

Long duration energy storage (LDES)

How BESS chemistries influence techno-economic performance

AUTHORS



Alexandria Dionigi
Senior project engineer
alexandriad@naturalpower.com



Kim Clark
Senior project engineer
kimc@naturalpower.com



Chris Ziesler
Commercial services lead, Advisory
and Analytics
chrisz@naturalpower.com



As renewable energy penetration rises on the US grid, the storage issue under scrutiny is shifting to understanding which chemistries can economically deliver the right duration, performance, and reliability for each application.

The promise and reality of long duration storage

As Battery Energy Storage Systems (BESS) continue to dominate new power installations in the US, the growing interest in Long Duration Energy Storage (LDES) is driven by a simple reality: renewable generation does not always align with electricity demand and finding the best technology to help manage that mismatch for a variety of use-cases is important for the continued success of the sector.

For the past decade, most battery storage deployments have been designed around four-hour applications. These systems excel at energy arbitrage, frequency response, and short-duration grid balancing. However, as solar and wind assets represent a larger share of generation portfolios, utilities increasingly face periods where generation deficits last far longer than four hours.

This has led to growing interest in storage technologies capable of delivering electricity for 8, 12, 24, or even 100 hours. In theory, these technologies could enable renewable energy plants to deliver dispatchable power and eventually displace conventional thermal generation in capacity markets. Some industry participants increasingly view LDES as a critical enabler of renewable baseload generation rather than simply a balancing technology.

While the opportunity is enormous, the path to commercialization remains challenging. Many of today's alternative storage chemistries promise lower costs, longer lifetimes, or enhanced safety relative to lithium-ion batteries; however, they must still overcome significant technical, commercial, and financing hurdles before they can achieve widespread adoption.

The graph below illustrates how total installed capital expenditure (CAPEX) scales with discharge duration across different storage chemistries. While lithium-ion, in this case lithium iron phosphate (LFP), offers a lower upfront cost for short discharge windows, its modular nature causes capital costs to increase linearly as duration extends. In contrast, emerging Long Duration Energy Storage (LDES) chemistries – such as flow batteries, iron-air, and sodium-ion – carry higher fixed balance-of-plant overhead but benefit from a significantly lower marginal cost per additional hour of capacity. As a result, an economic crossover window occurs between 6 and 8 hours of duration, beyond which LDES architectures become progressively more cost-effective for multi-hour and multi-day grid firming.

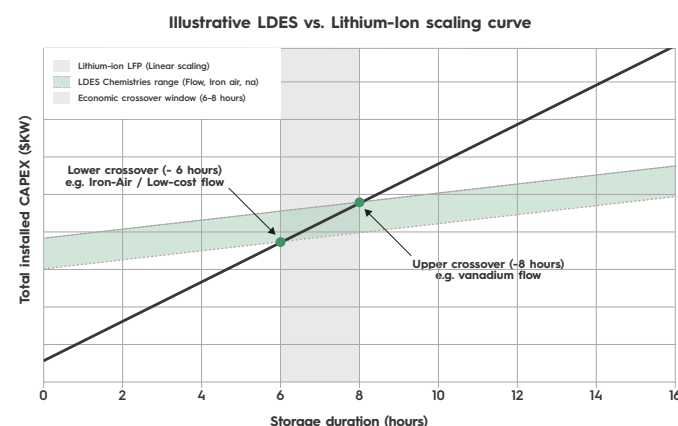


Figure 1: Economic trade-off between li-ion and other LDES chemistries

The overall picture is clear, although it is important to note that the width of the LDES cost envelope and the precise location of the economic crossover point are largely governed by raw material price volatility (such as vanadium commodity fluctuations), manufacturing production scale, and site-specific balance-of-plant requirements. In addition, variations in round-trip efficiency (RTE) and land footprints across different non-lithium chemistries – ranging from



lower-cost iron-air systems to higher-CAPEX vanadium flow installations – determine how quickly an LDES project achieves capital cost parity with lithium-ion.

Let's take a look in more detail at some of the strengths and weaknesses of the different choices of LDES chemistry available to developers.

Vanadium flow batteries: mature technology with cost challenges

Among the leading long-duration technologies, vanadium flow batteries are often viewed as one of the more technically mature options. Using liquid electrolytes stored in separate tanks, these systems decouple power capacity from energy capacity, allowing project developers to increase storage duration without proportionally increasing inverter capacity.

The chemistry offers several attractive features. Capacity degradation is generally low, thermal runaway risks are significantly reduced, and operational lifetimes may extend beyond those typically expected from lithium-ion systems. Many degradation mechanisms associated with lithium-ion batteries are largely absent, with pumps and balance-of-plant systems often becoming the primary maintenance considerations.

