REPORT

STRATEGIC PATHWAYS FOR ENERGY STORAGE IN INDIA THROUGH 2032

NIKIT ABHYANKAR[1*], UMED PALIWAL[1], SAMBIT BASU[2], HIMANSHU CHAWLA[2],

[1] India Energy and Climate Center, University of California, Berkeley
[2] Power Foundation of India, a Think Tank and Society under the aegis of Ministry of Power, GoI
[*] Corresponding author: nikit@berkeley.edu

Power Foundation of India

IECC INDIA ENERGY & CLIMATE CENTER

UC Berkeley Goldman School of Public Policy

AUGUST 2025

FOREWORD

by Srikant Nagulapalli

Director General, Power Foundation of India

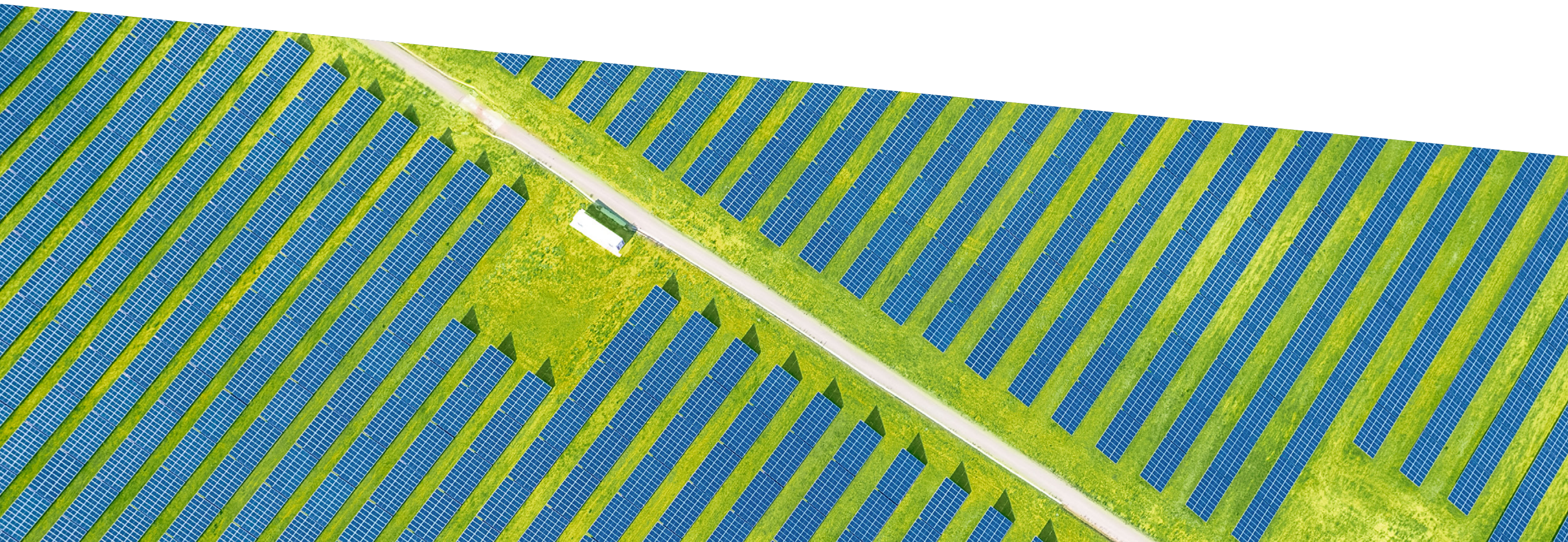
India stands at a pivotal moment in its energy journey. We are committed to transforming our energy landscape, balancing environmental responsibility with economic growth and energy access for all. Guided by our National Electricity Plan and bold climate pledges, we aim to achieve 500 GW of renewable energy capacity by 2030—a goal that reflects our resolve to lead globally in clean energy.

Energy storage is at the core of this vision. It's the key to harnessing the full potential of renewable energy, keeping our grid stable, and meeting demand efficiently. Storage isn't just technology—it's the backbone of a flexible, resilient power system that can handle peak loads and make every unit of clean energy count. To support this, the Ministry of Power introduced measures like funding for battery storage projects, eased transmission policies, and incentives to boost local manufacturing.

But the path forward requires clarity: Where should we deploy storage? What's the right duration for these systems? How do we ensure they're cost-effective while strengthening our grid? The report, Strategic Pathways for Energy Storage in India Through 2032, tackles these questions. With its sharp analysis and data-driven approach, it maps out practical, affordable ways to roll out storage, highlights priority areas, and explores how different technologies can work for us.

I commend the India Energy and Climate Centre and the Power Foundation of India for this thoughtful, timely contribution. Their work aligns seamlessly with our national goals and equips policymakers, utilities, and stakeholders with the insights needed to make informed choices. This report is a tool to help us move faster and smarter toward our shared vision.

We applaud the collaborative spirit that shaped this report and call on stakeholders across government, industry, and academia to make use of its findings.



ACKNOWLEDGEMENTS

We are grateful to the Sequoia Climate Foundation for supporting this work and for collaborating on its conceptualization alongside the Power Foundation of India and the India Energy and Climate Center. We thank Mr. Srikant Nagulapalli (Director General), Mr. Anshuman Srivastava (Executive Director), Mr. Sanjiv Nandan Sahai (Former Director General), Mr. Praveen Kumar Singh, and Mr. Pardeep Jindal of the Power Foundation of India for their insightful reviews and collaboration. We especially acknowledge the contributions of Nikita Gupta and Bhanu Pachouri from the Power Foundation of India in the preparation and completion of this report.

We thank Ms. Seema Paul, Mr. Amit Khare, and Mr. Rishabh Bansal of the Sequoia Climate Foundation for their insightful reviews and guidance. We also acknowledge Mr. Mohit Bhargava of the University of California, Berkeley, for thoughtful comments on the earlier drafts of this analysis. This analysis has been shared with various forums and agencies in India, including the Ministry of Power, the Ministry of New and Renewable Energy, the National Thermal Power Corporation Limited, the Central Electricity Authority, the Solar Energy Corporation of India, and the Central Electricity Regulatory Commission. Finally, we thank Mr. Fernando Augusto of the University of California, Berkeley, for designing the report and providing communications support. Any errors or omissions are our own.

AUTHORS

Dr. Nikit Abhyankar Co-Faculty Director, India Energy & Climate Center - University of California, Berkeley

Dr. Nikit Abhyankar is the Co-Faculty Director of the India Energy and Climate Center and an Associate Adjunct Professor at the Goldman School of Public Policy, University of California, Berkeley.

Abhyankar specializes in renewable energy, energy efficiency, electric vehicles, electricity markets & policy, and industrial energy, with a focus on the United States and India as well as major emerging economies, including China and Indonesia. He regularly advises national / state governments, regulators, and utilities in multiple countries on designing clean energy policies and programs. Dr. Abhyankar has over 100 journal articles, research reports, and conference papers, with his work frequently. Abhyankar holds a Ph.D. in Environment and Resources from Stanford University.

Umed Paliwal Scientist, India Energy & Climate Center - University of California, Berkeley

Umed Paliwal is a scientist at the India Energy and Climate Center at GSPP. Paliwal specializes in renewable energy integration, electricity markets and policies, electric vehicles, and advanced energy modeling, with a focus on pathways to rapidly decarbonize electricity sectors and transportation systems across multiple geographies including India, the United States, the United Kingdom, and Japan.

He has played a key role in several high-impact energy modeling studies that inform policy and investment decisions at state and federal levels. Paliwal's expertise spans techno-economic analysis, power system modeling, and advanced computational techniques, including AI-based models for renewable energy forecasting and resource assessment. Paliwal holds a Master of Public Policy from the University of California, Berkeley, and a B.Tech.-M.Tech. Dual Degree in Civil and Environmental Engineering from the Indian Institute of Technology, Kanpur. He is a recipient of the Berkeley Lab Director's Award for Exceptional Scientific Achievement in Societal Impact.

AUTHORS

Himanshu Chawla Head - Regulatory, PFI

Himanshu Chawla has an experience of around 16 years in the Power Sector across various domains i.e., State Electricity Regulatory Commissions (DERC & HERC), Commissioning of 2X600 MW Power Plant (Essar Power) and Consultancy (ICRA) wherein he has effectively utilised his Techno-Commercial Educational qualifications of B. Tech (Power), MBA (Power), and Climate Change from University of British Columbia. His last position was Joint Director (Tariff-Engineering) in DERC.

Dr. Sambit Basu Head - Research, PFI

Dr. Sambit Basu, Head- Research, Power Foundation of India, has over 30 years of experience as an Energy Policy & Regulatory Economist. He has worked extensively with regulators, governments, development banks, and private sector entities in India and abroad. An alumnus of Presidency College, Kolkata, and Jawaharlal Nehru University (MPhil & PhD), his expertise spans energy policy, regulatory economics, power system modelling, and sustainable infrastructure.

SUMMARY FOR POLICYMAKERS

This study, through comprehensive grid simulations, examines key aspects of energy storage in India, including required capacity, optimal locations, duration, technologies, costs, and policy framework, to meet growing electricity needs in a least-cost manner, while preventing the stranding of thermal assets.

KEY FINDINGS FROM THE STUDY ARE AS FOLLOWS:

- **India Can Meet the 2030 Clean Power Target Without Raising Costs**: Non-fossil capacity will exceed 500 GW by 2030 and 600 GW by 2032, with inflation-adjusted power procurement cost stable at ₹5.4/kWh. But unlocking $380 billion in financing and easing supply chain constraints is critical.
- **Significant Energy Storage Needed for Grid Stability**: India will need 61 GW/218 GWh of energy storage by 2030 and 97 GW/362 GWh by 2032 to ensure grid reliability. Battery storage will lead, though pumped hydro may gain ground if battery prices do not fall as anticipated.
- **Co-locating Storage with Solar is Cost-Effective**: Energy storage should be co-located with solar in high-capacity, high-demand regions like Gujarat, Rajasthan, Maharashtra, Uttar Pradesh etc.
- **2-Hour Storage Leads Initially, 4-Hour Storage Dominate Later**: Until 2027, 2-hour batteries will help meet evening peak demand. From 2027 onwards, 4-hour batteries will become predominant, offering deeper grid balancing and greater flexibility.
- **No Additional Coal Capacity Needed if Storage is Deployed**: Beyond the 27 GW of coal under construction, no new coal is economically justified by 2030—unless storage deployment is delayed, which may trigger additional coal capacity for firming needs.

KEY POLICY AND REGULATORY RECOMMENDATIONS TO ACCELERATE THE STORAGE DEPLOYMENT ARE AS FOLLOWS:

- **Co-located Storage**: Add 15–20 GW of storage at existing and under-construction solar plants without requiring new transmission. Encourage co-located storage in all new RE projects, targeting 25–30% of daily generation to meet peak demand and balance the grid.
- **Viability Gap Funding (VGF) for Solar + Storage**: Expand the VGF scheme to include solar + storage projects, unlocking 50–100 GW of solar and 16–32 GW of storage capacity by 2027.
- **Technology-Neutral ESOs**: Ensure all state regulators adopt national Energy Storage Obligations (ESO), with coordinated oversight by CERC, FOR, and SERCs.
- **Strengthen Resource Adequacy (RA) Planning**: Develop clear RA methodologies and performance-based capacity crediting to fully value storage across durations and regions.
- **Enable Revenue Stacking**: Update market rules to allow storage to participate in multiple services—energy arbitrage, capacity provision, and ancillary services.
- **Boost Domestic Manufacturing**: Expand PLI incentives, promote local mineral sourcing, and establish a national battery recycling program to build resilient, sustainable supply chains.

CONTENTS

EXECUTIVE SUMMARY

INTRODUCTION

India's electricity demand is witnessing a rapid surge, nearly doubling every decade, fueled by strong economic growth. Dramatic cost reductions over the last decade for wind, solar, and battery storage technologies position India to leapfrog to a more flexible, robust, and sustainable power system for delivering affordable and reliable power to serve the growing power needs. India has also set ambitious clean energy targets - aiming to install at least 500 GW of non-fossil based power generation capacity by 2030. Additionally, Renewable Purchase Obligations (RPOs) at the national and state levels require electric utilities to source at least 43% of their energy from renewable sources, including large hydro by 2030. As India's grid attains higher penetrations of renewables, balancing generation variability through a spectrum of flexible resources, particularly energy storage, becomes increasingly important for ensuring the affordability, stability, and reliability of grid power. India has already set a national target for energy storage, aiming to meet 4% of its electricity demand by 2030, which translates to approximately 200-250 GWh of grid-scale storage capacity.

In this context, the dramatic decline in energy storage costs—marked by a nearly 90% reduction in global storage prices over the last decade and recent energy storage auctions in India reflecting a 65% cost reduction since 2021—could be a pivotal moment. This cost reduction enables the cost-effective supply of low-cost renewable electricity during peak demand periods, addressing key limitations of renewable energy (RE). Furthermore, with a substantial portion of India's electricity grid infrastructure yet to be built, these cost declines present a unique opportunity for India to leapfrog to a more flexible, resilient, and sustainable power system, positioning it as a global leader in clean energy innovation.

The objective of this study is to assess: (a) a least-cost, operationally feasible pathway for India's electricity grid through 2032, (b) critical aspects of energy storage, including total energy storage requirement through 2032, optimal locations (co-located, standalone, solar regions, or load centers), ideal storage durations (2-hour, 4-hour, and longer systems), suitable technologies (Battery Energy Storage Systems, pumped hydro etc.), economics of energy storage in India given recent cost declines, and efficient dispatch and operational strategies, and (c) Provide key policy and regulatory recommendations to accelerate energy storage deployment.

The study uses the latest RE and storage cost data, an industry-standard power system modeling platform (PLEXOS), and exhaustive analytical methods (optimal capacity expansion and power plant-level hourly grid dispatch simulations).

KEY FINDINGS

1. India can meet its target of installing 500 GW of non-fossil power generation capacity by 2030

In the "Reference Case" scenario, which assumes utilities comply with the current state and national Renewable Purchase Obligations (RPO) and energy storage targets, India's total non-fossil capacity is projected to exceed 500 GW by 2030 and reach approximately 600 GW by 2032 (as shown in Figure ES-1). By 2030, a total renewable energy capacity (excluding large hydro) of 456 GW is identified as cost-effective, comprising 315 GW of solar, 119 GW of onshore wind, 7 GW of offshore wind, and 15 GW from small hydro and biomass. By 2032, this renewable energy capacity is expected to grow to 524 GW, with solar accounting for 372 GW, onshore wind for 122 GW, offshore wind for 15 GW, and small hydro and biomass contributing 15 GW.

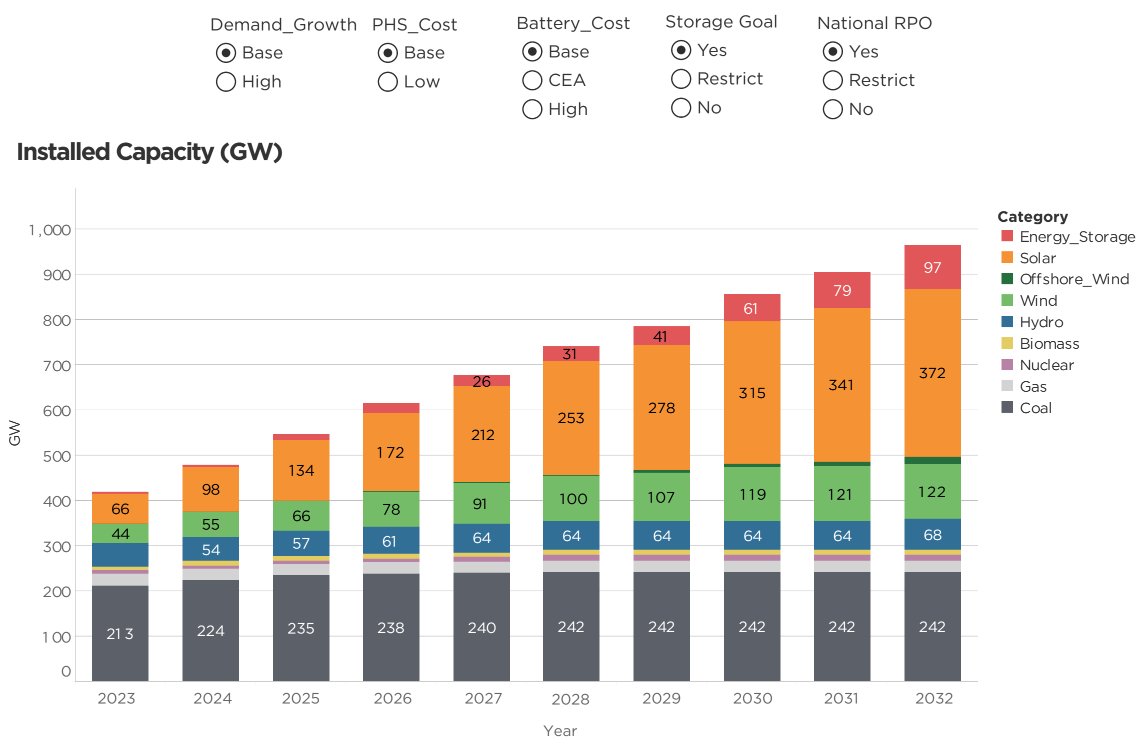


FIGURE ES-1: Installed Capacity in the "Reference Case" scenario that assumes utilities comply with the current state and national Renewable Purchase Obligations (RPO) and energy storage targets

By FY 2030, approximately 61 GW / 218 GWh of energy storage is found to be cost-effective to support RE deployment, aligning with India's national storage targets. As electricity demand and RE capacity expand, this storage requirement is expected to grow to 97 GW / 362 GWh by FY 2032.

This represents substantial growth from India's current energy storage capacity of approximately 6 GW (mostly pumped hydro), underscoring the need for robust policy and regulatory support to accelerate storage deployment at this scale.

The modeling study takes into account the 27 GW of new coal capacity currently under construction, slated for commissioning by 2030. However, apart from this under-construction capacity, no additional coal capacity is found to be cost-effective by 2030. The total cost-effective coal capacity by 2030 is projected to be 242 GW.

The non-fossil share of total electricity generation is expected to more than double between 2023 and 2030, increasing from 26% in 2023 (including large hydro and nuclear) to 58% by 2030, and reaching 60% by 2032. Despite nearly doubling electricity demand, thermal generation remains relatively stable, ranging between 950-1,000 TWh per year (ex-bus). In contrast, renewable energy generation (excluding large hydro) is projected to increase substantially, rising from 210 TWh in 2023 (13% of total generation) to 1,025 TWh by 2030 (44% of total generation), and further to 1,195 TWh by 2032 (47% of total generation).

The average power procurement cost, factoring in both fixed and variable costs of existing and new capacity as well as bulk transmission, is projected to decline slightly in real terms, from the historical level of Rs. 5.46/kWh to Rs 5.41/kWh by 2030 and further to Rs 5.37/kWh by 2032, despite significant clean energy expansion.

Remarkably, even without RPO or the national storage target, the least-cost resource mix for FY 2030 still consists of 504 GW of non-fossil capacity. This includes 303 GW of solar, 105 GW of onshore wind, 7 GW of offshore wind, 15 GW of biomass and small hydro, and 59 GW of large hydro, and 14 GW of nuclear. Additionally, the economical energy storage requirement is found to be approximately 51 GW, comprising 42 GW of battery storage and 9 GW of pumped hydro. By 2032, cost-effective non-fossil capacity is projected to increase to 590 GW, including 372 GW of solar, 105 GW of onshore wind, and 16 GW of offshore wind, supported by 86 GW of storage. Optimal coal capacity by 2030 is found to be 244 GW, implying only 2 GW of additional coal capacity beyond the 27 GW already under construction. By 2030, the average power procurement cost is expected to reduce slightly by 2% in real terms, to Rs. 5.35/kWh.

Table ES-1 summarizes the key scenario results.

TABLE ES-1: Installed capacities, average power procurement costs, and share of non-fossil resources in total electricity generation (2023 and 2030)

Property	Technology	Actual (2023)	Reference Case (2030)	No RPO and Storage Targets (2030)	High Battery Cost (2030)	Low PHS Cost (2030)	Restricted Storage Deployment (2030)
Installed Capacity (GW)	Coal	213	242	244	242	242	270
	Natural gas	25	25	25	25	25	25
	Nuclear	7	14	14	14	14	14
	Hydro (incl Small Hydro)	50	64	64	64	64	64
	Wind	44	126	112	127	126	127
	Solar	66	315	303	315	316	311
	Biomass	10	10	10	10	10	10
	BESS	0	51	41	41	42	10
	Pumped Hydro	5	9	9	18	17	11
	Total	420	856	823	856	856	842
Average Power Procurement Cost (Rs/kWh)		**5.46***	**5.37**	**5.35**	**5.48**	**5.36**	**5.59**
Share of non-fossil resources in total electricity generation (%)		**26%**	**58%**	**55%**	**58%**	**58%**	**57%**

*model estimate

The key drivers of these results are the inflation-resistant, low-cost nature of renewable energy and energy storage. Energy storage eliminates the need for additional thermal capacity to meet morning and evening peak demands, while agricultural and industrial load shifting from evening to solar hours significantly reduces nighttime load, thereby minimizing the requirement for new baseload coal-fired capacity.

