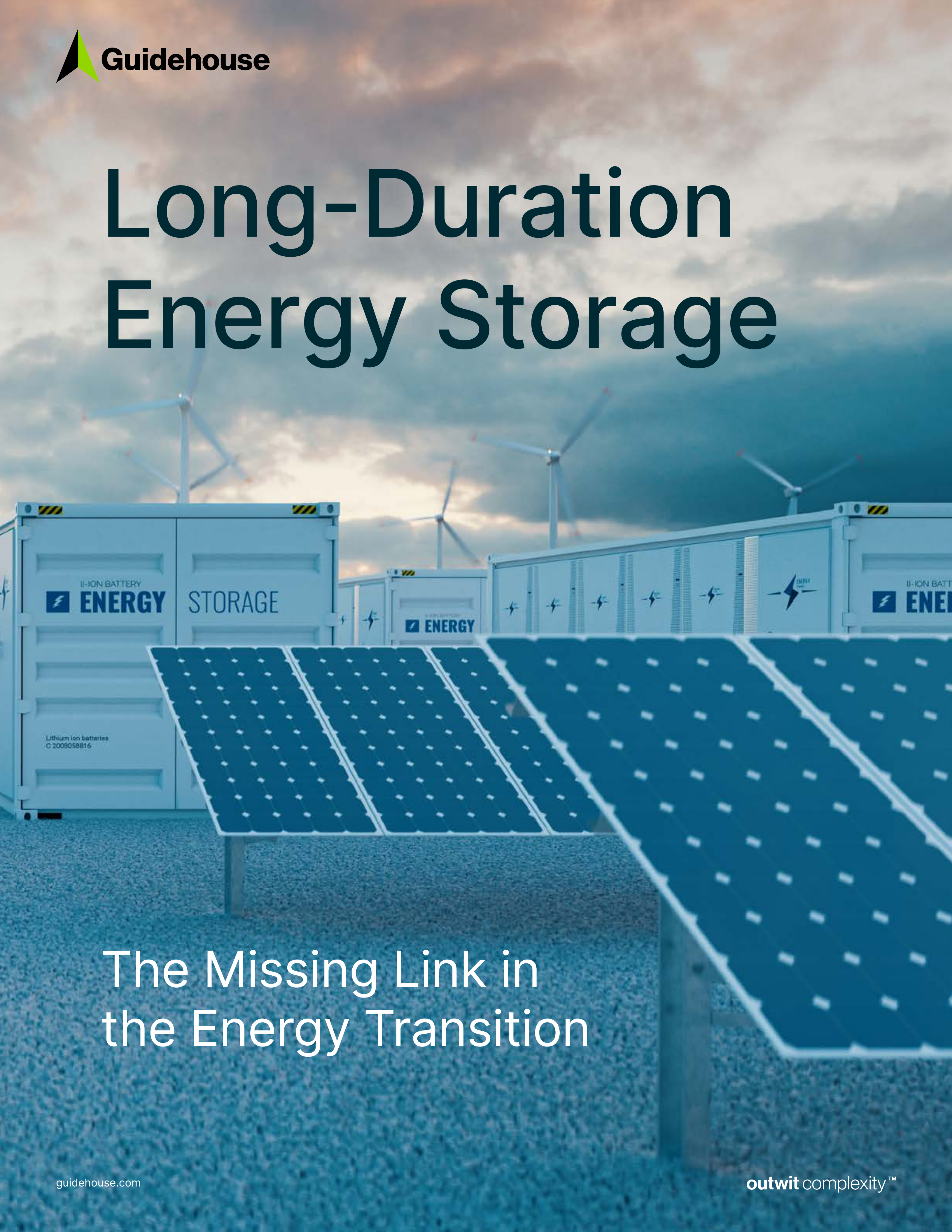
Guidehouse

Long-Duration Energy Storage



The Missing Link in the Energy Transition

Long-duration energy storage: A full spectrum of technologies addressing various use cases in our transitioning energy systems

Long-duration energy storage (LDES) is currently gaining attention from policymakers, energy providers, and investors alike thanks to their promising use cases for future energy system resilience, with 120 GW of capacity forecast by Guidehouse by 2030. Despite this progress, the ever-growing penetration of renewables and flexibility needs in energy supply mixes calls for even more investments in flexible, medium and long-term, large-scale storage technologies. Here Guidehouse examines the current state of the LDES market, the challenges it faces, and the opportunities it offers.

