International Journal of Electrical and Data Communication

E-ISSN: 2708-3977
P-ISSN: 2708-3969
Impact Factor (RJIF): 5.73
IJEDC 2025; 6(2): 21-29

www.datacomjournal.com
Received: 08-06-2025
Accepted: 10-07-2025

Moawia Ibrahim Ahmed Hamed
B.Sc. Electrical & Electronic Engineering, Omdurman Islamic University, Sudan; MBA (Ongoing), University of East London, UK; Nesma & Partners, Saudi Arabia

Correspondence Author:
Moawia Ibrahim Ahmed Hamed
B.Sc. Electrical & Electronic Engineering, Omdurman Islamic University, Sudan; MBA (Ongoing), University of East London, UK; Nesma & Partners, Saudi Arabia

Long duration energy storage technologies: A comprehensive research

Moawia Ibrahim Ahmed Hamed

DOI: https://www.doi.org/10.22271/27083969.2025.v6.i2a.75

Abstract
Long-duration energy storage (LDES), namely the storage technologies that have the potential of discharging as long as 8 hours or more (and up to days or seasons), is quickly gaining traction as grids without much thermal generation support high shares of variable renewable energy (VRE). LDES will focus on energy switching, staying resilient throughout multi-day low renewable events, and seasonal load balancing. This review characterizes the key classes of LDES technology (mechanical, electrochemical, fuel forming, and thermal), compares techno-economic indicators, provides a survey of demonstration projects and market signals, and lists environmental and supply-chain issues, as well as research and policy imperatives to scale LDES on an economically viable and sustainable manner. The most notable is that no one LDES technology has all the uses covered - pumped hydro in clear geographical locations is still by far the dominant, flow batteries, iron-air and hydrogen each have their market niches, and thermal stores as well as hydrogen are still being developed; that levelized cost and value is highly dependent on duration, pattern of discharge cycles, and system specifics; and risk-sharing instruments, market reforms, and coordinated RD&D are needed to bring promising technologies out of pilot to scale (IEA, 2024; NREL,2023; DOE, 2024).

Keywords: Long-duration energy storage, renewable energy, grid resilience, techno-economic analysis, energy policy

1.0 Introduction and Scope

The world is rapidly migrating towards low carbon energy systems thanks to the threats of climate change existentialism, advances in technology and shifting policy. These assets are increasingly finding a presence at a high level at the expense of more traditional fossil fuel technology but the intermittence and the reliance on the weather creates an unfavorable consequence in the flexibility and resilience of power system (IEA, 2024) [1]. As the VRE penetration grows even higher this will result in a more mismatch between the supply and demand of electricity and to equalize the demand and supply at hourly, daily and arguably even seasonal level, strong technologies and mechanisms will be needed.

There are the typical forms of energy storage batteries, which are proven to be very efficient in the short term micro-services, such as frequency control, ramping, and daytime energy arbitration (Lazard, 2023) [12], using lithium-ion (Li-ion) batteries. Nevertheless, limited access to compete long-duration applications is brought out by Li-ion technologies, through the financial and technological aspects of the systems. In particular, they will not increase the cost of power (USD/kW) accordingly to their demand, and their energy costs (USD/kWh) would grow exponentially as time goes by making them not as effective during discharge periods that surpass 68 hours (NREL, 2023) [2]. The thing that is left behind by this is the strategic inadequacy in requirements of energy storage, and cannot be contacted by the application of the conventional batteries.

Energy storage over long durations (LDES) has the capability of reducing such a gap, given the ability to last a minimum of eight hours of discharge. The received category of LDES has many alternative technologies, which include mechanical (e.g. Pumped hydro, compressed air), electrochemical (e.g. flow batteries, metal air chemistries), chemical and fuel based (e.g. Hydrogen, ammonia), and thermal times (e.g. molten salts, liquid air). These tend to have discharge times of 100+ hours, although some are on a seasonal basis, such as hydrogen based systems (Nature Communications, 2024).

The argument supporting LDES as being valuable is that, besides contributing to high VRE penetration, they also help to improve grid resiliency through low-renewable events (i.e. dunkel flaute) and the potential to deliver firm capacity and generate less renewable curtailment. In addition, LDES can produce energy that is quasi-integral following the integration of electricity with heat, cool, transportation, and industrial energy and thus, reinforce integration and decarbonization of the overall energy system even more quickly (DOE, 2024) [3]. In the meantime, the factors of cost-competitiveness, scale, environmental implications, and supply chains together with the necessity to have markets in order to commercialize LDES face it.

The paper is a multi-faceted technology-based critique of LDES that has been organized to include synthesis of the recent scholarly research published in the academic field, and reports released by governments and industries and demonstration projects in different sectors of the world. These are on four broad fronts:

1. **Screening technology:** Mechanical, electrochemical, fuel-forming, thermal storage categories and cross-tabulation.
2. **Techno-economic factors:** The role of capital cost, performance, life and system value, time and scale of deployment.
3. **Survey of deployment landscape:** What are the current and emerging usecases, demos and commercial pilots, national strategies.
4. **LDES ecosystem requirements:** what the policy-makers perceive as the market, as well as policy and supply chain enablers that will be necessary along the path to the scaling of LDES in a cost-effective and sustainable way.

In conclusion, this paper will summarize the challenges of LDES in the future energy system, compare trade-offs among technology pathways, and identify research and policies that can contribute to the commercialization of the technology. Lastly, results of the analysis warn against the leap from the various LDES technologies into a single one-size fits all tool under any one specific LDES technology for the latter to meet local systems' traits and policy goals to decarbonise in a comprehensive way.

