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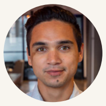
Analysis



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Contents

EMERGING TECH RESEARCH

Grid Storage Beyond Lithium

Alternative battery technology competes for dominance

Key takeaways

- The global energy crisis is accelerating the transition to clean energy sources, and this will involve substantial solar and wind projects. The intermittency of these power sources increases the need for grid flexibility, and grid-scale batteries are a core component of this.

- For grid-scale batteries, Li-ion chemistry is the current dominant technology, but alternative technologies such as redox flow and metal-air have potential in certain applications.

- Though most of the startups in the grid-scale battery storage space are focused on Li-ion batteries, there is a growing number using alternative chemistries, with some attracting significant funding.

- It is currently unclear whether alternative battery technologies have enough investment and potential to overcome Li-ion's maturity advantage in addition to the cost scaling that this brings—even if the alternative technologies are better suited to certain grid applications than Li-ion.

Grid battery space VC activity

VC investment in grid-scale battery technology startups has climbed sharply in the last five years, peaking at over $7 billion in 2021. Some of it, however, can be attributed to a few particularly large funding rounds for startups offering battery technologies in several areas—commonly electric vehicle (EV) batteries and grid-scale batteries. The two largest of these are SVOLT and Britishvolt, both of which are primarily EV battery developers that have moved into the stationary battery space. Driven by the falling costs of Lithium-ion (Li-ion), the bulk of investment has been in Li-ion cell startups, but there is also interest in approaches that could possibly provide lower cost installations or reduce reliance on potentially vulnerable resource streams. In the last few years, the largest funding round for a non-Li-ion grid battery startup was iron-air battery developer Form Energy's $450.0 million Series E.

Need for grid-scale energy storage

Global efforts are currently underway to transition energy systems from fossil fuels to cleaner sources. This trend is driven by several factors, including the now widely accepted view that carbon emissions must be reduced to limit the effects of climate change, but purely economic reasons are also relevant. Embracing clean energy sources can provide additional energy security and break existing dependencies on fossil fuel imports. 2022 has been a notable year for energy security following the energy crisis. This created a need to rapidly replace Russian fuel imports following both the sanctions placed on Russia upon its invasion of Ukraine, and the Russian response to these sanctions.

While the significant fuel price volatility that occurred earlier this year has lessened recently, we are now moving into the first winter since the energy crisis began, and it remains to be seen how European fuel stockpiles will withstand the need to provide heat. For the time being, it seems that Europe is somewhat well-prepared to weather the 2022/2023 winter, assisted by a relatively mild forecast, energy-saving initiatives, and by finding fuel elsewhere. These alternative fuel sources have been easier to obtain than expected due to reduced demand from China driven by COVID-19-related lockdowns.[1] These positive factors are by no means permanent, however, and renewable power provides an avenue to reduce exposure to this risk.[2]

Overall, the cost of replacing Russian fuels is accelerating the energy transition, which can provide a level of insulation from fuel price volatility. Countries with limited domestic fuel resources are now much more able to improve their energy independence. Even outside Europe, energy price fluctuations have been significant this year, fostering demand for local power generation.

There are many technological approaches to the energy transition, but in the immediate term, much of the burden will be borne by solar and wind, as two of the most mature renewable energy technologies available. Hydropower is also well-established but is much more limited in where it can be implemented, and

1: "Oil Slides as China Lockdowns Outweigh Proposed EU Russia Oil Ban," *Reuters*, Nia Williams, May 3, 2022.
2: "Europe Shifts Focus to Avoiding Energy Shortage Next Year," *AP News*, Courtney Bonnell, December 12, 2022.

regulatory hurdles tend to be significant due to its effects on river ecosystems.[3] Costs for both wind and solar energy generation have fallen sharply in recent years, and total installed capacity as a percentage of overall power generation capacity is growing.[4]

While these technologies are vital to global decarbonization efforts, they bring some challenges that require battery storage and grid flexibility:[5]

- **Daily solar output patterns.** Solar power is tied to sunlight intensity; while weather patterns can influence it, there is an underlying 24-hour pattern of solar power generation following sunlight intensity, with the specific hours shifting based on location and season. This pattern does not well-match the 24-hour pattern for energy demand, which tends to rise throughout the day and peak in the evening as solar output drops off. This leads to a situation for grid operators where solar fills a large percentage of demand around midday, but then when energy demand spikes in the early evening, solar generation falls off, leaving a large gap for other power sources to fill.

