Long-Duration, Large Battery Energy Storage

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1. Introduction

Battery energy storage technology is causing a revolution in how consumers use electric power. These systems (hereafter, battery energy storage systems or BESS) are making large impacts in transportation, consumer electricity-usage patterns and renewable energy sources. Whether BESS are imbedded in vehicles (battery-electric vehicles, a.k.a. BEVs or fuel-cell electric vehicles), major facilities, or residences (like your author's), they are completely changing the electric-utility landscape.

I'm sure everyone reading this paper has heard the phrase "fight fire with fire," well I have a new one for you, "accommodate consumers' BESS through your utility's own (larger and longer-duration) BESS." This will be the subject of this paper.

Note that I am not passing through secondary references from the information sources used for this article. There are only three sources, and the footnotes for each of these have links, where readers can access these sources and any secondary references.

2. Battery Revolution, Part 1

Over the past few years, lithium-ion batteries emerged as the default choice for storing renewable energy on the electrical grid. The batteries work fabulously for discharging a few hours of electricity, but they're too expensive to dispatch energy for much longer. Now several companies say they have developed cheaper technologies, including flow batteries and metal-air batteries, that promise to unlock long-duration energy storage. While private investors and government agencies have poured billions of dollars into these technologies, many utilities are hesitant to jump from lithium-ion systems that last a few hours to multiday batteries. But proponents of long-duration storage say there's no time to lose and that installing these batteries will help decarbonize electricity.[1]

The stationary energy storage business that Mateo Jaramillo started while working for Tesla was gaining momentum. At the end of 2016, the company had installed one of the world's largest lithium-ion battery systems for a utility in California.[2] *But Jaramillo felt that weaning the electrical grid off fossil fuels would require a cheaper form of energy storage.*

Although lithium-ion batteries excel at delivering short bursts of electricity, they were too expensive for long- duration storage. As solar and wind farms proliferated, he predicted, utilities would need batteries cheap enough to supply electricity for multiple days during cloudy spells or wind lulls.

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[1] Matt Blois, Chemical & Engineering News (C&EN), "The search for long-duration energy storage," February 21, 2025, https://cen.acs.org/energy/energy-storage-/search-long-duration-energy-storage/103/i5

[2] Tesla was selected to provide a 20 megawatt/80 megawatt-hour Powerpack system for public utility Southern California Edison. The utility-scale storage solution will be deployed at the Southern California Edison Mira Loma substation. The project is a response to a catastrophic rupture in the Aliso Canyon natural gas reservoir last October. https://www.nasdaq.com/articles/tesla-complete-massive-lithium-ion-battery-storage-project-california-2016-09-15

Jaramillo left Tesla and in 2017 started searching for technologies that could solve this problem. He was working with a scientist at Stanford University on a multiday battery when he learned about a group from the Massachusetts Institute of Technology pursuing a similar goal. Jaramillo flew to Boston to meet with them. The two teams decided to merge and start a company called Form Energy.

At their Somerville, Massachusetts, laboratory, Form scientists started testing all kinds of technologies. Near the end of 2018, they settled on an iron-air battery, which releases energy by reacting iron with oxygen in a process similar to rusting. The firm says its battery can supply electricity for at least 100 h.

Author's comment: When it comes to battery components, they don't come much less expensive than iron and air. Thus, scaling this chemistry up to multi-day is very inexpensive.

"That's the duration of weather events that really cause problems for the grid," Jaramillo says. "Getting through one tight day is manageable. Getting through three or four in a row (as caused by multi-day heat-waves), that's when things start to break."

Since Form's launch in 2017, private investors and government agencies have poured more than $1 billion into the firm's iron-air battery. In September, Form received a $150 million grant from the US Department of Energy (DOE) to fund its battery-manufacturing plant in West Virginia, which is slated to reach a production capacity of 500 MW by 2028. And the company has announced 141.5 MW of battery projects. Competing long-duration storage technologies, such as flow batteries and other metal-air batteries, have also attracted billions in investment and government support.

As Form has progressed, the number of utility-scale lithium-ion battery projects has shot up. But the market for long-duration energy storage is only just starting to materialize, and many utilities are hesitant to jump from lithium-ion systems that last a few hours to multiday batteries like Form's. Compared with fossil fuels, long-duration batteries are still relatively expensive, prompting many utilities to meet sustained surges of electricity demand by starting gas-powered standby turbines rather than drawing from batteries.

