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Electricity Markets & Policy
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Review of Grid-Scale Energy Storage Technologies Globally and in India

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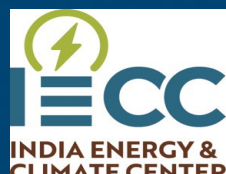
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Abstract

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 currently 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 through shared system components. 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) for standalone storage systems in India is also shown in Table 1, defined as:

$$LCOS = \frac{\text{Annualized CAPEX} + OPEX * \sum_n^{\text{Calendar life}} \frac{1}{(1+r)^n}}{\text{Cycles per year} * \text{Depth of discharge} * \text{Round trip efficiency}} \quad [1]$$

assuming the CAPEX is the annualized sum of the unit costs, 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). As can be seen in Table 1, the costs of most technologies are expected to fall. Exceptions include pumped hydro storage, a relatively mature technology whose costs are projected to remain stable over the coming years, as well as compressed air and liquid air storage. Accordingly, technologies with lower CAPEX and OPEX, longer lifetimes, higher depths of discharge and higher round trip efficiencies 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)	4-hr: 7.0 (India)	4-hr: 4.5 (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)
				10-hr: 26 (India)	10-hr: 5.9 (India)	10-hr: 3.5 (India)						
Nickel Manganese Cobalt	Electro-chemical	170 (pack)	67 (pack)	66 (India)	9.7 (India)	6.2 (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)	14.7 (India)	12.9 (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)	17.2 (India)	14.8 (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)	15.2 (India)	9.3 (India)	0-12	~110	5,000 cycles	<13.5 years	75%	(DOE 2019, Authors analysis)
Sodium-Ion ⁷	Electro-chemical	77 (cell)	40 (cell)	70 (India)	5.4 (India)	4.3 (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	14.0 (India)	10.6 (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)	3.5 (India)	2.4 (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		n/a	4-hr: 7.3 (India)	4-hr: 7.3 (India)	4-12	n/a	n/a	~60 years	80%	(DOE 2022, BNEF 2021b, Authors' analysis)
		10-hr: ~\$1,000/kW (system, India) ⁸			10-hr: 3.8 (India)	10-hr: 3.8 (India)						
Gravitational Storage	Mechanical	380 (system)	350 (system)	n/a	12.7 (India)	11.5 (India)	6-14	n/a	n/a	~60 years	80%	(DOE 2022, Tong et al. 2022, Authors' analysis)
Compressed Air	Mechanical	150 (system)	150 (system)	n/a	17.7 (India)	17.7 (India)	0-24	n/a	n/a	60 years	52%	(DOE 2022, Vecchi et al. 2021, Authors' analysis)
Liquid Air	Mechanical	150 (system)	150 (system)	n/a	14.8 (India)	14.8 (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 We calculate LCOS for India per Eqn. 1 with a 82 INR/USD exchange rate, a 6% interest rate, & is exclusive of taxes/duties. Costs reflect a standalone system with a 4-hr duration unless 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 is limited.

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).

Meanwhile, the costs of pumped hydro storage are expected to remain relatively stable in the coming years, maintaining its position as the cheapest form – in terms of \$/kWh – of grid-scale energy storage. Of all countries here compared, costs are cheapest in India, which already hosts a large installed capacity of 4700 MW (the 7th largest in the world) with more projects in the pipeline (CEA 2022). It should be highlighted, however, that pumped hydro projects typically require a large capital investment for the correspondingly large resulting storage capacity (typically up to 1,000 MW), as noted in Table 1.

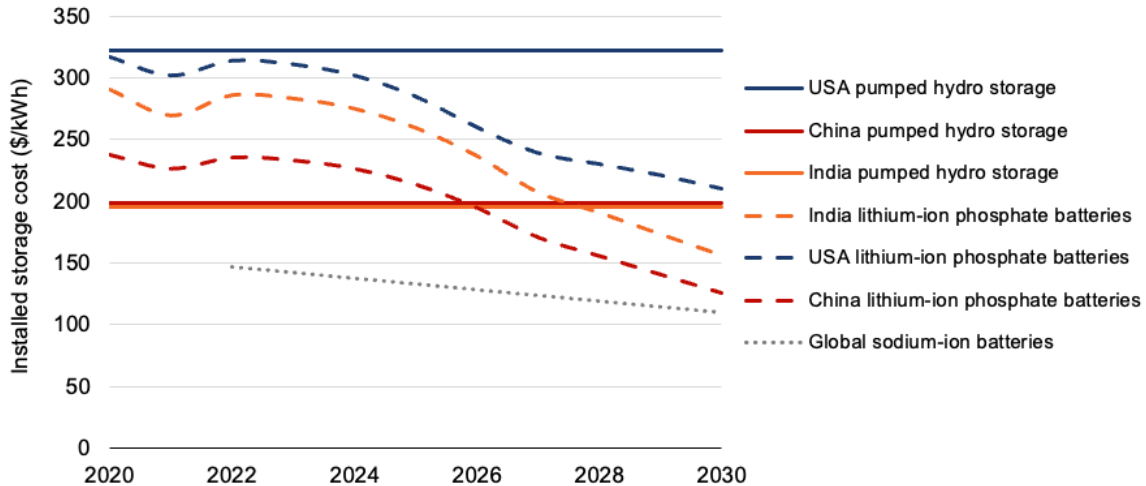


Figure 1. Recent & projected costs of key grid-scale standalone storage technologies for 4-hr storage duration in India, China, & the US¹

Source: (BNEF 2022a, BNEF 2022b, BNEF 2021a, BNEF 2021b, PNNL 2021, DOE 2022, Deorah et al. 2020, Ramesh 2022, Wang 2022, Authors’ analysis)

Since the previous figure with \$/kWh comparisons may not fully capture additional expenses incurred through operation and the lifetime of the asset, we next compare the LCOS of the three selected technologies, calculated with Equation 1, and the projected evolution up to 2035 in Figure 2. We show the LCOS in Indian rupees for better local context.