This paper examines five key questions associated with the development of LDES tech:

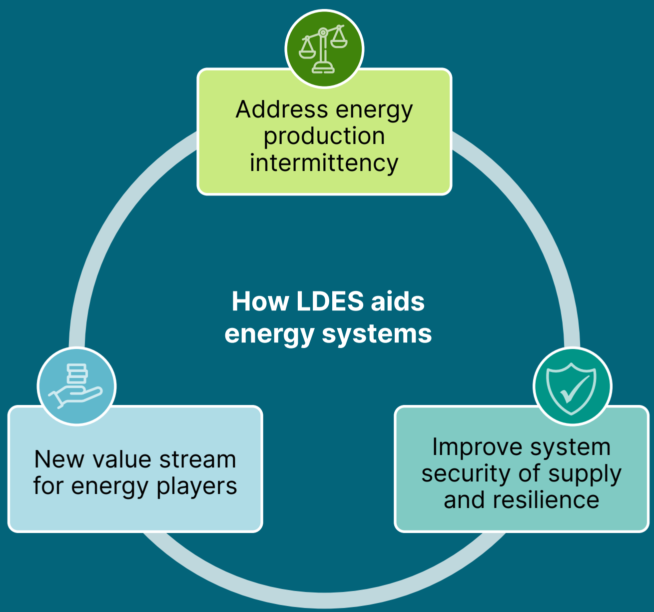
- What is LDES and what solutions can it bring to the energy system?
- How do LDES technologies work?
- What is the business case today and 10 years from now?
- What are the market drivers and barriers?
- What actions need to be taken now to accelerate uptake?

1.0 Part 1: The emerging energy system is requiring LDES **now**

1.1 LDES is the glue that will hold together future energy systems with high penetration of renewables

Energy systems are now seeing challenges from the introduction of intermittent renewable energies, ranging from the economical — price volatility and impacts on the load factors of other generators — to the technical, such as a critical loss of inertia in a system historically designed along spinning machines. LDES could provide a way of "firming" this renewable production, making a wind or solar resource look more like a conventional generator without the drawbacks in terms of emissions.

Figure 1: Three Added Values of LDES



Manage intermittency — LDES is modular and can be designed for various ranges of input power, output power, and energy capacity.

Their capacity to discharge over long periods of time is particularly well adapted to the highly intermittent nature of future energy systems. Current LDES technologies under development can discharge for more than eight hours, making them a complement to Li-ion systems, which typically target between one- and four-hour applications.

Support security of supply and resilience — Growing global geopolitical tensions, such as the European energy crisis caused by the Russian invasion of Ukraine, have also exacerbated the need for short- and long-term energy resilience and flexibility, something which LDES offers. As LDES supports greater mobilization of renewable energies at all levels of the grid, these technologies will also accelerate the push towards energy independence.

Add new value — That said, LDES also benefits from a unique business case for energy providers and network operators as they enable not only a range of ancillary services but also support new business models around the commercialization of renewable energies such as baseload PPAs. In addition, they also provide so-called local flexibilities by potentially avoiding costly grid upgrades to connect new capacities.

1.2 No one size fits all: Multiple LDES technologies can answer various environmental and use case questions

Storage technologies, including LDES and Li-ion, do not answer to a one-size-fits-all principle. A wide range of technologies, featured with a variety of technical parameters, can fit all kinds of use cases. LDES points to several technologies that can be grouped according to their energy conversion mean.