To respond to the impacts of climate change, US utilities are charting a path toward decarbonization, but many of those targets are decades away. Meanwhile, the Trump administration is pushing for policies that embrace fossil fuels rather than renewable energy. In this environment, some Form competitors say it could take years before utilities are ready for multiday batteries. They're planning to take gradual steps by selling shorter-duration batteries in the near term.

Jaramillo and other proponents of multiday batteries say the tipping point for these technologies will come soon, just as it did for solar power and lithium-ion batteries. They argue that multiday batteries offer the cheapest way to build a fossil fuel–free electricity system. Most importantly, Jaramillo says, the batteries will ensure that a grid powered by renewable energy can always provide electricity when people need it.

"Having cost-effective multiday duration storage enables a much more reliable grid while driving deep decarbonization," he says. "You have a more reliable, lower-cost grid."

Author's comment: There is a large valley between a 4-hr grid battery and a 100-hr grid battery, and this gap does not exist for smaller-scale battery systems. For instance, your author has a 10-kWh BESS, that serves very-well for our residences' (minimal) residential-load during late-nights and early mornings. As a result, my electric consumption charges have pretty-much gone away.

2.1. Lithium's Rise

Lithium-ion batteries became the default technology for storing renewable energy partly because companies were already mass-producing them for electric vehicles. Still, they have proven to be capable workhorses.

Connecting batteries to the grid allows utilities to shift energy generated by the midday sun to the high-demand hours of the evening, when TVs, and appliances turn on in droves. They also balance electricity supply with demand, a function that maintains the power grid at the right frequency to protect against black-outs or infrastructure damage.

Paired with renewable energy, these batteries can generate healthy profits by charging when electricity prices are low and discharging when they are high. In many cases, the ability of lithium-ion batteries to respond nearly instantaneously makes them better for fine-tuning the grid's frequency than gas-fired power plants, which take longer to start.

As a result, utility-scale battery installations in the US jumped from about 0.7 GW of power capacity in 2017 to more than 16 GW by the end of 2023, according to data from the US Energy Information Admin. Most of these projects use lithium-ion batteries.

Today, most lithium-ion battery systems provide power for only a few hours at a time, but the technology continues to get cheaper and better, says John-Joseph Marie, an energy storage analyst at the Faraday Institution who recently authored a report on stationary batteries. Production and engineering improvements are allowing some companies to plan lithium-ion storage projects that could, in the coming years, discharge up to 8 h of energy, about 4 times as long as an average battery in 2023. "That's made it really difficult for anything else to really compete," Marie says. "It's a constantly moving goalpost."

Author's comment: Adding some more context to the above paragraph, I looked at some recent price-curves for large (utility scale) BESS, and although they are decreasing in price over time, the rate of decrease is rather slow. I would say that if the amount of discharge duration for these systems is currently four-hours the price is decreasing at around 3% to 4% per year. Thus, it will probably require 5 to 10 years to move a utility to consider a six-to-eight-hour BESS, but with iron-air chemistry, batteries are probably there now.

On the flip-side, once a significant percentage of utilities start considering a 8-hr BESS, the accelerating demand for batteries will probably drive rapid volume increases in new, less-expensive chemistries, and this might accelerate price decreases for these.

Note that in the next few years, there will probably be decoupling of the EV storage market from the stationary BESS Market due to the ability of the latter to use heavier battery/chemistries that evolve in response to the stationary opportunity. The last three sections of this paper focus on these emerging technologies.

3. The Iron Age

One wall in Form's laboratory in Massachusetts hosts a dozen battery cells in rectangular plastic panels, each about the size of a residential windowpane. Each cell has a water-based electrolyte, a negatively charged anode made of iron powder, and a positively charged air cathode that pumps oxygen into the electrolyte.

Form envisions that 30 of these cells will be combined into modules about the size of a side-by-side washing machine and dryer. Those modules would be packed into shipping container–sized enclosures. A full-sized battery could include dozens of shipping containers spread out over a few hectares. The giant batteries are designed for utilities trying to stabilize their electricity supply, not homeowners, hospitals, or even big industrial sites trying to save on energy costs.