As seen previously, battery costs are projected to decline into the late 2020s, then remain relatively more stable after 2030. Meanwhile, PHS costs are expected to remain relatively stable over the entire shown time period. All costs are subject to change with improvements in technological efficiency as well as policy support schemes and the like. It should be noted, also, that although we depict standalone storage systems here, co-located solar plus storage systems typically have lower levelized costs of storage on the order of 20% due to a reduced CAPEX (from sharing of system components).

¹ Costs represent installed storage costs for 4-hr duration for all technologies, not including battery pack replacement. Curve-fitting applied if annual cost breakdown was not available. Sodium-ion battery costs per CATL-announced cell costs as regional breakdown was not available (Wang 2022).

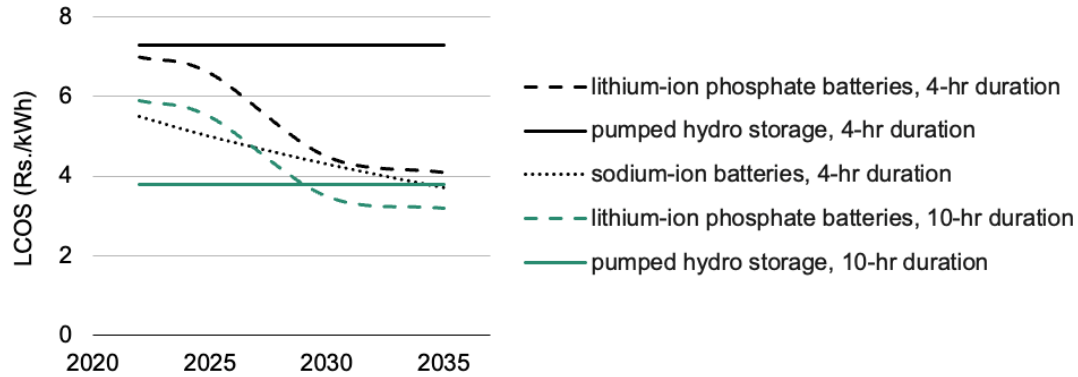


Figure 2. Estimated current & projected LCOS of key grid-scale storage technologies in India²

Source: Authors' analysis

3. Literature review on grid-scale energy storage in India

The literature on grid-scale energy storage in India examines its role as part of India's energy mix in the power sector, as well as studying batteries in the context of electric vehicles given the pipeline between EV batteries and grid-scale battery storage, especially on issues of the supply chain. In this section, we examine the literature about grid-scale energy storage in the context of the power sector, studies reviewing the techno-economic costs of grid scale energy storage options, and the supply chain policies/trajectories for batteries. Through this literature review, we provide a brief overview and summary of the other major recent reports pertaining to India's energy storage landscape, developments, policies, and cost projections to better understand India's trajectories as it relates to developing energy storage.

Assessing the Energy Storage Requirement

The "[Report on Optimal Generation Capacity Mix for 2029-30](#)" by the Central Electricity Authority (CEA 2023) highlight the importance of energy storage systems as part of India's generation mix by 2030. The report provides trajectories for the resource mix in India's power system for 2030, and as part of that trajectory highlighting two forms of energy storage - pumped hydro and battery energy storage. In terms of pumped storage, the report notes that it is a long term, technically proven, cost effective and highly efficient storage solution, with the ability to regulate frequency with load changes. They claim that off-river pumped storage is more environmentally friendly. The report identifies battery storage costs as reducing uniformly from 7 crores/MW in 2021-2022 to 4.3 crores/MW in 2029-2030 for a 4-hour battery system. The O&M cost is 2%. The report also IDs two sensitivity scenarios of battery cost projections in 2030 at \$100/kWh and \$125/kWh. In the more expensive scenario, battery energy storage installed capacity is cut from roughly 23 GW to 15 GW. The National Electricity Plan Identifies a requirement for ~43 GW overall energy storage by 2030.

² Note: Curve-fitting applied if annual cost breakdown was not available. Costs reflect standalone storage systems. LCOS is calculated per Eqn. 1.

In "[Least-Cost Pathway for India's Power System Investments through 2030](#)" by Lawrence Berkeley National Laboratory (Abhyankar et al. 2021), the report finds that achieving India's goal of 500 GW of non-fossil capacity (predominantly renewable) is the least-cost and most economical pathway to meet India's rising electricity demand, while safeguarding grid reliability, as long as renewable energy (RE) can be supplemented by flexible resources including 252 GWh (63 GW) of grid-scale battery storage and storage costs continue to decline. If adequate storage and RE capacity are not deployed at scale, substantial additional thermal capacity may be required to meet the rising demand. Deploying storage and renewables at a scale will require addressing supply chain challenges and securing adequate financing.

The base or mid-cost (or base-cost) case in the Primary Least Cost Case assumes the cost reductions for solar and wind technologies over the next decade are half the observed historical rate. Assumptions for Li-ion battery levelized cost of storage (LCOS) are Rs.6.0/kWh in 2020 and Rs.3.7/kWh in 2030 for 4-hour storage (Deorah et al. 2020). In the low-cost case, cost reductions are in line with historical trends, with the average LCOE in 2030 dropping to Rs.1.5/kWh for solar, Rs.2.5/kWh for wind; meanwhile, the LCOS of a 4-hour standalone storage project drops to Rs.3.0/kWh by 2030. The high-cost case assumes the cost trajectory of clean technologies is higher than in the base case (solar and wind LCOE of Rs.2.3/kWh and Rs.3.1/kWh by 2030, respectively, and 4-hour standalone battery LCOS of Rs.4.9/kWh by 2030), which could occur for various reasons, such as slower reductions in global prices, restrictions on imports, or solar and battery supply chain disruptions that limit the capacity that could be installed in the first few years of the decade (10 GW/yr).