Figure 2: Overview of LDES Technologies

Chemical Storage

Energy storage through chemical reaction.

Includes all kinds of Power-to-X (i.e. hydrogen, ammonia, methane)

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- ✓ Complete decorrelation of power and energy capacity
- ✓ Very large scale
- ✓ Very long storage duration
- ✓ Direct use of the molecule
- ✓ Retrofit of depleted underground reservoirs (i.e. methane storage)

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- ✓ Low conversion efficiency
- ✓ Geographical and geological dependency
- ✓ Off-takers to be found

Mechanical Storage

Convert electricity into mechanical energy (i.e. gravitational pressure).

Includes compressed air energy storage, liquid air energy storage, pumped-hydro storage, gravity-based storage, etc.

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- ✓ Complete decorrelation of power and energy capacity
- ✓ Very large scale
- ✓ Daily cycle
- ✓ Low lifecycle analysis
- ✓ Low energy-based CAPEX (/kWh)

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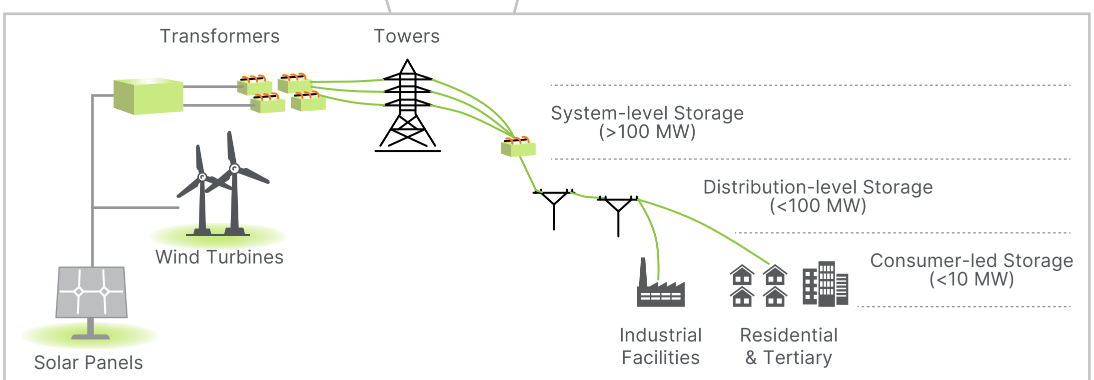
- ✓ High space requirements
- ✓ Geographical constraints
- ✓ High power-based CAPEX (/kW)
- ✓ Relatively low round-trip efficiency



Thermal Storage

Various combinations of thermal storage medium and heat-to-power/power-to-heat conversion units.

Includes sensible heat, latent heat, and thermo-chemical storage.

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- ✓ Complete decorrelation of power and energy capacity
- ✓ Wide variety of scale
- ✓ Wide variety of operational modes
- ✓ Low lifecycle analysis possible
- ✓ Low energy-based CAPEX (/kWh)
- ✓ Heat integration opportunities

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- ✓ High power-based CAPEX (/kW)
- ✓ Low maturity
- ✓ Relatively low efficiency

Electrochemical Storage

Includes all kinds of electrochemistry with a variety of material involved (i.e. flow batteries, zinc-air batteries, Li-ion, NaS).

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- ✓ Short to medium scale
- ✓ Medium to high discharge duration
- ✓ Low space and geographical constraints
- ✓ High round-trip efficiency
- ✓ Low power-based CAPEX (/kW)

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- ✓ High energy-based CAPEX (/kWh)
- ✓ Potentially low maturity
- ✓ Potentially very high lifecycle analysis