2. Storage Requirement: India will need 61 GW of energy storage capacity by 2030 and 97 GW by 2032 to support its clean power targets

By 2030, a total of 61 GW/218 GWh of energy storage is projected to be cost-effective to support 500 GW of clean power capacity. This requirement is expected to grow to 97 GW/362 GWh by 2032 (as illustrated in Figure ES-2).

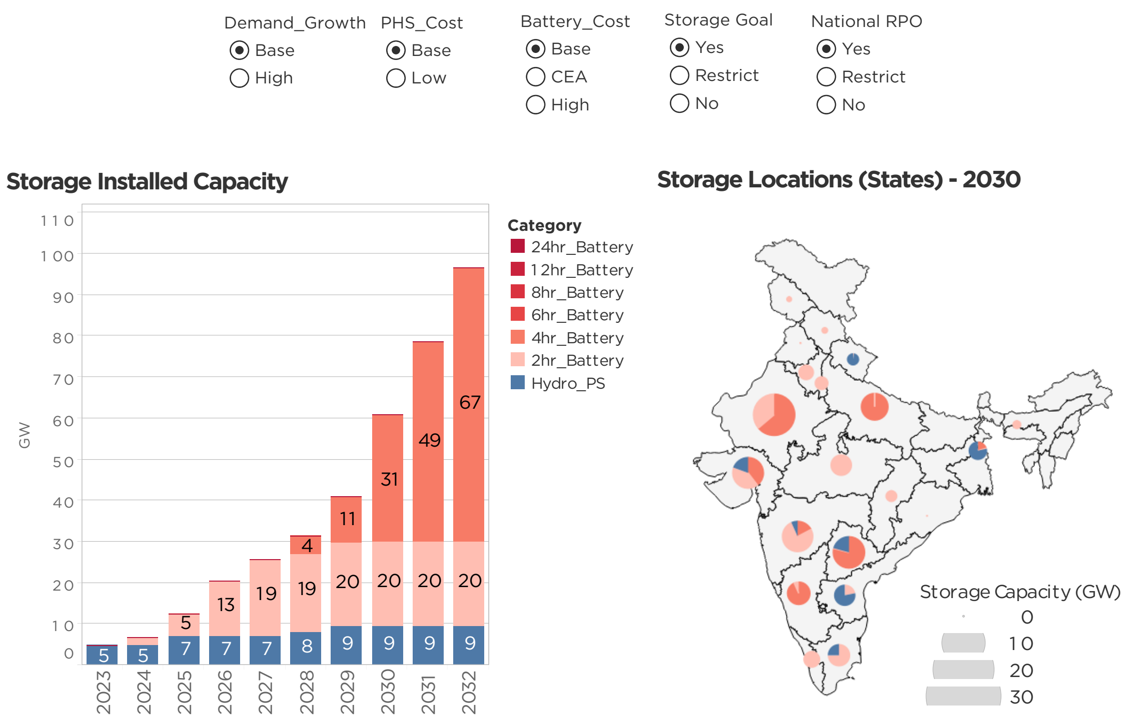


FIGURE ES-2: Energy storage installed capacity in the "Reference Case" scenario

Note: Totals may not match due to rounding

Due to the significant reduction in battery costs, battery storage is anticipated to dominate the overall energy storage mix. By 2030, 51 GW/164 GWh of battery storage is found to be cost-effective, comprising 20 GW of 2-hour batteries and 31 GW of 4-hour batteries. By 2032, the storage requirement will rise to approximately 97 GW/362 GWh, with battery storage making up 87 GW/308 GWh—consisting of 67 GW of 4-hour batteries and 20 GW of 2-hour batteries. Additionally, around 9 GW of pumped hydro capacity, including 2.7 GW currently under construction, is found to be economically viable by 2030.

It is important to note that the cost-effectiveness of battery storage versus pumped hydro depends largely on the underlying cost assumptions, with battery storage likely to play a dominant role given recent and expected future cost reductions. However, as shown in figure ES-3, if battery costs remain high ("High Battery Cost" Case that projects 4-hour BESS capital cost to be Rs 7.8 Cr/MW by 2030 compared with Rs 4.8 Cr/MW in the Reference Case), pumped hydro investments become more economical and their capacity increases significantly to over 18 GW by 2030 and 22 GW by 2032, while the total storage requirement remains almost the same (59 GW/ 232 GWh by 2030 and 94GW/ 380GWh by 2032). While 2-hour battery capacity remains almost the same as the Reference Case (20 GW), 4-hour battery capacity reduces significantly to 21 GW by 2030 and 52 GW by 2032. Similarly, in the "Low PHS Cost" Case, if pumped hydro projects could be developed at low cost (Rs 4.1 Cr/MW vs Rs 6.6 Cr/MW in the Reference Case), their cost-effective capacity would increase to 17 GW by 2030, and battery capacity would drop to 42 GW.

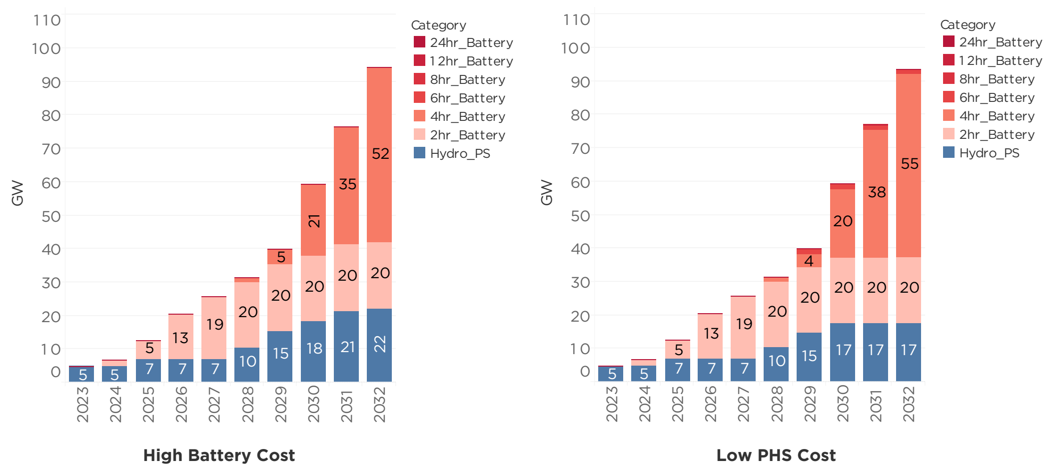


FIGURE ES-3: Energy storage installed capacity in the "High Battery Cost" case (left) and "Low PHS Cost" case (right)

However, the regional distribution of energy storage changes significantly. As pumped hydro potential is driven by the geographical location of the project, storage capacity may not necessarily be concentrated in solar-rich states.

3. Storage Duration: 2-hour batteries dominate until 2027; 4-hours thereafter

Until 2027, 2-hour batteries are expected to dominate the energy storage landscape, primarily providing support during evening peak demand. As demand patterns evolve, 4-hour batteries are projected to take the lead from 2027 onwards, offering extended support for longer periods (Figure ES2). By 2027, approximately 21 GW of new storage capacity will be required to prevent evening and nighttime power shortages. After accounting for 2.7 GW of pumped hydro storage (PHS) currently under construction, the analysis finds that around 19 GW of new battery storage capacity—mostly 2-hour batteries, although frequently discharged over 4-6 hours at slower rates—will be the most cost-effective option.

By 2030, the total cost-effective battery storage capacity is projected to be 51 GW/164 GWh, comprising 20 GW of 2-hour batteries and 31 GW of 4-hour batteries. By 2032, the storage requirement is expected to increase to approximately 97 GW/362 GWh, including 87 GW of battery storage. This capacity will be made up of 67 GW of 4-hour batteries and 20 GW of 2-hour batteries. Most of these batteries are anticipated to cycle only once per day, charging primarily during periods of high RE generation during the day and discharging during evening and nighttime peak demand periods. On average, these batteries will complete around 300-350 cycles annually, reflecting their role in daily peak load management.

4. Storage Location: Storage locations largely coincide with solar capacity, large load centers, and states with limited hydro / peaking capacity

Battery storage locations are expected to align closely with regions that have significant solar capacity, large load centers, and states with limited peaking capacity, such as Gujarat, Rajasthan, Maharashtra, Uttar Pradesh, Andhra Pradesh, and Telangana (Table ES-2). In contrast, states with high wind penetration, like Tamil Nadu and Karnataka, are likely to have lower storage value, making battery installations less cost-effective in these regions.

TABLE ES-2: Required Energy Storage Capacity in 2030 in Key States in "Reference Case"

State	2030 Storage Capacity
Rajasthan	13.0 GW / 43 GWh
Gujarat	6.3 GW/ 28 GWh
Telangana	7.8 GW/ 34 GWh
Uttar Pradesh	6.7 GW/ 27 GWh
Andhra Pradesh	3.8 GW/ 23 GWh
Maharashtra	6.6 GW/ 19 GWh
Karnataka	5.1 GW/ 15 GWh
Other States	11.7 GW/ 29 GWh
All-India	**61 GW / 218 GWh**

Additionally, some energy storage will be needed in the North-Eastern region to integrate local solar generation and reduce the need for new transmission infrastructure. Co-locating batteries with solar power plants offers a substantial cost-saving opportunity, reducing capital costs by 15-20% due to shared Balance of System (BOS) components. Batteries and solar can share inverters, other power electronics, and grid interconnections, streamlining infrastructure costs. Moreover, solar power (DC) can charge batteries directly without the need for a converter, increasing their roundtrip efficiency as well as increasing the capacity utilization of the transmission infrastructure. In contrast, pumped hydro storage does not benefit from co-location with renewable energy in this manner. Moreover, pumped hydro projects will be highly site/location dependent.

5. Energy storage helps maintain grid reliability

Existing and under-construction thermal power plants combined with hydropower, nuclear, and energy storage capacity enable India to meet electricity demand dependably—in every hour of the year in each state—with 456 GW of installed RE capacity in 2030 and 524 GW in 2032 (excluding large hydro). India's RE generation, particularly wind generation, is highly seasonal. Energy storage helps to maintain grid dependability throughout the year, including times of high system stress such as periods with peak annual load, high RE variability, and high net load.

On most days, energy storage typically charges during the day and discharges during evening and morning peak hours (4 hours/day) as shown in Figures ES-4 and ES-5. Agricultural load shift offers significant night time load reduction potential. Energy storage provides the critical arbitrage service by charging during high RE generation / low electricity price periods and discharging during peak / high electricity price periods. In winter (December-January), due to low night time and early morning demand and excess wind generation at night due to reverse monsoon, some storage capacity also charges during early morning to be discharged during the morning peak hours. Storage would be a critical source of flexibility starting as early as 2024, especially in states with high solar penetration such as Rajasthan, Gujarat etc.

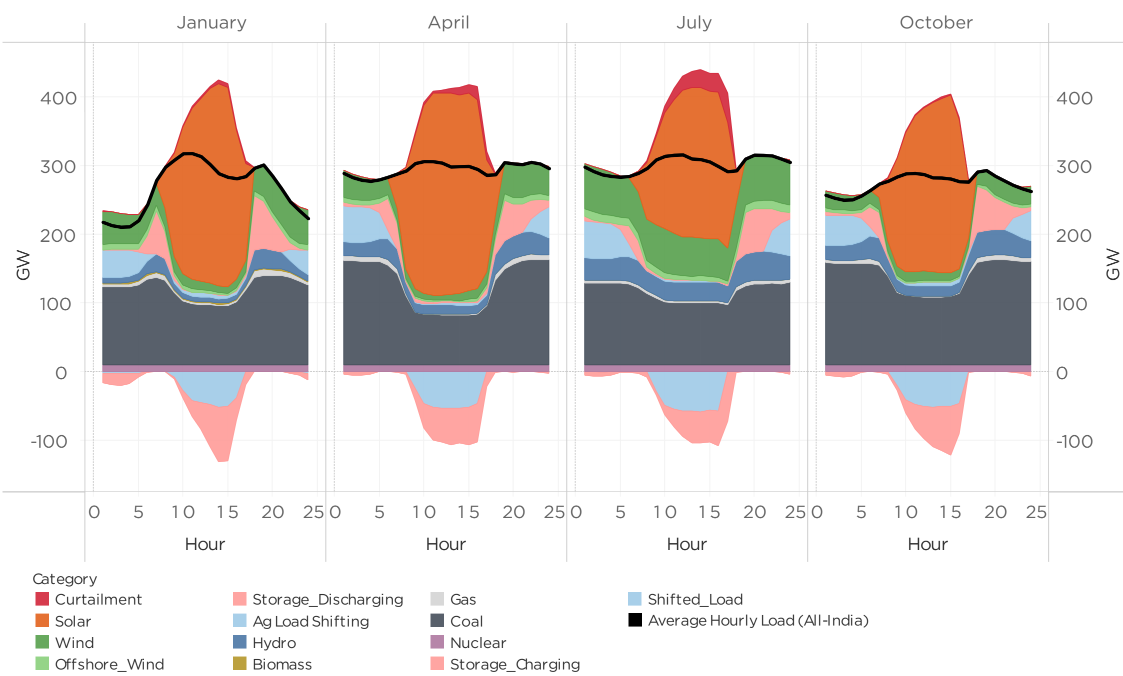


FIGURE ES-4: All-India average hourly dispatch in key months in 2032 in the "Reference Case" scenario

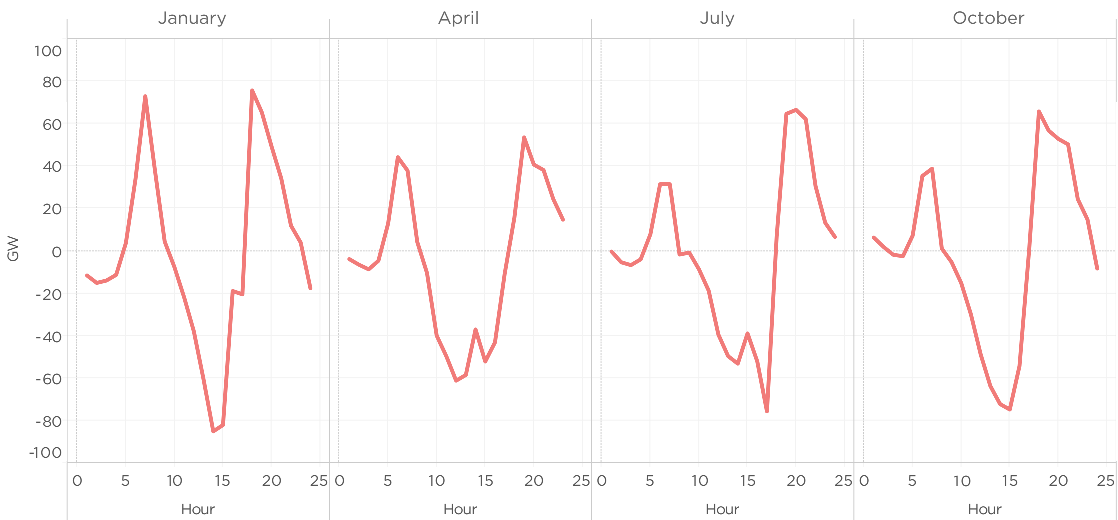


FIGURE ES-5: All-India average net hourly storage output in key months in 2032 in the "Reference Case" scenario Storage capacity = 97 GW/318 GWh. Positive storage output indicates discharge, while negative indicates charging.

Coal power plants continue to provide base load support; however, by 2032, approximately 120 GW of coal capacity will operate with a gross capacity factor above 60%, while more than 70 GW of coal capacity is expected to function at less than 30% capacity factor. This suggests that a significant portion of coal capacity will likely be utilized primarily during peak demand seasons, serving as seasonal balancing. Although no new gas power plants are found to be cost-effective, existing gas capacity offers limited seasonal balancing support during the low renewable energy season (October to February). However, its availability is heavily constrained due to the shortage of low-cost domestic gas.

About 2.7% of RE curtailment is found to be necessary for reliable grid integration, mostly during monsoon due to significant increase in wind generation and reduction in load in the western and southern states.

6. Storage helps the grid meet significant variability and ramping needs introduced by solar and wind

Renewable energy introduces significant variability into the system, particularly with "up" and "down" ramps during sunrise and sunset due to sudden increases or drops in solar generation. However, the system can manage this variability with the aid of energy storage and limited curtailment (~2.7%).

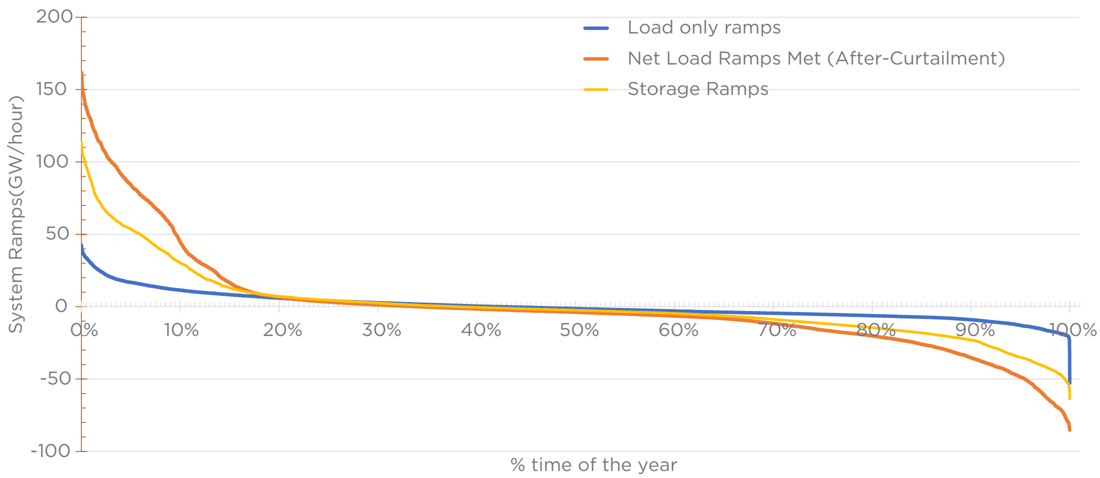


FIGURE ES-6: Hourly load, net-load, and storage ramp duration curves in FY 2032 in the "Reference Case" scenario. The chart shows the hourly ramps for all 8760 hours in FY 2032 sorted in a descending order. Positive ramps indicate "up" ramps, while negative ramps indicate "down" ramps.

Maximum net load ramps by FY 2032 could be as high as 160 GW/hr (net additional "up" ramps due to RE as high as 110-120 GW/hr by 2032, on top of load-only ramps). These ramps could be met by storage (providing ~110 GW/hr of "up" ramps), along with other resources including thermal and hydro. "Down" ramps become particularly problematic especially when thermal capacity is operating at technical minimum levels. However, storage is found to be able to handle such ramps as well, by providing additional down ramps of -65 GW/hr, against the maximum need of -85 GW/hr.

7. Energy storage helps prevent the stranding of coal capacity while maintaining grid dependability and enabling existing coal assets to operate more efficiently

If energy storage deployment lags, India may need to build significant new coal resources primarily as a firm capacity resource, even if the country achieves the 500 GW clean power target by 2030 (and ~600 GW clean power by 2032). If energy storage cannot be deployed fast enough ("Restrict" case), storage capacity may be restricted to 21 GW by 2030 and 29 GW by 2032, and about 57 GW of new thermal capacity would be needed by 2030 and 80 GW by 2032 (both numbers including 27 GW under construction coal capacity), implying total coal capacity will be 270 GW by 2030 and 294 GW by 2032, even if utilities meet their RPO targets. However, such a coal buildout—in tandem with the RE buildout—would likely cause the average fleet-level coal capacity factor to drop to 43% (gross) by 2030 and 41% by 2032, with nearly 125 GW of coal capacity (mostly existing plants with high variable cost) operating at capacity factors of under 30%. This result could put such assets at increased risk of being stranded and needing regulatory support. Deploying energy storage can prevent the stranding of coal capacity by reducing the new coal buildout while maintaining grid dependability and enabling existing coal assets to operate more efficiently. In the Reference Case, the average fleet-level coal capacity factor could be maintained at 51% (gross) in 2032, still significantly lower than about 64% in 2023. Moreover, only 70 GW of coal capacity with high variable costs may still operate at capacity factors below 30%.

ECONOMICS OF ENERGY STORAGE IN INDIA

Recent battery storage auctions in India have received an overwhelmingly positive response, with energy storage prices falling by nearly 65% in a span of three years. Figure ES-7 shows the estimated battery storage capital cost in India in $/kWh, as discovered through reverse auctions over years. SECI conducted 2000 MW solar + co-located 1000 MW/4000 MWh battery storage auctions in December 2024. The winning bid was ₹3.52/kWh, which indicates a dramatic reduction in battery storage cost. Assuming a solar LCOE of ₹2.5/kWh, this implies an evening peak storage adder of about ₹1/kWh. This implies a battery storage capital cost of $100-120/kWh. Co-location of batteries with solar offers significant BOS cost savings, reducing the overall capital cost by ~20%. Pumped hydro projects, especially off-river plants, have also seen significant cost reduction over the years, with recent pumped hydro auctions in Maharashtra revealing a levelized cost of storage of Rs 3.2/kWh for 1000 MW pumped hydro projects with a greenshoe option up to 3000 MW.