2.0 Why LDES Matters: System Needs and Value Streams: The change towards high wind and solar energy, however, also raises system questions that will only be resolved through combinations involving long-life time power storage sources. LDES is playing a key role to the achieving the energy storage goal in high-renewable power systems that are reliable and cost effective. The value of LDES can be articulated as an aggregation of four top-level system requirements and value streams energy shifting, resilience and reliability, capacity firming and transmission deferral and market/ancillary services.

Energy Shifting (Diurnal to seasonal)

Arguably the cheapest idea that LDES brings is that it will be possible to transfer vastly larger volumes of energy when it is more plentiful and then back down to when it is scarcer. The problem with variable renewable energy (VRE) sources, especially wind turbines and solar PV, is due to timing which does not match demand. Use a case scenario, in the middle of the day, there is unnecessary amount of solar PV producing electricity yet, the most probable scenario is that the electric demand is high in the evenings. Similarly, wind power is able to produce much on nights and minimal during windless peak-demand days. Short duration lithium-ion batteries which have a typical discharge duration of less than 1-4hours can be effective at managing intraday variability of energy changes but are exponentially more expensive to scale to the 10s and 100s of days of seasonal energy change (NREL, 2023) [2].

LDES technologies bridge this gap since it allows a storage of up to 8 hours or several weeks. This allows diurnal balancing and seasonal reallocation of energy i.e. tapping excess spring/autumn wind or solar power generation and storing it, to use during off-set winter weaker-generation periods. Quantitative modelling finds that with greater VRE levels (above 7080 per cent) seasonal storage is seen to reduce renewable overgeneration by up to 2030 per cent and prevent cost increases by avoiding excessive generating overbuild (Nature Communications, 2024; IEA, 2024) [1].

Resilience and Reliability

Power networks will further need to be reliable at these periods of fluctuating stress like low renewable days, or as it is called in Europe dunkel flaute. Such activities characterized with a series of days of cloudy and without-wind conditions indicate weaknesses of short-duration batteries and flexibility on demand. LDES such as pumped hydro, compressed air energy storage (CAES), hydrogen based, and emerging metal air batteries can supply many hours to days of power distribution and thus will supply power when VRE is spare (DOE, 2024) [3].

As well as the usual services provided on the grid, LDES can also be critical in resiliency during extreme weather crisis, or other power failure, or emergency. It is also piloted that thermal storage and hydrogen fuel cells are employed as backup supply in Japanese, American, and European hospital and data center (IEA, 2024) [1]. Facilitating multi-day provision of dispatchable capacity not only increases technical resilience, but social resilience, in regard to protecting critical services during perturbations.

Capacity Firming and Transmission Deferral

Another system value of LDES is that it alleviates the need of introducing firm fossil-based back-up and delays the relatively costly grid reinforcements. Firming of renewable power LDES can effectively secure intermittent wind and solar power to firm up power and produce capacity. This reduces the reliance on gas Peaker plants or coal reserves, just like it promotes the decarbonization agenda and is still able to maintain adequacy.

In addition, distribution and transmission networks are faced with wear-outs as renewable capacity is enlarged in the areas of distant resource wealth. LDES deployment at a local level can ease congestion when it is most needed, time-shift energy closer to the load and delay costly transmission investments. Distributed LDES has also been cited as a realistic alternative to transmission build up in countries such as India and China where transmission building projects have a high social and capital cost (IRENA, 2022) [13].

Market and Ancillary Services Stacking
LDES has positioned itself as not only electricity bulk shifting provider but as a multifunctional one in the electricity markets. LDES will potentially commercialize multiple value streams through the stacking process depending on the system rules.
These include:

- **Energy arbitrage:** charging when the price is low and pay the high price during the high price period.
- **Capacity payments:** being on hand as firm capacity in the hope of ensuring revenue.
- **Ancillary services:** the provision of spinning reserves, regulation, black-start capabilities, inertia-like capabilities.

Non-energy services: the heat storage systems can find use to provide industrial heat and decarbonize transport and chemical industries with hydrogen-based storage.
The possibility of stacking revenues is of particular importance because LDES technologies have large upfront capital requirements. In fact, the analysis in the study of the vanadium redox flow battery has demonstrated that alone arbitrage would not yield sufficient returns that would be sufficient to neither justify nor support the project but when combined with ancillary services and capacity contracts it can augment the project economics significantly (Nature Communications, 2024). Also, there are pilot projects in Europe that all integrate power, heat, and industrial feedstocks value streams, so as to trigger optimal deployment of hydrogen storage (IEA, 2024) [1].