To charge the battery, electricity converts iron hydroxide at the anode into metallic iron, releasing hydroxide ions. The hydroxide ions migrate to the air cathode on the other side of the battery where they form water and oxygen. The oxygen bubbles out of the battery. During discharge, the process is reversed. Pumping oxygen into the water-based electrolyte generates hydroxide ions. At the anode, the hydroxide ions react with iron to form iron hydroxide, and electrons flow out of the battery.

The simple, inexpensive components of this system are what make the technology so attractive. But it also comes with trade-offs.

For iron-air batteries, the catch is efficiency. Scientists at NASA first developed the batteries in the 1960s, and during the oil crisis of the 1970s, firms including Matsushita Electric Industrial, Siemens, and Westinghouse Electric considered commercializing the technology for electric cars. But they never moved far beyond the laboratory, because the batteries discharged a fraction of the electricity that went in.

During charging, some of the electricity going into the battery splits water from the electrolyte into hydrogen. And during discharge, even more energy is lost when oxygen is reduced into hydroxide ions.

Form's battery returns about 40% of the energy used to charge it, an improvement over early iron-air designs. Lithium-ion batteries often reach 90% efficiency or higher. But Jaramillo argues that it's worth sacrificing efficiency for a system that costs 10% of a lithium-ion battery. "How much efficiency do you want to pay for if the problem you're solving is one of multiday duration capacity?" he asks.

The company expects that customers will use iron-air batteries to sop up ultracheap electricity that would normally go to waste. About 3% of renewable energy is wasted when solar and wind farms stop delivering electricity to the grid either because transmission lines are congested or because there's ample supply. Renewable energy waste can even reach 9% in places with lots of wind and solar, such as California. "If you have renewable fuel, (like wind or sunlight) then your fuel is very low cost (try zero), and you should care less about the efficiency," Jaramillo says.

But some experts are skeptical that existing electricity markets offer viable ways to justify the cost of multiday batteries—or that they're needed at all to decarbonize the electrical grid.

"One hundred hours is really out there," says Shawn Wasim, an energy industry analyst who recently left the research firm E Source. "There's going to have to be completely new programs created for that… There's no market set up for it right now."

Companies often cycle lithium-ion batteries every day or even multiple times per day to maximize the amount of electricity they can sell. The main purpose of a 100-hr. battery is to ensure grid reliability by serving as a backup source of energy, which might mean they're fully discharged only a few times a year, when weather strains the electricity grid.

Many battery operators receive payments for simply being connected to the grid, but those payments top out after a few hours, so they don't provide much incentive for long-duration storage. Wasim argues that it will be hard to justify building long-duration batteries that cycle so infrequently without better mechanisms to compensate battery operators for reliability.

Varnika Agarwal, an energy storage analyst with the research firm Rho Motion, agrees that 100 hr. might be overkill. She says these batteries could find a niche, but it will likely be smaller than that for short-duration batteries. "The technologies that are going to have the major market share are going to range from 4 to 10 h duration space," she says. "That's where your lithium-ion and flow batteries fit in."

Form says short-duration batteries complement its technology. But unlike lithium-ion batteries, Jaramillo says, the value of Form's batteries isn't from the amount of electricity they crank out. He says utilities are interested in them because they make it possible to build fewer power plants and transmission lines without sacrificing reliability. Form's target customers are integrated utilities that run power plants, string transmission lines, and distribute to customers. Jaramillo says a 100-hr. battery is often the cheapest way for such firms to ensure they can fulfill their obligations, even if the battery is used only occasionally.

"They are the ones that have the ultimate responsibility that the grid is reliable and stable," he says. "They put their own internal price on reliability."

4. The Promise of Flow

Before Form set out to commercialize iron-air batteries, other companies hoped to smooth the intermittency of renewable energy with flow batteries.

Flow batteries store electricity in two tanks of electrolyte solution. To dispatch electricity, the two electrolytes are pumped into a membrane-separated chamber. Electrons flow through a circuit out of the negative electrolyte into the positive electrolyte, and ions from the more positively charged solution move across the membrane to balance the charge. Reversing the process charges the battery.

Flow batteries have been around for decades, and there are dozens of chemistries. Increasing the amount of energy storage is as simple as switching to bigger electrolyte tanks, so they can be configured to discharge for short or long durations. Many companies developing flow batteries are targeting durations between those typical of lithium-ion and metal-air batteries, or between 10 and 24 h.