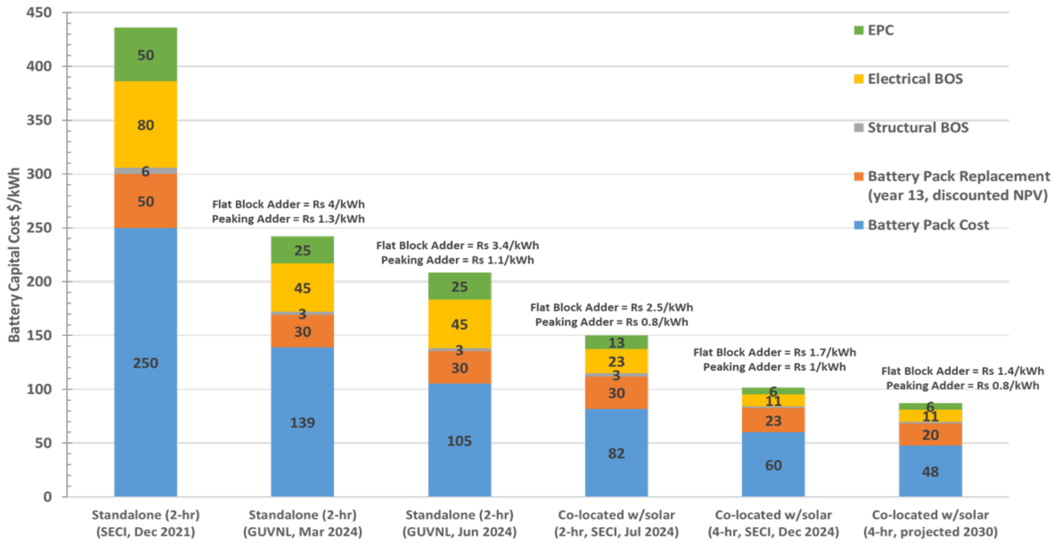


FIGURE ES-7: Estimated battery storage capital cost split into key components

Batteries are energy (MWh) constrained, while pumped hydro resources are power (MW) constrained. For low storage hours, batteries are cheaper. For up to 6-8 hours/day of storage, battery storage is more economical (already economical up to 5-6 hours/day). By 2030, we find that India will need 4-6 hours of energy storage to integrate 500 GW of clean power (along with ~240 GW of thermal). If pumped hydro projects could be developed in a time-bound manner under Rs. 4 Cr/MW, they should be encouraged.

BATTERY SUPPLY CHAINS

Declining material costs and an overcapacity in battery manufacturing are driving a substantial reduction in storage costs. As of 2024, the global battery production capacity has reached over 5,000 GWh per year, with more than 80% of this capacity concentrated in China. This supply level is nearly four times the current global demand of 1,200 GWh per year, including electric vehicles. Battery manufacturing capacity is expected to nearly double to over 9,000 GWh by 2026, with China maintaining approximately 65% of the market share. By 2030, even with a significant rise in battery demand, production overcapacity is projected to persist, with capacity estimated to reach 200% of projected demand. This sustained overcapacity suggests that downward trends in battery costs are likely to continue through 2030. Although battery supply chains are a concern in India, the power sector is unlikely to strain them, as electric vehicle (EV) demand is approximately 10 times greater than that of stationary storage. Major Indian automakers, such as Tata and Mahindra, are actively securing battery supply chains. Additionally, over 200 GWh of battery manufacturing capacity is planned by 2030 by several major Indian companies including Amara Raja, Ola Electric, JSW Group, Exide, Reliance Industries, Adani Group etc.

POLICY AND REGULATORY RECOMMENDATIONS

India's energy storage framework incorporates several key policies to drive early adoption and growth. The Ministry of Power's Energy Storage Obligations (ESO) require utilities to progressively increase storage to 4% of electricity demand by 2030 (equivalent to 200–250 GWh), a critical step for grid stability as renewable capacity expands. The Viability Gap Funding (VGF) scheme offers up to 40% capital cost support for battery energy storage systems (BESS), with a target of 4,000 MWh by 2030. Additionally, transmission charge waivers for storage projects commissioned by 2025 lower project costs, and the Production-Linked Incentive (PLI) scheme promotes domestic manufacturing of advanced battery technologies. Both central and state regulators have established clear tariff structures, compensating storage for services such as energy arbitrage and ancillary support. Key recommendations to strengthen this framework and accelerate deployment include:

1. **Adding energy storage to existing RE projects**: With over 90 GW of installed solar capacity and nearly 50 GW under construction, MOP and MNRE should prioritize adding 15-20 GW of energy storage at these solar sites without the need for additional transmission infrastructure. Recent SECI auctions for co-located solar and storage projects have demonstrated that this integration can be achieved with a storage adder of approximately Rs 0.8/kWh. Co-locating ESS at existing solar sites would also allow for additional solar capacity to be deployed at the same locations, maximizing grid infrastructure efficiency. However, to fully capture these benefits, regulatory challenges around dispatch, operations, and existing PPAs must be addressed. Potential solutions could include adopting conditional "must-run" policies, for example by treating dispatch during non-solar hours differently, or allowing limited economic RE curtailment, accompanied by compensation mechanisms to incentivize balanced operations etc.

2. **Mandatory co-located storage for new RE projects**: The MNRE/MoP should mandate new solar auctions over the next three years to include co-located ESS, covering around 20% of daily solar generation. This could involve annual auctions targeting 15–20 GW of solar power paired with 5–10 GW (or 20–40 GWh) of storage each year, aiming for a cost target of Rs 3/kWh by 2027. For example, a 100 MW solar project could be paired with a 30–50 MW, 4-hour ESS to deliver affordable peak power at Rs 3–3.5/kWh, as demonstrated in SECI's recent solar + storage auctions.

3. **Expanding VGF to solar + storage projects**: MOP/MNRE should expand the existing Viability Gap Funding (VGF) scheme applicable to standalone battery storage systems to solar + storage projects. This could potentially enable an additional 50–100 GW of solar and 16–32 GW of storage capacity by 2027.

4. **Technology-Neutral Energy Storage Obligations**: Only a few states have adopted MOP's Energy Storage Obligations (ESO) into their regulations. It is recommended that all state regulators expedite the adoption of the ESO, with monitoring and compliance oversight by CERC in conjunction with FOR and the SERCs in order to ensure a coordinated and unified approach. To meet the ESO requirements effectively, states can consider a mix of storage solutions, each tailored to their unique operational needs. Potential approaches include: (a) Storage installations to assist system operation, allowing system operators to directly manage grid stability and support real-time balancing, (b) standalone storage solutions procured by utilities directly or through SECI, and (c) storage co-located with renewable generation, particularly solar installations.

5. **Strengthening Resource Adequacy (RA) Planning and Procurement**: ESS can play an important role in meeting RA requirements under India's emerging RA framework; however, state-level RA frameworks need to be closely aligned with long-term planning and resource procurement processes to support cohesive and economic implementation. Regulators should prioritize establishing clear methodologies for evaluating storage value streams, determining storage capacity requirements and RA/capacity credits, creating frameworks for duration-specific capacity crediting, hybrid RE and storage project planning, and providing performance-based seasonal and/or regional adjustments.

6. **Modify Market Rules and Allow Value Stacking**: Regulators should modify market rules to enable energy storage to deliver a full spectrum of services, including energy arbitrage, RA capacity provision, and ancillary services (AS). Such modifications will ensure that storage can compete on an equitable basis with other resources in the wholesale electricity market. Allowing storage to "stack" revenues from different services – energy arbitrage revenues, RA payments, and AS revenues – requires rules or contracts that clarify when storage must provide AS or be available to provide RA instead of earning revenues through energy arbitrage.

7. **Domestic Manufacturing and Supply Chains**: Developing sustainable supply chains and competitive domestic manufacturing presents an opportunity for the Indian industry to develop as a key manufacturing hub and create jobs for the future in order to maintain global competitiveness. The expansion of existing schemes, such as the PLI program, specifically targeted at advanced chemistry cells (ACC) as well as R&D, will encourage domestic production of lithium-ion batteries, solid-state batteries, and other emerging storage technologies. Moreover, making strategic investments to secure key supply chains (such as strategic lithium or rare earth reserves with partner countries) would be critical for scaling India's storage industry. Additionally, establishing manufacturing hubs in key regions with access to raw materials, skilled labor, and robust infrastructure can create a well-integrated supply chain. In order to reduce dependence on imported materials, build resilience against global supply

fluctuations, and drive cost efficiencies in domestic battery production, policies promoting indigenous sourcing and processing of key minerals—such as lithium — are essential. India has already made significant lithium discoveries in several states such as Jammu and Kashmir, Karnataka, Rajasthan etc. Studies have shown that large portions (up to 95%) of lithium in spent batteries can be recycled and reused. This implies that battery recycling alone could meet between a quarter and a half of the annual lithium demand by 2040 or so. The creation of a national battery recycling program is essential for supporting such sustainable supply chains as well as a circular economy.

1. INTRODUCTION

India's electricity demand is rapidly increasing, nearly doubling each decade, driven by strong economic growth. Over the past decade, India has achieved some of the lowest renewable energy (RE) costs globally, with the levelized cost of energy (LCOE) for solar falling well below that of new coal power plants. This positions India to transition toward a more flexible, sustainable power system capable of delivering affordable, reliable energy to meet its growing power needs.

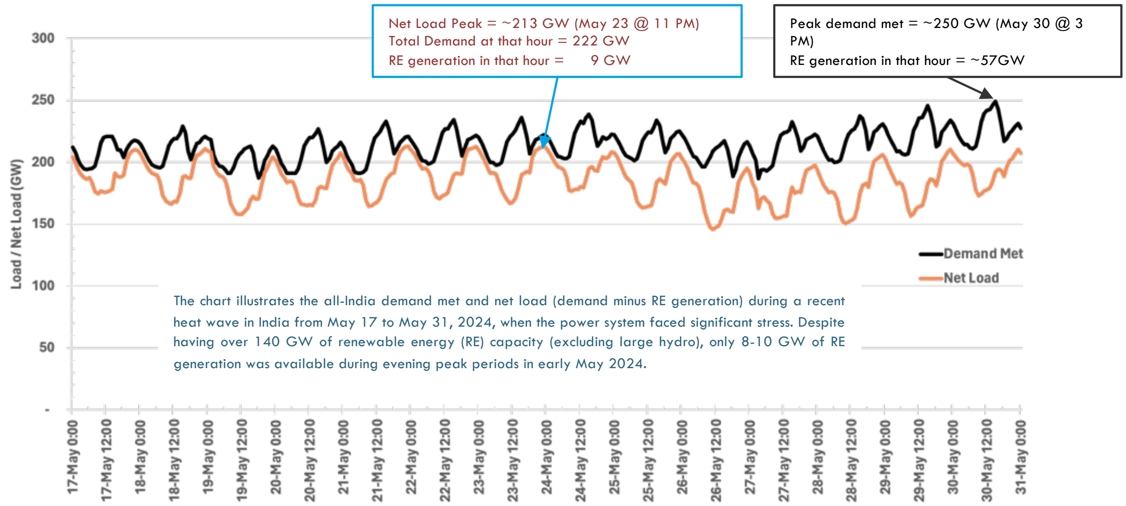
India has set ambitious targets, aiming to install at least 500 GW of non-fossil fuel-based generation capacity by 2030. National and state-level Renewable Purchase Obligations (RPOs) require utilities to source at least 43% of their energy from renewables, including large hydro, by 2030. The pace of renewable deployment is accelerating, with 113 GW added between 2015 and 2024, compared to 52 GW of coal capacity in the same period. In FY 2024 alone, approximately 70 GW of renewable energy has been tendered.

India has set a national target to meet 4% of its electricity demand with energy storage by 2030, translating to around 200-250 GWh of grid-scale storage capacity (Ministry of Power Order, 22 July 2022). Currently, about 17 GWh of energy storage is in the execution stage, and an additional 47 GWh is in the tendering process, including 7.1 GWh by September 2024.

1.1. NEED FOR ENERGY STORAGE

Despite dramatic cost reduction and significant capacity addition, RE alone cannot fully meet grid requirements due to several challenges such as, (a) its intermittent nature, which demands significant system flexibility for effective integration, (b) the mismatch between RE generation and peak electricity demand, and (c) legacy planning and regulatory frameworks that may not fully recognize the value and potential of RE and energy storage technologies.

This is demonstrated by figure 1, which depict all-India demand met and net load (demand minus RE generation) during recent heat waves, highlighting how renewables struggled to meet evening peak demand, necessitating substantial support from thermal and other generators. As India's grid incorporates higher renewable penetration, balancing generation variability through a range of flexible resources, particularly energy storage, will become increasingly critical to ensuring grid affordability, stability, and reliability.



Source: CSEP Carbon Tracker (www.carbontracker.in)

FIGURE 1: All-India demand met and net load (demand minus RE generation) during the heat wave between May 17 and May 24, 2024.

1.2. OBJECTIVES OF THE STUDY

The dramatic decline in energy storage costs—nearly 90% globally over the past decade and a 65% reduction in India since 2021—marks a pivotal moment. These cost reductions enable the affordable supply of renewable electricity during peak demand periods, addressing key limitations of RE. With much of India's grid infrastructure yet to be built, this presents a unique opportunity for India to leapfrog to a more flexible, resilient, and sustainable power system, positioning itself as a global leader in clean energy innovation.

The objectives of this study are as follows:

- Assess a least-cost, operationally feasible pathway for India's electricity grid through 2032

- Address critical aspects of energy storage, including

  a. total energy storage requirement through 2032
  b. optimal locations (co-located, standalone, solar regions, or load centers),
  c. ideal storage durations (2-hour, 4-hour, and longer systems),
  d. suitable technologies (Battery Energy Storage Systems (BESS), pumped hydro etc.),
  e. economics of energy storage in India given recent cost declines, and
  f. efficient dispatch strategies.

- Provide key policy and regulatory recommendations to accelerate energy storage deployment.

2. METHODS, DATA, AND ASSUMPTIONS

2.1. OPTIMAL CAPACITY EXPANSION AND ECONOMIC DISPATCH

We use PLEXOS to build a capacity-expansion model to assess the least-cost ("optimal") generation mix at the state level and interstate/inter-regional transmission investments for each year between FY 2023 and FY 2032. The model minimizes total generation cost (fixed plus variable costs) for the entire system, including existing and new generation capacity and transmission networks. We assess the optimal resource mix under a range of scenarios examining whether utilities meet the RPO targets, storage deployment constraints, technology costs, and demand growth. For FY 2032, we also model economic dispatch at the power plant level to ensure that the grid can run reliably for all 8,760 hours in the year, including the hours when the system is most constrained. We model the Indian electricity grid using 36 nodes: one node for each state/Union Territory (Figure 2).

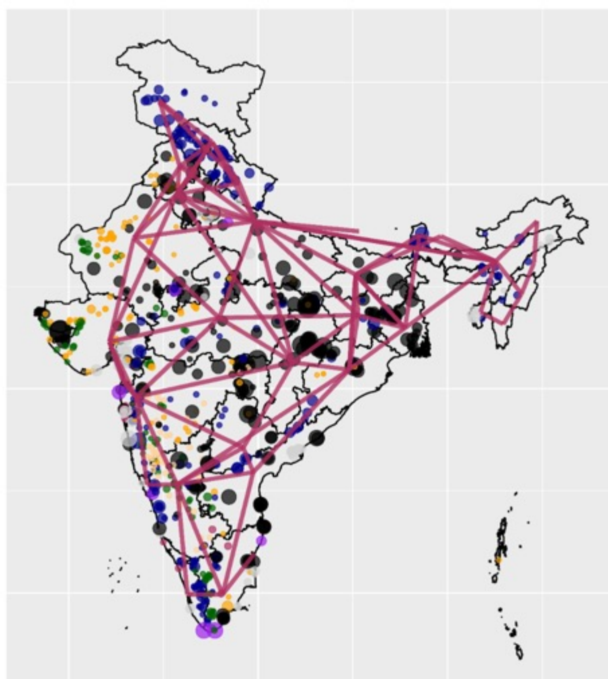


FIGURE 2: Representation of India's transmission network with a simplified interstate network (36 nodes) along with the location of existing power generation plants

For additional details on the methodology, please refer to Appendix 1.

2.2. SCENARIOS FOR ANALYSIS

We model over 30 scenarios using a combination of the following key parameters (see table 1). The scenarios examine the impact of whether utilities meet their existing RPO targets (state and national), whether the national storage goal is met and if there are any constraints in storage deployment, technology costs – especially of battery storage and pumped hydro, and high demand growth.

TABLE 1: Parameters for scenario analysis

RE DEPLOYMENT	STORAGE DEPLOYMENT	BATTERY STORAGE COST	PUMPED HYDRO COST	DEMAND GROWTH
Existing RPOs are met *(National + State)*	**National Energy Storage Goal is met** *(4% of demand)*	**Base** *(Historical and recent trends)*	**Base** *(Historical and recent trends)*	**Base** *(20th EPS; load growth CAGR of 5.7%)*
No RPO *(Least Cost)*	**No National Energy Storage Goal** *(Least-Cost)*	**NEP** *(per CEA NEP 2023)*	**Low** *(Avg capital cost of Rs 4.1 Cr/MW)*	**High** *(Load growth CAGR of 7%)*
Restricted RE deployment *(Historical trends)*	**Restricted** *(Restricted storage deployment)*	**High** *(Cost reduction delayed by 5-7 years)*		

Our "Reference Case" scenario assumes that existing RPOs are met, National Energy Storage Goal is met, "Base" battery storage costs, "Base" pumped hydro costs and "Base" demand growth. Reference Case scenario serves as the reference point to compare the results of other scenarios.

2.3. KEY ASSUMPTIONS

This section summarizes the key assumptions in this study. For additional details on assumptions including power plant operational assumptions, hydro and renewable energy profiles etc., please refer to Appendix 1.

2.3.1. CLEAN TECHNOLOGY COST

Our assumptions are summarized in table 2. Additional details can be found in Appendix 1.

TABLE 2: Capital cost of renewable energy and storage technologies

Wind & Solar Capital Cost (Rs Cr/MW, 2023 real)

	Solar	Wind
2024	4.0	6.7
2027	3.7	6.5
2030	3.3	6.3
2032	3.2	6.1

BESS Capital Cost Rs. Cr./MW (2023 real)

		Base	High	NEP
2024	2-hr	4.3	4.9	4.7
	4-hr	7.4	8.4	8.0
2027	2-hr	3.5	4.7	3.9
	4-hr	5.9	7.9	6.6
2030	2-hr	2.9	4.5	3.4
	4-hr	4.8	7.4	5.6
2032	2-hr	2.7	4.0	3.4
	4-hr	4.4	6.6	5.6

Pumped Hydro Capital Cost (Rs. Cr./MW 2023 real)

	Low	Base
2024	4.1	6.6
2027	4.1	6.6
2030	4.1	6.6
2032	4.1	6.6

2.3.2. RENEWABLE PURCHASE OBLIGATION AND NATIONAL STORAGE GOAL

National and State level Renewable Purchase Obligation (RPO) and energy storage goals have been included, with national RPO reaching about 43% (including large hydro) by 2030 and national storage goal of 4% of demand by 2030. Yearly details can be found in Appendix 1.

2.3.3. CAPACITY UNDER CONSTRUCTION

51 GW of under-construction firm capacity, including 27 GW of coal, 12 GW of hydro, 2.7 GW of pumped hydro, and 8.7 GW of nuclear (2025-2032) is included in the model (CEA NEP 2023).

2.3.4. FUEL COSTS

The variable cost of existing coal plants is taken per actuals in 2023, which ranges from Rs. 1.0 – Rs. 7.0/kWh, increasing by 1% each year. Details are provided in the appendix. The variable cost of new pithead coal plants is taken as Rs. 2.0 – 2.3/kWh (2023), increasing at 1% annually, based on the typical pithead coal prices (including taxes and duties) and assuming heat rates and auxiliary consumption as per CERC norms. Gas price Free On Board (FOB) is assumed to be $6/ Million British Thermal Units (mmbtu) for Administered Pricing Mechanism (APM) gas, and $9/mmbtu for imported Liquified Natural Gas (LNG), increasing at 1% each year.

2.3.5. DEMAND

Demand projections are taken from the 20th Electric Power Survey (EPS). Per 20th EPS, the national coincident peak load in FY 2032 would be 366 GW. Several states have separated distribution feeders for agricultural consumers from other feeders, and some states (e.g., Karnataka, Maharashtra, and Gujarat) have already shifted a major part of the agricultural load to solar hours. We assume the same trend to continue in the future, and by 2032, about 60 GW of agricultural load (non-coincident national aggregate) and 10 GW of heavy industrial load (non-coincident national aggregate) could be shifted from night-time to solar hours.

2.3.6. TRANSMISSION

The model also optimizes new interstate / inter-regional transmission buildout. The transmission line expansion cost is assumed to be Rs 10,162/MW-km (~$220/MW-mile). In hilly regions, the transmission cost is assumed to be twice this number.

2.3.7. RESERVE MARGIN

In the capacity expansion phase, we model a planning reserve margin of 5% (on top of planned and fixed outages of power plants) and a spinning reserve of 3% of load in each hour. In the economic dispatch phase, we also model operational reserves such as regulation and load following, as explained in Appendix 1.