"[Energy Storage in South Asia: Understanding the Role of Grid-Connected Energy Storage in South Asia's Power Sector Transformation](#)" by the National Renewable Energy Laboratory (NREL 2021) is an assessment of cost-effective opportunities in grid-scale energy storage deployment in South Asia in the near and longer term as well as barriers, drivers and the role of storage in overall operations. Using scenario-based capacity expansion modeling to assess how much energy storage can be cost effectively deployed in India through 2050, the study finds that energy storage becomes cost-competitive with other technologies due in part to projected cost declines through 2030. Results show that cost-effective energy storage capacity grows quickly with an average year-over-year growth rate of 42% between 2020 and 2030. Initial deployments are primarily 2-hour duration battery systems. Beginning in the mid-2020s, 4-hour battery storage deployments dominate the energy storage landscape. Pumped-hydro development is limited to those projects that are currently under construction or planned as per the Central Electricity Authority. Battery storage investments are found to be cost-effective in 26 of the 34 states and union territories by 2030.

The report finds that 4-hour battery storage has the largest potential to provide peaking capacity with a 100% capacity credit (67 GW in 2030 and 140 GW in 2050) in the Reference Case. They also find the ability of energy storage to count towards long-term capacity adequacy requirements has the second-largest impact on overall storage deployment. In scenarios where energy storage cannot receive revenue for capacity adequacy, overall investments in energy

storage technologies fall by 22%. In the near term, pumped storage is a cost-effective solution at 6.9 crore/MW. Further reductions in this cost could result in delayed investment in battery storage. Operational modeling of the 2030 power system shows energy storage can play a major role in providing operating reserves in the future power system and there are significant system benefits to allowing these technologies to do so.

Estimating the Storage Cost

In “[Estimating the Cost of Grid Scale Lithium-Ion Battery Storage in India](#)” By Lawrence Berkeley National Laboratory (LBNL 2020) the study estimates costs for utility-scale lithium-ion battery systems through 2030 in India based on recent U.S. power-purchase agreement (PPA) prices and bottom-up cost analyses of standalone batteries and solar PV-plus-storage systems. Scaling unsubsidized U.S. PV-plus-storage PPA prices to India, accounting for India’s higher financing costs, they estimate PPA prices of Rs. 3.0–3.5/kWh (4.3–5¢/kWh) for about 13% of PV energy stored in the battery and installation years 2021–2022. These estimates are 34% higher than U.S. prices, excluding any impact of taxes and import duties. Bottom-up estimates of total capital cost for a 1-MW/4-MWh standalone battery system in India are \$203/kWh in 2020, \$134/kWh in 2025, and \$103/kWh in 2030 (all in 2018 real dollars). When co-located with PV, the storage capital cost would be lower: \$187/kWh in 2020, \$122/kWh in 2025, and \$92/kWh in 2030. The tariff adder for a co-located battery system storing 25% of PV energy is estimated to be Rs. 1.44/kWh in 2020, Rs. 1.0/kWh in 2025, and Rs. 0.83/kWh in 2030; this implies that the total prices (PV system plus battery storing 25% of PV energy) are Rs. 3.94/kWh in 2020, Rs. 3.32/kWh in 2025, and Rs. 2.83/kWh in 2030. Such low battery storage prices could disrupt how India plans to meet its growing energy needs.

Assessing BESS Supply Chains

In “[Addressing Vulnerabilities in the Supply Chain of Critical Minerals](#)” by the Council on Energy, Environment and Water, the International Energy Agency, UC Davis, and the World Resources Institute (CEEW, IEA, UC-DAVIS and WRI 2023), focuses on the vulnerabilities associated with the supply chain of critical minerals used for batteries. The report highlights the following vulnerabilities and risk in the global supply chain including geopolitical risks because minerals are concentrated in a few countries, limited production capacities leading to supply shortages and price volatility, environmental and social concerns around the extraction process of critical minerals which can have impacts on habitat, pollution, and human rights, and a dependence on few countries for minerals making supply chains vulnerable. The paper recommends that countries should foster the development of domestic reserves along with partnerships with other countries, invest in sustainable mining practices to minimize negative impacts of extraction, grow the mineral recycling industry to reduce waste and reliance on extraction alone, and conduct research and development around alternative materials to reduce dependence on minerals while encouraging international collaboration to ensure resilient supply chains.

[“The Need for Advanced Chemistry Energy Storage Cells in India”](#) by Niti Aayog and the Rocky Mountain Institute (NITI Aayog, RMI, and RMI India 2022) estimates India’s future demand for batteries under two scenarios - an accelerated scenario and a conservative scenario. The accelerated scenario assumes that current policy momentum for clean technology will trigger the market and lead to high penetration of these technologies. In the accelerated scenario, battery demand rises in line with expected success of India’s ambitions and incentives around vehicle electrification. The conservative scenario assumes a slower rate of battery demand. In the accelerated scenario, battery demand is expected to rise to 260 GWh by 2030 and the report estimates that this would require nearly 26 gigafactories with an average advanced battery production capacity of 10 GWh per year. The conservative scenario battery demand would require 10 gigafactories by 2030. Since India has no manufacturing plants at this scale now, developing and rapidly scaling its advanced battery manufacturing industry is expected to require focused and coordinated public-private actions. The report identifies the production-linked incentive (PLI) scheme as the most important lever for enabling this opportunity to come to fruition.

