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Lawrence Berkeley National Laboratory

Review of Grid-Scale Energy Storage Technologies Globally and in India

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Abstract

India has set an ambitious target to reach 500 GW of installed non-fossil energy capacity by 2030. However, increasing penetrations of renewables - mostly wind and solar - will require the corresponding deployment of flexible resources - such as energy storage and demand response - to support generation variability. To this regard, alongside rapid demand growth for renewables and electrification, grid-scale energy storage will be key to ensuring power system reliability and resilience in the coming years. Here, we conduct a review of grid-scale energy storage technologies, their technical specifications, current costs and cost projections, supply chain availability, scalability potential, and policy frameworks focused on the Indian market and contextualized in the global landscape.

1. Introduction

Grid-scale energy storage has a crucial role to play in helping to integrate solar and wind resources into the power system, helping to ensure energy security along the road to decarbonization. The technologies used to support the build out of storage capacity are likely to see major changes in levelized costs and system parameters in the coming decade. Therefore, understanding the current and projected states of these technologies – including their costs, materials, policy schemes, etc. – is key for stakeholders in order to guide decision-making. Ultimately, the top technologies that emerge will have significant implications across supply chains and continents.

Like in many places, the grid-scale energy storage sector is just beginning to develop in India, where the power sector is set to undergo significant changes in the coming years. The country has ambitious goals to deploy hundreds of gigawatts of renewables by 2030 while also needing to meet rapidly growing electricity demand. Since India will thus be a key market of grid-scale energy storage, this review aims to give a holistic picture of the global energy storage industry and provide some insights into India's growing investment and activity in the sector.

This review first conducts a techno-economic assessment of the different grid-scale storage technologies, outlining what they are and how they differ from each other, their cost trajectories, system size, storage duration and lifetime. The next section focuses on an overview of the battery supply chain with a focus on lithium (only commercially available battery storage technology) but also including details about the expected supply chain for other emerging storage technologies. The review also provides an overview of Indian and other country battery policy as well as a literature review of other studies that analyze the Indian battery supply chain. We focus on India as a rapidly growing but ultimately underdeveloped storage market and utilize the global techno-economic and supply chain context as well as literature review about the Indian battery supply chain to understand where the Indian energy storage industry is headed.

2. Techno-economic review of energy storage technologies

We begin with a non-exhaustive list of various zero-carbon grid-scale storage technologies, which can be divided into three main types: electro-chemical, mechanical, and chemical. The electro-chemical technologies are primarily batteries, encompassing both widely deployed technologies like lithium-ion batteries as well as promising technologies that currently remain in early stages of development, like iron air batteries or sodium-ion batteries. The mechanical technologies include pumped hydro storage, which is already in widespread use, as well as gravitational storage, compressed air and liquid air energy storage.

For all potential grid-scale storage technologies, we compile key techno-economic parameters, including costs and technical specifications, in Table 1 for a straightforward comparison. Costs for electro-chemical technologies i.e. batteries reflect standalone system costs for accurate comparison, although it should be noted that batteries are often co-located with generation such as solar which in turn helps to reduce costs due to economies of scale. Unit costs reflect the global benchmarks of storage unit costs (a pack for batteries and the system for mechanical technologies). Balance-of-system (BoS) and development costs are also provided for the India context, as they can vary by country and tend to be lower than for example in the US (Deorah et al. 2020). The Levelized Cost of Storage (LCOS) is also shown in Table 1, defined as:

$$LCOS = \frac{CAPEX + OPEX * \sum_{n}^{Calendar\ life} \frac{1}{(1+r)^n}}{Cycles\ per\ year * \ Depth\ of\ discharge} \qquad [1]$$

assuming the CAPEX is the annualized sum of the unit cost, BoS and development costs and the OPEX reflects the net present value of the operation and maintenance expenses (assumed to be constant over the lifetime *n* of the asset with an interest rate *r* =6%) (Deorah et al. 2020). Considering that the costs of all technologies are expected to fall and technical parameters like cycling lifetimes are expected to improve (we assume 275 cycles/year in 2022 and 300 cycles/year in 2030) with further development, LCOS values are correspondingly also set to decline across the board. The one exception is pumped hydro storage, a relatively mature technology whose costs are projected to remain stable over the coming years. Accordingly, technologies with longer lifetimes and higher number of cycles have a lower LCOS.