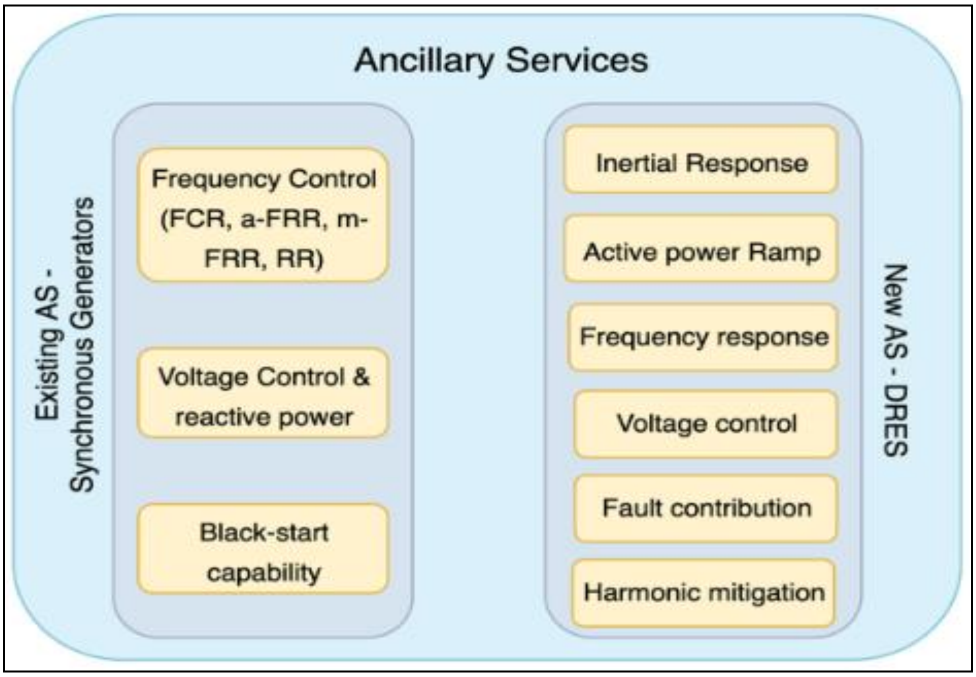

Fig 1: Ancillary Services Market Design in Distribution Networks

System-Level Impacts
LDES has an extremely situational value. Modelling exercises point to maximum benefits under a scenario of:

1. When renewables are high enough (>70%), then curtailment would increase.
2. Mixed with limited growth in transmission, however, this enhances the role of local stores further.
3. Seasonal dependency of supply and demand, as is the case with Northern Europe, or North America.
4. Due to falling technology prices of LDES, it increases the cost-competitiveness against fossil peakers and renewable over-build (NREL, 2023; IEA, 2024) [1, 2].

In this case, LDES may reduce the total cost of this entire system by up to 20 per cent compared to that of portfolios comprising battery storage of limited, short durations and fossil peakers. The kind and period of its deployment are nonetheless arguable due to the barriers of cost, policy, and-market, which shall be addressed in the other part of this paper.

3.0 LDES technology classes — principles, maturity and comparative traits: Mechanical storage: Pumped-storage hydropower (PSH) is an advanced LDES and is the form representing about 90 percent of global stored energy capacity. PSH employs 2 crafts with different levels of power in it that serves as a potential energy storage. It has long operating life (decades), great storage capacity (multi-hour to seasonal), but very high initial costs, long permitting period and geographic constraints to build. The closed-loop and underground alternatives of PSH can contain the environmental impacts and bring an advantage of more siting places where the natural topography is not accessible.
Compressed Air Energy Storage (CAES) utilizes cavern (or vessels) that are used to compress air then expanded to drive turbines. Conventional (diabatic) CAES deployment uses fossil-fuel reheating, meaning reduced effective roundtrip efficiency and emissions; advanced adiabatic, and isothermal CAES would recover some of the compression energy to decrease overall emissions and roundtrip efficiency. AES is best suited in large, long-term installations that are done under conditions that have preferable or appropriate geology (Renew Sustain Energy Rev, 2022) [14].
Gravity based systems (lifting heavy blocks or masses etc.) are also new concepts, which have demonstrated a long life, and modular siting. These systems are relatively immature in commercialization and suffer scaling, cost and land

limitations. Pilots are being conducted in the industries in both engineering and economics that are also compared with the commercial contracts.

Electrochemical storage: Flow batteries thereof include vanadium redox flow, iron-based, zinc-bromine and organic chemistry types of Flow batteries and yield flexibility in energy capacity (size of tank) and power (size of stack), and are consequently predisposed towards longer durations (8-100+ hours). The most commercialized flow cell, to date, is seen with RFBs, having high cycle durability and the aspect of ease of scale-up it has; however, the cost of a vanadium and its price fluctuation has been a slowdown factor. Reduced literature costs (iron, organic redox couples) are in demonstration towards reducing the energy-specific capital cost and supply-chain risk (Science Direct reviews, 2024-2025) [6, 7].

One within metal-air is iron-air, as it can achieve multi-day run-times (such as 100-hour batteries), and at low material cost, such as companies and pilots targeting grid demonstration (Form Energy, Ore Energy). These chemistries often trade round-trip efficiency at very low kWh cost of storage, and can have the lowest cost per kWh to use in applications where the electricity arbitrage premium is less time sensitive and where long duration is required (News and Industry sources, 2024) [15].

Lithium-ion is currently routinely applicable in short duration applications, but rapidly loses cost-competitiveness at excess of ~6-8 hours length due to issues related to both scale up of the energy-tank and energy-tank degradation; manufacturers and researchers are making improvements to the cell chemistry and balance-of-plant to enable slightly longer duration applications (NREL ATB, 2024) [9].

Fuel-forming storage: Electrolytic Hydrogen and Power-to-X JP, such as seasonal and very long-duration storage at large scale can be stored in salt caverns, tanks, or converted into other chemicals. Hydrogen can provide cross-sector capitalism (industry feedstock, transport fuel); there are potential efficiency losses with extended-chain storage (electricity-to-hydrogen-to-electricity), and cost-competitive options are available in other storage modalities (electrochemical, mechanical) or do not require storage (DOE, 2024; IEA, 2024) [1, 3].

Chemical carriers (ammonia, metal hydrides) are advantageous at higher volumetric density, and represent an R&D challenge in terms of material cost, conversion kinetics and losses.

Thermal energy storage (TES)

Sensible, latent and thermochemical TES do so by storing it as heat. Molten salt particle (sand/rock) systems have the interest space of long-duration use when coupled with highly efficient power cycles (e.g., ORC or supercritical CO 2). The NREL ENDURING concept also utilizes low-cost particle TES with an optimized cycle to achieve low dollar per kilowatt-hour energy cost over many days, an example of how thermal routes intend to compete with batteries in the long-duration arena (NREL ENDURING, 2023) [2]. The LAES liquefies air and stores it in a cryogenic state; hybrid LAES can be coupled to a thermal store to enhance roundtrip efficiency, making this an option to consider as long-duration bulk storage.