3. KEY FINDINGS

We calibrated the model to actual system operations in FY 2023 (base year) so that the technology level aggregate the annual generation for thermal power plants is within +/-1% of the actual generation (see following Figure 3 and Table 3). For hydro and renewable generators, the model calibration is close, yet not within the 1% band. This could be because of the multiple factors including the spatial resolution of our transmission model (interstate only), the multipurpose nature of hydropower plants, and the non-availability of plant-level generation data for calibration for renewable sources.

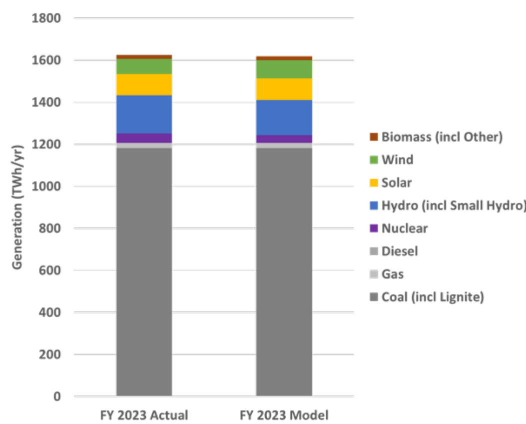


FIGURE 3: Actual generation vs modeled generation for FY 2023

TABLE 3: Actual installed capacity and actual and modeled generation for FY 2023

	Installed Capacity (GW)	Gross Generation (TWh)	
	Actual	**Actual**	**Model**
Coal (incl Lignite)	213	1182	1182
Gas	25	24	24
Nuclear	7	46	37
Hydro (incl small hydro)	50	180	169
Biomass	10	19	19
Solar	66	102	101
Wind	44	72	87
Total	**416**	**1624**	**1618**

3.1. IF UTILITIES MEET THE EXISTING RPO, NON-FOSSIL CAPACITY REACHES OVER 500 GW BY 2030

In the "Reference Case" scenario, which assumes utilities comply with the current state and national Renewable Purchase Obligations (RPO) and energy storage targets, India's total non-fossil capacity is projected to exceed 500 GW by 2030 and reach approximately 600 GW by 2032 (see Figure 4).

By 2030, total RE capacity (excluding large Hydro) of 456 GW (Solar = 315 GW, onshore wind = 119 GW, offshore wind = 7 GW, and small hydro + biomass = 15 GW) will be built. By 2032, total RE capacity (excluding large hydro) is ~524 GW.

About 61GW (218 GWh) of energy storage will be cost-effective to support this RE by FY 2030. By FY 2032, storage requirement will increase to 97 GW (362 GWh).

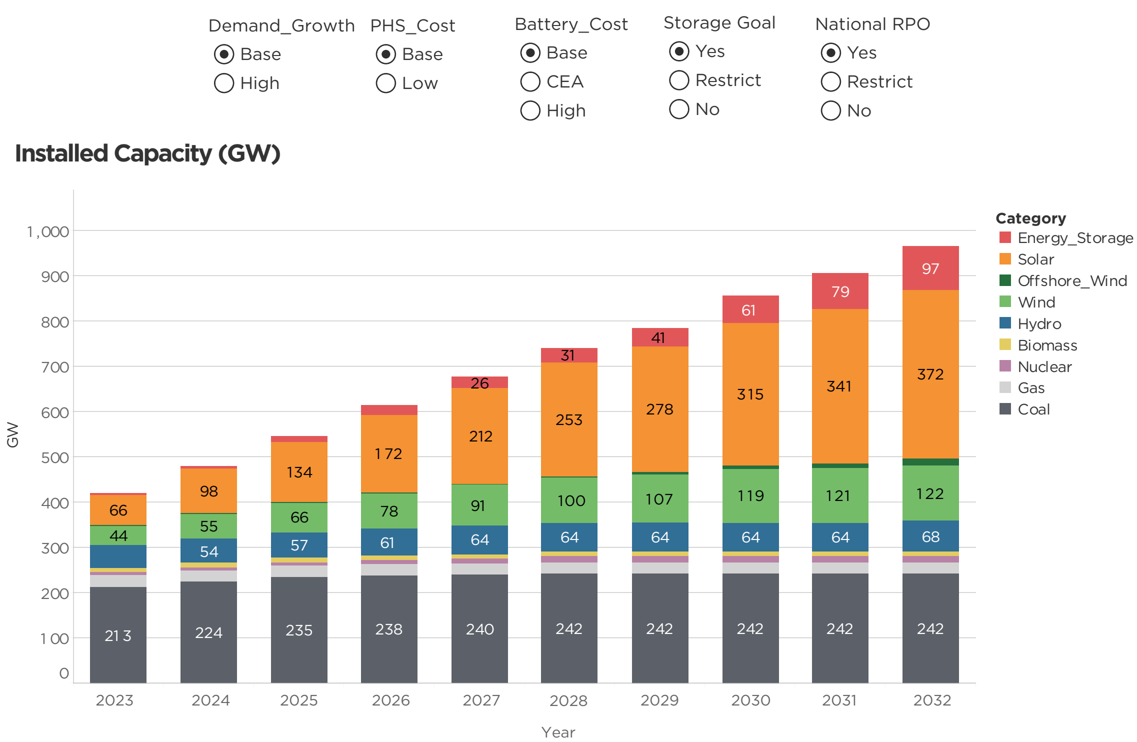
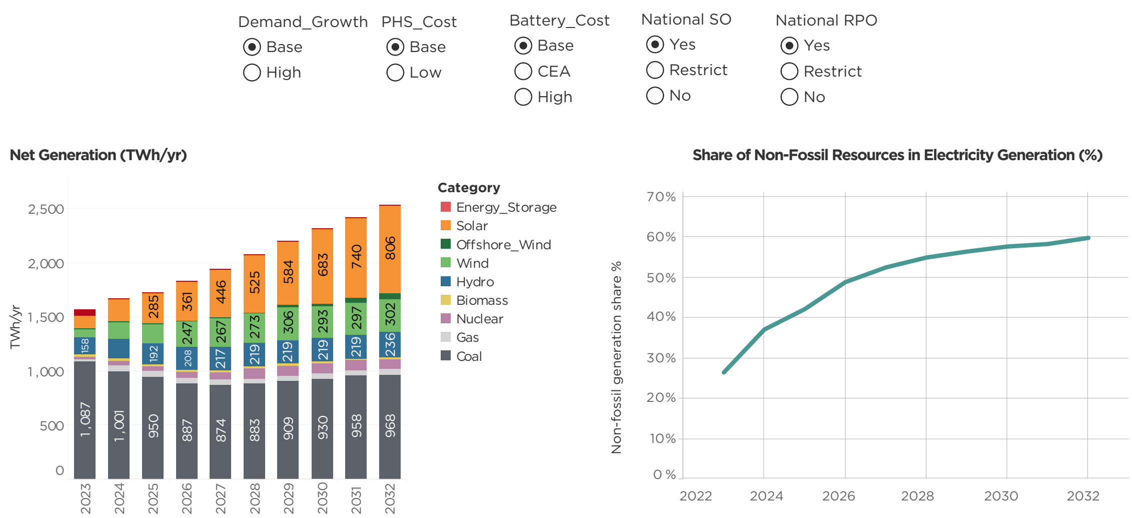


FIGURE 4: All-India Installed Capacity in the "Reference Case" Scenario

Economical coal capacity by 2030 is found to be 242 GW. **No new thermal capacity (apart from ~27GW under construction) is found to be cost-effective.**

3.2. BY 2030, CLEAN ENERGY SHARE IN ELECTRICITY GENERATION WOULD BE 58%, MORE THAN DOUBLE THE 2023 SHARE

In the Reference Case, non-fossil share in total net generation increases to 58% by 2030 and 60% by 2032, compared with just 26% in 2023. Thermal generation stays almost flat around 950-1000 TWh/yr despite the near doubling of demand. RE generation (excluding large hydro) would increase from 210 TWh in 2023 to ~1,025 TWh in 2030 (~44% of net generation) and 1195 TWh in 2032 (47% of net generation).



Note: Chart shows ex-bus net generation

FIGURE 5: All-India ex-bus electricity generation by source and share of non-fossil sources in total electricity generation in the Reference Case

The fleet-average coal plant load factor (PLF) or capacity factor could drop to ~51% (gross) in 2032, significantly lower than about 64% in 2023. Approximately 120 GW of coal capacity will operate with a gross capacity factor above 60%, while more than 70 GW of coal capacity is expected to function at less than 30% capacity factor.

3.3. RE BUILDOUT IS COST-EFFECTIVE: AVERAGE POWER PROCUREMENT COST WILL STAY FLAT AT HISTORICAL LEVELS

In the Reference Case, the average power procurement cost, factoring in both fixed and variable costs of existing and new capacity, is expected to remain largely stable in real terms at historical levels of Rs. 5.4/kWh[3] through 2032, even with significant clean energy expansion.

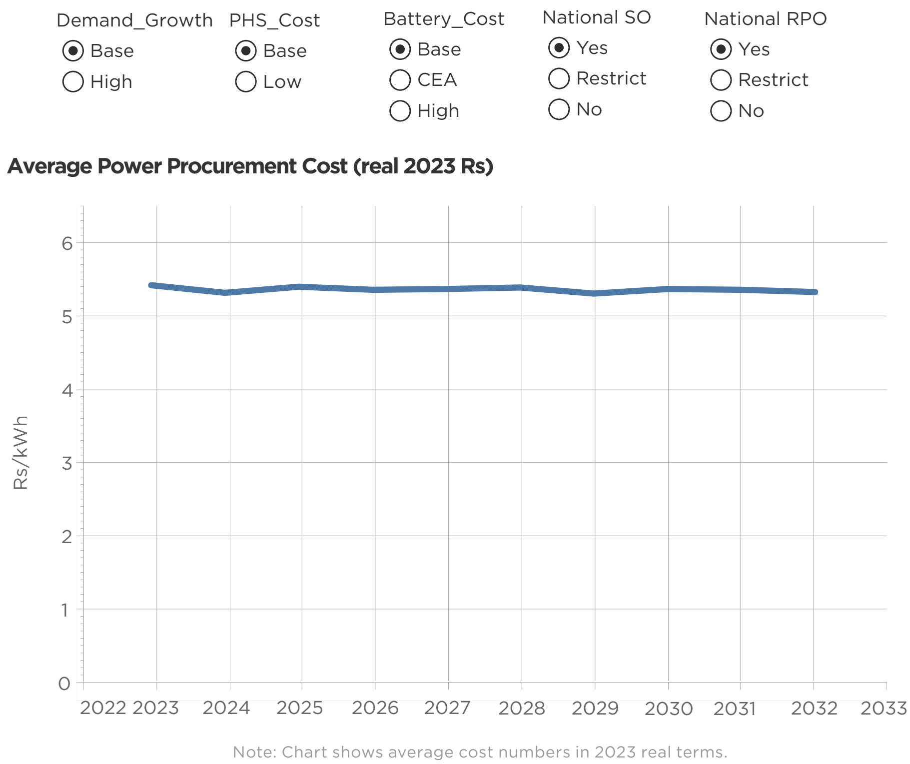


FIGURE 6: Average Power Procurement Cost in the Reference Case

The key drivers of these results are the inflation-resistant, low-cost nature of renewable energy and energy storage.

3 Source: PFC Reports on Performance of Power Utilities (https://pfcindia.co.in/ensite/Home/VS/29)

3.4. STORAGE REQUIREMENT: INDIA WILL NEED 61 GW OF ENERGY STORAGE BY 2030 AND 97 GW BY 2032

In the Reference Case, by 2030, 61 GW / 218 GWh of energy storage is found to be cost-effective to support 500 GW of clean power. As PHS plants under construction (~2.7 GW) get built, the total PHS capacity by 2030 will be ~9 GW. Given the deep reduction in battery prices, battery storage is found to be more cost-effective than new PHS plants.

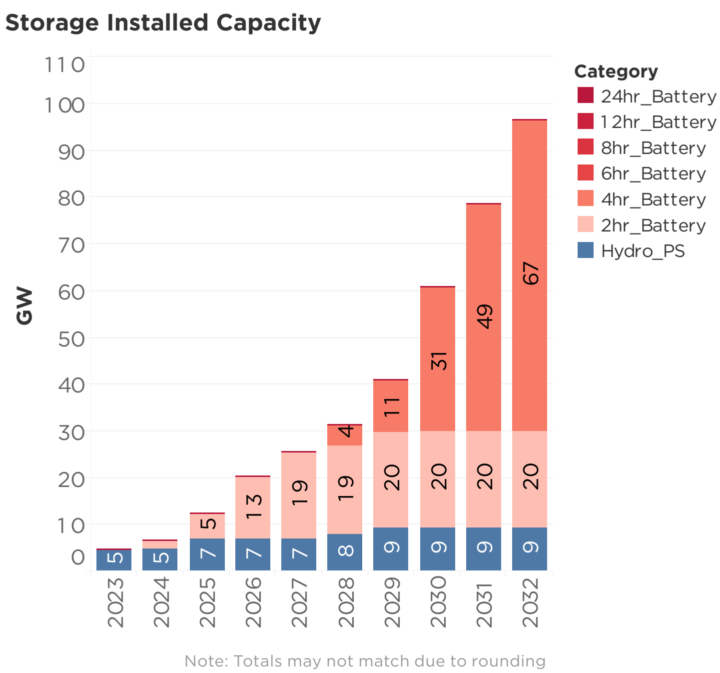


FIGURE 7: Energy storage installed capacity by duration in the Reference Case

By 2030, 51 GW / 164 GWh of battery storage (20 GW x 2 hours, 31 GW x 4 hours) is found to be cost-effective. By 2032, the storage requirement will be as high as ~97 GW / 362 GWh. Out of this, the battery storage capacity will be 87 GW/308 GWh – with nearly 67 GW x 4-hour batteries and 20 GW x 2-hour batteries.

Note that the economical choice between battery storage and pumped hydro would largely depend on cost assumptions, as shown in the sensitivity analysis section.

3.5. STORAGE DURATION: 2-HOUR BATTERIES DOMINATE UNTIL 2027; 4-HOURS THEREAFTER

In the Reference Case, 2-hour batteries dominate until 2027 indicating mostly evening peaking support, while 4-hour batteries dominate in later years, indicating longer hours of support (Figure 8).

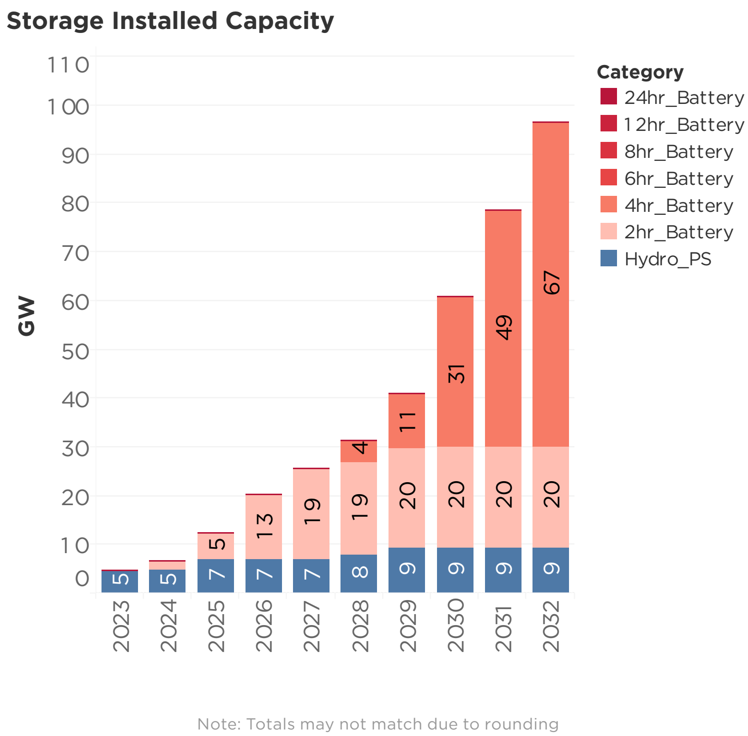


FIGURE 8: Energy storage installed capacity by duration in the Reference Case

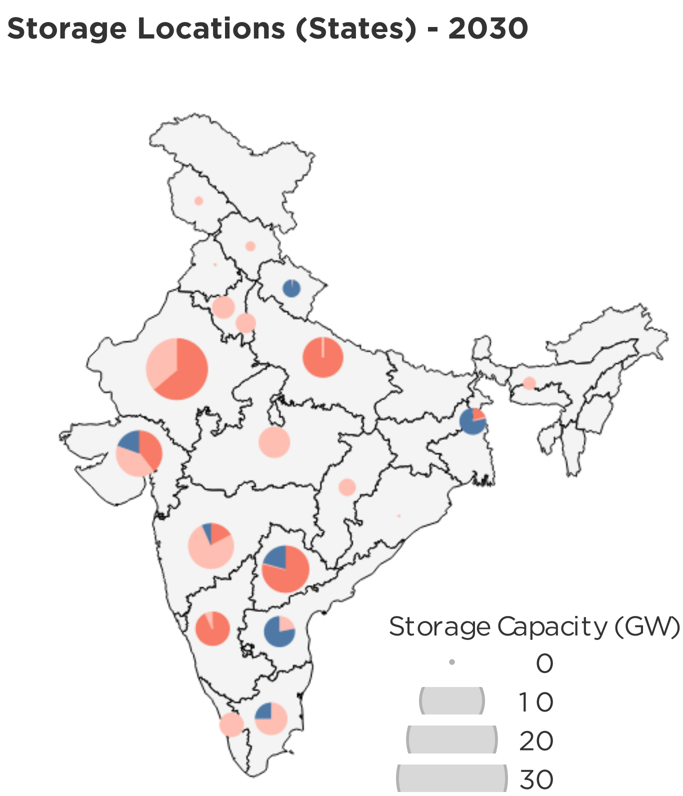
By 2027, ~20 GW of new storage capacity will be needed to avoid evening / night power shortages. After accounting for ~2.7 GW of PHS under construction, we find ~19 GW of new battery storage capacity (mostly 2-hour, albeit discharged at slower rates over 4-6 hours on most occasions) will be cost-effective.

By 2030, 51 GW / 164 GWh of battery storage (20 GW x 2 hours, 31 GW x 4 hours) is found to be cost-effective. By 2032, the storage requirement will be as high as ~97 GW / 362 GWh. Out of this, the battery storage capacity will be 87 GW/308 GWh – with nearly 67 GW x 4-hour batteries and 20 GW x 2-hour batteries.

.

3.6. STORAGE LOCATION: STORAGE LOCATIONS LARGELY COINCIDE WITH SOLAR CAPACITY, LARGE LOAD CENTERS, AND STATES WITH LIMITED HYDRO / PEAKING CAPACITY

As shown in Figure 9, Battery location largely coincides with solar capacity, large load centers, and states with limited peaking capacity e.g. Gujarat, Rajasthan, Maharashtra, Uttar Pradesh, Andhra Pradesh, Telangana etc. States with high wind penetration have limited value of storage and therefore batteries are not as cost-effective there e.g. Tamil Nadu and Karnataka. Some storage will also be needed in the North-Eastern region to integrate the local solar energy and avoid building new transmission.



Note: Totals may not match due to rounding

FIGURE 9: Energy storage installed capacity 2030 locations (states) in the Reference Case

Siting batteries in the solar-rich regions also offers an opportunity to co-locate them with solar power plants, thereby further reducing their capital costs by 15-20% due to saving in BOS. Batteries and solar can share inverter and other power electronics, along with grid interconnection. Moreover, solar power (DC) can directly charge batteries without the need of a converter. PHS cannot benefit from co-location with RE.

3.7. INTER-STATE & INTER-REGIONAL TRANSMISSION NETWORK NEEDS TO BE DOUBLED BY 2032

By 2030, significant additional interstate and inter-regional transmission capacity will need to be built to support the growing demand and share of renewables. All transmission corridors need to be strengthened.