The most-mature flow batteries are made with vanadium-based electrolytes, but vanadium is expensive. A 2024 report from the research firm BloombergNEF found that flow batteries are more expensive than lithium-ion batteries. So, companies are looking for cheaper options.

Eugene Beh, founder of the flow-battery start-up Quino Energy, is betting that an electrolyte composed of organic quinones will make the batteries more economical. Quino's raw material is a cheap orange-brown dye made from coal tar or petroleum aromatics. "It goes into an electrolyzer, we give it a little tickle, and it gets converted into the final product," Beh says. "That has allowed us to move down the cost curve very rapidly."

Historically, the problem with organic flow batteries was that constantly donating and accepting electrons caused unwanted side reactions that degraded the electrolyte. Beh says Quino's electrolyte degrades more slowly than do other organic materials. The company can also regenerate degraded electrolyte using a special discharge cycle.

Moreover, Beh says, the organic electrolyte doesn't catalyze the formation of hydrogen. As in iron-air batteries, hydrogen formation in flow batteries lowers efficiency and depletes the electrolyte's ability to store electricity in future cycles. "Organics are just really bad at making hydrogen," Beh says.

Michael Marshak, founder of the flow-battery start-up Otoro Energy, studied organic flow batteries in the same Harvard University chemistry laboratory where Quino's electrolyte was born. But he says the technology's low voltage limits its utility. At Otoro, he's reviving a flow battery chemistry that uses iron- and chromium-based electrolytes.

Like the founders of Form, Marshak likes the price of iron. But previous iron-chromium flow batteries were also plagued by low voltage and low power. Otoro's innovation is to bind an organic chelate to chromium. Marshak says the result is a void for the chromium ions to expand into when they accept electrons. That increases the speed of electron transfer, boosting voltage and power.

The chelate can also block water from binding to chromium ions, allowing the battery to operate at higher voltages without forming hydrogen. "I did my PhD in some water-splitting and hydrogen reactions," Marshak says. "I applied basically the opposite. How do we prevent molecules from making hydrogen?"

ESS Tech, which is developing an iron-based flow battery, is tackling the problem of hydrogen formation in a different way. Hugh McDermott, who oversees sales at ESS, says the company's system includes a step that reincorporates the hydrogen into the electrolyte after it flows through the power module.

Most flow batteries can achieve efficiencies of 50–80%, less than those of lithium-ion batteries but more than those of metal-air batteries. Taking issue with Form's view of the market, Marshak says efficiency will be a key characteristic for long-duration batteries. He argues that, like lower-efficiency metal-air batteries, higher-efficiency flow batteries can increase resiliency by bridging long periods of low generation of renewable energy, but they can also economically go through short daily cycles to help customers shave energy costs.

Flow batteries have their own challenges, though. Many flow battery companies are targeting less than a day of energy storage, a duration that lithium-ion batteries could also cover. Marie, the Faraday Institution analyst, says it will be hard for flow batteries to catch up to lithium-ion batteries because flow-management systems are inherently complex, and they don't benefit from advances in other industries…

5. Emerging Battery Energy Storage Chemistries

Lithium-ion batteries (LIBs) have been at the forefront of portable electronic devices and electric vehicles for decades, driving technological advancements that have shaped the modern era. Undoubtedly, LIBs are the workhorse of energy storage, offering a delicate balance of energy density, rechargeability, and longevity. They are utilized in various electronic devices, such as smartphones and electric cars, and have become a fundamental component of modern portable power. However, as devices become more advanced, and electrification of transportation accelerates, some challenges still exist. Resource scarcity, safety risks of liquid electrolytes, and theoretical limitations of lithium-ion chemistry are areas of concern. Researchers are exploring alternative materials, solid-state electrolytes, and new chemistries/technologies, such as lithium-sulfur and lithium-air batteries, to overcome these challenges and develop the next frontier in energy storage.[3]

The world is shifting towards renewable energy at a fast pace, and the demand for clean energy solutions is increasing globally. This has made it imperative to innovate battery technology. In particular, solid-state batteries have the potential to improve safety and energy density and could revolutionize energy storage paradigms. Additionally, lithium-sulfur chemistry boasts a theoretical energy density that exceeds that of conventional lithium-ion batteries, providing a glimpse into a future where energy storage is not limited by the past. Other alternative chemistries involving sodium, potassium, magnesium and calcium offer sustainable and scalable energy storage solutions. These emerging frontiers in battery technology hold great promise for overcoming the limitations of conventional lithium-ion batteries.