4.0 Performance Measures, and Techno-Economics Tradeoffs: The technologies in LDES from several aspects on performance and cost should be compared by multi-dimensional indexes. Flow batteries and thermal storage, which disaggregate energy and power capacity, are cost-effective to extend storage duration at low marginal cost. This is a plus as they are ideal for multi-day or seasonal storage. Figure 2: design space interaction of duration and round-trip efficiency for LDES technologies:

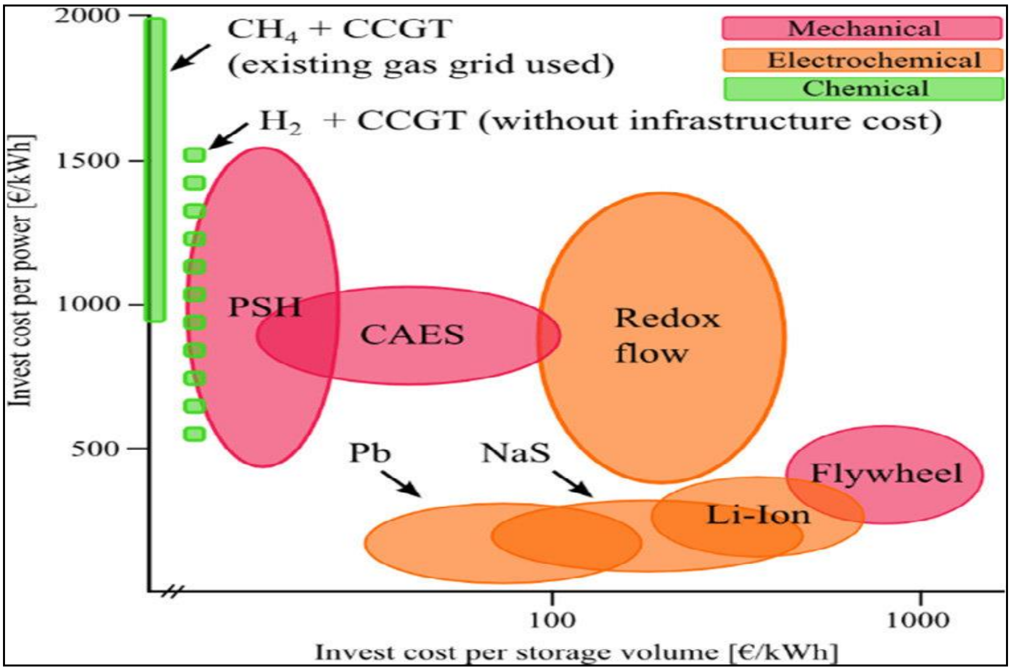

Fig 2: Interplay between duration and round-trip efficiency across LDES technologies:

One other important performance metric is round-trip efficiency (RTE) because it can indicate the worthiness of arbitrage opportunities. Lithium-ion and other electrochemical batteries have generally high efficiencies (70% to 95%), whereas pumped storage hydropower has an efficiency of about 70%-85%. Hydrogen and thermal-based storage forms of storage can have lower efficiencies, but can be cost-effective where price spreads are large or when accompanied by co-benefits like district heating and industrial uses.

The capital cost analysis of LDEs systems again reveals competition between power-related costs ($/kW) and energy-related costs ($/kWh). Energy storage in many long-duration technologies is the most important cost factor. This necessitates lowering the cost of storage tanks (e.g., heat reservoirs or electrolyte tanks) in order to obtain a cost-price competitiveness at many-day time scale.

Technical feasibility is also the product of lifetime and degradation. Pumped storage hydropower and flow batteries are long cycle power sources, with lives measured in decades with little degradation. On the other hand, there are newer technologies that are yet to achieve durability such as metal-air and some chemical storage chemistries. Energy storage cycle life has a direct effect on the levelized cost of storage (LCOS), and cycle life is of paramount importance in these decisions.

The other level of differentiation is response characteristics. The different technologies differ in ramp rates, minimal discharge time, and quickness of reaction, which determine their appropriateness to take part in the business of ancillary services. Likewise, lithium-ion batteries, which have quick response times, can be used as an alternative to frequency control although they are unable to extend at a long period. In comparison, technologies that have non-rapid dynamics and longer-lasting discharge times are perhaps more suited to capacity firming and energy shifting.