- **Intermittency.** In addition to daily patterns for solar power generation, both solar and wind suffer from intermittency—the variation in power generation due to changing wind and sun cover. Maximum power output at a given time can be predicted, but not controlled, and predictions are not always correct.

When implemented at a small scale, these factors can be absorbed by power grids' existing ability to balance power generation and load—currently built into power grids to manage power demand volatility and challenges in forecasting demand. In many regions though, wind and solar provide large amounts of energy. As intermittent renewables account for a larger proportion of total generation capacity, additional means to manage intermittency are necessary, and grid-scale battery energy storage systems (BESS) are a key method to achieve this.[6] Grid BESSs allow storage of electricity when generation outstrips demand, and this energy can then be released when demand is high. This effectively smooths out the peaks and troughs of intermittency and daily generation patterns. Smoothing solar's daily patterns, however, requires long duration energy storage (LDES)—defined typically as storage capable of maintaining output for over four hours—and technologies for LDES are at a lower state of technological readiness.

3: "Challenges in the Development of Hydropower in Selected European Countries," MDPI, Pawel Tomczyk and Miroslaw Wiatkowski, December 16, 2020.
4: "Renewable Power Generation Costs in 2021," IRENA, Michael Taylor, et al., 2022.
5: Note: Grid flexibility is defined as the ability to absorb and manage variation/volatility in electricity demand and generation.
6: "U.S. Battery Storage Capacity Will Increase Significantly by 2025," EIA, December 8, 2022.

Lithium-ion's dominant technology

Li-ion battery chemistries are well-established, having benefitted from substantial development outside of grid implementations—including portable devices and EVs—and leading to a sharp reduction of cost-per-Watt. The ability to simply connect many individual cells to create BESSs simplifies the design process and allows the use of mass-produced cells, for which manufacturing infrastructure is already in place. The cost of Li-ion cells has fallen sharply in the last 10 years, though there have been indications that 2022 will break this trend.[7]

Average pack price of Li-ion batteries*

Source: IEA, derived from Creative Commons | Geography: Global
*As of October 26, 2022

Li-ion implementations are somewhat well-established, and this provides benefits over other options, particularly when purchasers consider maintenance and approval for BESS projects. Though Li-ion batteries can pose a higher fire risk than other chemistries and approaches, this danger and the mitigation practices for it are well-known, simplifying debate over necessary safety measures and permitting for installations. Similarly, although Li-ion installations are not yet common, expertise is available for its maintenance.

Even though there is proficient understanding of how to safely use and maintain Li-ion batteries, its downsides must still be considered. While battery health monitoring and fire suppression systems can reduce the likelihood and impact of incidents, Li-ion chemistries can still be fire risks due to the nature of the materials involved. This is evidenced by recent examples, such as a fire outbreak at PG&E Corp's energy facility,[8] though in other cases, safety features were activated and the fires did not spread to other units. The materials involved can be problematic beyond their chemical volatility—Li-ion chemistries all rely on lithium, the supply of which could be strained by the rapidly increasing demand. Further, cathode materials for Li-ion chemistries include some resources with particularly vulnerable or limited supply chains, such as cobalt, nickel, and manganese.

7: "Electric Vehicle Battery Costs Soar," IER, April 25, 2022.
8: "Fire at PG&E's California Tesla Battery Facility Fully Under Control," *Reuters*, Akash Sriram, Juby Babu and Hyunjoo Jin, September 20, 2022.

The declining cost of Li-ion batteries has been crucial in securing their place as a key grid technology, and the characteristics of Li-ion batteries are well-suited to short-term energy storage, however, boosting the duration quickly increases the costs. Due to the falling prices of Li-ion cells, energy storage of up to eight hours can be viable.[9] While Li-ion installations that supply energy for even longer time periods are possible, other BESS or non-battery options do not rise in cost as rapidly when duration is increased.

Alternative approaches

The most widely deployed grid-scale energy storage approach is pumped hydro, though installation of new capacity is somewhat dependent on geography and terrain. Grid-scale BESS installations are rising, and they have the advantage of being able exist essentially wherever they are needed; their lack of significant land footprints allow them to be installed wherever existing grid connections are.

Outside of Li-ion batteries, there are a couple of options that are currently being developed: redox flow batteries and metal-air batteries. Redox flow batteries, or ‘flow batteries,’ store energy as liquid electrolytes in large vessels. When the battery is discharged, the two electrolyte solutions are pumped through an electrochemical cell that outputs electrical energy. The size of the electrochemical cell dictates the power output, and the size of the electrolyte storage vessels determines the total energy stored—increasing these electrolyte tanks is relatively low-cost and allows for increasing battery duration. The basic design is such that the batteries do not suffer from ‘depth of discharge’ problems—in Li-ion cells, fully discharging the cell can reduce its lifespan, but this is less the case for flow batteries.