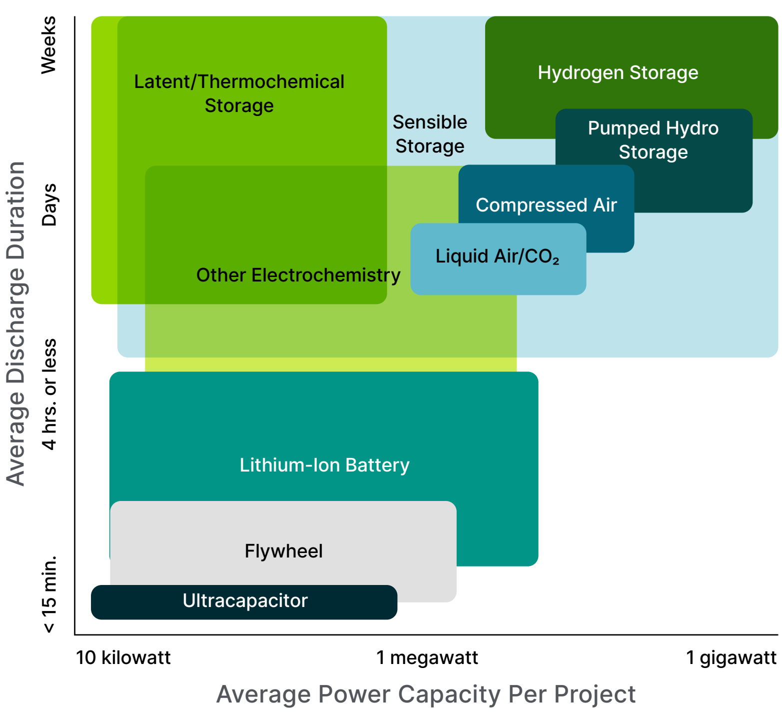
CAES: Compressed Air Energy Storage; LAES: Liquid Air Energy Storage; PHS: Pumped-Hydro Storage; LCA: Lifecycle analysis

Long-duration storage technologies are almost all getting close to commercialization (if not already) but are still lacking very high round-trip efficiency even though the long hours storage duration possibilities that they provide.

Table 1: Key Characteristics of Selected LDES Technologies[1]

Category	Technology	Market readiness	Max. deployment size (MW)	Storage duration (hours)	Degradation	Round-trip efficiency (%)	Footprint (kWh/m²)
Mechanical	Novel CAES	Commercial	200-500	6-24	0.5-1%/year	40-70	12.5
	Liquid Air	Commercial	50-100	10-25	0.5%/year	60-75	59-74
	Liquid CO_2	Pilot (commerical announced)	10-500	4-24	0.1%/year	70-80	4-5
Thermal	Sensible heat	Pilot to commercial	10-500	200	Minimal (0.02%/ year for molten salts)	55-90	30-800
	Latent heat	Pilot to commercial	10-100	25-100	Minimal	20-50	30-450
	Thermochemical	R&D/pilot	N/A	N/A	N/A	N/A	N/A
Chemical	H_2 storage	Commercial	10-1,000	500-1,000	0.1-0.4%/1000h	40-70	5-50
Electrochemical	Flow batteries	Commercial	>100	25-50	0.40%/year	55-75	15-30

Figure 3: Sweet Spot Discharge Duration Against Installation Power Capacity[2]



The variety of technologies increases the options of storage implementation and scale-up: all use cases, required power capacities and discharge duration needs, could be accommodated by LDES. For example:

- **Chemical storage** is meant for long discharge time and energy capacity, perfectly matching a seasonal storage need.
- **Electrochemistry** is meant for daily storage as a coverage for renewable intermittency or back-up power source.
- **Thermal storage** technologies benefit from a large energy density, modularity of its power conversion unit[3] and low energy degradation over time.
- **Mechanical storage** fits for large-scale and long-duration use cases.

[1] LDES council report "Net-zero power – Long duration energy storage for a renewable grid. Conversion units' footprint. Storage happens underground.

[2] Guidehouse analysis

[3] Conversion units' footprint. Storage happens underground.