While it should be noted that other zero-carbon energy storage technologies exist, we focus on those that are attractive and applicable to the particular case of grid-scale storage in the coming years. The excluded technologies include electro-chemical forms of storage – such as lead acid batteries, solid state batteries, and molten salt energy storage – as well as other energy vectors – notably hydrogen. These technologies' high costs, challenges related to scalability, poor efficiencies and lack of applicability to commercial grid-scale storage in the near-term, among others, bar them from serious consideration. While a few of the emerging technologies considered here may face similar challenges, we include them in the comparison in Table 1 due to either renewed commercial interest in recent years, technological advancements or other signs of promising potential.

Table 1. Grid-scale storage technologies and their techno-economic parameters[1,2]

Storage Tech	Type	2022 global unit cost ($/kWh)[3]	2030 global unit cost ($/kWh)[3]	BoS & development cost[4] ($/kWh)	2022 LCOS (Rs./kWh)[5]	2030 LCOS (Rs./kWh)[5]	Storage duration[6] (hours)	Typical specific energy[6] (Wh/kg)	Typical cycle life[6]	Technical calendar life[6]	Round trip efficiency[6]	Source(s)
Lithium-Ion Phosphate	Electro-chemical	142 (pack)	67 (pack)	4-hr: 66 (India) 10-hr: 26 (India)	4-hr: 7.3 (India) 10-hr: 6.1 (India)	4-hr: 4.6 (India) 10-hr: 3.5 (India)	0-12	90-160	3,000 cycles	<16 years	86%	(BNEF 2022a, BNEF 2022b, BNEF 2021a, Lazard 2023, DOE 2022, Deorah et al. 2020, Authors' analysis)
Nickel Manganese Cobalt	Electro-chemical	170 (pack)	67 (pack)	66 (India)	8.5 (India)	5.0 (India)	0-8	190-270	2,000 cycles	<13 years	83%	(BNEF 2022a, BNEF 2022b, DOE 2022, Deorah et al. 2020, Authors' analysis)
Vanadium Redox Flow	Electro-chemical	284 (system)	237 (system)	95 (India)	10.4 (India)	8.4 (India)	6-12	~35	5,000 cycles	<12 years	65%	(Doetsch and Pohlig 2020, Huang et al. 2022, Ramesh 2022, DOE 2022, Authors' analysis)
Zinc Bromine Flow	Electro-chemical	258 (system)	206 (system)	116 (India)	13.1 (India)	10.3 (India)	2-12	~70	5,000 cycles	<10 years	70%	(Doetsch and Pohlig 2020, Yuan et al. 2020, Authors' analysis)
Sodium Sulfur	Electro-chemical	280 (pack)	120 (pack)	200 (India)	12.5 (India)	6.9 (India)	0-12	~110	5,000 cycles	<13.5 years	75%	(DOE 2019, Authors analysis)
Sodium-Ion	Electro-chemical	77 (cell)	40 (cell)	70 (India)	5.2 (India)	3.7 (India)	0-12	~160	<3,500 cycles	<10 years	92%	(Abraham 2020, Crownhart 2023, Wang 2022, Faradion 2023, Authors' analysis)
Aluminum Air	Electro-chemical	500 (system)	400 (system)	n/a	12.2 (India)	8.4 (India)	0-20	1,300	<6,000 cycles	n/a	83%	(Farsak and Kardas 2018, Authors' analysis)
Iron Air[7]	Electro-chemical	20 (pack)	10 (pack)	200 (India)	1.9 (India)	1.2 (India)	0-100	600	<10,000 cycles	n/a	50%	(Form Energy 2023, Authors' analysis)
Pumped Hydro Storage	Mechanical	4-hr: ~$780/kW (system, India)[8] 10-hr: ~$1,000/kW (system, India)[8]		n/a	4-hr: 6.4 (India) 10-hr: 3.3 (India)	4-hr: 5.9 (India) 10-hr: 3.0 (India)	4-12	n/a	n/a	~60 years	80%	(DOE 2022, BNEF 2021b, Authors' analysis)
Gravitational Storage	Mechanical	380 (system)	350 (system)	n/a	11.1 (India)	9.2 (India)	6-14	n/a	n/a	~60 years	80%	(DOE 2022, Tong et al. 2022, Authors' analysis)
Compressed Air	Mechanical	150 (system)	123 (system)	n/a	9.7 (India)	8.8 (India)	0-24	n/a	n/a	60 years	52%	(DOE 2022, Vecchi et al. 2021, Authors' analysis)
Liquid Air	Mechanical	150 (system)	100 (system)	n/a	12.9 (India)	11.8 (India)	10-100	n/a	n/a	30 years	n/a	(DOE 2022, Vecchi et al. 2021, Authors' analysis)