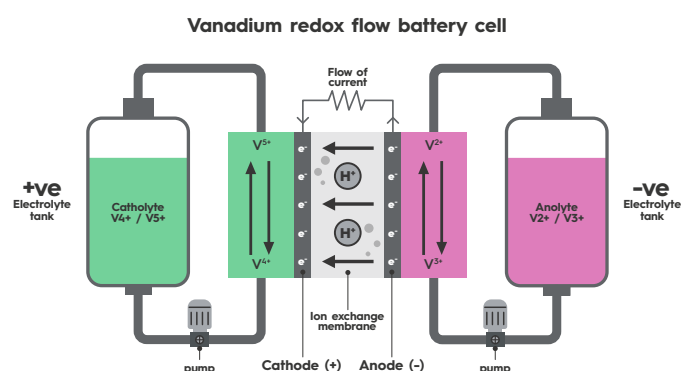


Figure 2: Redox flow batteries diagram.

However, vanadium flow batteries face their own challenges. The systems are mechanically more complex than lithium-ion batteries, requiring pumps, piping, reservoirs, and fluid management systems. Their economics can also be sensitive to vanadium pricing, which has historically experienced volatility. It is worth noting though, that unlike fossil-fuel price volatility which affects project economics throughout the whole life of the project, vanadium price volatility only impacts the project at the outset. Put another way, if the project is economically viable during the development phase, that will not change once it has been built. In addition, while flow batteries can add duration relatively efficiently, their overall footprint often exceeds that of lithium-ion installations, creating design issues that may require special consideration for certain projects.

Despite these challenges, market momentum continues to build. Large vanadium flow deployments in China are important proof points for commercial scalability and long-duration operational performance. They will be watched closely by developers and investors evaluating whether flow batteries can move from technically credible to widely bankable.

Iron-air storage: potentially transformational, but not yet proven

Perhaps no emerging storage technology has received more attention than iron-air batteries. One such product from Form Energy stores energy through the reversible oxidation and reduction of iron, using one of the world's most abundant and inexpensive materials.

The potential attraction is obvious: dramatically reducing the cost of storing large amounts of energy for multiple days. Projects such as Form Energy's deployment at Xcel Energy's Sherco site, a former 2.2-GW coal-burning thermal plant in Minnesota, replaced with a 710-MW solar array, have become closely watched industry demonstrations. These projects are significant because they target a market segment that lithium-ion batteries struggle to address economically: multi-day energy shifting and replacement of retiring thermal generation.

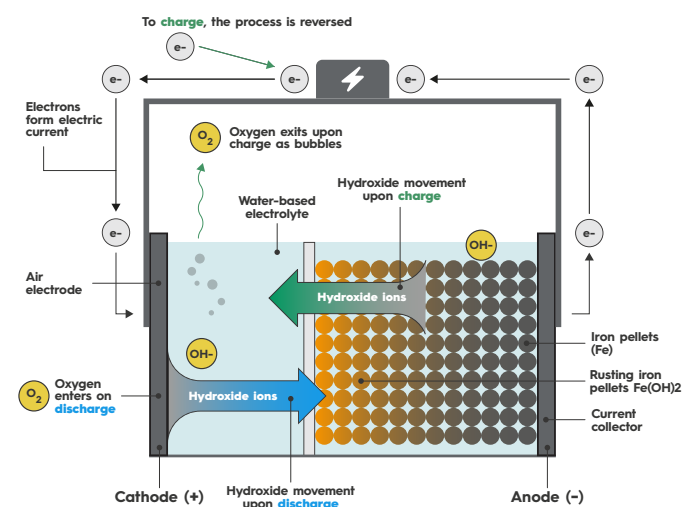


Figure 3: Iron-air battery technology (Form Energy)

It should be noted that iron-air technology remains relatively early in its commercialization journey. Questions remain regarding operational lifetime, round-trip efficiency, manufacturing scale-up, long-term maintenance requirements, warranty structures, performance guarantees, and project financing. Most importantly, the industry still lacks a large fleet of operating projects with lengthy performance histories.

For utilities, lenders, and Independent Engineers, this means technical due diligence carries additional uncertainty compared with established lithium-ion technologies. The technology's success ultimately depends not only on achieving technical performance targets, but on demonstrating reliable operation over many years at utility scale.



Sodium-ion: supply chain advantages, performance questions

Natural Power's recent experience, it appears that sodium-ion batteries are one of the closest new battery technologies to achieving commercialization. This impression was corroborated by a recent Wall Street Journal article, "China-Free Batteries Made from Salt Are Finally Here," by Christopher Mims, which highlighted the growing interest in sodium-ion batteries. The article discussed the fact that recent developments in sodium-ion technology suggest that the battery industry may be approaching a viable alternative to lithium-based storage for certain grid applications. By leveraging abundant raw materials and offering improved safety characteristics, sodium-ion batteries could help reduce both supply chain risks and long-term storage costs, particularly for medium- and long-duration stationary energy storage. While commercial deployment is still in its early stages, the technology is attracting significant investment and could become an important component of the future LDES landscape.

Sodium-ion technology has emerged as one of the most intriguing alternatives to lithium-ion systems. Unlike vanadium flow or iron-air technologies, sodium-ion batteries share many architectural similarities with conventional lithium-ion systems, potentially allowing manufacturers to leverage existing production infrastructure.