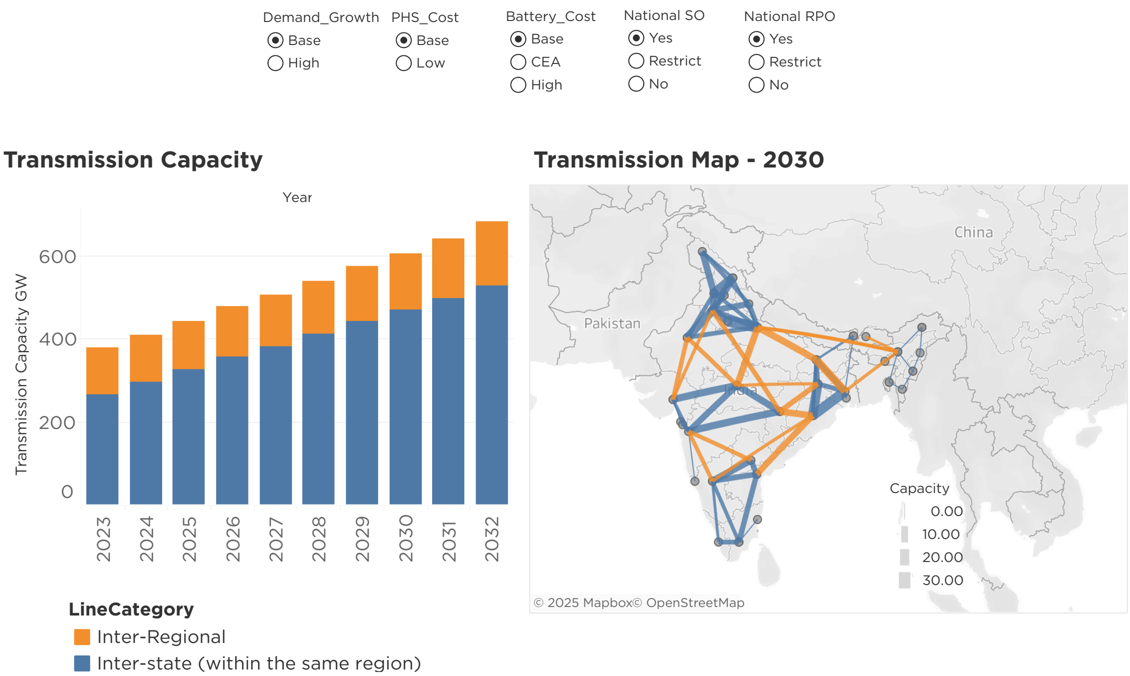


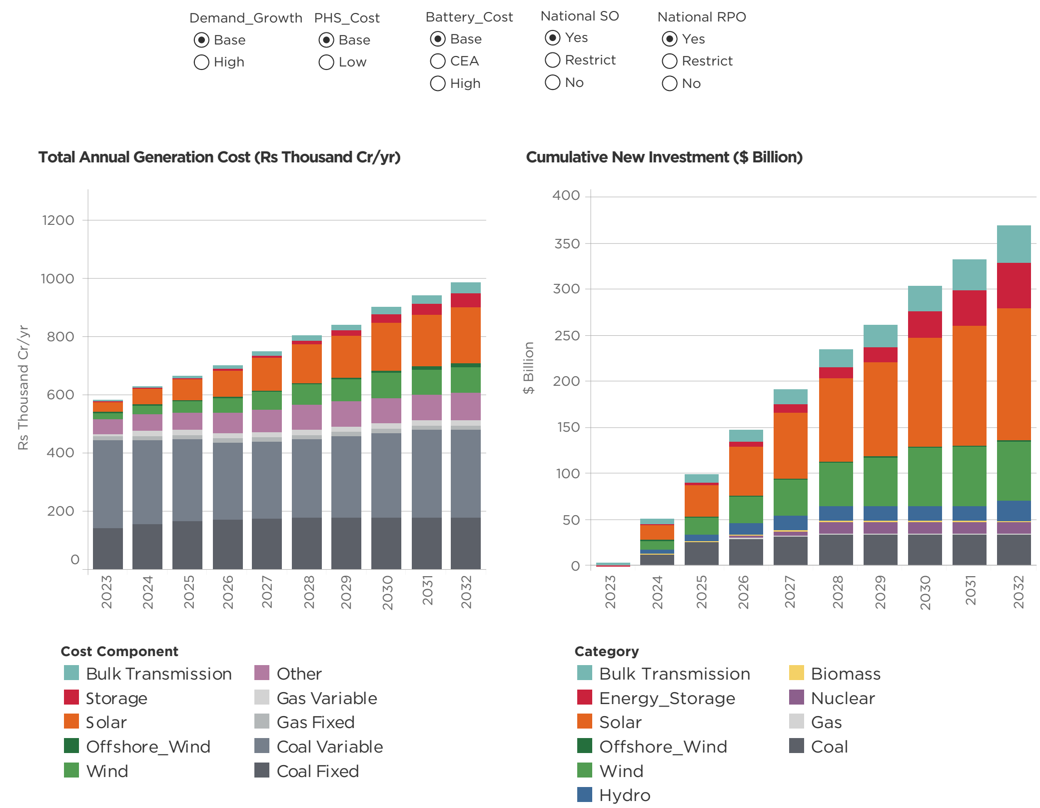
FIGURE 10: Transmission capacity needed on the interstate and inter-regional corridors in India through 2032 in the Reference Case

In the Reference Case, between 2023 and 2030, the total interstate and inter-regional transmission capacity will need to be increased by nearly 65%, and nearly 85% by 2032.

By 2030, ~200 GW of additional transmission capacity will be needed on the interstate corridors, while ~30GW additional will be needed on inter-regional corridors. In general, as RE penetration increases, the need for additional transmission increases; if Merit Based Economic Dispatch (MBED) is implemented fully covering all power plants, the cost-effectiveness of additional transmission investments increase significantly.

3.8. BY 2032, THE ELECTRICITY GENERATION SECTOR WILL NEED $380 BILLION OF NEW INVESTMENTS

As India adds more RE capacity, between 2023 and 2032 (and beyond), the generation cost structure will change significantly (figure 11). By 2032, nearly half of the annual generation costs will be fixed costs. However, despite massive RE and storage expansion, the bulk of the generation costs will still be fixed, and the variable costs of coal power plants will remain.



Note: All numbers in 2023 real currency

FIGURE 11: Total annual generation costs (left) and cumulative new investments in power generation (right) in the Reference Case

Between 2023 and 2030, ~$300 billion of new investment will be needed in power generation and ~380 billion by 2032. About $260 billion, or ~68% of the new investment by 2032, will be for new solar, wind, and energy storage, and about 10% ($40 billion) for interstate / inter-regional transmission. Energy storage alone (~80-90% batteries) will need ~$30 billion of new investments by 2030 and ~$50 billion by 2032.

3.9. THE GRID IS DEPENDABLE IN EVERY HOUR OF THE YEAR

Our dispatch modeling validates that the resource mix from the capacity expansion model can meet demand in every hour of the year in 2032. There is no loss of load, even during days when the system is stressed, such as days of peak load, highest net load, highest RE variability, etc. Figure 12 shows the average hourly system dispatch in FY 2032 for key months in the Reference Case.

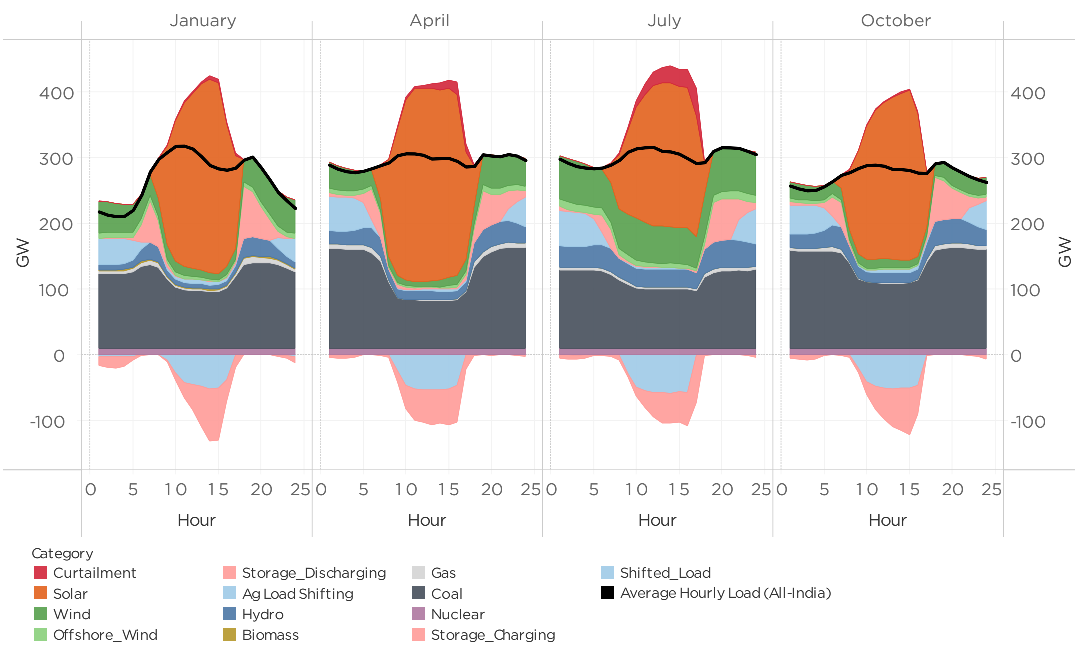


FIGURE 12: Average hourly power system dispatch in FY 2032 for key months in the Reference Case scenario

Existing and under-construction thermal power plants combined with hydropower, nuclear, and energy storage capacity enable India to meet electricity demand dependably—in every hour of the year in each state—with 456 GW of installed RE capacity in 2030 and 524 GW in 2032 (excluding large hydro).

Coal power plants continue to provide base load support; however, by 2032, out of the 242 GW of total coal capacity, approximately 120 GW of coal capacity will operate with a gross capacity factor above 60%, while more than 70 GW of coal capacity is expected to function at less than 30% capacity factor. The remaining 52 GW of coal capacity operates at a capacity factor between 30% and 60%. This suggests that a significant portion of coal capacity will likely be utilized primarily during peak demand seasons, serving as seasonal balancing.

Although no new gas power plants are found to be cost-effective, existing gas capacity offers limited seasonal balancing support during the low renewable energy season (October to February). However, its availability is heavily constrained due to the shortage of low-cost domestic gas.

Storage meets the evening and morning peak. Storage typically charges during the day (except in winter when some early morning charging is required due to low solar generation), and discharges during evening and morning peak hours (4 hours/day). Agricultural load shift offers significant night time load reduction potential.

About 2.7% of RE curtailment is found to be necessary for reliable grid integration, mostly during the monsoon due to significant increase in wind generation and reduction in load in the western and southern states.

3.10. ENERGY STORAGE GREATLY ENHANCES THE ENERGY VALUE OF RE BY SHIFTING THE RE GENERATION TO PEAK HOURS

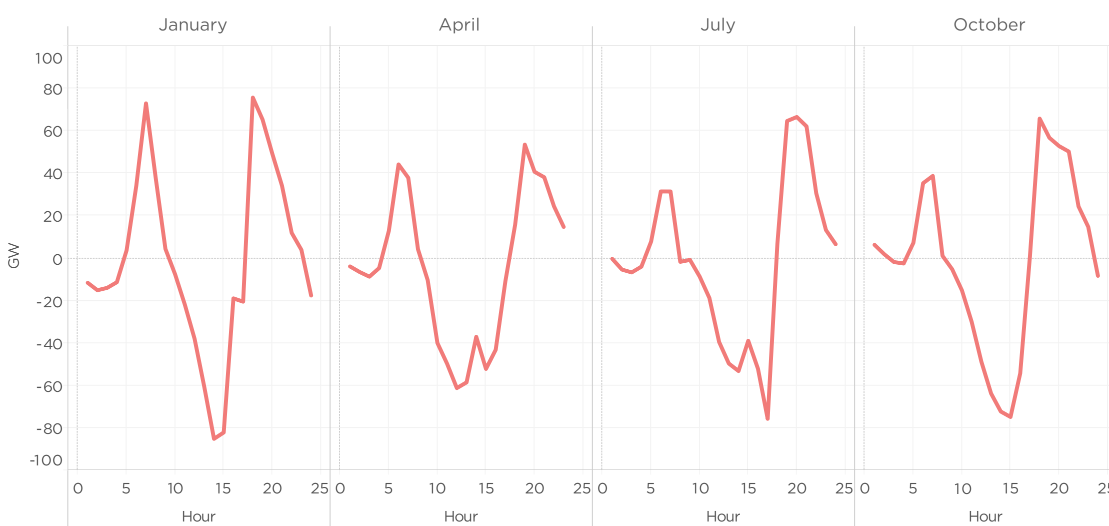


FIGURE 13: Average hourly storage net output (all-India) in FY 2032 for the Reference Case scenario (total storage capacity of 97 GW/362 GWh). Note that the positive output implies discharge and the negative output implies charging.

On most days, energy storage typically charges during the day and discharges during evening and morning peak hours (4 hours/day) as shown in the figure. Agricultural load shift offers significant night time load reduction potential. Energy storage provides the critical arbitrage service by charging during high RE generation / low electricity price periods and discharging during peak / high electricity price periods. In winter (December-January), due to low night time and early morning demand and excess wind generation at night due to the reverse monsoon, some storage capacity also charges during early morning to be discharged during the morning peak hours. Storage would be a critical source of flexibility starting as early as 2024, especially in states with high solar penetration such as Rajasthan, Gujarat etc.

3.11. SYSTEM IS ABLE TO RELIABLY MEET THE DEMAND EVEN DURING THE MOST STRESSED PERIODS

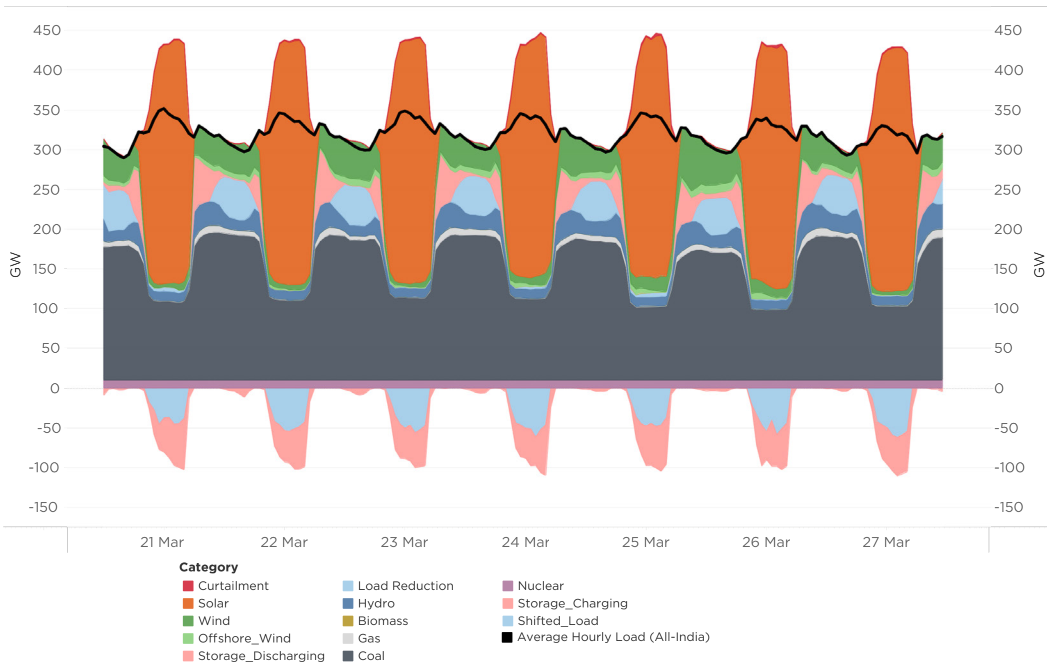


FIGURE 14: System dispatch (national) during the highest net load week in FY 2032 (Base Case)

Figure 14 shows results from simulating the hourly power plant level dispatch (8760 hours x ~2,500 generation units x 80 interstate transmission corridors) during the highest net load week in FY 2032 in the Reference Case. Net load (or residual load) is defined as load minus the output from variable RE sources (solar and wind). Net load is critical from the system planning and operations perspective because it is the effective load that the rest of the system resources, such as thermal, nuclear, and hydropower, have to meet.

In the Reference Case, the national net load peak in FY 2032 will be 302 GW and will likely occur on March 22, 2032 at 7:00 PM. Note that for each region/state, the times of their net load peaks will be different from the national net load peak.

In the net load peak hour, coal and nuclear power plants generate at high capacity factors. Net coal generation would be about 180 GW, implying the on-bar capacity will be ~190 GW in order to maintain some reserves. Although many high Variable Cost (VC) coal units will need to back down to technical minimum during the day (at certain heat rate loss), they are able to ramp up in the evening to meet the peak load. Nuclear output will be 10 GW and will be largely flat through the year.

Due to season constraints, hydro would have limited availability in March (unlike in monsoon). In the net load peak hour, hydro output (including small hydro) will be about 31 GW.

Energy storage charges in the afternoon through excess solar generation and discharges in the evening/night and plays a critical role in meeting the evening peak demand. During the net load peak hour, energy storage discharge would be ~73 GW.

3.12. STORAGE HELPS THE GRID MEET SIGNIFICANT VARIABILITY AND RAMPING NEEDS INTRODUCED BY SOLAR AND WIND

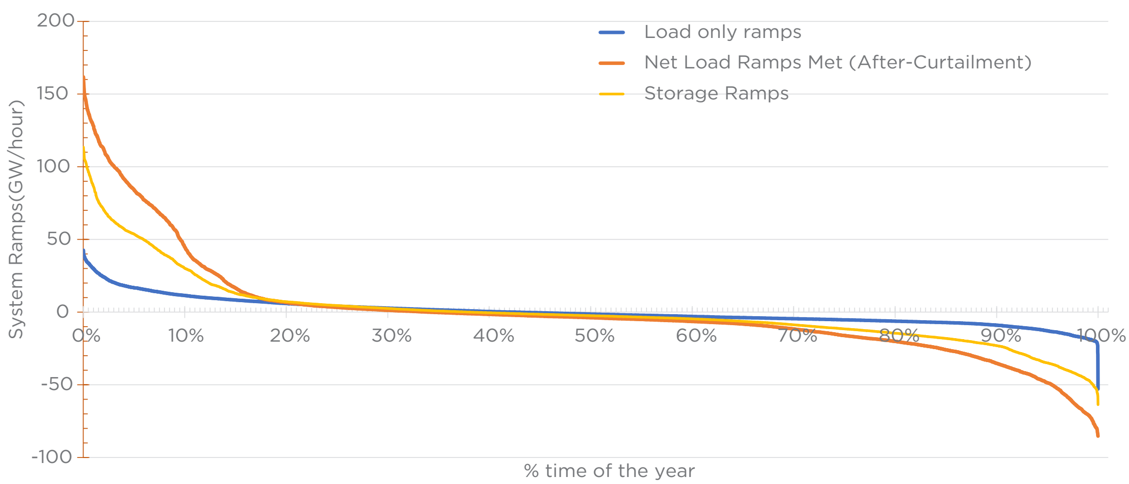


FIGURE 15: System hourly ramping needs (all-India duration curve) in the Reference Case in FY 2032 – load only ramps, net-load ramps (ramping needs of the system after integrating RE), and ramping support provided by energy storage

RE introduces significant variability into the system, particularly with "up" and "down" ramps during sunrise and sunset due to sudden increases or drops in solar generation. However, the system can manage this variability with the aid of energy storage and limited curtailment (~2.7%).

Maximum load-only ramps by FY 2032 would be as high as ~45GW/hr. However, net load ramps could reach as high as 160GW/hr, implying net additional "up" ramps due to RE as high as 110-120 GW/hr by 2032, on top of load-only ramps.

These ramps could be met by storage (providing ~110GW/hr of “up” ramps), along with other resources including thermal and hydro.

“Down” ramps become particularly problematic especially when thermal capacity is operating at technical minimum levels. By 2032, the maximum down ramp need could be as high as -85 GW/hr. However, storage is found to be able to handle down ramps as well, by providing additional down ramps of -65 GW/hr.

4. SENSITIVITY ANALYSIS

4.1. EVEN IF THERE ARE NO RPO TARGETS OR STORAGE GOAL, BUILDING ~500 GW OF CLEAN POWER CAPACITY BY 2030 WILL BE THE MOST COST-EFFECTIVE PATHWAY

FIGURE 16: Installed capacity, generation, average cost, and non-fossil share in generation if there are no RPO targets or storage goals

Even if there are no RPO targets or storage goals, it is still economical for India to install ~500 GW of non-fossil capacity by 2030 and about 600 GW by 2032, implying that it is the no-regrets strategy for the Indian power sector.

By 2030, 303 GW of solar, 105 GW of onshore wind, 7 GW of offshore wind supported by ~51 GW of energy storage is found to cost-effective. By 2032, cost-effective solar capacity increases to 372 GW and offshore wind to 15 GW, supported by 86 GW storage. Overall, non-fossil installed capacity of ~504 GW by 2030 and 590 GW by 2032 will be the most economical pathway for power sector investments. As a result, the clean energy share in total generation will still reach about 55% by 2030 and 58% by 2032, while the average power procurement cost will reduce slightly by 1% to Rs 5.35/kWh (in real terms).

Even in the absence of RPO mandates or storage goals, only 2 GW of new thermal capacity is found to be economical (beyond 27 GW that is under construction).