[1] Not all parameters are provided for each technology due to low technological readiness level, lack of commercialization and/or inapplicability/unavailability of information.
[2] Costs are in real 2022 dollars and generally reflect global benchmark prices unless otherwise noted.
[3] Costs reflect systems of 10 MW & 4 hours of duration for batteries and systems of 1,000 MW & 10 hours of duration for mechanical technologies, yet scale may affect final cost.
[4] Includes Balance of System (BoS), power equipment, system integration, inverter, and development costs in India. Costs reflect a 4-hr storage duration unless otherwise noted.
[5] LCOS is calculated for India with an exchange rate of 82 INR/USD, an interest rate of 6%, & exclusive of taxes/duties per Equation 1. Costs reflect a 4-hr storage duration unless otherwise noted.
[6] Values reflect technical capability & known commercial development; subject to change with future development. Specific energy reflects cell-level values.
[7] Although a promising technology with low purported costs, current commercial development of iron air batteries is limited to one company (Form Energy 2023).
[8] For pumped hydro, costs are shown on a per unit power basis to indicate the large capital investment that is required, although costs per unit energy may be relatively low.

Going beyond these basic facts and figures, we next provide a summary of each individual technology's main characteristics:

- **Lithium-ion Phosphate (LFP) batteries** – one of two basic types of lithium-ion batteries. Popular due to their relatively long lifespans and high cycling lifetimes and high energy density. Location agnostic, best suited for short-term durations, i.e., under 6 hours (Lazard 2023). Have seen significant cost declines over the past few years. However, face high competition with electric vehicle (EV) makers and are sensitive to price shock due to highly concentrated supply chains, especially regarding lithium (BNEF 2022a).
- **Nickel Manganese Cobalt (NMC) batteries** – the second of two basic types of lithium-ion batteries, but with slightly higher energy densities but lower lifespans than LFP. Like LFP batteries, also face high competition with EV makers and concentrated lithium supply chains. However, NMC batteries are more reliant on materials – particularly cobalt – that are less abundant and more expensive - mostly cobalt to extract and come with concerns about ethical mining practices (BNEF 2022a).
- **Vanadium Redox Flow (VRF) batteries** – potential alternative to lithium-ion batteries for grid-scale storage, with better degradation properties and easier scalability but higher weights due to the aqueous electrolyte (Yang 2017). Increased commercialization will likely depend on the rate of scaling of vanadium manufacturing, since as will be discussed later on, production is highly concentrated (mostly China, then Russia) and thus expensive (USGS 2020).
- **Zinc Bromine Flow (ZBF) batteries** – like VRF, utilize liquid electrolytes and more common, low-cost materials. However, they have lower round-trip efficiencies and charge/discharge rates than lithium-ion batteries, with high costs and low levels of commercialization.
- **Sodium sulfur** – utilize liquid sodium and sulfur electrodes, achieving similar energy densities to lithium-ion batteries from common, low-cost materials; however, due to high operating temperatures along with safety concerns and low lifespans, they are not significantly commercially deployed (DOE 2019).
- **Sodium-ion** – similar in principle to lithium-ion batteries but replace the lithium with sodium; recently, have seen rapid technological developments, increasing energy densities and the beginnings of commercial deployment as they utilize far more common raw materials than lithium; may also be simultaneously coupled with lithium-ion batteries in hybrid packs, to reduce the lithium quantity and thus the battery cost per kWh while maintaining adequate performance (Abraham 2020, Crownhart 2023, Wang 2022).
- **Aluminum air** – known for their high energy densities and utilization of common, low-cost materials; however, experience issues related to anode corrosion whose amelioration involves high costs, with further development and improvement necessary to bring them to market (Farsak and Kardas 2018).
- **Iron air** – operates on the principle of reversible rusting, utilizing common, low-cost materials, but are heavy, only suited for grid-scale, stationary storage applications; although a promising technology with low purported costs, current commercial

