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## News & Highlights

### Can Batteries Meet the Looming Demand for Grid-Scale Storage?

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On 16 January 2025, flames erupted, and smoke rose more than 300 m in Moss Landing, CA, USA, at what was until early 2024 the world's largest battery energy storage system (BESS) [1]. Prompted by the potential danger of exposure to toxic gases from the blaze [2], local authorities closed schools and the coast's iconic Highway 1, evacuated hundreds living close to the facility, and instructed residents of the nearby communities of Santa Cruz and Salinas to stay indoors and keep their doors and windows shut. The burning lithium-ion batteries (LIB) also raised concerns about contamination of communities and farmland in the area, as well as in the adjacent Elkhorn Slough State Marine Conservation Area and Monterey Bay National Marine Sanctuary [3]. Locating the BESS facility on the coast next to a relatively isolated 75-year-old natural gas-powered thermal generating station had allowed its owner, Vistra Corp. (Irving, TX, USA), to minimize zoning issues and easily access existing grid infrastructure [4].

Before the fire, the Moss Landing BESS stored 3 GW·h and provided 750 MW, enough to power more than 600 000 homes for up to four hours [5]. At that capacity, it ranked second largest in the world behind the 3.287 GW·h/875 MW Edwards & Sanborn installation in Mojave, CA, USA [6], and ahead of the 2 GW·h/500 MW Bisha installation in Bisha, Saudi Arabia [7]; these two facilities were completed in January 2024 and January 2025, respectively. Vistra had stated that its Moss Landing BESS could scale up to 6 GW·h/1.5 GW [4]. Any expansion is now on hold, however, after the fire destroyed the 300 MW phase one of the project completed in 2020, burning approximately 100 000 LIB modules [3–5]. Because LIB fires are extremely difficult to extinguish, firefighters allowed the fire to slowly burn out on its own over several weeks, but a second flare up occurred on 18 February [8].

The fire risk associated with LIB—especially with the Moss Landing facility's older, less stable nickel–manganese–cobalt (NMC) batteries rather than the newer lithium–iron–phosphate (LFP) batteries that have become the standard for battery storage [4]—is among the many challenges engineers face in creating safe and cost-effective grid-scale storage. The Moss Landing fire was not the first such mishap, but it may have been the largest to date. Three smaller fires had previously occurred at Moss Landing since 2021 [4], and fires have also been reported at other lithium-ion BESS installations in the United States (California) and the Republic of Korea [9,10].

“This is really a Three Mile Island event for this industry,” one local politician was quoted as saying [4]. Others called for closer scrutiny of a 200 million USD, 200 MW BESS just proposed at the

end of 2024 to be built at a location near Watsonville, a city just north of Moss Landing and not far from Santa Cruz [4]. The proposed facility has, however, been designed for improved safety; its LFP LIB will be stored in steel containers, each separated by almost a meter and outfitted with heat-monitoring and fire-suppression systems [4]. In the event of a fire, the arrangement traps smoke inside the steel container, keeping it from being dispersed into the air.

But while the Moss Landing disaster may have jeopardized the future of grid-scale lithium-ion BESS in Santa Cruz County, it seems unlikely to stall its recent acceleration elsewhere. After decades of development, the world now produces renewable energy from wind turbines and solar panels on a massive scale [11,12]. With their price dropping to become competitive with fossil fuels [12], these renewables, according to the International Energy Agency, currently account for about 15% of the electricity now produced globally [13]. However, unlike fossil fuels, which are easily transported and stored via long-established systems, solar and wind supplies fluctuate on a daily and seasonal basis.

Because power grids must maintain a delicate balance to deliver the electricity needed, the intermittent nature of wind and solar energy is problematic for them. If supply and demand fall out of balance, the result could be blackouts, which have the potential to be deadly [14], or utilities wasting money by producing extra energy that goes unused [15].