Maturity, spatial footprint, and cost are key items to take into consideration when deploying a storage facility. The use cases (Table 2) addressed by LDES are various based on the following pillars: Creation of different market valuation and service system revenue streams, maximization of renewable productivity, and security of supply.

Table 2: Use Cases for LDES[4]

Use case	Description	Electrochemical	Mechanical	Chemical	Thermal
Integration of renewable production assets	Supply side: Avoid expensive grid upgrade investments and curtailment of large-scale renewable farms by shaving peak production to smooth out renewable intermittent output	✓	✓	✓	✓
Process & site demand optimization	Demand side: Increase the security of supply of large-scale, energy-intensive industries with a variable demand by storing	✓	– *	✗	✓
Site resilience & back-up power	Demand side: Provide an efficient and low carbon back-up system	✓	– *	✗	✓
Market valuation & capacity provision to other parties Transmission System Operators/ Distribution System Operators (TSO/DSO)	Supply and grid side: Participation in wholesale energy market, as well as in ancillary services and capacity markets, thus generating different revenue streams	✓	✓ ** Except fast frequency response*	✓ ** Except fast frequency response*	✓
Power-to-X & feedstock production	Demand and supply side: Convert electricity into storable chemical, also unable as a feedstock of a fuel itself	✗	✗	✓	✗
Transmission/ Distribution deferral	Supply side: Delay/avoid investment in development of new or updated transmission and/or distribution assets	✓	✓	✓	✓

* Usually too large-scale to fit into space-constrained industrial demand site

** Slow ramp-up rate disqualifies chemical and mechanical storage for frequency response

[4] Guidehouse analysis

1.3 High Reduction Cost Potential

Storage implementation success is closely tied to the actual business case of the previously mentioned storage technologies. Indeed, each technology has been assessed for their optimal design (power and energy capacities).

- Electrochemical, thermal, and mechanical storage for a system of 200 MW and eight-hour discharge duration
- Chemical storage for a system of 1 GW and a four-week discharge duration

Guidehouse used its proprietary LCOS calculation model to assess all the technologies against their optimal design and presented the results in Fig. 4.

Figure 4: Levelized Cost of Storage (LCOS) Range of Selected LDES Technologies in 2022[5]