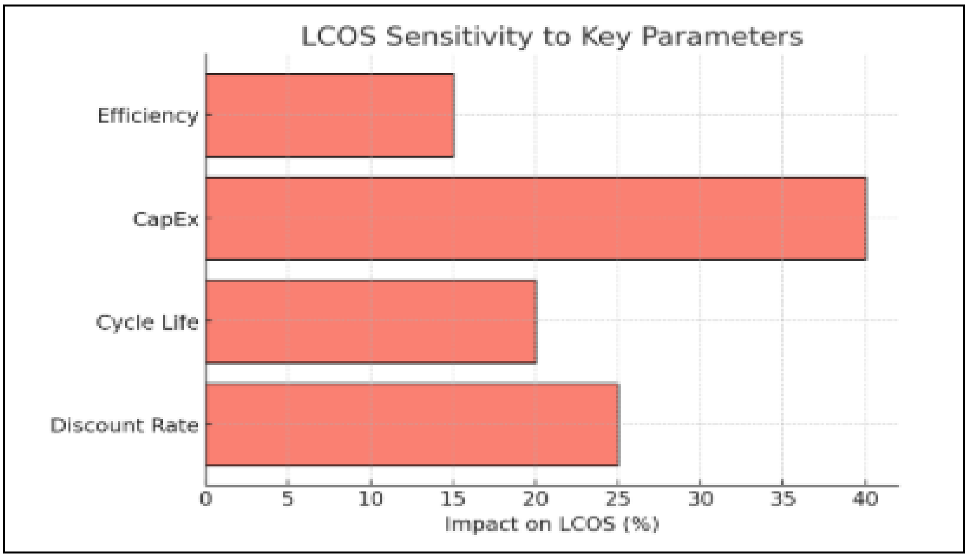

Fig 3: Horizontal bar chart showing LCOS sensivity to parameters

Finally, LCOS can be used as the main comparison factor but still it also depends upon some very critical assumptions like the frequency of cycling, the choice of discount rate and life of the system. Analyses by DOE, NREL, and IEA indicate that around breakthroughs in ultra-low-cost energy tanks (thermal, gravity-based, or flow chemistries) or changes in the market rewarding long-duration services will be necessary to enable multi-day storage to be competitive. Without both, any LDES pathway can become underutilized as its technical potential remains.

Table 1: Key Metrics by Storage Type

Metric / Tech	Li-ion Batteries	PSH	Flow Batteries	Metal-Air	Hydrogen
Typical RTE	~90-95%	~70-85%	50-75%	~40%	~40%
Energy-Specific Cost Role	Low	Moderate	High	High	High
Duration Suitability	Short (hours)	Hours to Days	Days	Multi-day	Seasonal
Lifetime & Degradation	Moderate life	Long life	Good	Unproven	Unproven
Response Speed	Very fast	Moderate	Moderate	Slow	Slow
LCOS Sensitivity	Low	Moderate	Moderate	High	High

5.0 Evidence Modelling Where LDES can add most Value

1. Higher VRE Penetration and More Often Curtailed

In conditions of plenty of variable renewable energy (VRE), there is a consistent development of LDES minimizing the waste of the Venice sun, storing and deploying excess generation during periods of shortage. The impact of such effect is very clear in the Nature Communications as seen in the figure below across various zones of the load in the west and south of the grid

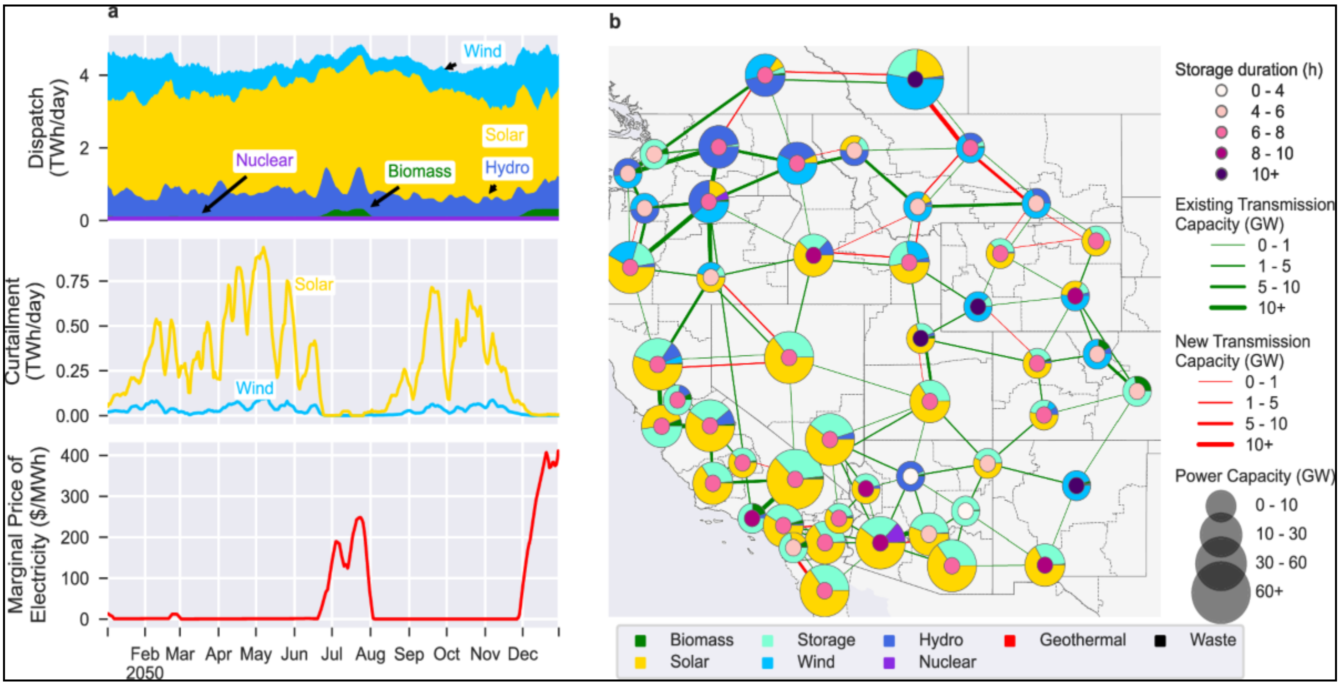

Fig 4: The Western Interconnect in a baseline 2050 zero-emissions future.

These models indicate why LDES is becoming even more valuable when VRE above 70-80% is met, realizing renewable capacity and stabilizing supply.

2. Limited Expansion of Transmission

Local LDES can serve as a geographic insurance to the extent that transmission build-out may be limited by cost, environmental, or regulatory factors. It successfully minimizes the use of remote generation in correcting local mismatches. Modeling studies show that transmission constrained systems can also benefit greatly through the widespread adoption of LDES, providing a cost effective alternative to building new lines or dispatchable facilities in regions where expansion is constrained or limited by building new lines or facilities powered by dispatchable generation sources that can be accessed by the grid in the same way hook up electricity to your house.