In [“Developing Resilient Renewable Energy Supply Chains for Global Clean Energy Transition”](#) by the Council on Energy, Environment and Water and the Ministry of New and Renewable Energy (CEEW 2023), the report presents a comprehensive analysis of the current structure of global supply chains for solar photovoltaic, onshore, and offshore wind, lithium-ion batteries, and green hydrogen. The report highlights the manufacturing landscape for critical components in these supply chains, including requirements of key minerals, skills, logistics, infrastructure, and associated innovations. It also captures the evolution of exports and imports of key components and equipment in these sectors over the last decade, assessing the concentration and dependency of and on key components and products. One of the key findings of the report is that the manufacturing capacities of renewable energy technologies and their sub-components are highly concentrated in a few geographies, making supply chains vulnerable to risks. The report also finds that many countries with lower incomes have a highly concentrated import mix across solar, wind, and lithium-ion batteries and this has only increased with time. The report also highlights the need for a collaborative effort to develop resilient supply chains and provide access to green hydrogen, which is in its nascent stages of development.

4. Overview of storage bids, tenders, and ongoing projects in India

To further contextualize the grid-scale energy storage market in India, Table 2 provides an overview of the renewable (RE) and energy storage recent bids, tenders, and ongoing projects. While some specifically delineate lithium-ion batteries as the desired type of storage, other tenders have been technology-agnostic. These latter tenders have been won by both pumped hydro storage projects as well as battery projects. The projects range significantly in size, from a few MWhs to thousands of MWhs, also depending on the needs of the location. While some projects are for stand-alone systems, other projects are co-located with either solar PV or wind farms as well. However, the recent tenders reflect a growing grid-scale energy storage market in India, which will likely expand in the coming years with the increasing penetration of renewables.

Table 2. Overview of recent tenders for grid-scale energy storage in India.

Issuer	Location	RE (MW)	Storage (MW)	Storage (MWh)	Project Type	Bid Type	Storage Duration (Hours)	Project Duration (Years)	Winner(s)	Tariff (Rs./kWh)	Source(s)	Date
SECI	Pan-India	NA	900 (storage only)	3000	Pumped Hydro	Peak Tariff ³	NA	25	Greenko ⁴	4.04, 2.88, 6.12 (weighted average, off-peak, peak)	CleanTechnica , SECI Tender	Jan-20
		300 (RE+Storage)			Solar + Battery Storage				Renew Power	4.3, 2.88, 6.85 (weighted average, off-peak, peak)		
SECI	Pan-India	400 ^{5,6}		100	Technology Agnostic	Round the Clock (RTC) Tariff ⁷	NA	25	Renew Power	3.6 ⁸	SECI Tender ; Prayas Group ; ReNew Press Release	May-20
SECI	Ladakh	20	20	50	Solar + Battery Storage	Project Cost ⁹	2.5	10	TATA Power	12.55 ¹⁰	SECI Tender ; Mercom India	Aug-21
GSECL	Gujarat	35	12	57 ¹¹	Solar + Battery Storage	Project Cost	4.75	12	L&T	6.91 ¹²	GSECL Tender	Sep-21
SECI	Chhattisgarh	100	40	120	Solar + Battery Storage	Project Cost	3	10	TATA Power	6.79 ¹³	SECI Tender	Dec-21
KSEB	Kerala	NA	10	20	Battery Storage	Capacity Charge ¹⁴	2	15	Hero Future Energy ¹⁵	11.25 ¹⁶	Mercom India ; PV Magazine India	Jul-22
SECI	Rajasthan	NA	500	1000	Battery Storage	Capacity Charge	2	12	JSW Energy	10.84 ¹⁷	SECI Tender	Aug-22
NTPC	Pan-India	NA	500	3000	Pumped Hydro	Capacity Charge	6	25	Greenko	4.76	Mercom India	Dec-22
RUVNL	Rajasthan	500		3600	Solar + Storage	Peak Tariff	6	25	ACME Solar	6.69 ¹⁸	Mercom India	June-23
		100							BluPine Energy	6.68		
MSEDCL	Maharashtra	150		750	Solar + Battery Storage	Two Part Tariff ¹⁹	6	25	Ayana Renewables	6.74 (weighted average); 9 (non-solar); 2.42 (solar)	MSEDCL Tender	Dec-22
		100			Technology Agnostic				NTPC Renewables			

³ This tender calls for bids in INR/kWh to supply of electricity during peak demand periods such as mornings and evenings using renewables + storage.

⁴ The tender was awarded to two winners, splitting the total capacity of the bid

⁵ Informal discussions with industry suggest that BESS capacity for this project will be 25 MW, but not finalized.

⁶ Bid signed for 400 MW round the clock PPA, ReNew plans to install 1300 MW of renewable capacity

⁷ This tender calls for bids in INR/kWh to supply round the clock electricity capacity from renewables+storage, but only requires an 80% capacity factor so it will not provide full around the clock electricity generation.

⁸ The bid starts at 2.9 Rs/kWh in the first year with an annual escalation of 3% after first year tariff price for next 15 years; after that price stays constant. We report the levelized number.

⁹ This tender comprises the entire work of design, supply of equipment and materials, and construction and installation

¹⁰ Authors estimations based on reported total project cost, including O&M, of 386 crores

¹¹ The bid is listed as minimum 57 MWh generation but 12 MW capacity for 4 hours

¹² Authors estimations based on reported total project cost, including O&M, of 335 crores

¹³ Authors estimations based on reported total project cost, including O&M, of 945 crores

¹⁴ These are usually standalone storage projects

¹⁵ Informal discussion with industry has suggested that execution of the tender may be on hold because tariff is too high.

¹⁶ Calculated based on provided information about spending/MW/month, assumption of 300 cycles

¹⁷ Calculated based on provided information about spending/MW/month, assumption of 300 cycles

¹⁸ Tender documents note that the prices are listed as higher because of the storage component.