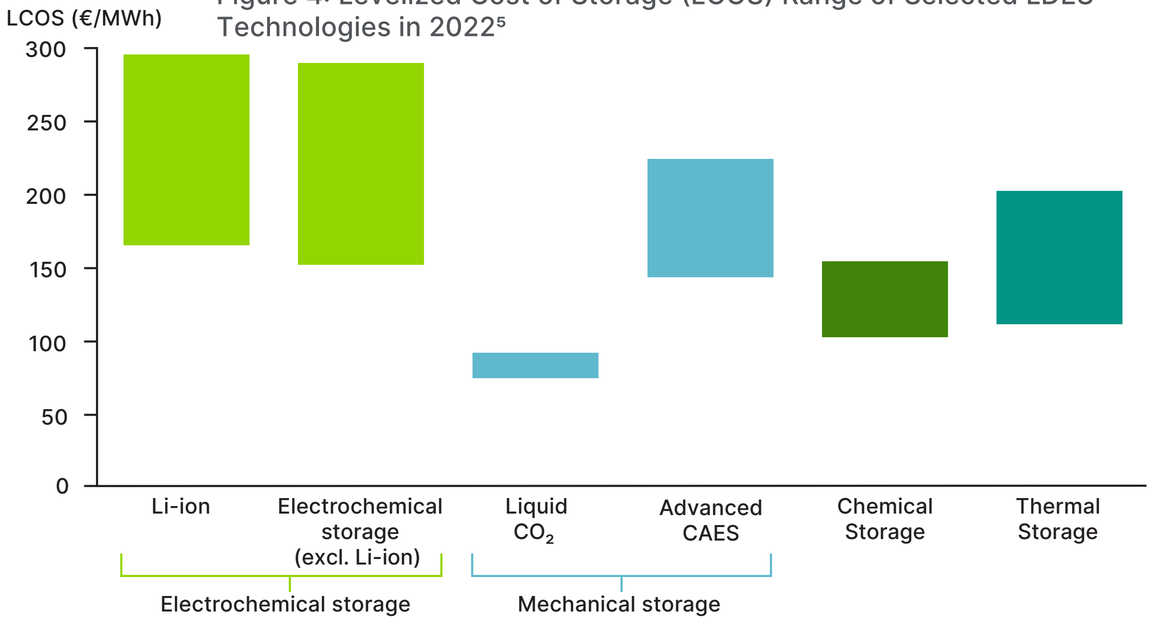
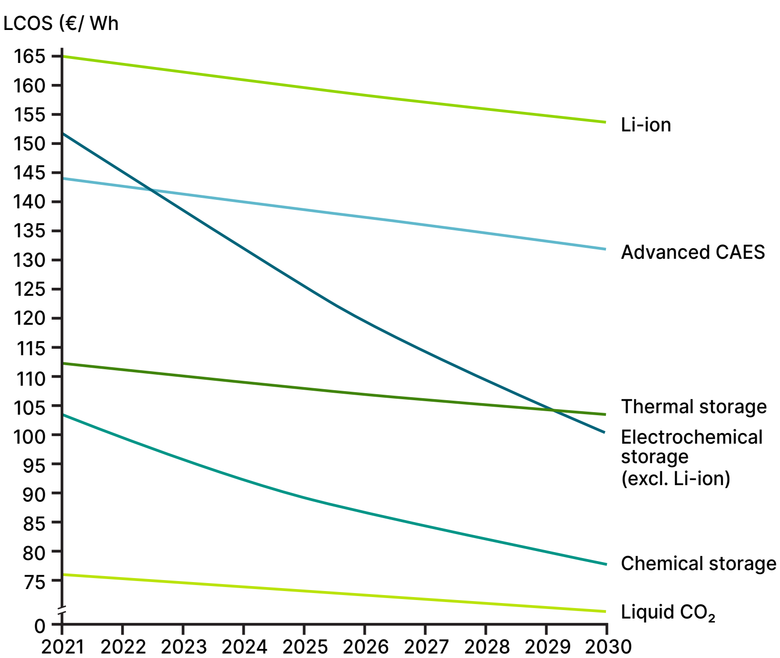


Figure 5: LCOS Evolution to 2030 Based on the Low-cost Boundary of Selected LDES Technologies[6]



With reference to the foreseen decrease in costs for LDES (see Fig. 5), storage is expected to be a cost-efficient solution, particularly in the context of substantial grid expansion needs, as well as the significant growth of carbon price that decreases the competitivity of flexible fossil-based assets, such as combined cycle gas turbine.

Guidehouse expects LDES technologies to control the market sooner rather than later and provide a wide range of services to the grid. Cost reduction can be attributed to learning curves due to scaling in number of projects and size and a decreased tension in the supply chain. But LDES also faces challenges in achieving the same reductions in price as Li-ion batteries did in 30 years, in less than 10 years (commercially ready by 2030). To address the last challenges of LDES — cost and maturity — policy incentives from the governments will be key to accelerate their deployment.

[5,6] Guidehouse analysis

2.0 Part 2: LDES market development is growing **fast**

How is LDES populating the energy market across the world?

2.1 Attracting growing attention from diverse stakeholders that hold out the prospect of a rapid scale-up of LDES

LDES is experiencing an uptick in interest from a variety of organizations and institutional bodies ranging from the Massachusetts Institute of Technology (MIT), International Renewable Energy Agency (IRENA)[8], and dedicated industry associations.[9]

This enables more and more initiatives from states and public administrations such as the LDES funded by the UK government and provisioned with £1 billion for commercial and demo project on LDES. Among others, four flagship projects launched by EDF partnering with three storage technology providers have been announced in this context.