3. Seasonal Inexactness in the Supply and Demand

Areas with very strong seasonal mismatches (such as heating-intensive winters or solar-peaky summers) can benefit a lot by seasonal-sized storage (hydrogen or thermal storage). The graph above demonstrates that the southern WECC is more dependent on ~6 8 hour storage cycles of solar generation, and the northern WECC may have an even greater variation in its variable storage duration and up to 18 hours in some zones it is even more important to customize LDES to seasonality and geographical diversity.

4. High Cost or limitation to firming alternatives

In the pathways that aim at deep decarbonization, models are likely to conclude that firm fossil generation (e.g. gas, coal) becomes less economically and politically viable. LDES steps in to fill in the gap as a more lower-carbon alternative to ensure reliability. DOE research, as well as NREL studies, show that net-zero investment portfolios integrating LDES will achieve system savings of between 10B and 20B per year in 2050-through reductions in operational costs deferral of generation build-out and decreased renewable curtailment

5. Side- spaces of Marginal Value Diminishing of LDES when there is a high Flexibility

First, if there is a shortage of power supplies or if the proportion of VRE (variable renewable energy) becomes very high, LDES might seem to be worthwhile after all; although in fact its actual function shrinks somewhat from working with other flexible sources such as demand response devices or small batteries that can respond to load and even relocation of transmission lines. In all sorts of applications, (LDES) can be implemented-in part or whole systems, but, as the MIT people always emphasize, context-aware planning is necessary. Where will this energy form actually bring value to the power grid? Verry is still in line with so maybe it's different in every context. Besides, depending on regional demand patterns, the VRE mix and policy environment, you need different mixes for storage.

6.0 Demonstrations, Commercialization Status and Industry Signals

As a long-term storage program, pumped hydro has a vast position and long lifespan in this field we have to do both renew it and also make it more friendly to the environment for future generations. However, the new Greenfield pumped hydro schemes are increasingly brought before higher environmental tests than ever before. It's slowing down projects and delaying the time taken for getting statutory Permissions (IEA, 2024) [1]. Vanadium redox-based systems are already in commercial use and batteries of this type can be found in more than one country. However, question marks remain over cost the raw material supply chain. This has led to pilot schemes investigating alternatives configurations including iron- and organic-based flow systems (Science Direct reports) [6].

Emerging iron-air and other metal-air technologies, such as Form Energy and Ore Energy have also attracted tons of venture capital and government dollars. These initiatives are ramping-up production and starting grid interconnection pilots with major outcomes anticipated between 2024 and 2025 to make decisions about their future profitability (Financial Times; industry news) [11]. In parallel, the national

laboratories and governmental agencies, such as NREL and the U.S. DOE through efforts such as ENDURING and the DOE LDES strategy are funding pilot projects in thermal and hybrid storage to be able to consider low cost and multi-day storage options (NREL, DOE, 2023-2024) [2, 3].
The influence of policy-signals adds support to the industry activities more. LDES is experiencing growing government support as a strategic enabler of decarbonization and resilience at the state level in state-level procurement programs and state-level grant mechanisms. As an example, the California Energy Commission has already made iron-flow storage grants, indicating that there is a clear policy towards iron-flow storage development (California LDES program 2024) [8].

Fig 5: NREL LDES Demonstration

7.0 Environmental, Social and Supply-Chain factors.
The LDES technologies present an attractive option in terms of energy system flexibility, but its environmental, social and supply-chain impact are varied, and need to be handled sensibly to enable sustainable deployment.
Pumped-storage hydro (PSH) and compressed air energy storage (CAES) may cause a heavy environment impact. They can be constructed in an area that necessitates bulk land usage, water diversion, and disturbance of the habitat. Additionally, appropriate locations are geology and topography-dependent, and hence constrain flexibility in deployment. Whereas conventional (open-loop) systems can potentially modify the river ecosystem, advanced closed-loop PSH systems lower environmental pressure by not constantly connecting the rivers (IEA; Science Direct).
In regard to electrochemical storage technologies, there are both supply-chain and environmental issues, such as a shortage of cobalt, nickel, and vanadium based batteries. But the mining of these minerals may result in natural and social disruption, and can be especially severe where there are few regulations. But then, there is a simple solution. A kind of iron based battery or an organic flow battery is obtainable from researchers that could eliminate the possible harm of scarcity and toxicity. They are not used on a large scale, but it still needs to be examined how they function in applicational terms. (Science Direct) Well-supplied and recyclable life cycle standards are driving future sustainability (NREL docs) some points of distinctiveness are introduced by hydrogen and power-to-X (PtX) storage approaches. The environmental footprint of such a project hinges on the type of electricity that will be used to feed the electrolysis process. Green hydrogen (using renewable energy) is capable of possessing low-carbon potential; in contrast, hydrogen that is made with fossil fuels loses all its environmental benefits. Besides, there are conversion losses and leakage during storage: overall efficiency is less. Strict regulations are necessary to prevent geological storage (e.g. in salt caverns) from leaks--originated either by the high pressures created when gas condenses and expands, or otherwise brought about for some completely different geomechanically structural reason. (Department of Energy)
Thermal storage technologies (molten salts, ceramics and thermal blocks) employ more readily available materials that have in general lower impact profiles. Though the embodied emissions aspects of manufacturing processes can lead to a favorable lifecycle emissions profile, these very emissions can hand manufacturing procedures a good jwt: provided materials are repurposed to end-of-life or reprocessed. (NREL documentation)
In addition to technical and environmental aspects, it is essential in deployment of LDES to consider social and regulatory dimensions. Technological readiness is only as important as site acceptance, environmental justice and community engagement. Projects may be stalled or be thwarted by issues of land use, aesthetics and process safety. Lifestyle disclosure, responsible sourcing and post-consumer content policies can be embedded to build trust and accelerate permitting in a fashion that does not compromise environmental and social stewardship.