¹⁹ This was awarded to two parties, both producing power during solar generation and non solar generation hours

Indian tender prices on average are higher than global benchmarks, attributable to storage technologies not yet reaching scale of installation. Table 3 showcases an overview of recent US storage tenders to provide a comparison to the tenders in India.

Table 3. Overview of recent tenders for grid-scale energy storage in the US.

State	Plant Name	RE (MW)	BESS (MW)	BESS (MWh)	Storage Type	PV+BESS (\$/MWh)	PV+BESS (Rs/kWh)	Tender Date
CA	RE_Slate_SVCE/CCCE	160.5	80.25	321	Lithium Ion	32.9	2.70	Feb-20
NV	Chuckwalla	200	180	720	Lithium Ion	36.4	2.98	Mar-20
NV	Boulder_3	127.86	58	232	Lithium Ion	28.9	2.37	Apr-20
HI	Barbers Point	15	15	60	Lithium Ion	84.3	6.92	Sep-20
NM	Rockmont	100	30	120	Lithium Ion	29.7	2.44	Sep-20
HI	Kahana	20	20	80	Lithium Ion	67.5	5.53	Sep-20
CA	Arlington_Energy_Center_II	233	132	528	Lithium Ion	35.1	2.88	Oct-20
CA	RE_Slate_Stanford	63	50	200	Lithium Ion	34.4	2.82	Nov-20
CA	RE_Slate_PWRPA	26	10	40	Lithium Ion	31.3	2.57	Nov-20
NY	Tracy	119	5	20	Lithium Ion	47.4	3.89	Jan-21
NV	Hot_Pot	350	280	1120	Lithium Ion	35.3	2.89	Jun-21
NV	Iron_Point	250	200	800	Lithium Ion	36.9	3.03	Jun-21

Source: Bolinger et.al, 2022

5. Overview of supply chains

As was seen previously, supply chains play an important role in determining a technology’s availability and costs in a particular country and thus the technology’s adoption for grid-scale storage. Therefore, we next assess the current state of the supply chains of storage technologies, as well as potential issues and their potential remedies. Considering that batteries are composed of various raw materials, metals, and minerals whose extraction and processing is global in nature, we place a strong emphasis and focus on the supply chain of batteries, which is summarized in Figure 3.

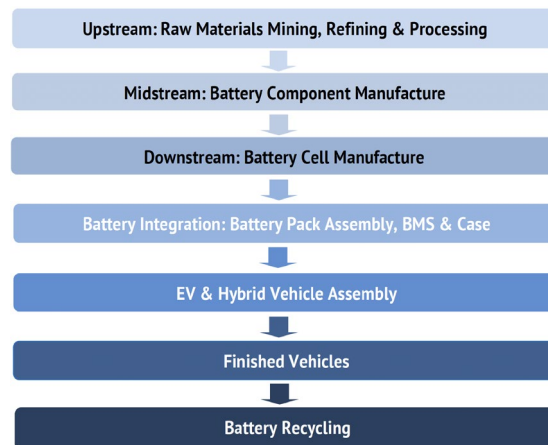


Figure 3. Battery supply chain by segment

Source: (Harrison and Ludwig 2021)

By far, China is the dominant producer in upstream segments of the industry, providing over 50% of world production in materials processing, component, and cell manufacturing, and in electric vehicle production (BNEF 2022a). In 2021, China produced 75% of all batteries, and played a major role in graphite and lithium mining (International Energy Agency 2022).

Lithium-ion batteries are made up of battery packs, which are built from thousands of cells with electronic systems managing battery charge and temperature regulation. Each individual cell in the battery pack consists of an anode, cathode, electrolyte, separator, and outer casing, which are arranged in a module that is then equipped with a battery management system (BMS) and a thermal management system (TMS) to form a battery pack.

There are three types of cathodes in batteries that are dominant in the market - lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA) which are predominantly used for EV batteries because they have a higher energy density (Li, Erickson, and Manthiram 2020). The third chemistry is lithium iron phosphate (LFP), which doesn't use nickel or cobalt. It is lower in cost, has a more stable chemistry with a lower risk of catching fire, and higher cycling lifetime but typically only 65-75% of the energy density of high-nickel batteries (International Energy Agency 2022). LFP batteries are currently the standard in stationary battery energy storage systems, where the weight disadvantages of lower energy density are less important. As explored in the previous section, other battery chemistries, most prominently sodium ion batteries, are currently under development as an alternative to lithium-based chemistries. Nevertheless, lithium is projected to hold, the largest market share.

In terms of the lithium supply chain, there are four components - mining extraction, materials processing, manufacturing, and end-of-life repurposing and disposal.

Mining Extraction + Processing

Often, the refining is done by the mining company together with the extraction. For the most part, Chinese firms account for 60% of the world's lithium processing and refining facilities.

Lithium

Lithium production in 2022 was estimated at 130,000 tons, with four countries (Chile, Australia, Argentina, and China) accounting for 93% of total world production. Of the global total, Australia produced 45% (61,000 tons) of the lithium through hard-rock mining. In the 'lithium triangle' in South America, Bolivia has 21 million tons of identified lithium resources, Argentina 20 million and Chile 11 million with extraction of these resources done (primarily in Chile) through salar (salt brine reservoir) mining (Jaskula 2022). There are eight corporations that extract most of the world's including Albemarle; Jiangxi Ganfeng; Tianqi Lithium; SQM, Mineral Resources Ltd.; Pilbara Minerals; Allkem; and Livent. Though likely far from commercial operation, the Indian government recently announced the discovery of nearly 6 million tons of inferred lithium reserves in Jammu and Kashmir (Ministry of Mines 2023).