“As the fraction of total electric power generated increasingly becomes intermittent renewables like solar and wind, then you better have storage because there is not enough slack in the system to tolerate unreliable electricity,” said Donald Sadoway, the John F. Elliott Professor Emeritus of Materials Chemistry at the Massachusetts Institute of Technology in Cambridge, MA, USA. “That is why storage is a key piece.”

To ensure electricity is always available when needed, energy companies have traditionally relied on natural gas-powered “peaker plants.” As the name indicates, they only run when electricity demand peaks, such as on extremely hot days when people blast their air conditioning. Designed for purpose, peaker plants are typically less efficient and produce more pollution than other power plants [16,17]. But while peaker plants work well to support grids steadily powered by fossil fuel plants, they are at best a poor—and self-contradictory—solution to cover the lapses in clean energy generated by solar and wind power. For the successful transition to clean energy now promised by most of the world's countries [18], it is widely agreed that infrastructure enabling grid-scale storage of excess renewable energy will be a key component [19].

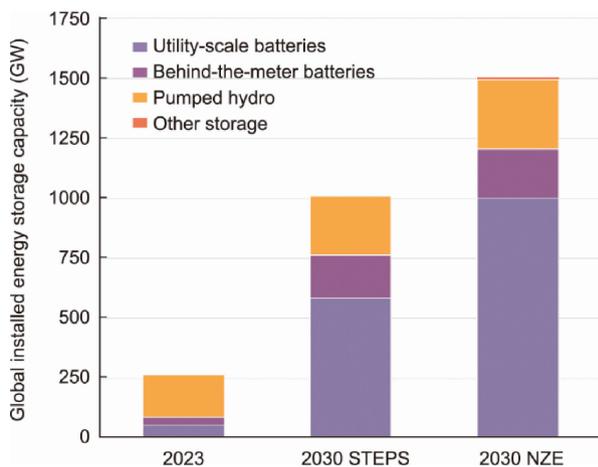
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To meet climate and energy security goals set at the 28th United Nations (UN) “Conference of the Parties” (COP28) climate conference, renewable energy capacity will need to triple by 2030 [18]. Supporting this increase means global energy storage must increase sixfold from its current capacity to 1500 GW, 1200 GW of which will likely come from battery storage (Fig. 1) [20]. An estimated more than 900 million USD was invested in storage technologies in 2021, up from 360 million USD the year before, according to the Long Duration Energy Storage Council (Brussels, Belgium), a coalition of 24 global energy companies formed during the 26th United Nations (UN) “Conference of the Parties” (COP26) climate meeting [21]. The group predicts that by 2040, large-scale, renewable energy storage investments could total 3 trillion USD. That sum assumes the future availability—to a significant degree—of innovative storage systems, including novel batteries, yet to be realized at scale.

Pumped-storage hydropower is currently the most widely used energy storage technology [22,23], providing an estimated 160 GW of storage in 2021 and accounting for more than 90% of the world’s current total electric storage capacity [21]. China has more pumped hydropower storage capacity than any other country, about 51 GW, and is reported to be constructing 66 new such facilities [24,25]. But while pumped storage hydropower is relatively cost-effective to implement, it is location-dependent, typically feasible only in mountainous areas [22].

In contrast, batteries offer a cheap energy storage solution that can be deployed nearly anywhere. The ubiquitous LIB that now power the world [26] can provide high-performance energy storage for a price that has dropped nearly 97% since they were first commercialized more than three decades ago, mainly owing to their development for use in electric vehicles (EV) [27]. Indeed, it has been suggested that EV LIB should be reused for grid-scale storage when they are replaced rather than immediately recycled, as such used batteries still retain about 80% of their capacity [19]. While it sounds good, the practice would face the challenges of refurbishing and adapting the many different LIB used by different EV manufacturers; it could perhaps be easier in China which has implemented more standardization and rules requiring the EV producers themselves to take responsibility for the entire product life cycle, including end-of-life recycling for the batteries in their EV [28].