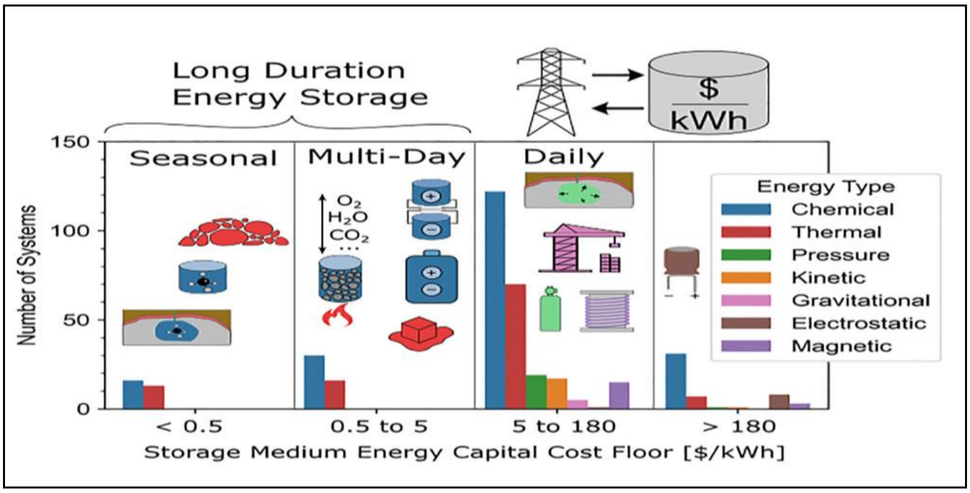

Fig 6: lifecycle environmental impact of various long-duration energy storage (LDES) technologies

8.0 Market, Regulatory and Financing Barriers

LDES is emerging as a key enabler of net-zero systems, but a large number of barriers still exist and limit its large-scale deployment.

Revenue uncertainty: The existing wholesale markets and ancillary service structures are slanted towards short run/high power services like frequency regulation and short term balancing. This biases revenue potential to lithium-ion batteries as opposed to multi-day or seasonal storage. In the absence of explicit market products to provide long-duration flexibility, apparent cash flow uncertainty discourages investor confidence in LDES developers.

Market design mis-matches: Time is not a system property in conventional capacity and energy markets. Future supply-side investment in multi-day shifting, or seasonal shifting, has not been considered, despite its potential resilience value. As a result, it causes LDES to be implemented unequally. Markets need to incorporate longer discharge on a duration-sensitive procurement process, product definitions that value longer discharge, and system planning efforts that value LDES as the firming options of preference.

These barriers increase the project development time and the cost of financing of the projects, often distorting the projects as unattractive alternatives to smaller and modular storage limits and flexible gas.

Early commercial risk, and financing

Other technologies such as novel electrochemical chemistries (e.g., flow batteries, iron-air, organic redox), and thermal storage remain in their infancy. Perceptions of untested technology risk make access to affordable capital a problem. Demonstration projects at early stages are vital in derisking, however, the valley of death phase cannot be shouldered by the only private investors. Public de-risking mechanisms-i.e., government guaranteed contracts for difference, concessional loans, and demonstration grants are important as outlined in U.S. DOE programs and those in the European Union innovation investments.

Policy levers for overcoming barriers

1. Technology-independent procurement informed by the necessary discharge time as opposed to the technology employed so as to even the competitive landscape.
2. Targeted RD&D and demonstration in order to shorten learning curves and verify emergent chemistry.
3. Duration-sensitive capacity markets which reward resilience values that extend beyond 4-hour storage.
4. Standardized testing, measures, and certification so that ones can compare various technologies on an apple-to-apple basis, thus minimizing perceived risk to investors.

Unless these market, regulatory and financing barriers are effectively dealt with, the existence of LDES will continue to be a niche application despite the significance of LDES at the system level of the energy system. Forward-looking reforms can be made to ensure that LDES scales up in time to market complements variable renewable energy and weaning off fossil-based firming sources.

9.0 Research Gaps and Priority Actions

There is still a number of research gaps to fill in transforming long-duration energy storage (LDES) to large-scale likeability and all those gaps are necessary to be closed in order to reduce costs, efficiency and gain investor confidence. Reducing cost of capital energy specific is made one of the most critical priorities. Advances in low-cost storage materials including any type of thermal particles, any type of inexpensive electrolyte, and any type of abundance of mass to use in a gravity based system, are also required to make technologies more competitive with conventional ones. Research in this field should be directed at scalable, that is, have the potential to decrease upfront investment significantly without compromising on performance (NREL Docs; Science Direct).