5.1. Solid State Batteries

Solid-state batteries are a new type of battery technology that aims to overcome the safety concerns associated with traditional batteries that use liquid electrolytes. They offer higher energy density, which is a significant advantage. The recent advancements in solid electrolytes, interface engineering, and the integration of solid-state technology into practical applications make them crucial candidates for next-generation energy storage. However, they face significant challenges such as manufacturing scalability, cost-effectiveness, and long-term stability that need to be addressed. As the demand for advanced energy storage solutions continues to increase, solid-state batteries are becoming an increasingly important area of research. The "Solid-State Revolution" presents a groundbreaking frontier that is well-positioned to tackle the significant limitations associated with conventional lithium-ion batteries.

Solid-state batteries are transforming energy storage, offering enhanced safety, energy density, and overall performance when compared to traditional lithium-ion batteries. The latter uses a liquid electrolyte to facilitate ion movement between the positive and negative electrodes during charge and discharge cycles. Although effective, this design poses safety risks such as leakage, thermal runaway, and flammability. This has been observed in high-profile incidents involving lithium-ion batteries. The solid-state battery design seeks to eliminate these risks by replacing the liquid electrolyte with a solid electrolyte, resulting in a more stable and secure energy storage solution.

[3] Balaraman Vedhanarayanan, Assistant Professor, SRM Institute of Science and Technology, Chennai, India and Seetha Lakshmi K C, Researcher, Chiba University, Chiba, Japan, "Beyond lithium-ion: emerging frontiers in next-generation battery technologies," April 4, 2024, https://www.frontiersin.org/journals/batteries-and-electrochemistry/articles/10.3389/fbael.2024.1377192/full

Developing solid-state batteries has been a major challenge, but recent advancements in materials science have allowed the attainment of solid electrolytes with enhanced conductivity, making solid-state battery technology practically feasible. Solid ceramic electrolytes, polymer electrolytes, and composite electrolyte materials have emerged as frontrunners in the quest for suitable solid electrolytes that can match the ionic conductivity of their liquid counterparts. With these exceptional advancements, researchers are now more confident in their ability to create solid-state batteries that can revolutionize energy storage technology.

The shift towards solid-state batteries brings about significant improvements in terms of safety. By eliminating flammable liquid electrolytes, solid-state batteries reduce the risk of thermal runaway, making them inherently safer for applications that prioritize safety, such as electric vehicles. Additionally, solid electrolytes are more robust, contributing to longer battery life and addressing concerns about degradation and capacity fade often encountered in traditional lithium-ion batteries over time.

Apart from being safer, solid-state batteries also have the potential for significantly higher energy density. The inherent properties of solid electrolytes allow for the utilization of high-capacity materials without compromising safety or stability, resulting in batteries that can store more energy within a given volume or weight. This is especially important in applications that require maximized energy density, such as electric vehicles looking for extended ranges between charges.

Despite the promising potential of solid-state batteries, there are still challenges that need to be overcome in order for them to be widely adopted. The manufacturing of scalable solid-state batteries at a competitive cost is an obstacle that researchers and engineers are actively addressing. Another challenge is related to the interface between solid electrolytes and electrode materials, as well as the mechanical stresses that occur during charge-discharge cycles. Ongoing investigations are focused on these areas. Despite these challenges, the “Solid-State Revolution” is making its way into various industries. Electric vehicle manufacturers are investing in solid-state battery technology to improve safety and range. In addition, portable electronics, medical devices, and aerospace applications are exploring the potential benefits of solid-state batteries. As research progresses, the possibilities of large-scale applications, including grid-scale energy storage, are becoming more achievable.

Final author’s comment: One final element could strongly incentivize electric utilities to move from fossil-fueled peakers to batteries. The current administration’s approval ratings are low and getting lower. This might lead to one, or both houses of the U.S. congress (both houses now have a very slim Republican majority -- see below) to flip to Democratic-control this fall, becoming much more environmentally-inclined. Battery technologies, in general, are much better for our environment than fossil-fueled peakers.

The 119th Congress (2025–2027) convenes with Republicans holding the Senate majority—53 seats to the Democrats’ 45, plus two independents who caucus with Democrats.

In the House, reporting across congressional directories and data aggregators describes a slim Republican majority following the 2024 elections—commonly summarized as a three-seat GOP edge.