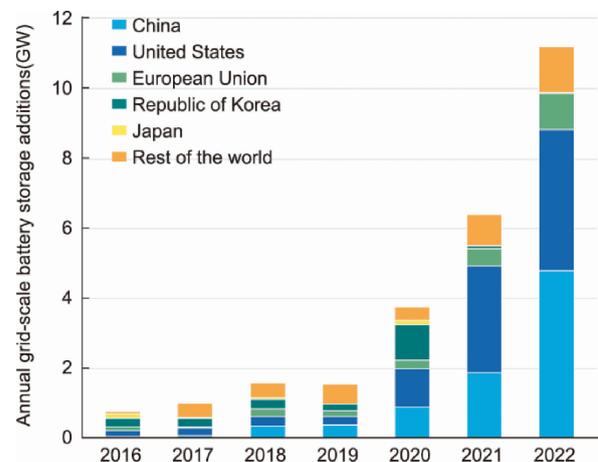
**Fig. 1.** Global installed energy storage capacity in 2023 and 2030 under two scenarios: Stated Policies Scenario (STEPS) and Net Zero Emissions by 2050 (NZE) Scenario. STEPS reflects current policy settings based on a sector-by-sector and country-by-country assessment of the energy-related policies in place as of August 2024, as well as those that are under development. NZE Scenario is a scenario showing a pathway for the global energy sector to achieve net zero CO<sub>2</sub> emissions by 2050. “Other storage” includes compressed air energy storage, flywheel, and thermal storage. Credit: International Energy Agency (CC BY 4.0).

To meet the booming demand for grid-scale storage, massive BESS installations have popped up around the globe in recent years (Fig. 2) [19]. “Around 2020, lithium-ion batteries achieved lifecycle cost parity with new ‘peaker’ gas turbines,” said Paul Denholm, Senior Energy Analyst at National Renewable Energy Laboratory in Golden, CO, USA. “That created the big rush we now see with tens of gigawatts of new energy storage being placed on the grid in the US, of which about 99% is some form of lithium-ion batteries.”

China and the United States lead the rush, installing 5 and 4 GW, respectively, in lithium-ion BESS in 2022 [19]. But even with the price of LIB continuing to fall [29], making lithium-ion BESS the current leading grid-scale storage technology for renewables (Fig. 3), environmental and supply chain concerns, as well as capacity and storage-duration limitations, have innovators searching for alternative solutions. Aside from the risk of fire, and various ethical [30] and environmental [31] concerns, the global supply of lithium is finite [32]. “Fortunately, quite a bit of the lithium is located in places that are geopolitically more stable, but it is an open question whether we can scale up lithium extraction and production quick enough to meet the world demand,” Denholm said. “That is one of the reasons why people are looking at other materials.”

Leading candidates as alternatives to LIB for grid-scale BESS include sodium-ion batteries, iron-air batteries, and flow batteries. Several companies in Asia, Europe, and North America are working to commercialize batteries that replace lithium with sodium, which is much more abundant and cheaper to extract and purify [33]. Despite the lower cost of materials, the price per unit of energy stored remains higher for sodium-ion batteries because the energy they hold per kilogram tends to be lower than for LIB. The current assessment is that this increased cost would limit widespread commercial adoption, unless research breakthroughs can be made, such as moving away from designs that include the relatively expensive metal nickel [34].

Another battery based on a relatively inexpensive material, iron, harnesses the energy released when iron reacts with air and water to form iron hydroxide, or rust. Recharging the battery involves dumping energy into the system to unrust it [35]. One downside is that compared with the round-trip energy efficiencies of about 80% to 90% for LIB and 70% to 80% for hydropower, iron-air batteries return just 50% to 60% of the energy that is put into them, partly because they gradually discharge with no current applied. However, the lower efficiency of iron-air batteries can be made up



**Fig. 2.** Annual grid-scale battery storage additions between 2017 and 2022 for the five leading regions in battery storage, and the rest of the world. Credit: International Energy Agency (CC BY 4.0).