Redox flow batteries have somewhat low energy density, which limits their use outside of stationary applications, but as a grid-supporting technology, they are well-suited and generally use fewer problematic resources than Li-ion. Redox flow batteries can be recharged through application of energy to their electrochemical cell, or alternatively through a replacement of electrolyte fluids in their storage tanks. The technology behind redox flow batteries shares a common physical design, but the specific chemistry used can vary. The most common approach is to use vanadium-based chemistry, though other options are being widely investigated, including bromine- and polymer-based chemistries.

Similarly to redox flow batteries, metal-air batteries have strong potential for use as grid-scale BESSs. They essentially store energy as solid metal, and discharging the batteries provides electricity from the ‘rusting’ process, hence the alternative name ‘rust batteries.’ The two most used metals for them are zinc and iron. Zinc-air batteries have potentially very high energy density, which opens up use cases outside of grid energy storage, whereas iron-air batteries have low energy density—too low for non-stationary applications. The benefits offered by these batteries, though, is largely in the low cost of materials involved, particularly for iron-air batteries. This low overall cost has strong benefits for scaling, potentially allowing

9: “Second Eight-Hour Lithium-ion Battery System Picked in California Long-Duration Storage Procurement,” *Energy Storage News*, Andy Colthorpe, March 8, 2022.

very long duration energy storage, likely supported by Li-ion for short duration applications. As with redox flow, metal-air batteries can be recharged in multiple ways, including applying electrical energy to reverse the reaction and form solid metal, or by simply adding additional metal to the cell.[10]

Both redox flow and metal-air batteries provide longer duration grid energy storage and can function as a complement to Li-ion, though the two technologies do compete at some level for medium- and long-term durations.

Battery type	Advantages	Disadvantages
Li-ion	• High maturity of technology, manufacturing, and supply chains. • High energy density. • Low overall cost. • Cells from high-performance applications, such as EVs, can be repurposed as BESSs.	• High cost to scale storage duration. • Dependent on rare natural resources for electrolyte and cathodes. • Flammable materials.
Redox flow	• Simple, low-cost scaling through increasing electrolyte storage tanks. • Long lifespan for installations, performance does not degrade for 25 to 30 years.[11] • Inherent fire safety—non-flammable energy storage medium. • Not reliant on rare resources or those with problematic supply chains • Energy storage capacity (electrolyte tank size) uncoupled from power output (electrochemical cell size), simplifying tailored installations.	• Low energy density, not well suited to mobile applications, thus limiting shared research and development. • Low technological maturity relative to Li-ion, hindering effective evaluation of performance.[12] • High costs for short duration installations. • Relatively low numbers of installations, complicating assessments of safety and maintenance.
Metal-air	• High energy density—such as for zinc-air batteries. • Uses low-cost, abundant raw materials. • Inherent fire safety—non-flammable storage medium. • Cost to scale duration lower than Li-ion.	• Low energy density (for iron-air batteries). • Some challenges to be mitigated in charging/discharging. • Relatively low numbers of installations, complicating assessments of safety and maintenance.

Efforts to increase grid-scale BESSs are rising in various geographies, including substantial investment from China, who recently announced the commission of the world's largest flow battery at 800 megawatt-hours.[13] Investment in the US is also well poised following the signing of the Inflation Reduction Act, which includes a tax credit for stand-alone grid storage projects; the specific total dollar value of this investment though is open-ended and depends on how many entities use the credit. Several European Union countries have policies in place to bolster investment in grid-scale BESS, including Germany's innovation auctions to pair renewable energy projects with energy storage. Additionally, Spain aims to install 20 gigawatts of grid-scale energy storage by 2030, although the composition of this storage is unspecified but will likely involve Li-ion plus alternative batteries and possibly non-battery options—such as pumped water storage or thermal energy storage.

10: "Metal-Air Batteries: Will They Be the Future Electrochemical Energy Storage Device of Choice?" ACS Publications, Yanguang Li, May 5, 2017.
11: "Grid-Scale Storage," IEA, Max Schoenfisch, Amrita Dasgupta and George Kamiya, September 2022.
12: "Assessment Methods and Performance Metrics for Redox Flow Batteries," ResearchGate, Yao Yanxin, et al., February 2021.
13: "First Phase of 800MWh World Biggest Flow Battery Commissioned in China," *Energy Storage News*, Andy Colthorpe, July 21, 2022.