4.2. IF RE AND STORAGE DEPLOYMENT IS SLOW, INDIA WILL NEED 80 GW OF NEW THERMAL CAPACITY TO MEET THE RAPIDLY GROWING ELECTRICITY DEMAND

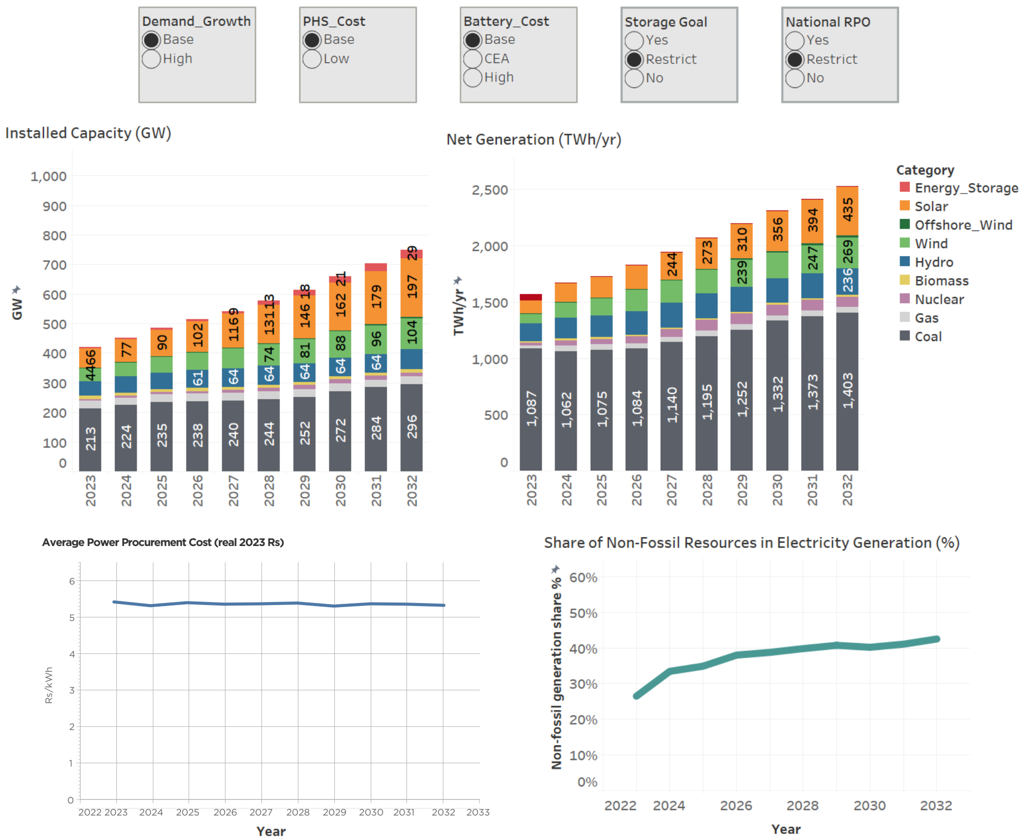


FIGURE 17: Installed capacity, generation, average cost, and non-fossil share in generation if RE and storage capacity additions are restricted to historical levels (“Restrict” case)

If RE and storage are not be deployed fast enough (“Restrict” case, in which new capacity additions limited to historical levels), about 80 GW of new thermal capacity (including 27 GW under construction) will be required by 2032. The coal capacity requirement would be 296 GW.

In the Restrict RE and Storage case (new additions limited to historical levels), RE capacity will be limited to 250 GW by 2030 and 300 GW by 2032. Energy storage capacity will be limited to 21 GW by 2030 and 29 GW by 2032. As a result, over 80 GW of new thermal investments (including 27 GW under construction) will be needed by 2032 to meet the rapidly growing electricity demand. Coal-based generation would increase by over ~300 TWh from 2023 levels. The clean energy share in total electricity generation would be only 40% by 2030, while the average power procurement cost would increase by ~3% to Rs. 5.61/kWh.

4.3. IF STORAGE DEPLOYMENT LAGS, 80 GW OF NEW THERMAL INVESTMENTS WILL STILL BE NEEDED DESPITE ACHIEVING THE 500 GW CLEAN POWER TARGET

FIGURE 18: Installed capacity, generation, average cost, and non-fossil share in generation if India meets the 500 GW clean power target by 2030 (RPO mandates met by utilities), but energy storage deployment lags ("Restrict" case for storage)

If the energy storage deployment lags, India may need to build significant new coal resources primarily as a firm capacity resource, even if the country achieves the 500 GW clean power target by 2030 (and ~600 GW clean power by 2032). If energy storage cannot be deployed fast enough ("Restrict" case), storage capacity may be restricted to 21 GW by 2030 and 29 GW by 2032, and about 57 GW of new thermal capacity would be needed by 2030 and 80 GW by 2032 (both numbers including 27 GW under construction coal capacity), implying total coal capacity will be 270 GW by 2030 and 294 GW by 2032, even if utilities meet their RPO targets.

However, such a coal buildout—in tandem with the RE buildout—would likely cause the average fleet-level coal capacity factor to drop to 43% (gross) by 2030 and 41% by 2032, with nearly 125 GW of coal capacity (mostly existing plants with high variable cost) operating at capacity factors of under 30%. This result could put such assets at increased risk of being stranded and needing regulatory support. Additionally, it results in an increase in the average cost of power procurement to Rs 5.52/kWh by 2030 and to Rs 5.59/kWh by 2032. Deploying energy storage can prevent the stranding of coal capacity by reducing the new coal buildout while maintaining grid dependability and enabling existing coal assets to operate more efficiently.

4.4. EVEN WITH NEP BATTERY COST ASSUMPTIONS, COST-EFFECTIVENESS OF BATTERY STORAGE LARGELY REMAINS UNCHANGED

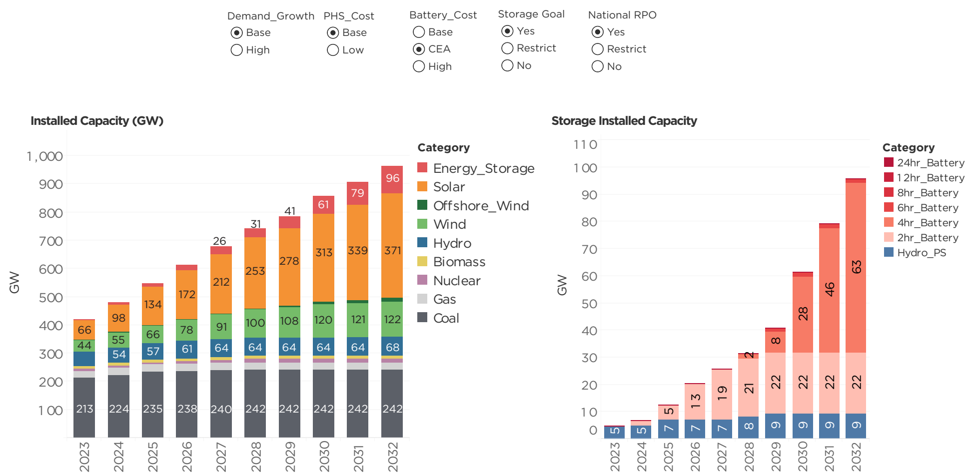


FIGURE 19: Installed capacity of all generation sources (left) and energy storage (right), using the CEA NEP battery cost assumptions and assuming the RPO mandates and storage goals are met

Even with NEP battery cost assumptions, which are slightly more conservative than our base cost assumptions, battery storage is still found to be more cost-effective than pumped hydro.

The total storage requirement is similar – 61 GW / 222 GWh by 2030 and 97 GW / 362 GWh by 2032. Only 9 GW of pumped hydro capacity is found to be economical with the remaining storage needs met by batteries.

The RE resource buildout is also very similar to the Reference Case – with solar capacity of 313 GW and onshore wind capacity of 120 GW by 2030, and total non-fossil capacity of ~500 GW. The average power procurement cost remains largely flat and very similar to that of Reference case – Rs 5.43/kWh by 2030 and Rs 5.40/kWh by 2032.

4.5. IF BATTERY COSTS DO NOT REDUCE BELOW 2025 LEVELS, PHS INVESTMENTS INCREASE SIGNIFICANTLY TO OVER 22 GW BY 2032

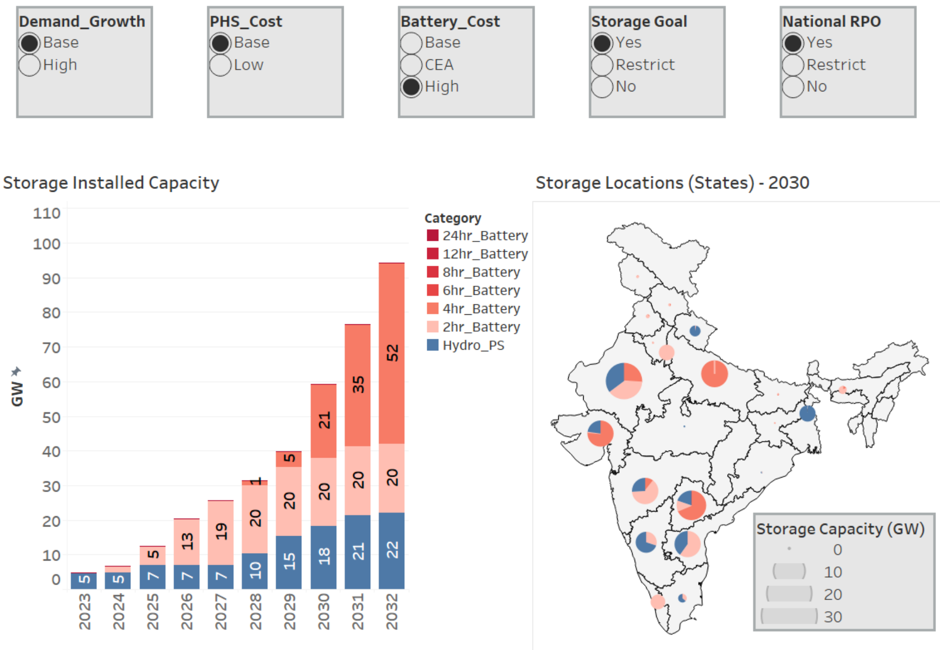


FIGURE 20: Energy storage installed capacity by duration (left) and 2030 locations (states) (right) if battery prices do not reduce below 2025 levels

If battery costs do not reduce below the 2025 levels, the cost-effectiveness of new PHS investments will increase significantly. While the total storage requirement remains almost the same (59 GW/ 232 GWh by 2030 and 94GW/ 380GWh by 2032), PHS capacity increases significantly to 18 GW by 2030 and 22 GW by 2032.

While 2-hour battery capacity remains almost the same as the Reference Case (20 GW), 4-hour battery capacity reduces significantly to 21 GW by 2030 and 52 GW by 2032. Because of the high capital cost of BESS projects, the average power procurement cost increases somewhat compared to the Reference Case to Rs 5.48/kWh by 2032.

The regional distribution of energy storage changes significantly. As PHS potential is driven by the geographical location of the project, storage capacity is not necessarily concentrated only in the solar-rich states.

4.6. IF PHS COULD BE DEVELOPED AT LOW COSTS, NEED FOR BATTERY STORAGE DROPS BY 2030. ABOUT 17 GW OF PHS IS FOUND TO BE COST EFFECTIVE BY 2030

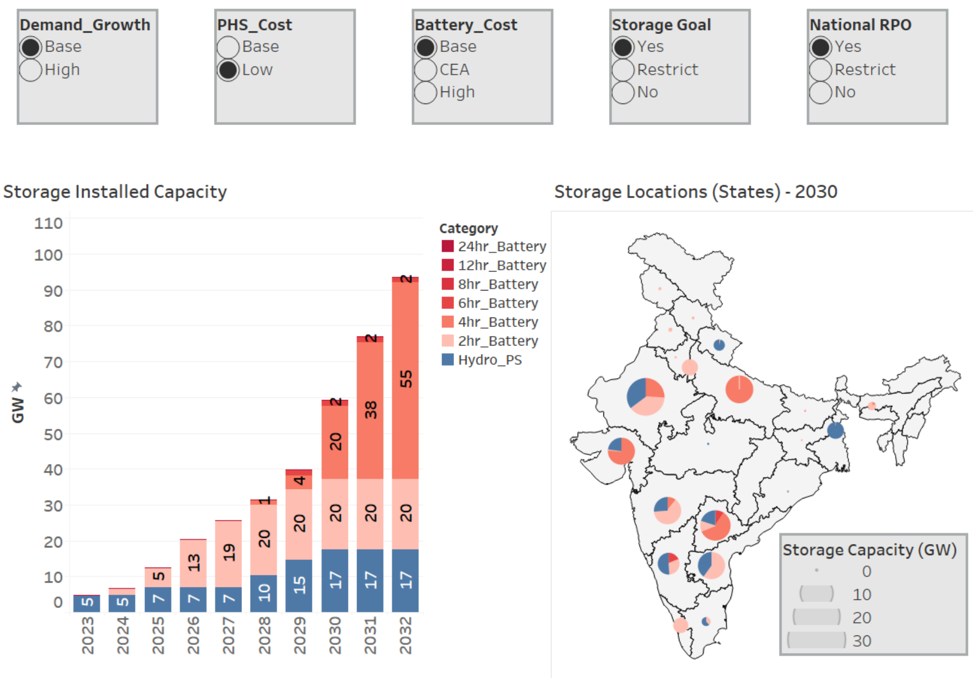


FIGURE 21: Energy storage installed capacity by duration (left) and 2030 locations (states) (right) if average pumped hydro capital costs remain low

If PHS could be developed at low costs at $500/kW or Rs 4.1 Cr/MW (e.g. off-river sites), its cost-effectiveness increases in the near-medium term compared with batteries. By 2030, the economical PHS capacity increases to 17 GW and battery capacity drops to ~41 GW.

However, beyond 2030, as battery costs continue to decline, they start becoming more cost-effective compared with PHS. By 2032, battery capacity increases to ~76 GW, while PHS capacity stays at 17 GW. Total storage capacity needs would still be similar to the previous cases – about 58 GW by 2030 and 93 GW by 2032. Because of the low capital cost of PHS projects, the average power procurement cost reduces somewhat to Rs 5.36/kWh by 2032.

The regional distribution of energy storage changes significantly. As PHS potential is driven by the geographical location of the project, storage capacity is not necessarily concentrated only in the solar-rich states.

4.7. IF ELECTRICITY DEMAND GROWS FASTER THAN PROJECTED, SIGNIFICANT ADDITIONAL RE AND STORAGE INVESTMENTS ARE FOUND TO BE COST-EFFECTIVE

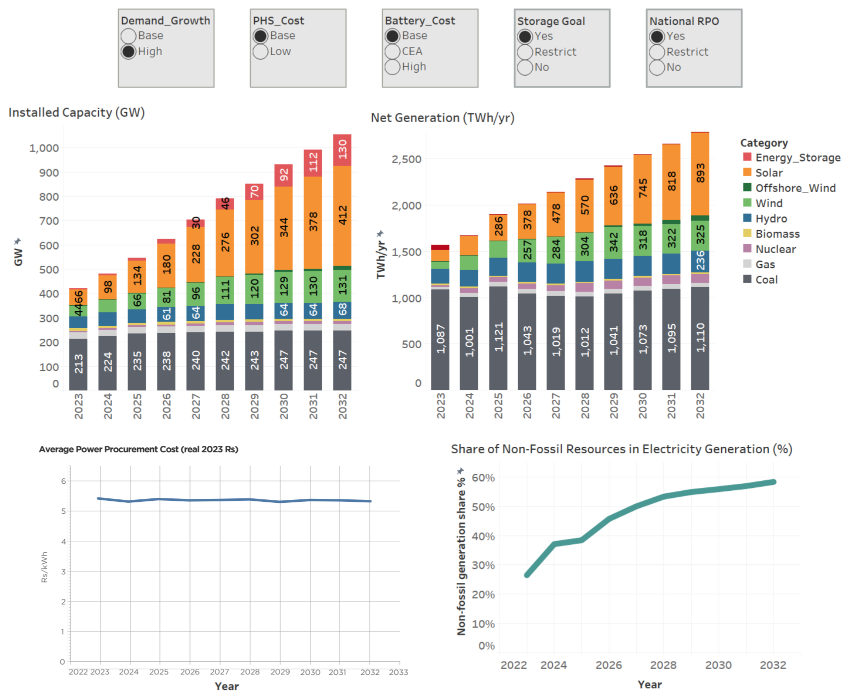


FIGURE 22: Installed capacity, generation, average cost, and non-fossil share in generation if the electricity demand growth is higher than anticipated in the 20th EPS

If electricity demand grows faster than anticipated ("High" demand growth case, where peak demand of ~400 GW by 2032), significant additional RE and storage investments will be needed to meet the growing demand cost-effectively.

By 2030, the solar capacity requirement increases to 344 GW, onshore wind to 129 GW, with non-fossil capacity reaching as high as 568 GW. Storage deployment will have to increase rapidly to meet the demand reliably. Storage capacity needs to expand to 30 GW/ 108 GWh by 2027, 92 GW / 356 GWh by 2030, and 130 GW / 508 GWh by 2032. About 5 GW of additional thermal capacity investments (in addition to ~27 GW under construction) will also be needed by 2030.

The increased demand could still be met by keeping the average power procurement cost nearly flat at Rs 5.44/kWh in real terms by 2030 and thereafter dropping slightly to Rs 5.39/kWh by 2032.

5. ECONOMICS OF ENERGY STORAGE IN INDIA

5.1. SURGING INTEREST IN BATTERY STORAGE: COMPETITIVE BIDDING FROM MAJOR DEVELOPERS IN RECENT LARGE-SCALE AUCTIONS

Recent battery storage auctions have received an overwhelmingly positive response, with multiple major developers, including JSW Neo, NTPC Renewables, Renew Power etc. bidding aggressively. In each auction, there have been at least 5-6 developers that bid within 5% of the winning bid, indicating the winning bids are not outliers, as shown in the following figures.

S#	Bidder's Name	Quoted Value	Loaded Value	Currency	Date/Time of Bidding	Bidder's Quantity	% Difference greated than Rank-1 Bid Value
1	Gensol Engineering Limited	448996.00	448996.00	Indian Rupee	06-Mar-2024 22:23:30 RTZ	70.00	0.00%
2	IndiGrid 2 Limited	449996.00	449996.00	Indian Rupee	06-Mar-2024 22:20:20 RTZ	250.00	0.22%
3	JSW Neo Energy Limited	449997.00	449997.00	Indian Rupee	06-Mar-2024 22:19:49 RTZ	250.00	0.22%
4	Limited Hero Solar Energy Private Limited	538000.00	538000.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	70.00	19.82%
5	NTPC Renewable Energy Limited	949999.00	949999.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	100.00	111.58%
6	ACME Solar Holdings Private Limited	990000.00	990000.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	70.00	120.49%
7	SJVN Green Energy Limited	991000.00	991000.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	70.00	120.71%
8	VENT RENEWABLES PRIVATE LIMITED	995000.00	995000.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	70.00	121.61%

S#	Bidder's Name	Quoted Value	Loaded Value	Date/Time of Bidding	Bidder's Quantity	Special Remarks	Difference in % (Bid-Value vs Start-Price)
1	Gensol Engineering Limited (ETS-IN-2019-RS0000329)	372978.00	372978.00	11-Jun-2024 18:59:34 RTZ	250.00	Field Not Filled	20.81%
2	IndiGrid 2 Limited (ETS-IN-2023-RS0000456)	372978.00	372978.00	11-Jun-2024 19:04:43 RTZ	250.00	Field Not Filled	20.81%
3	JSW Neo Energy Limited (ETS-IN-2021-RS0000180)	373979.00	373979.00	11-Jun-2024 18:53:06 RTZ	250.00	Field Not Filled	20.60%
4	PACE DIGITEK INFRA PVT LTD (ETS-IN-2024-RS0000210)	375900.00	375900.00	11-Jun-2024 18:31:55 RTZ	100.00	Field Not Filled	20.19%
5	CONTINENTAL MILKOSE (INDIA) LIMITED (ETS-IN-2023-RS0000579)	383000.00	383000.00	11-Jun-2024 18:39:11 RTZ	70.00	Field Not Filled	18.68%
6	ACME Solar Holdings Private Limites (ETS-IN-2029-RS00000080)	383983.00	383983.00	11-Jun-2024 18:08:58 RTZ	250.00	Field Not Filled	18.47%
7	JBM RENEWABLES PRIVATE LIMITED (ETS-IN-RS0000188)	420500.00	420500.00	11-Jun-2024 16:30:37 RTZ	250.00	Field Not Filled	10.72%
8	HINDUJA RENEWABLES ENERGY PRIVATE LIMITED (ETS-IN-RS0000181)	466000.00	466000.00	11-Jun-2024 15:28:37 RTZ	130.00	Field Not Filled	1.06%
9	VIKRAM SOLAR CLEANTECH PRIVATE LIMITED (ETS-IN-2019-RS0000333)	542000.00	542000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-15.07%
10	Apraava Energy Private Limited (ETS-IN-RS0000031)	600000.00	600000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-27.39%
11	NTPC Renewable Energy Limited (ETS-IN-RS0000051)	662000.00	662000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-40.55%
12	SOLARCRAFT POWER INDIA 12 PRIVATE LIMITED (ETS-IN-2024-RS0000054)	766000.00	766000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-62.63%
13	SVJN Green Energy Limited (ETS-IN-RS0000261)	795000.00	795000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-68.79%

Note: Quoted Values are in Rs/MW-month, Bidders Quantity in MW of storage

FIGURE 23: GUVNL bid results for 250 MW/500MWh double cycling standalone storage, March 2024 (left) and for 250 MW/500MWh double cycling standalone storage, June 2024 (right)

For GUVNL standalone storage auctions, the winning bid was Rs 448,996/MW-month or Rs 4.6/kWh in March 2024, which dropped by about 18% in just 3 months; the winning bid in June 2024 was Rs 372,978/MW-month or Rs 3.8/kWh.