Graphite

Graphite is the key component of battery anode material. China accounted for 65% of total global graphite production in 2022, producing a total of 850,000 tons (USGS 2023). Mozambique, Madagascar, and Brazil make up 28% of total global production. In addition to these countries, there are known reserves of graphite in Turkey and Tanzania. Otherwise, natural domestic resources of graphite are relatively small across countries (International Energy Agency 2022). Artificial graphite can be used for anode production and is more consistent, stable, and has better operating consistency compared to natural graphite. However, it is also more expensive, adding to manufacturing costs. Often, blends of natural and artificial graphite are used for anode manufacturing (Tsuji 2022).

Manufacturing

To manufacture batteries, the components of the lithium-ion batteries must be created (cathode, anode, electrolyte etc.) and then assembled into battery cells and packs. The anode and cathode are the electrical conductors that carry the energy back and forth in the battery. Manufacturing is dominated by Chinese, Japanese and Korean companies, with the top three producers CATL (China), LG Energy Solutions (Korea), and Panasonic (Japan), accounting for 65% of global production (Figure 4). China currently hosts 75% of all battery cell manufacturing capacity and 90% of anode and electrolyte production (Bloomberg New Energy Finance 2022).

	Cathodes	Anodes	Electrolyte Solution	Separators
	CNGR, BASF, JM, Umicore, Sumitomo, Nichia, Toda Kogyo, Beijing Easpring,	Hitachi Chemical, BTR, Nippon Carbon, Ningbo Shanshan, Human Shinzoom Technology, Jiangxi	BASF, CapChem, GTHR, Tinci Materials Tech, Panax-Etec,	Furukawa Electric, UACJ, Nippon Denkai, Doosan, Asahi Kasei, Toray Tonen, SKI, Celgard, Senior Technology Material
Leading Firms:	Ningdo Jinhe	Zeto New Energy Tech	Ningbo Shanshan	
Country				
China	42%	65%	65%	43%
Japan	33%	19%	12%	21%
South Korea	15%	6%	4%	28%
U.S.	-	10%	2%	6%
Rest of World	10%	-	17%	2%

Figure 4. Leading firms of lithium-ion battery component manufacturing

Source: FCAB 2021, Bridge 2022, Harrison and Ludwig 2022

Battery Breakdown

What accounts for the cost of lithium-ion cells?

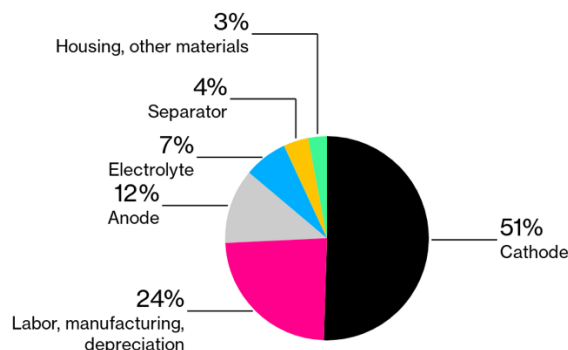


Figure 5. Cost breakdown of a lithium-ion cell

Source: (BNEF 2022)

Cathodes account for most of the cost of a lithium-ion battery (roughly half the cost) with manufacturing of electrodes the second most expensive, accounting for between 20 and 40 percent of total battery pack cost (Figure 5). Major producers of cathodes include BASF, Sumitomo Metals, CNGR, Beijing Easpring, and Ningbo Jinhe (Reuters 2022).

The process for manufacturing anodes is similar - graphite, binders, and conductive additives are mixed in a slurry, coated onto a copper foil substrate and dried to form a consolidated electrode film. China (75%) and Japan (14%) dominate the global production of anodes for lithium-ion batteries (IEA 2022). Prominent companies involved in anode production include Hitachi Chemical, BTR, Nippon Carbon, Ningbo Shanshan, Human Shinzoom Technology, Jiangxi Zeto New Energy Tech.

Battery manufacturers are made up of incumbent manufacturers like Panasonic, LG, Samsung, but also emerging players like SKI, CATL and BYD. There is also Statevolt, Northvolt or Freyr, and new joint enterprises being established by OEMs and battery companies, such as BlueOvalSK (Ford and SKI), Ultium (GM and LG) and Prime Planet Energy (Toyota with Panasonic).

Collection, Repurposing and Recycling

One of the most important parts of the battery storage supply chain is the recycling and repurposing at the end of battery life, which can prevent environmental waste and sustain battery materials for reuse.

Repurposing batteries for storage applications can happen once the battery in the EV has degraded to the point where it cannot provide capacity to power the vehicle. Repurposing is still relatively new, but it's estimated that it can extend battery's usable life by 10-15 years (Karali and Shah 2022). Currently, the industry is in its infancy in part because there is a low volume of retired EV batteries. Moreover, even in cases of car retirement, OEMs are split on

whether batteries should be repurposed by third parties. This is due to liability reasons and interest by automakers to set up recovery operations to reuse their expired batteries.

Another challenge is the cost of repurposing, which involves diagnosing the state-of-health of the battery, then disassembling and rearranging modules. Once the modules are rearranged, they must be equipped with new battery and thermal management systems for storage applications. If more testing is required, the cost of the process increases, making it difficult to compete with new batteries (Neubauer et al. 2015). One way to reduce the cost is by making more information about the car battery, the mileage and state of the car, and the potential degradation of the battery so repurposers can make informed purchasing decisions (Slattery, Dunn, and Kendall 2021). This information while easy to attain while the battery is inside the car, is much more difficult to obtain once the battery is removed.

If the battery is not repurposed, it is broken down and recycled. Most battery recycling companies use a mechanical pretreatment followed by hydrometallurgical processing. During pretreatment, the batteries are disassembled to their constituent parts, and the outer casing is removed. The modules are then shredded, and the shredded materials are sorted into different metals for further processing. The lithium, cobalt, nickel, manganese, and graphite are contained in a black powder known as “black mass” which requires additional hydrometallurgical treatment to leech those materials from the battery. These metals are purified into battery grade metal sulfates and subsequently can be used to manufacture new cathodes.