There's another key area of business: enhancing round-trip efficiency (RTE), particularly chemical storage route. Double Adiabatic Compressed Air Energy Storage (CAES) and high efficiency hydrogen re-conversion can increase competitiveness, lose less at conversion, and thus be good for Steelmakers and Ironworkers all the industries that absorb it. One of the most important requirements for this is conversion loss reduction. With hydrogen in particular, it means creating systems which can increase efficiency in all stages such as electrolysis, storage and use to effectively bring green hydrogen into operation as a long duration option (Science Direct; DOE Energy.gov).Apart from this long life cycle and low O&M cost are also of concern There are (metal air battery chemistry) and flow batteries with extended calendar life for which extensive six- to eight year pilot demonstrations must first prove enduring capabilities. Overall, these pilots will have to prove that resilience, reliability, and continuity of performance can indeed last over a long haul (that is a prerequisite saturate one's funders to be seen as risk) (Science Direct). The research should also include demonstrations and innovative business models. Hybrid systems that combine different energy technologies such as thermal energy storage (TES) with hydrogen or flow batteries; or solar photovoltaic (PV) together with integrated flow batteries provide more streams for return and stronger economics at remote locations. Many services delivered at once also make it easier to set up joint evaluations (NREL Docs).Thirdly, standardizing how you measure performance and life cycle products is an essential precondition for eliminating uncertainty from investors' minds. Joint methodologies help calculate levelized cost of storage (LCOS), performance tests and environmental impacts make it possible for technologies to be transparent comparisons. With emphasis on lifecycle disclosure and consistent test models providing an apples-to-apples basis of comparison, organizations are starting to take notice - Councils like LDES have thus broadened their own horizons (ldescouncil.com).A lucrative procurement mechanism that favours long duration storage is one way to save costs on the whole integrated system. Many “buttons” will lower LDES’s costs, for instance” hand-in-hand “public-private pilot projects. Essential will be one test protocols and commercially viable procurement mechanisms that encourage longer lives. If we are to develop a feasible long duration storage solution, policy and research in these key areas should go hand in hand.

Conclusion: Yet this is the question: how to do literary criticism in modern times? When two such processes for completing conversion were examined side by side, it was clear a difference existed. A technology, if it is on the verge of completely demonstrating full-scale, or its original islet model already received widespread attention, then we can say that it is now mature. This may add a bit to those around it-if only slightly. In the long run, as advanced technology is thawed, costs will be cut and market introduction will be faster. Nevertheless, early obstacles are obviated by nothing other than a lack of coordination at the ideational level, litigation over projects not in anyone's financing accounts and failure to enter markets such as electric power generation. By this year, three to seven is the crucial time for renewable energy businesses. Next, advanced technologies such as the iron-air battery, advanced wind-energy system, particulate thermal storage and adiabatic compressed air energy storage (CAES) will all be important ingredients in deciding which technologies truly compete at grid scale and are accepted widely in markets. With strong policy frameworks and collaboration between industry and government, LDES can provide a foundation for a flexible, robust fully decarbonized energy system (DOE, NREL, IEA studies; industry pilots).

References

1. International Energy Agency (IEA). Energy storage - grid-scale storage overview [Internet]. Paris: IEA; 2024 [cited 2025 Sep 3]. Available from: https://www.iea.org/energy-system/electricity/grid-scale-storage
2. National Renewable Energy Laboratory (NREL). Economic long-duration electricity storage by using low-cost thermal energy storage and high-efficiency power cycle (ENDURING) [Internet]. Golden (CO): NREL; 2023 [cited 2025 Sep 3]. Available from: https://docs.nrel.gov/docs/fy23osti/84728.pdf
3. U.S. Department of Energy (DOE). Achieving the promise of low-cost long duration energy storage [Internet]. Washington (DC): DOE Office of Electricity; 2024 [cited 2025 Sep 3]. Available from: https://www.energy.gov/sites/default/files/2024-08/Achieving%20the%20Promise%20of%20Low-Cost%20Long-Duration%20Energy%20Storage_FINAL_08052024.pdf
4. Day T, *et al*. The value of long-duration energy storage under various grid futures. Nat Commun [Internet]. 2024 [cited 2025 Sep 3];15:53274. Available from: https://www.nature.com/articles/s41467-024-53274-6
5. National Renewable Energy Laboratory (NREL). Storage futures study — analysis and insights [Internet]. Golden (CO): NREL; 2023 [cited 2025 Sep 3]. Available from: https://www.nrel.gov/analysis/storage-futures
6. Science Direct. The rise of vanadium redox flow batteries; State-of-the-art electrolyte systems for VRFBs [Internet]. Amsterdam: Elsevier; 2024-2025 [cited 2025 Sep 3]. Available from: https://www.sciencedirect.com
7. Science Direct. Advanced compressed air energy storage systems: fundamentals. Renew Sustain Energy Rev [Internet]. 2022-2024 [cited 2025 Sep 3]. Available from: https://www.sciencedirect.com
8. California Energy Commission (CEC). Long duration energy storage program [Internet]. Sacramento (CA): CEC; 2024 [cited 2025 Sep 3]. Available from: https://www.energy.ca.gov/programs-and-topics/programs/long-duration-energy-storage-program
9. National Renewable Energy Laboratory (NREL). Solar thermal energy storage: salt, sand, brine and electrons [Internet]. Golden (CO): NREL; 2024 [cited 2025 Sep 3]. Available from: https://docs.nrel.gov/docs/fy24osti/90759.pdf
10. LDES Council. Annual report 2024 [Internet]. Geneva: LDES Council; 2024 [cited 2025 Sep 3]. Available from: https://www.ldescouncil.com/assets/pdf/2024_LDES_Annual_Report.pdf
11. Financial Times. Metal-air and iron-air pilots and investments: Form Energy and Ore Energy [Internet]. London: Financial Times; 2024 [cited 2025 Sep 3]. Available from: https://www.ft.com
12. Lazard. Levelized Cost of Energy+ report [Internet]. 2023 [cited 2025 Sep 3]. Available from: https://lazard.com
13. International Renewable Energy Agency (IRENA). Renewable Energy Statistics 2022 [Internet]. Abu Dhabi: IRENA; 2022 [cited 2025 Sep 3]. Available from: https://www.irena.org/Statistics
14. Renew Sustain Energy Rev. Evaluating emerging long-duration energy storage technologies [Internet]. 2022 [cited 2025 Sep 3]. Available from: https://www.sciencedirect.com
15. News and industry sources. Energy storage and hydrogen industry updates [Internet]. 2024 [cited 2025 Sep 3]. Available from: https://www.reuters.com