S#	Bidder's Name	Quoted Value	Loaded Value	Currency	Date/Time of Bidding	Bidder's Quantity	% Difference greater than Rank-1 Bid Value
1	PACE DIGITEK INFRA PVT LTD	3.41	3.41	Indian Rupee	16-Jul-2024 17:55:47 RTZ	100.00	0%
2	Hero Solar Energy Private Limited	3.42	3.42	Indian Rupee	16-Jul-2024 17:54:31 RTZ	250.00	0.29%
3	ACME Solar Holdings Limited	3.42	3.42	Indian Rupee	16-Jul-2024 17:54:35 RTZ	350.00	0.29%
4	JSW Neo Energy Limited	3.42	3.42	Indian Rupee	16-Jul-2024 17:54:53 RTZ	600.00	0.29%
5	NTPC Renewable Energy Limited	3.43	3.43	Indian Rupee	16-Jul-2024 17:36:52 RTZ	300.00	0.59%
6	Solarcraft Power India 8 Pvt Ltd	3.50	3.50	Indian Rupee	16-Jul-2024 17:07:37 RTZ	150.00	2.64%
7	Rays Power Infra Limited	3.50	3.50	Indian Rupee	16-Jul-2024 17:08:53 RTZ	100.00	2.64%
8	Hexa Climate Solutions Private Limited	3.67	3.67	Indian Rupee	16-Jul-2024 15:38:37 RTZ	200.00	7.62%
9	ReNew Solar Power Private Limited	3.71	3.71	Indian Rupee	16-Jul-2024 15:19:43 RTZ	300.00	8.80%

Note: Quoted Values are in Rs/kWh, Bidders Quantity in MW of solar

FIGURE 24: SECI bid results for 1200 MW + 600 MW/1200 MWh co-located battery storage, July 2024

For SECI solar + co-located storage auctions (~20% solar energy stored in batteries), the winning bid was Rs 3.41/kWh. Assuming a solar price of Rs 2.6/kWh, the storage adder for 20% solar stored in batteries is Rs 0.81/kWh.

5.2. INDIA'S STORAGE MOMENT: WHY SECI SOLAR + STORAGE AUCTION RESULTS ARE SO IMPORTANT?

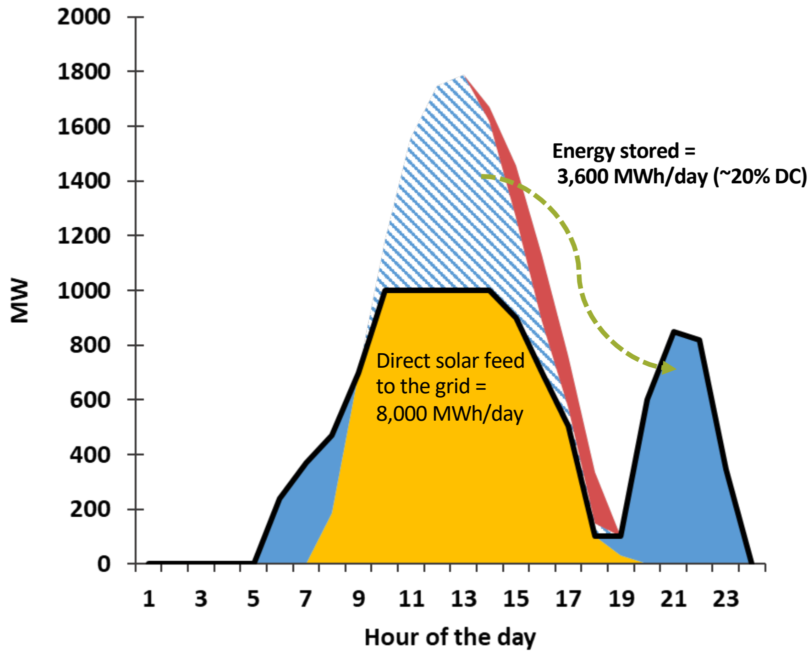


FIGURE 25: Operational simulation of SECI's 2000 MW solar + 1000 MW/4000 MWh storage (~25% AC and 33% DC solar energy stored in batteries).

SECI conducted 2000 MW solar + co-located 1000 MW/4000 MWh battery storage auctions in December 2024. The winning bid was ₹ 3.52/kWh, which indicates a dramatic reduction in battery storage cost. Since this is a co-located solar + storage project, the storage would cycle only once in a day.

Assuming a solar LCOE of ₹ 2.5/kWh, this implies an evening peak storage adder of about ₹1/kWh. This implies a battery storage capital cost of $100-120/kWh (Assumptions: storage availability = 95%, round trip efficiency = 90%, and annual cycles = 365 cycles/yr).

Similarly, GUVNL's standalone storage auction revealed the price of ₹3.73 lakh per MW per month, for 250 MW/500 MWh battery for 2 cycles/day (June 2024). This implies a standalone storage capital cost of $200/kWh, or the cost of standalone storage of ₹3.8/kWh for two cycles/day or 730 cycles/yr (₹3.73 lakh divided by 120 MWh throughput in a month, adjusted for 85% roundtrip efficiency and 95% availability per bid conditions).

If standalone storage completes only one cycle/day (~365 cycles/yr), the cost of standalone storage would be ₹6.5/kWh.

5.3. CO-LOCATED BATTERY STORAGE CAPITAL COST HAS ALREADY FALLEN TO ~$150/KWH AND WILL LIKELY DROP FURTHER BY ~15-20% BY 2030

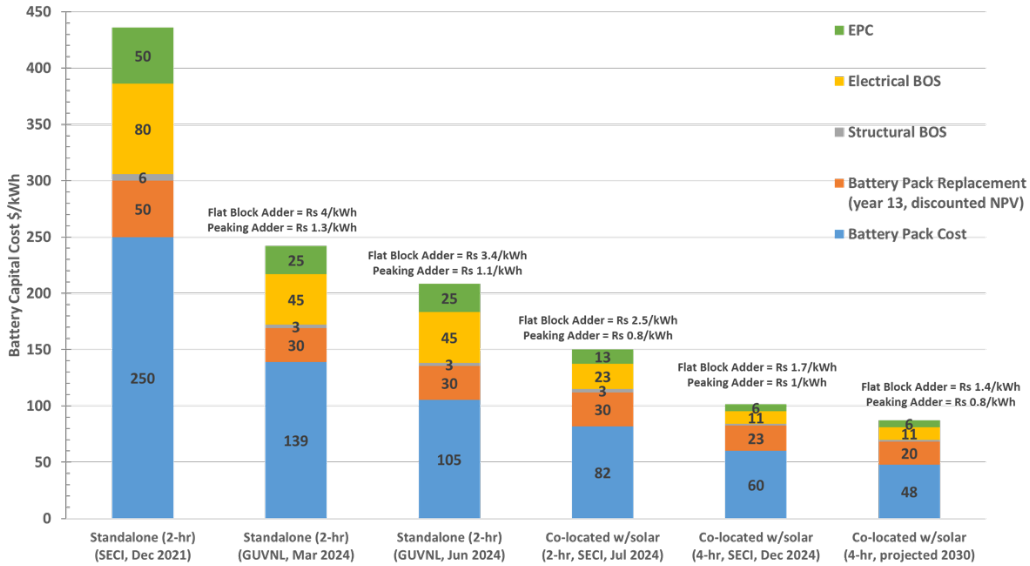


FIGURE 26: Estimated battery capital costs split into key components (reverse engineered from winning bids and other market data)

Over the last 2-3 years, battery storage prices have seen a dramatic reduction in India with standalone battery storage capital cost estimated at ~$150-200/kWh and co-located battery storage capital cost estimated at ~$100-120/kWh.

Co-location of batteries with solar offers significant BOS cost savings, reducing the overall capital cost by ~20%.

As of December 2024, based on the auction results, the evening peaking storage adder on top of RE LCOE would be about Rs. 1/kWh. By 2030, these costs would likely drop further by 15-20%, indicating a significant shift in how India should plan future power sector investments.

5.4. COMPARATIVE ECONOMICS OF BATTERY STORAGE AND PUMPED HYDRO

Figure 26 shows levelized cost of storage as a function of hours of storage for co-located battery storage systems and off-river pumped hydro projects.

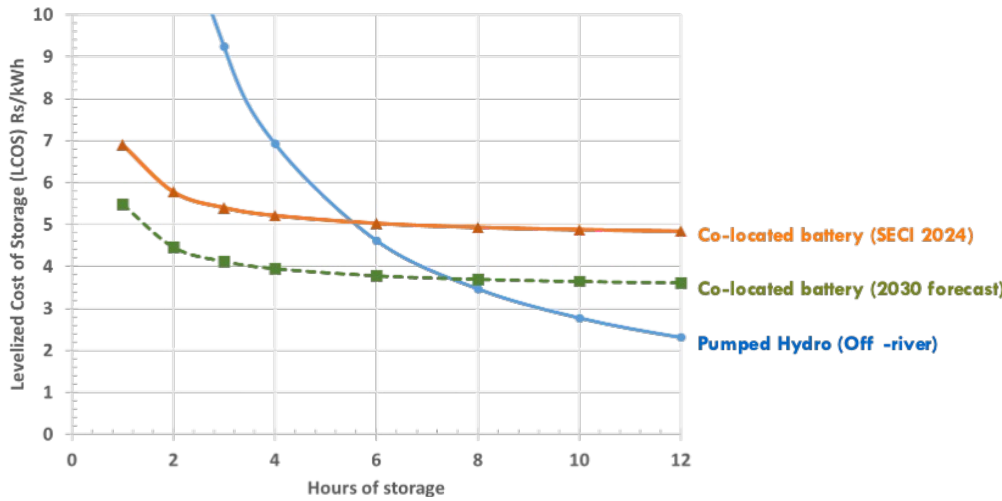


FIGURE 27: Levelized cost of storage (LCOS) for co-located battery storage and off-river pumped hydro in India.

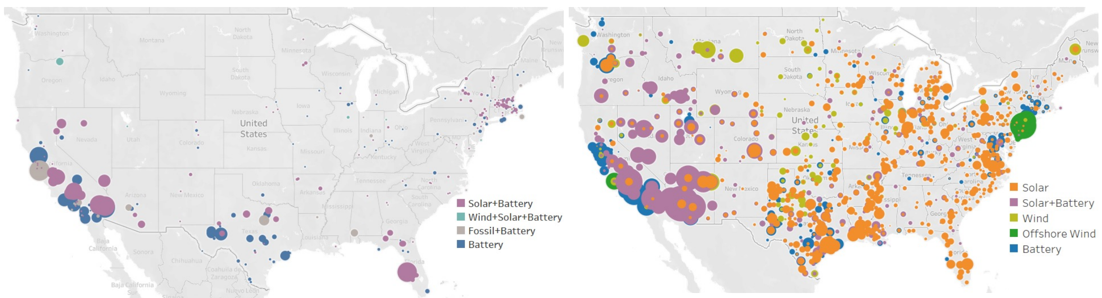
Key assumptions for this comparative economics are given as follows:

Assumptions:	
Co-located battery capex (2024)	= $150/kWh for 2 hours per SECI bids
Co-located battery capex (2030)	= $120/kWh for 2 hours (authors' projections)
Pumped hydro capex (Off-river, 2024-2030)	= Rs 4.5 Cr/MW
Cycles per year	= 300
Roundtrip efficiency	= 80% (PHS); 90% (BESS)

We find that given the recent reduction in battery storage prices in India (as evidenced in SECI and GUVNL bids), co-located batteries are already economical for up to 5-6 hours/day, compared with off-river pumped hydro. By 2030, as battery prices continue to decline, they will be more economical up to 8 hours of storage as well. As mentioned in the previous results, we find that by 2030, India will need ~4 hours of energy storage to integrate 500 GW of clean power (along with ~242 GW of thermal).

In general, batteries are energy (MWh) constrained, while pumped hydro resources are power (MW) constrained. Therefore, for low storage hours (low MWh to MW ratio), batteries would be cheaper. However, as storage hours increase (high MWh to MW ratio), pumped hydro starts getting more economical. If pumped hydro projects could be developed in a time-bound manner under Rs 4 Cr/MW, they may be cheaper than batteries even for low storage hours.

5.5. DEEP STORAGE COST DECLINES IS DRAMATICALLY IMPACTING RESOURCE CHOICES IN THE US

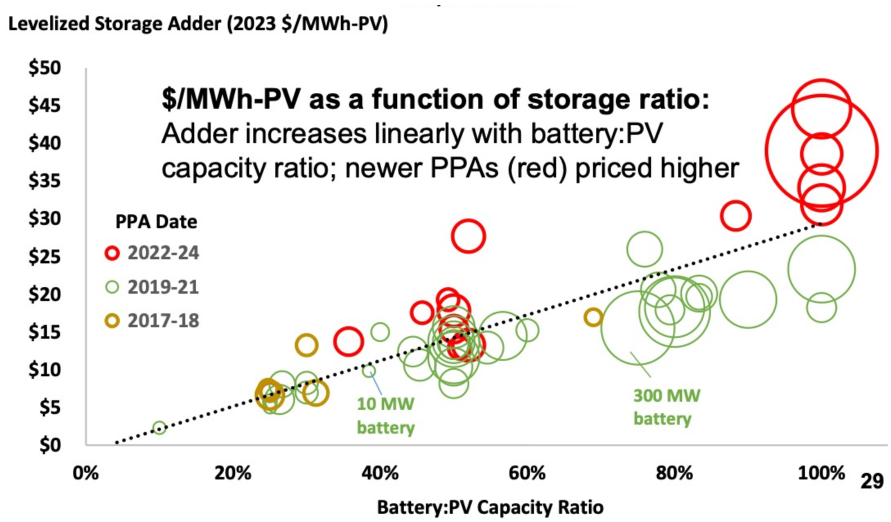


Data Sources: EIA (2023); Bolinger et al (2023); Rand et al (2024)

FIGURE 28: Existing battery installations (left) and interconnection queue in the U.S. (right)

By September 2024, about 20 GW of battery capacity has been installed in the US. The typical duration is 2-4 hours. Over 50% of the batteries are co-located with solar, while 40% are standalone. California alone accounts for nearly 50% of the existing battery installations.

The U.S. also has nearly 2,000 GW of renewable energy and storage projects in the interconnection queue, consisting of ~1100 GW Solar (including ~500GW of solar co-located storage), ~350 GW Wind (including offshore wind), and 500 GW of Standalone Batteries.



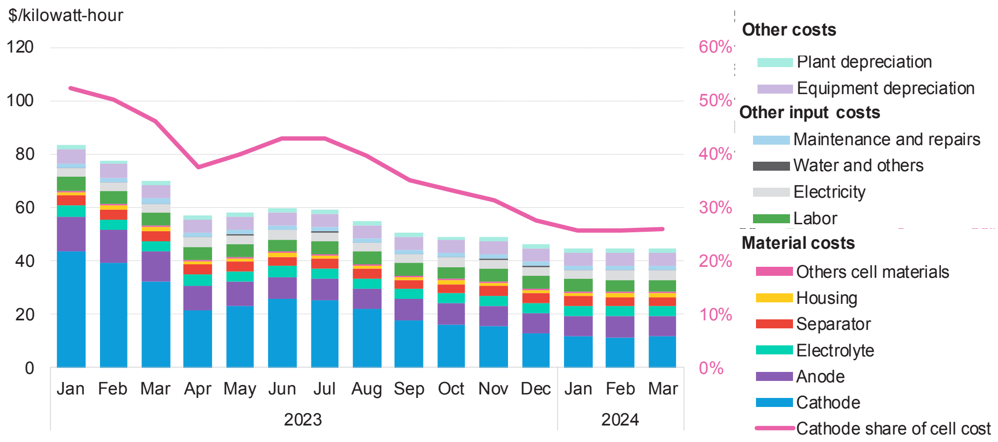
State	Plant Name	Solar (MW)	BESS (MWh)	Solar+BESS PPA price ($/MWh)	Date
CA	RE_Slate_SVCE	161	321	32.9	20-Feb
NV	Chuckwalla	200	720	36.4	20-Mar
CA	Arlington_Energy II	233	528	35.1	20-Oct
NV	Hot_Pot	350	1120	35.3	21-Jun
NV	Iron_Point	250	800	36.9	21-Jun
AZ	Sonoran Energy Center	250	1,000	41.4	23-Dec
NM	Quail Ranch	100	400	62.1	25-Nov
NV	Boulder_Solar_III	128	511	59.2	27-Jun
NV	Dry_Lake_East	200	800	72.8	26-Dec
NV	Libra	700	2,800	64.4	27-Dec

Data Source: Bolinger et al (2023)

FIGURE 29: Co-located solar + storage configurations (top) and PPA prices (bottom) in the U.S.

The typical solar + co-located storage configuration in the US is 50% of PV MW x 4 hours, amounting to about ~20-30% of daily solar generation. Typical solar + co-located storage PPA prices (subsidized) are ~$30-40/MWh or Rs. ~2.5-3/kWh, implying the average storage cost adder of $12/MWh (Rs. 1/kWh). Note that these are subsidized prices; unsubsidized costs would be ~25-30% higher.

5.6. IN CHINA, LFP PACK PRICES HAVE ALREADY FALLEN TO $75/KWH



Source: Bloomberg NEF, ICC Battery.

Note: The cost breakdown uses BNEF's BattMan Cost Model to calculate the production cost of a 120Ah lithium iron phosphate (LFP) and artificial graphite prismatic cell produced in a 10-gigawatt-hour LFP battery cell plant located in China. Cathode costs are adjusted using the cathode spot price from ICC Battery.

FIGURE 30: Cell level LFP battery manufacturing costs in China split into key components and share of cathode in cell costs

Owing to declining material costs, the manufacturing costs of LFP cells in China have dropped by nearly 50% in just one year, with the cathode share of the total cell manufacturing costs nearly halving.

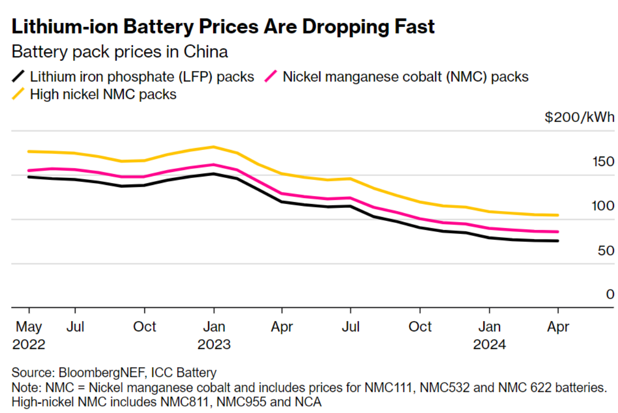


FIGURE 31: Lithium-ion Battery Pack Prices in China

Owing to significant production overcapacity and declining material costs, pack-level prices for the most-sold battery chemistries have been below the often-referenced $100/kWh benchmark in China since October 2023, and LFP pack prices are now at $75/kWh.

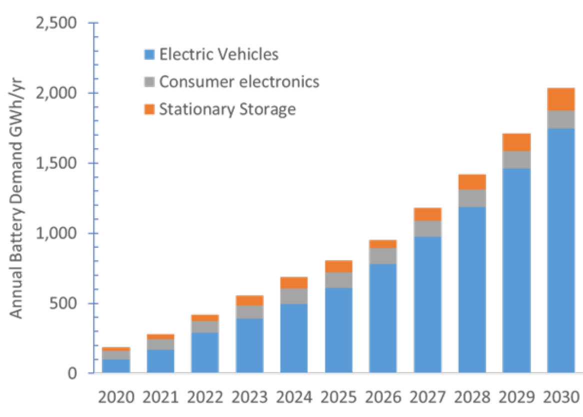
6. BATTERY SUPPLY CHAINS

Supply chains would play a crucial role in determining any storage technology's availability and costs in India and thus potential for rapid deployment. Of the two main technologies analyzed in this report, the pumped hydro supply chain is largely domestic and therefore in this section, we focus primarily on battery supply chains where there are potential issues on domestic manufacturing, mineral and other raw material availability, and concentration with 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.

6.1. BATTERY SUPPLY CHAINS WILL BE DOMINATED BY THE AUTO SECTOR

Figure 32 illustrates the annual global battery demand by sector, highlighting projections up to 2030. The chart underscores the significant growth in battery demand, driven primarily by the electric vehicle (EV) sector, which constitutes the vast majority of global battery consumption. The data reveals that battery demand is expected to rise exponentially from less than 500 GWh/year in 2022 to over 2,000 GWh/year by 2030, a fourfold increase in less than a decade.

Electric vehicles dominate this growth, accounting for approximately 80–85% of the total demand, while consumer electronics maintain a steady, smaller share. Stationary storage, which plays a crucial role in integrating renewable energy into power grids, forms a relatively modest proportion, contributing around 10% of the annual battery demand by 2030.