**Fig. 3.** The Crimson Energy Storage Project BESS opened in Riverside County, CA, USA in October 2022. Built with LFP batteries rather than older, less safe NMC LIB, the facility stores up to 1.4 GW·h of energy generated by a nearby massive solar panel installation. Credit: US Bureau of Land Management (public domain).

for by increasing their size. And utilities may tolerate the loss, especially when iron–air batteries have the potential to be ten times cheaper and last 17 times longer than LIB [35]. At least one company, Form Energy (Weirton, WV, USA), has bet big on the technology with a 760 million USD investment in a factory to make iron–air batteries [35]. The company reports that its first customers will be utilities in the US states of Colorado, Georgia, and Minnesota.

Another take on stationary grid-scale batteries is the “redox flow” battery, in which chemical reactions occur not at electrode surfaces but in two fluid-filled tanks that function as electrodes [36]. The technology has already made its debut in several big real-world projects. Sumitomo Electric’s Hokkaido flow battery farm in Hokkaido, Japan, was the biggest in the world when it opened in April 2022 with a 51 MW·h/17 MW capacity [37]. Just a month later, however, China completed one in Dalian, that is eight times bigger with a capacity of 400 MW·h/100 MW [38].

Most flow batteries employ the metal vanadium, which, while it makes them durable and easy to maintain, also makes them at least twice as expensive to build as LIB [36]. Flow batteries could eventually be cheaper than LIB, however, because they might last about twice as long. But sourcing enough vanadium remains a major challenge for building a lot of flow batteries, with three-quarters of the world’s supply generated as a by-product from ten steel mills in China and Russia. Some flow battery start-up companies are exploring alternatives to vanadium that are easier to procure, such as iron, chromium, zinc, and organic compounds called quinones [36].

Like iron–air batteries, however, flow batteries are only about 60% efficient [36]. But for both alternatives this may not matter if the capital cost is low and the technology has a long lifecycle. “What matters is the cost per kilowatt hour of storage capacity,” said Eric Hittinger, an associate professor of public policy at the Rochester Institute of Technology (Rochester, NY, USA), whose research focuses on energy storage. “Good efficiency feels important, but if the energy at certain times would be wasted and otherwise has zero value, then efficiency does not really matter.”

In addition to weight-based systems [22], other solutions that do not involve traditionally defined batteries are being explored. Some firms are developing pumped thermal systems where compressed air is stored in large caverns, with electricity generated when the gas is released and allowed to expand through a turbine generator [39]. Pumped thermal energy systems usually require natural caverns, but the company Hydrostor (Toronto, Canada) carves out its gas-storing cavities in hard rock. In 2019, Hydrostor

launched the first commercial compressed-air storage facility in Goderich, Ontario, with a capacity of about 10 MW·h—enough to power 2100 homes for more than five hours [39]. The company said it plans to build several much larger facilities in California in the United States, as well as a 200-MW facility in the Australian town of Broken Hill [40].

Like compressed-gas, sand, stored in enormous steel vats, can also be used to store renewable energy for prolonged periods of time. The sand is first heated to around 500 °C by a resistance heater, which also heats air that swirls through the sand. A fan circulates the flow of heat continuously, until it is ready to use, holding the power for weeks or months at a time. Finnish company Polar Night Energy (Tampere, Finland) has built an 8 MW·h/200 kW sand battery; it also reports plans to build a second sand battery with a 500 MW·h/2 MW capacity [41].

While many of these novel storage technologies may find use in niche markets, the field awaits a breakthrough that will help facilitate the transition to renewable energy. “We do not get that many fundamental shifts in the energy power sector,” Denholm said. “We have had the shale gas revolution, the low-cost availability of natural gas, the declining cost of solar, and now the declining cost of battery storage. Otherwise, there has been basically almost no growth in storage of any other type.” Sadoway, who has spent his career developing batteries for the long-term storage of renewable energy (including the liquid metal battery [42]), agreed. “We have got to invent our way out,” he said. “Right now, everything is too expensive to make an impact.”

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