Internationally, the most significant markets for recycling are China and Korea. Battery recycling in China is often part of a larger operation combining production and/or recycling other products. Taisen and Quzhou Huayou Cobalt New Material Co. both recycle batteries and refine battery grade cobalt. In South Korea, two of the largest companies are SungEel Hi Tech and Posco Hy Clean Metal.

Supply Chains for Other Technologies

The supply chain for other technologies is much less stratified and global compared to the lithium battery supply chain, both because the technologies are still under research and development and many of them require less critical minerals compared to batteries that are developed with lithium. Emerging technologies like sodium sulfur, sodium-ion batteries, aluminum air and iron air batteries can be domestically produced more easily in terms of raw materials. As these technologies develop over the coming decade, the supply chain will also be determined.

The main exception in this trend is VRF batteries, which utilize vanadium, see the supply chain heavily concentrated in China and Russia due to the amount of vanadium naturally found in those places (Government of Australia 2023). Recovering the resource is expensive and will require scaling of a different manufacturing process.

In part, this is why established technologies like hydrogen and pumped hydro storage are appealing. Both rely on either domestic renewables or large connected bodies of water for their storage capabilities. In the case of hydrogen, the costs are still much higher than other battery chemistries. However pumped hydro is a form of storage that is cost effective and avoids the dynamics of the global supply chain.

6. Global policy overview

China

China has one of the largest battery energy storage markets in the world with a total capacity upwards of 40 GW as of 2022 (Chinese Energy Storage Alliance 2022) and plans to install an additional 30 GW of non-hydro energy storage in the next year. In terms of battery storage, the government is focused on deploying lithium-ion batteries as well as investing in the development of other storage technologies like electrochemical, compressed air, flywheel, and supercapacitor systems. With the rising demand for resilience and stability of the power grid, ancillary services for the energy storage market are projected to achieve exponential growth. China is exploring new financial models to support the development of stationary energy storage powered by wind and solar energy (i.e., “wind and solar power + energy storage”), by incorporating electrochemical and compressed-air energy storage into ancillary services in the power market rather than solely for solar+storage (National Energy Administration 2021). This helps raise the profitability and financial value of energy storage and attract investments.

The National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) set the overarching policy guidance for storage deployment, jointly releasing the [Implementation Plan for the Development of New Energy Storage Technologies during the 14th Five-Year Plan Period](#) (the 14th FYP for Energy Storage), which calls for a wider ecosystem of government and private entities to build the energy storage sector and emphasizes the role of market forces, including generation utilities and independent service providers, in investing in storage projects (National Development and Reform Commission 2022). The 14th FYP for Energy Storage outlines the collective development of various new energy storage technologies, such as compressed air, hydrogen, battery, and thermal energy, and aims for self-reliance in key fields. It also sets out ambitious targets for the development of [30GW from non-pumped hydro energy storage technologies](#) as well as their commercialization and large-scale implementation (Murray 2022). PowerChina, the country’s largest builder of hydro power projects, [plans to construct 200 pumped hydro stations with a combined capacity of 270 GW by 2025](#) (Rogers 2022). China focuses on the front of the meter market – based on the 14th Five-Year Plan, provinces have introduced relevant policies including peak regulation, frequency control, and renewables-related policies on the generation side. Currently, two-thirds of the country’s provinces or cities have issued such policies. As of June 2022, many provinces and cities have adopted sub-national versions of the Central Energy Storage 5-Year Plan, including energy storage commitments (Yuan 2022).

South Korea

South Korea is home to three of the world's leading domestic battery manufacturers: LG Energy Solution, Samsung SDI, and SK Innovation. These companies have formed a "grand alliance" to build a long-standing industrial network and establish a fund to support battery technology, parts, and materials development in collaboration with other companies and academia. The government also provides significant support for battery development through tax incentives, R&D, and capital investments, and this has been the case since the development of South Korea's battery industry in the late 80s/early 90s (International Energy Agency 2022).

Dominance in the supply chain is further bolstered by the Chaebol structure. The Chaebols are large industrial South Korean conglomerates, receiving support and coordinating with the national government to expand South Korean industries. Two of the four largest Chaebols are SK and LG and they have invested in developing battery technology expertise over the past four decades, utilizing government contracts and financial support to become a global player in the industry (Mu-Hyun 2015). Korea is responsible for 15% of global cathode material production capacity, and LG dominates the production of battery cells and other battery components such as separators (IEA 2022).

Europe

The European Union has been making strides in developing its battery storage market. Grid scale battery deployment across Europe recently reached a total of 5GW, with almost half in the Great Britain market (Timera Energy 2023). Western Europe is likely to require at least 50-70 GW of grid scale BESS investment by 2030 to support its expected renewable capacity. Italy follows Great Britain in the amount of battery storage capacity. This is due to its 15-year capacity agreements in the Italian Capacity Market, short term fast reserve contracts with fixed payments for frequency services, and intraday, ancillary & balancing markets in Italy (Timera Energy 2023).

Outside of that, the EU has primarily relied on pumped hydro storage as the main energy storage reservoir. Battery projects are on the rise, albeit slowly. Second-life batteries from electric vehicles are being used for smart charging and vehicle-to-grid applications but a lot of this development is sporadic. This relatively slow pace of deployment, despite overarching decarbonization commitments, is a result of multiple factors. Supply chain dynamics and the current Russia-Ukraine war has shifted priorities towards short term emergency management of energy security and supply over long term development of a Union wide battery market (Timera Energy 2023).

