70%
Inter-day RTE

50%
Multi-day / week RTE

25+
Inter-day players meeting these indicators

15+
Multi-day / week players meeting these indicators

$75 / kW-year
Consistent capacity market access for LDES

Lagging indicators by 2030

6-15 GW
Deployed LDES capacity

$10-25B
Private capital mobilized for projects

3 GW
Domestic manufacturing capacity

Thank you!

Download the report: liftoff.energy.gov

For feedback: liftoff@hq.doe.gov

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