In the U.S., the Inflation Reduction Act of 2022 introduced through tax credits a commitment of $369 billion to climate change mitigation and energy security. This means the introduction of investment tax credit (30%-70% of CAPEX) for standalone and co-located energy storage assets, which gives for the first time revenue foresight to investors.

However, the European Commission only made a few mentions of energy storage in its REPowerEU plan, published in May 2022. Although it recommends a €10 billion investment for energy storage (no specification on which kind) and actively promotes the development of many clean energy concepts such as renewable energy, energy efficiency, renewable gases, and energy savings, it only refers to energy storage here and there without a specific plan. There is a slight emphasis on developing a hydrogen infrastructure involving storage capacity.

Hence, the momentum has been created but needs to be accelerated significantly in the coming years to meet the grid transition targets. The LDES council foresees in their report the global need for 1.5-2.5 terawatts (TW) of LDES-installed capacity (85–140 TWh energy capacity) by 2040 to support our clean energy systems.[10]

[8] "Electricity Storage Valuation Framework 2020." n.d. www.irena.org. https://www.irena.org/publications/2020/Mar/Electricity-Storage-Valuation-Framework-2020.

[9] Department of Energy, U. 2020. "Energy Storage Grand Challenge." https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf.

[10] LDES Council, "Long Duration Energy Storage to accelerate energy system decarbonization." www.ldescouncil.com. https://www.ldescouncil.com/insights/.

Investment is flowing in LDES technologies

LDES is also attracting the attention of major investors. Form Energy has raised €450 million from investors, including ArcelorMittal. Hydrostor, an advanced CAES startup, secured $250 million preferred equity financing from Goldman Sachs at the end of 2021. Energy Dome raised $11 million in bridge financing and secured nearly $25 million in advance of its Series B funding. Large industrial corporations are also doling out funds, convinced that energy storage will be on the levies for their decarbonization.

ArcelorMittal launched its Xcarb Innovation Fund in 2021 to invest in clean technologies that could support global steel industry decarbonization (already $197.5 million investment commitments).[11] They recently invested a second time in Form Energy (long-duration iron-air battery energy storage) with $17.5 million in 2022, following a first investment of $25 million. The scope of work under this investment is the adaptation of Form's technology to steelmaking process.

[11] ArcelorMittal Makes Further Investment in Form Energy via XCarb® Innovation Fund | ArcelorMittal." n.d. Corporate. arcelormittal.com. Accessed December 21, 2023.

https://corporate.arcelormittal.com/media/press-releases/arcelormittal-makes-further-investment-in-form-energy-via-xcarb-innovation-fund.

2.2 Accelerated project implementation and players emerging driving the LDES technology providers markets

The market is driven by a number of innovative providers at every stage of maturity that enable movements in the market. Depending on the technology, the competition is high or virtually reduced to a monopoly. We interviewed four providers, each leading the market on their technology segment: Energy Dome, Fluence, Storengy, and Hydrostor.

Energy Dome uses CO_2 in a closed-loop thermodynamic process with no atmospheric emissions, achieving high round-trip efficiency (AC-AC) of +75% without any site dependency or performance degradation over the entire plant lifetime, 25-30 years.

"[Our CO_2 battery] can participate in hourly day ahead markets, ancillary service markets as well as real-time energy markets, allowing for revenue-stacking. Because the system uses rotating machinery, it also provides inertia."

Fluence commercializes lithium-ion based energy storage (electrochemical storage) and "the Fluence IQ Platform, which delivers AI-enabled SaaS products for managing and optimizing renewables and storage from any provider".

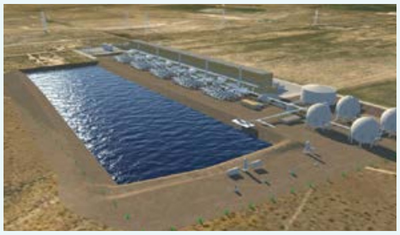
"We have repeatedly pioneered new use cases for grid-scale energy storage. Some of the uses we have supported include frequency regulation, generation enhancement, capacity peak power, energy cost control, microgrids/islands, renewable integration, virtual dams, training and development enhancement, and critical power."