development is limited to one company – Form Energy – whose first pilot project is planned for deployment in the coming years (Form Energy 2023).

- **Pumped hydro storage (PHS)** – a mature, conventional form of energy storage, with widespread deployment in existing power grids. Pumps water from a lower elevation to a higher elevation during off-peak periods, then releases the stored water during peak periods to generate electricity. Typically, longer lifetimes than battery energy storage systems.
- **Gravitational storage** – utilizes a mechanical process of hydraulic lifting a sort of block or rock, acquiring potential energy which is then released during peak periods to generate electricity. Barriers to commercialization include efficiency and charging time.
- **Compressed air energy storage (CAES)** – based upon the principle that air or another gas is compressed during off-peak periods, then stored under pressure until peak periods when it is used to turn a turbine and generate electricity. The primary disadvantage is energy loss via heat during compression, leading to low efficiencies (Vecchi et al. 2021).
- **Liquid air energy storage (LAES)** – applies electricity to cool air until the air liquifies, which is then stored in a tank until peak periods when it is used to turn a turbine and generate electricity. The primary disadvantage is energy loss via heat during compression, leading to low efficiencies (Vecchi et al. 2021).

From all these technologies, we select a few of the top technologies to dive into further. The selection criteria focus on their feasibility of deployment (i.e., costs, scalability, supply chain availability, technological readiness) for grid-scale storage in the near-medium term (i.e., 10-15 years) in India. The two top contenders are lithium-ion phosphate batteries and pumped hydro storage, with their attractiveness reflected in their high market share today. Given recent commercial developments, particularly in China, we also include sodium-ion batteries. We discard the remaining technologies for various reasons: high operating costs, low technological readiness levels, low commercialization levels, low cycling lifetimes, reliance on expensive raw materials, etc. This is particularly pertinent for lithium nickel manganese cobalt batteries as well as vanadium redox flow batteries, which rely on materials with highly concentrated supply chains.

Figure 1 shows how India's current and projected costs of different energy storage technologies compare to costs in the US, China and globally. The costs of battery storage are cheapest in China, reflecting China's large domestic manufacturing capacities with integrated supply chains contributing to lowering costs, as well as the relative immaturity of other markets (BNEF 2022a). Meanwhile, the costs of batteries are highest in India and the US, at least in part given the need to import cells and packs. With regards to the total project cost, in India, financing costs may be higher than in the US although costs of BoS components and development may be lower (Deorah et al. 2020). However, in general, costs of batteries have seen significant declines over the past decade, with further declines projected through 2030. The most recent estimates expect pack prices to remain elevated in 2023, drop in 2024 as more extraction and refining capacity comes online, and fall below the $100/kWh point (on global average) in 2026 (BNEF 2022a).