With investment in grid-scale batteries rising, coupled with an increasing need for grid-scale BESS due to intermittent renewable energy trends, grid-scale BESS will see substantial deployment in the next five to 10 years. What is less certain is the technologies that this will involve. Li-ion will cover short duration energy storage, but medium- and long-term storage will experience competition between the maturity of Li-ion and the potentially more suitable characteristics of alternative approaches.

Select company highlights

Form energy

Form Energy

- **Founded:** 2017
- **Employees:** 347
- **Total VC raised:** $816.0 million
- **Last financing:** $450.0 million in Series E funding
- **Last financing valuation:** $1,950.0 million
- **Lead investors:** TPG

US-based Form Energy focuses on iron-air battery chemistry, which has very low costs relative to other chemistries and approaches, thanks to abundant raw material inputs. These batteries are not viable for mobile implementations due to their low energy density. Capacities required for mobile applications would be too large and heavy, but the batteries are well suited to permanent stationary installation. The individual cells are similar in size to a kitchen appliance, and the system is modular, allowing varied installations based on the same hardware. Form Energy claims potential energy durations of over 100 hours.[14] Of all startups we are tracking in the alternative battery chemistry space, Form Energy has the highest total VC funding raised, and its recent Series E funding was also the largest amongst alternative battery startups. The company has signed a joint development agreement with ArcelorMittal to explore supplying Form Energy with low-carbon, direct reduced iron.[15] In December 2022, Form Energy announced that it would build its first full-scale iron-air battery manufacturing facility in West Virginia to provide grid-scale batteries for US power grids—battery manufacture is expected to start in 2024.[16]

14: "Battery Technology," Form Energy, n.d., accessed December 20, 2022.
15: "ArcelorMittal Makes Further Investment in Form Energy via XCarb Innovation Fund," ArcelorMittal, October 4, 2022.
16: "West Virginia Plant to Make Batteries for US Energy Grid," *AP News*, John Raby, December 22, 2022.

e-Zinc

- **Founded:** 2012
- **Employees:** 50
- **Total VC raised:** $42.7 million
- **Last financing:** $25.0 million in Series A funding
- **Last financing valuation:** N/A
- **Lead investors:** Anzu Partners

e-Zinc uses similar technology to Form Energy but utilizes zinc-air rather than iron-air. This provides higher energy density than iron-air but uses more expensive raw materials. Based in Canada, it provides zinc-air batteries that have long lifespans, flexible installation options, recyclability, and can act as long-duration energy storage. Its Series A, raised in April 2022, will be used to continue development of long duration battery storage, and additional venture funding will be put toward expanding production at its Ontario facility. e-Zinc provides zinc-air batteries for several applications, including grid-integrated energy storage, energy resilience/back-up power, and remote/off-grid energy storage.

XL Batteries

- **Founded:** 2019
- **Employees:** 6
- **Total VC raised:** $8.0 million
- **Last financing:** $8.0 million in Seed funding
- **Last financing valuation:** $33.0 million
- **Lead investors:** Catalus Capital Management

US-based XL Batteries develops flow batteries based on organic chemistry dissolved in salt water, aiming to provide stationary energy storage that can be applied to grid or microgrid applications. One of the most frequently deployed chemistry for such flow batteries relies on vanadium, which can result in electrolyte corrosivity that brings additional engineering challenges. XL Batteries bypasses this issue using organic chemistry through its saltwater battery, derived from low-cost industrial feedstocks. Having previously received grants and funding through an innovation program, XL Batteries raised $7.0 million in Seed funding on September 7, 2022.

Elestor

- **Founded:** 2014
- **Employees:** 38
- **Total VC raised:** $30.5 million
- **Last financing:** $30.5 million in Series A funding
- **Last financing valuation:** N/A
- **Lead investors:** Equinor Ventures, Invest-NL

Based in the Netherlands, Elestor develops redox flow batteries centered around bromine-hydrogen chemistry. The use of this particular chemistry aims to keep scaling costs very low, as Elestor's battery chemistry was specifically chosen for its low-cost chemical inputs. Additional safety features are present to mitigate the use of potentially flammable hydrogen. The cell stacks of its flow battery are easily accessible, allowing maintenance and replacement as needed, thus increasing the lifespan of the battery and further reducing the levelized cost of storage—the cost of electricity discharged from a battery, taking into consideration the incurred costs and electricity provided for the entire life of the storage unit. Elestor's most recent funding in Q3 2022 was led by Norwegian energy giant Equinor and will be used to accelerate the commercialization of its battery technology.