Storengy is developing a fast-cycling Underground Hydrogen Storage (UHS) in France that allows it to transform surplus of renewable electricity into hydrogen by electrolyzing water and storing it. UHS offers the flexibility to store hydrogen for one day or for one year. This solution is assumed to decrease final green H_2 price by more than 20%.

"Storengy is convinced large-scale hydrogen infrastructures have a leading role in supporting the development of an affordable clean hydrogen market.

"As a pioneer in high cycling frequency hydrogen storage, the Storengy HyPSTER project (fast-cycling salt cavern hydrogen storage) aims to facilitate the replication of these key assets at a European scale."

Hydrostor is developing large-scale, long-duration CAES. Their system is usually intended to be stand alone or co-located with large renewable power parks and to either rely on existing disused salt cavities or mines or to use purpose-built cavities in hard rock geologies.



"Hydrostor is seeing clear market signals for the requirement of LDES in many jurisdictions, the most notable example being California's procurement order for 1 GW of eight-hour storage. While in the long-term market mechanisms (such as capacity markets valuing long durations) can provide the solution to incentivizing LDES, such initiatives take significant time and stakeholder engagement to properly implement. In the near term, similar to California, we expect to see targeted LDES procurement through long-term contracts as an interim measure while the market mechanisms are developed."

2.3 Quick wins and what it takes to develop LDES at large scale

2.3.1 Policymakers: create a compelling framework to facilitate LDES uptake

Sound policy is playing a key role in enabling the expansion of the LDES market and can draw from the successes of the renewables by first creating financing incentives and similar revenue support systems. We can quote contract for difference, feed-in-tariffs, or other measures to support financing plans.

At the energy system level, LDES must become at least as attractive as installing a gas-fired turbine. Governments can do this by raising carbon prices, but in order to specifically foster LDES growth, it will also require new energy market mechanisms, driven by TSO/DSOs, such as a bidding process to encourage local flexibility capacities installation (or the same process as capacity market). LDES can decrease the need and amount of grid upgrades investments locally while avoiding renewable peak shaving and acts as a buffer that can help build an optimally designed grid.

2.3.2 Market players: scale and secure LDES projects' deployment

LDES is an opportunity for revenue stacking for energy providers, including renewable producers. In addition to collecting revenue from the energy sold at each discharge cycle, the storage can be easily valued on a market with an ever-growing renewable capacity penetration. It will also allow the providers to build larger parks, meaning more revenues, by decreasing the need for grid connection voltage increase.

Energy providers should therefore think about an action plan to enter the LDES market quickly and benefit from the first mover advantage. Following are the first steps to take:

1. Market and use case analysis:
   Engage a deep market analysis and select the technology that best fits their priority, geographical presence, and use cases. This phase can be completed by revenue stream modeling and optimization at zonal and/or nodal levels, and detailed business case analysis.

2. Opportunity watch:
   Pay attention to watching opportunities from the LDES ecosystem. This phase includes watching competitors' moves and announcements of subsidies and support programs from governments and supranational organizations. Be prepared to act as quickly as possible.

3. Technology and commercial partner identification:
   Identify the best technology providers to partner with to build this new activity. Depending on the project and the financing plan, energy providers should examine their options in order to share the risks: internal growth, external growth by acquisition, joint venture creation, or consortia.

4. Project implementation:
   For such LDES deployment, project build-out and execution require a structure approach and efficient PMO. This encompasses a holistic approach with several workstreams: grant management, commercial and business model, financing, policy and regulation, and digital and data throughout the different phases of a LDES project, from feasibility and FEED to execution and commissioning. A specific attention is done on stakeholder engagement with local authorities and communities, offtakers, and power TSO/DSO. Guidehouse has experience in this complex program management.

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