Yet sodium-ion is not a simple drop-in replacement. Current systems generally exhibit lower energy density than lithium-ion batteries, which can increase transportation, installation, and land-use requirements for equivalent energy storage capacity. Manufacturing volumes remain relatively limited outside China, meaning economies of scale have not yet been fully achieved.

The future competitiveness of sodium-ion may therefore depend less on whether the chemistry can work and more on whether the industry can achieve sufficient manufacturing scale, bankable supplier warranties, and acceptable performance under utility operating conditions. The conclusion of the WSJ article was the salutary message that, "Without the right support from the U.S. and allied governments, the U.S. might again find itself having developed a novel energy technology, only to see China achieve a monopoly on its production, says Mukesh Chatter, CEO of Alsym Energy".

Learning from early commercial deployments

The next phase of the LDES market will likely be defined by execution rather than invention. The storage sector has already shown how quickly a promising chemistry can move from niche technology to becoming a mainstream solution. Utility-scale lithium-ion markets transitioned from NMC to LFP in less than a decade as developers prioritized cost, safety, and operating life.

Long-duration storage technologies now face a similar challenge. Form Energy's iron-air projects in Minnesota and its utility partnerships, ESS Inc. iron-flow battery deployments, Eos Energy zinc-based storage projects, and large-scale vanadium flow facilities in China are all serving as important industry test cases.

Peak Energy's sodium-ion systems are also emerging as an important test case, helping to determine whether sodium-based batteries can offer a commercially viable alternative to lithium-ion by improving supply chain resilience, safety, and long-term storage economics.

These projects are demonstrating far more than technical performance. They are testing supply chains, O&M requirements, financing assumptions, warranty structures, availability guarantees, and long-term operational reliability. In many respects, the industry's biggest challenge is no longer proving that these technologies can work. It is proving that they can generate consistent returns for investors and reliable performance for system operators.

Techno-economic trade-offs: there is no perfect chemistry

It is a mistake when evaluating storage technologies to search for a single winner. The reality is that every chemistry involves trade-offs. A technology that offers low energy-capacity cost may have lower round-trip efficiency. A chemistry with strong safety characteristics may require a larger physical footprint. A system with long theoretical life may still struggle to secure project finance without a proven operating fleet.

Developers therefore face a balancing act between capital cost, operational risk, efficiency, lifetime performance, technology maturity, and market application. The lowest-cost technology on paper may not be the lowest-risk investment. Similarly, the most mature technology may not provide the most economical solution for very long storage durations.

Chemistry	Key strengths	Key limitations	Likely best fit
LFP lithium-ion	High efficiency, fast response, mature supply chain	Duration extensions require more cells; economics become harder at very long duration	2-8 hour storage and fast grid services
Vanadium flow	Long life, low degradation, strong safety profile, duration scalability	Mechanical complexity, larger footprint, vanadium price exposure	6-24 hour energy shifting and frequent cycling
Iron-air	Potentially low energy-capacity cost and multi-day capability	Early commercialization, lower efficiency, limited operating history	Multi-day storage and thermal generation replacement use cases
Sodium-ion	Better raw material availability and potential supply chain resilience	Lower energy density and limited large-scale operating history	Medium-duration applications where supply chain diversity matters
Zinc/iron variants	Use of abundant materials and long-duration potential	Technology maturity, warranty, bankability, and scale-up challenges	Long-duration shifting where cost and safety are prioritized



Conclusion

The future energy storage market is unlikely to be dominated by a single chemistry. Instead, we are moving toward a portfolio approach in which different battery technologies occupy distinct niches based on their technical and economic strengths.

Lithium-ion batteries will likely remain the preferred choice for short-duration applications, while vanadium flow, iron-air, sodium-ion, zinc-based, and other emerging chemistries compete to serve increasingly demanding long-duration requirements.

For utilities, developers, investors, and Independent Engineers, the key challenge is no longer determining whether long-duration storage will play a role in the energy transition. The challenge is understanding which technology delivers the optimal balance of cost, risk, performance, and duration for a given application.

The winners may not be the batteries with the highest efficiencies or the lowest headline costs. They may ultimately be the technologies that can demonstrate dependable performance, scalable manufacturing, and bankable economics at utility scale. And that is where the next chapter of the energy storage industry will be decided.

For more information, or to set up a meeting to discuss your battery storage project in more detail please contact

Alexandria Dionigi, Senior project engineer
alexandriad@naturalpower.com

Kim Clark, Senior project engineer
kimc@naturalpower.com

Chris Ziesler, Commercial services lead, A&A
chrisz@naturalpower.com

Reference links noted in source material:

- [LDES technologies LinkedIn article](#)
 - [Vanadium flow battery article](#)
 - [PV Magazine vanadium flow project article](#)
 - [CleanTechnica iron-sodium storage article](#)
 - [Utility Dive Google/Xcel storage article](#)
 - [Energy Live News iron-air article](#)
 - [Iron-Air Batteries — The Future of Long-Duration Energy Storage — Form Energy — Impact on Other Sectors](#)
 - [China-Free Batteries Made from Salt Are Finally Here by Christopher Mims WSJ August 7, 2026.](#)
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