The European Commission has however developed more stringent battery regulation, known as the European Battery Regulation, which are expected to be adopted by the European Parliament and Council in 2023 and applied thereafter. The regulations would require new circular partnerships between battery manufacturers and recyclers, the utilization of recycled material in battery second life applications (like storage systems), and battery tracking to ensure traceability. The framework will start applying by mid-2025, with higher collection targets being

introduced over time. For portable batteries the targets will be 63% in 2027 and 73% in 2030, while for batteries from light means of transport, the target will be 51% in 2028 and 61% in 2031. All collected batteries must be recycled and high levels of recovery must be achieved, of valuable materials such as copper, cobalt, lithium, nickel, and lead. Minimum levels of recovered cobalt (16%), lead (85%), lithium (6%) and nickel (6%) from manufacturing and consumer waste must be reused in new batteries. Stricter recycling efficiency and material recovery targets for lithium will be 50% by 2027 and 80% by 2031. Companies placing batteries on the EU internal market will have to demonstrate that the materials used for their manufacturing were sourced responsibly to identify and prevent social and environmental risks associated with the extraction, processing and trading of the raw materials used for the battery manufacturing (The European Parliament 2023).

United States

The passage of the Inflation Reduction Act in 2022 has mobilized investments, consumer subsidies and private sector mobilization in battery manufacturing with multiple companies announcing at least 50 new manufacturing [projects](#) across the EV supply chain, totalling over 500 billion dollars in investment since the passage of the legislation.

The Inflation Reduction Act has significant incentives for a domestic battery value chain to be built in the United States. The Advanced Manufacturing Production Tax Credit provides a tax credit equal to 10% of the cost of production to the producer of the critical minerals that are found in batteries, including lithium, cobalt, graphite, and nickel ([IEA](#) 2023). Additional legislation like the Bipartisan Infrastructure Act, promotes the development and commercialization of advanced battery technologies with \$2.8 billion in funding for a portfolio of 21 projects that support new, retrofitted, and expanded commercial-scale domestic facilities to produce battery materials, processing, and battery recycling and manufacturing demonstrations ([DOE](#) 2022).

India

India has begun to invest in energy storage and develop policy to support the development of battery storage. The Ministry of Power in India has taken a significant step in promoting the adoption of energy storage systems (ESS) by introducing an Energy Storage Obligation (ESO) alongside the Renewable Purchase Obligation (RPO). The ESO requires procurement of ESS as part of generation, transmission, and distribution assets, and it will be calculated as a percentage of the total electricity consumption for DISCOMs (utilities). The ESO can only be considered fulfilled when at least 85% of the total energy stored in ESS is procured from renewable energy (RE) sources annually (Ministry of Power 2022). India's RPO program, which required obligated entities like utilities to purchase a minimum percentage of electricity from renewable energy (RE) sources, was instrumental in becoming a leader in renewable energy deployment.

To support the adoption of ESS, the Ministry of Heavy Industries approved applications from three companies for the Production-Linked Incentive (PLI) scheme for technology-neutral

Advanced Chemistry Cells (ACC). The companies include Reliance, Ola, and Rajesh Exports, and they will be producing 30 GWh of energy storage with an allocation of INR 181 billion (243 million USD). Along with another PLI scheme for Faster Adoption of Manufacturing of Electric Vehicles (FAME), while the focus remains on automotive technology and components, it will also likely boost the production of ESS in the country. Looking forward, the Indian government intends to propose a comprehensive policy on energy storage in the power sector. The policy will focus on regulatory, financial, taxation, demand management, and technological aspects to speed up the implementation of storage capacity. The need for increased flexibility in the power system has driven the government's efforts to promote energy storage in the country (Joshi 2022).

Another area of focus for the government is pumped hydro storage. The Ministry of Power has identified approximately 96 GW of potential capacity, and the government plans to roll out a policy to promote this technology (Koundal 2021). Pumped hydro storage is a mature and reliable technology that has been used globally for several decades to provide flexibility and balance to the power system. The Indian government has also recently announced the provision of Viability Gap Funding to support 4000 MWh of battery energy storage systems and the formulation of a detailed framework for pump storage projects (Ministry of New and Renewable Energy 2023). The initiative is aimed at encouraging private sector participation in the development of energy storage projects (Singh 2023).

The 2023 Budget has committed Rs. 35,000 crores of capital investments towards energy transition, net-zero objectives, and energy security, including energy storage systems (Press Trust of India 2023). This is a clear indication of the government's commitment to transitioning to clean energy and promoting energy security in the country.

7. Conclusion

As India strives to meet its ambitious renewable energy targets amidst rapid electrification, the need for grid-scale energy storage systems to maintain grid reliability will only continue to grow. This report has provided a high-level overview of the top grid-scale energy storage technologies and their costs, supply chain availability, relevant policies, ongoing market developments and appraisals from other assessments. Though we focus on India, we contextualize these parameters against benchmarks from around the globe, most notably the US and China.

While costs - particularly of battery energy storage - are expected to decline, these technologies remain exposed to supply chain shocks, due to concentrated extraction and processing activities, as well as strong competition from electric vehicle manufacturers. Although not discussed here, targeted policy measures, incentive schemes, and the like will be required to deploy grid-scale energy storage systems efficiently and cost-effectively. However, if proper steps are taken, India is well positioned to domestically build up its own battery manufacturing supply chains. It is also well positioned to take advantage of pumped hydro

storage, which is not affected by global supply chain dependencies like batteries and can help differentiate the installed storage capacity.

Future work is planned to assess the actual capacity requirements of grid-scale energy storage in India through capacity expansion modeling, considering load growth, renewable development, transmission development and the like. Simultaneously, we aim to explore and quantify the potential for demand-side management and flexibility assets within the power system, which may help meet and/or reduce energy storage requirements.

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