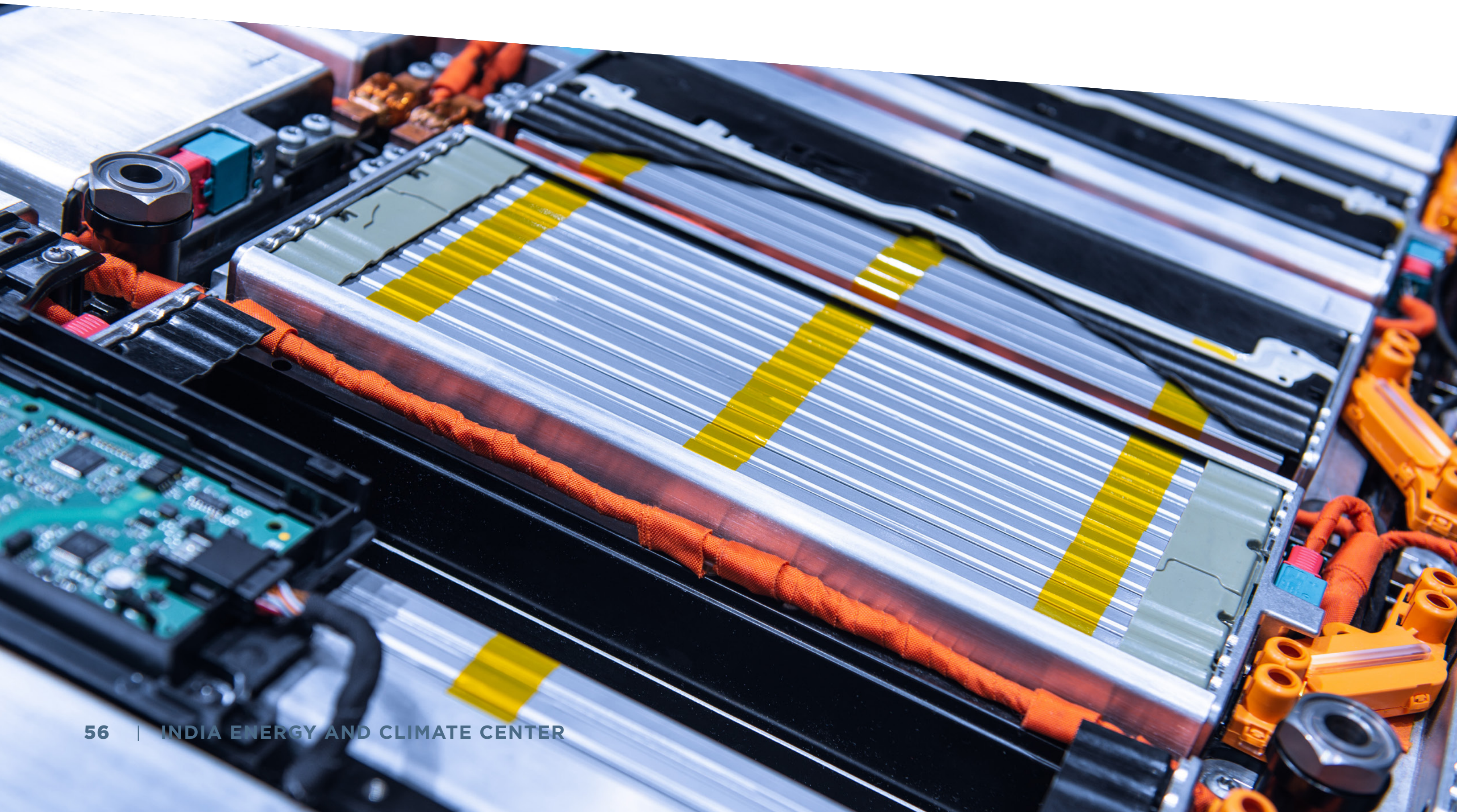
Data Sources: BNEF (2023); DOE (2021); Statista (2023)

FIGURE 32: Annual battery demand from key sectors (actuals up to 2023, and projections up to 2030)

The dominance of EVs in battery consumption has significant implications for global supply chains and energy security. Since EV batteries require nearly ten times the capacity of stationary storage batteries, the power sector's demand for storage is unlikely to exert substantial additional pressure on global supply chains. This insight alleviates concerns about competition for critical materials between the transportation and energy sectors, suggesting that the scalability of stationary storage solutions is feasible without major bottlenecks.

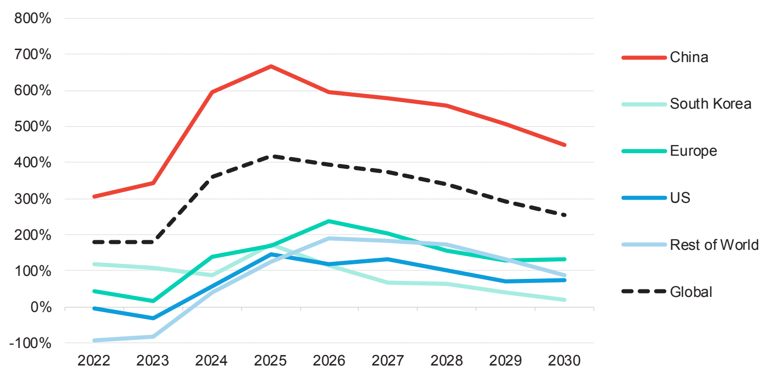
India is taking proactive steps to address the challenges and opportunities associated with battery supply chains. The country is rapidly building domestic battery manufacturing capacity, with over 200 GWh of production facilities currently planned or under construction. These developments involve contributions from some of India's largest industrial conglomerates, ensuring a robust and localized supply chain. Furthermore, major Indian automakers, including Tata Motors and Mahindra, are already manufacturing EVs domestically and have secured stable battery supply chains to support their operations. This integration of local production with secured material sourcing reduces India's reliance on imports and enhances its energy security.

To further bolster energy independence, India is investing in strategic lithium processing and recycling initiatives. With significant lithium deposits recently discovered in states such as Jammu and Kashmir, Karnataka, and Rajasthan, the country is positioning itself to reduce dependence on global markets. Moreover, studies indicate that up to 95% of lithium in spent batteries can be recycled, with projections suggesting that battery recycling could meet 25–50% of India's annual lithium demand by 2040 (Abhyankar et al, 2023).



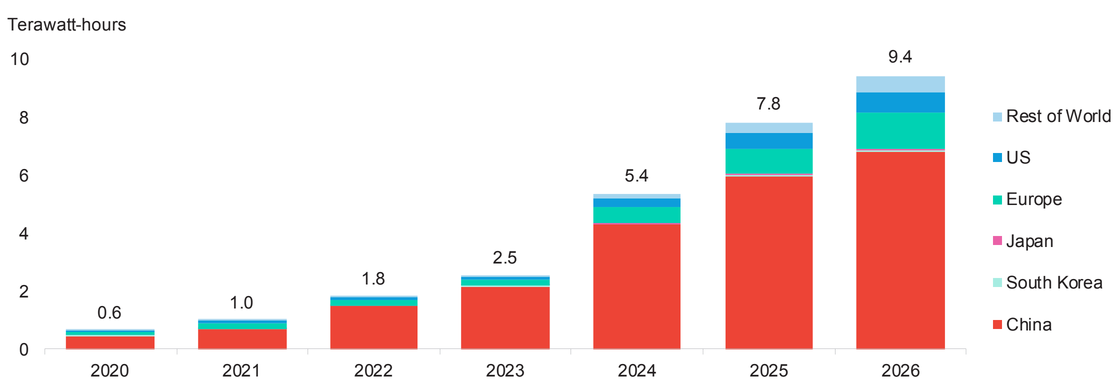
6.2. LITHIUM-ION BATTERY CELL MANUFACTURING OVERCAPACITY WILL PERSIST AT LEAST UNTIL 2030

Globally the lithium-ion battery cell manufacturing capacity is nearly 400% of the annual demand in 2024. Even by 2030, due to significant new investments in battery manufacturing, the overcapacity will likely continue, despite a substantial increase in battery demand. By 2030, the battery manufacturing capacity would be over 200% of the projected demand.



Source: BloombergNEF.
Note: Overcapacity ratio based on the manufacturing capacity over the same year's demand. Demand is based on BNEF's EVO 2024. Nameplate manufacturing capacity as of May 9, 2024. Includes plants that are fully owned by battery makers, as well as joint ventures with automakers, however, pack assembly plants are excluded. The 2023 manufacturing capacity includes only fully commissioned capacity. Future capacity is based on non-de-risked capacity tracked by BNEF's battery manufacturing database based on commissioning date before December 31 of the respective years.

FIGURE 33: : Lithium-ion battery cell manufacturing overcapacity ratio from 2022 to 2030



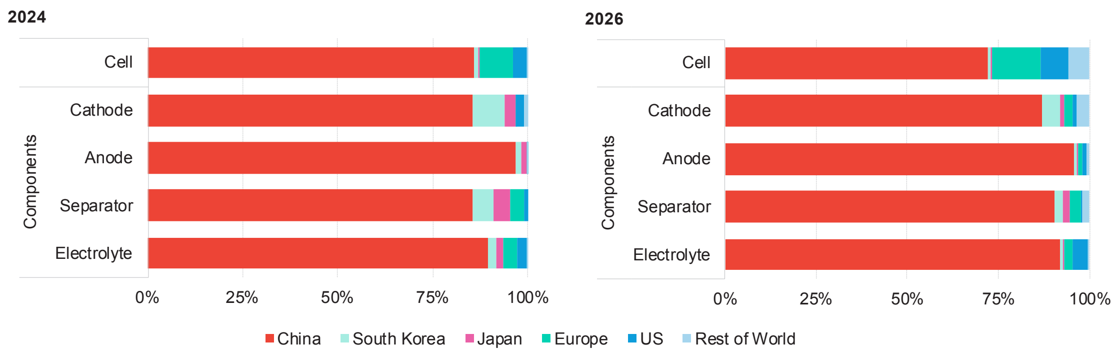
Source: BNEF (2024)

FIGURE 34: Commissioned and announced annual lithium-ion battery cell manufacturing capacity

In 2024, global battery manufacturing capacity is over 5000 GWh/yr, with over 80% concentrated in China. By 2026, the battery manufacturing capacity is expected to nearly double to more than 9,000 GWh/yr. While other regions will expand battery manufacturing substantially in the coming years, it will still be dominated by China (~65%).

6.3. CHINA WILL CONTINUE TO DOMINATE THE MANUFACTURING OF ALL BATTERY COMPONENTS

China is by far the dominant player in upstream segments of the battery industry, accounting for over 50% of global production in materials processing, component and cell manufacturing, and electric vehicle production (BNEF 2024a). In 2024, China produced more than 75% of all batteries worldwide and played a significant role in graphite and lithium mining (BNEF 2024) (Figure 35).



Source: BNEF (2024)

FIGURE 35: Geographic distribution of lithium-ion cell and component manufacturing capacity, by region of plant location

Lithium-ion batteries, the backbone of modern energy storage, are composed of battery packs built from thousands of cells managed by advanced electronic systems for charge regulation and temperature control. Each individual cell consists of an anode, cathode, electrolyte, separator, and outer casing. These cells are arranged in modules equipped with a battery management system (BMS) and a thermal management system (TMS) to form a complete battery pack.

In recent years, lithium iron phosphate (LFP) batteries have emerged as the dominant choice for the majority of electric vehicles (EVs) and stationary energy storage systems. This shift is driven by the chemistry's stability, reduced risk of fire, longer cycling lifetime, and lower cost. Technological advancements have significantly improved the specific energy of LFP batteries at the cell level, increasing from 120 Wh/kg in 2015 to approximately 200 Wh/kg in 2024 (BNEF 2024). This development has further cemented LFP's position as a standard for high-volume applications.

Meanwhile, alternative chemistries such as sodium-ion batteries are under active development to reduce reliance on lithium-based systems. While these alternatives show promise, lithium-ion technologies, particularly LFP, are projected to maintain the largest market share due to their proven performance and cost-effectiveness. The discussion on emerging battery chemistries is further explored in the following section.

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

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 (Table 4).

TABLE 4: Overview of battery supply chains

	Cathodes	Anodes	Electrolyte Solution	Separators
Leading Firms:	CNGR, BASF, JM, Umicore, Sumitomo, Nichia, Toda Kogyo, Beijing Easpring, Ningdo Jinhe	Hitachi Chemical, BTR, Nippon Carbon, Ningbo Shanshan, Human Shinzoom Technology, Jiangxi Zeto New Energy Tech	BASF, CapChem, GTHR, Tinci Materials Tech, Panax-Etec, Ningbo Shanshan	Furukawa Electric, UACJ, Nippon Denkai, Doosan, Asahi Kasei, Toray Tonen, SKI, Celgard, Senior Technology Material
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%

Source: Mohanty et al (2023)

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 the 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 the total global graphite production in 2022, producing a total of 850,000 tons (USGS 2023). Mozambique, Madagascar, and Brazil make up 28% of the 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 (Table 4). China currently hosts 75% of all battery cell manufacturing capacity and 90% of anode and electrolyte production (Bloomberg New Energy Finance 2022).

7. NON-LITHIUM ENERGY STORAGE TECHNOLOGIES

Promising emerging battery technologies that are potential alternatives to lithium-ion batteries include the following:

- **Sodium-ion batteries** – Similar in principle to lithium-ion batteries, replacing the lithium with sodium. These batteries have recently seen increasing energy densities and nascent commercial deployment. They may also be coupled with lithium-ion batteries to reduce the lithium quantity and battery cost per kWh.
- **Vanadium Redox Flow (VRF) batteries** – Better degradation properties and easier scalability but higher weights due to the aqueous electrolyte. Increased commercialization will likely depend on the potential scale of vanadium manufacturing.
- **Iron air batteries** – Operates on the principle of reversible rusting, utilizing common, low-cost materials, but are heavy, making them most suitable for grid-scale, stationary storage applications.

However, given the scale, maturity, and planned investments in Lithium-ion supply chains, it is unlikely that other technologies would catch up in the near future.

Table 5 summarizes some of the nascent non-Li-ion storage technologies

TABLE 5: Brief review of nascent storage technologies

Storage Tech	Type	2022 global unit cost ($/kWh)	2030 global unit cost ($/kWh)	BoS & development cost ($/kWh)	2022 LCOS (Rs./kWh)	2030 LCOS (Rs./kWh)	Typical cycle life	Technical calendar life	Round trip efficiency	Source(s)
Vanadium Redox Flow	Electro-chemical	284 (system)	237 (system)	95 (India)	14.7 (India)	12.9 (India)	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)	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)	5,000 cycles	<13.5 years	75%	(DOE 2019, Authors analysis)
Sodium-Ion	Electro-chemical	77 (cell)	40 (cell)	70 (India)	5.4 (India)	4.3 (India)	<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)	<6,000 cycles	n/a	83%	(Farsak and Kardas 2018, Authors' analysis)
Iron Air	Electro-chemical	20 (pack)	10 (pack)	200 (India)	3.5 (India)	2.4 (India)	<10,000 cycles	n/a	50%	(Form Energy 2023, Authors' analysis)
Gravitational Storage	Mechanical	380 (system)	350 (system)	n/a	12.7 (India)	11.5 (India)	n/a	~60 years	80%	(DOE 2022, Tong et al. 2022, Authors' analysis)
Compressed Air	Mechanical	150 (system)	123 (system)	n/a	17.7 (India)	17.7 (India)	n/a	60 years	52%	(DOE 2022, Vecchi et al. 2021, Authors' analysis)
Liquid Air	Mechanical	150 (system)	100 (system)	n/a	14.8 (India)	14.8 (India)	n/a	30 years	n/a	(DOE 2022, Vecchi et al. 2021, Authors' analysis)

8. POLICY AND REGULATORY FRAMEWORK FOR ENERGY STORAGE IN INDIA

As renewable energy (RE) penetration increases in India, energy storage systems (ESS) will play a vital role in balancing intermittent RE generation, enhancing grid stability and resiliency, and efficiently meeting peak demand. This study projects that by 2030, a total of 61 GW/218 GWh of ESS capacity will be required to cost-effectively support the 500 GW clean power goal. By 2032, this cost-effective storage need is expected to rise to 97 GW/362 GWh. This represents substantial growth from India's current energy storage capacity of approximately 6 GW (including pumped hydro), underscoring the need for robust policy and regulatory support to accelerate storage deployment at this scale.

In this section, we discuss the existing policy and regulatory framework for energy storage in India and recommend the next steps. India's energy storage sector has undergone a transformative evolution since 2019, driven by the imperative to integrate RE sources and maintain grid stability. This report examines the current policy landscape and presents strategic recommendations for future development, drawing from both international best practices and domestic market conditions (CEA, 2024).

8.1. EXISTING FRAMEWORK (2019-2024)

India's evolving energy storage policy framework underscores its commitment to enhancing grid flexibility and supporting renewable energy integration. Since 2019, a robust regulatory ecosystem has been crafted to support energy storage deployment through national initiatives around technical standards, legal frameworks, transmission charges, resource adequacy planning, market mechanisms, and financial incentives, as well as state-level initiatives. This framework has laid the foundation for the rapid expansion of energy storage capacity, bolstering system reliability and economic viability.

8.1.1. TECHNICAL STANDARDS AND LEGAL FRAMEWORK

The **Inclusion of ESS in Grid Connectivity Technical Standards** was introduced in February 2019 when the Central Electricity Authority (CEA) updated its regulations. Initially notified in 2007 and amended in 2013, 2019, and 2023, these standards ensure that Energy Storage Systems (ESS) can connect to the grid at 33 kV and above, streamlining integration and enhancing compatibility with existing infrastructure.

In a significant regulatory development, the MoP clarified the **Legal Status to ESS** on January 29, 2022. The order identifies ESS as an essential component of the power system under the Electricity Act of 2003, permitting ESS to function as a standalone or integrated element within generation, transmission, or distribution networks. The ESS can be operated by various entities, and standalone ESS projects can be licensed independently and granted connectivity under specific rules, encouraging broader ESS applications and ownership models.

In October 2022, the **Recognition of Energy Storage as Essential Infrastructure** placed ESS within the Harmonized Master List of Infrastructure subsectors, facilitating access to credit and concessional financing. This classification is extended to dense charging infrastructures and grid-scale ESS with capacities of 200 MWh or more, making ESS projects eligible for financial incentives provided they are not established on a merchant basis.

8.1.2. PROJECT DEVELOPMENT AND CONNECTION CHARGES

In June 2023, the CEA issued guidelines on **Timely Detailed Project Report (DPR) Concurrence for PSPs**. These new guidelines reduced the concurrence timeline from 90 days to 50 days, expediting approval processes for PSP projects and fostering efficient development.

The **Waiver of Inter-State Transmission System (ISTS) Charges** for solar, wind (onshore and offshore), and green hydrogen projects was mandated by the Ministry of Power (MoP) on November 23, 2021, with subsequent amendments in November 2021, December 2022, and May and June 2023. This waiver also applies to Hydro Pumped Storage Projects (PSP) and Battery Energy Storage Systems (BESS) commissioned up to June 30, 2025. Covering a period of 25 years for PSPs and 12 years for BESS, the waiver supports projects drawing at least 51% of their annual energy from solar or wind power.

8.1.3. RESOURCE ADEQUACY

The Central Electricity Authority (CEA) on 28th June 2023, has already established RA planning guidelines at both national and state levels, an important step forward, and has recently come up with state-wise RA reports with up to 5-year or 10-year RA projections. The CEA Resource Adequacy (RA) guidelines also outline a framework for incorporating energy storage systems (ESS) in RA planning. A draft of these guidelines has been released, and feedback has been requested from stakeholders. Several states have also notified Draft and Final RA Regulations. Madhya Pradesh (March 5, 2024), Punjab (March 15, 2024), Meghalaya (May 9, 2024), Arunachal Pradesh (May 14, 2024), Maharashtra (June 21, 2024), and Karnataka (September 23, 2024) have notified Final Regulations while Sikkim (March 14, 2024), Jharkhand (May 9, 2024), Odisha (June 4, 2024), Tamil Nadu (June 13, 2024), Uttar Pradesh (July 3, 2024), Haryana (July 28, 2024), Chhattisgarh (September 04, 2024) and Assam (September 6, 2024) have notified Draft Regulations.

8.1.4. MARKET DEVELOPMENT AND BUSINESS MODELS

The **Bidding Guidelines for Round-the-Clock (RTC) Renewable Energy (RE) Supply** were issued in July 2020 and further amended in November 2020, February 2021, February 2022, and August 2022. These guidelines focus on tariff-based competitive bidding, encouraging storage usage to balance renewable generation, supporting continuous power supply, and enhancing grid stability. The establishment of ESS has been promoted to facilitate efficient grid management and aid in the transition to renewable energy sources.

With the **RE Must Run Rules** issued on October 22, 2021, the Electricity Rules of 2021 ensure that power from must-run RE plants remains uncurtailed except when technical or grid security concerns arise. This provision protects renewable generation from unnecessary interruptions, encouraging ESS deployment to reduce curtailment and avoid associated penalties, thus supporting continuous RE availability on the grid.

To address future storage needs, the MoP set out a **Renewable Purchase Obligation (RPO) and Energy Storage Obligation (ESO) Trajectory** in July 2022, establishing a roadmap through 2029-30. This trajectory mandates a gradual increase in ESO requirements from 1% of total electricity consumption in FY 2023-24 to 4% by 2029-30, with an annual increment of 0.5%. The obligation requires that at least 85% of energy stored in ESS, on an annual basis, is procured from renewable sources, underscoring the emphasis on renewable-backed storage capacity.

The introduction of the **High Price Day Ahead Market (HP-DAM)** in March 2023 offers ESS developers new avenues by enabling participation in high-cost generation sales. The MoP's March 9 order leverages tariff differences between peak and off-peak periods to enhance the profitability and feasibility of ESS operations, creating opportunities for ESS projects to capitalize on peak demand.

In June 2023, MoP released **Guidelines for Tariff-Based Competitive Bidding Process for Procurement of FDRE from Grid-Connected RE Power Projects with ESS**. These guidelines, marking a shift toward "demand-following" storage solutions, led to thirteen firm and dispatchable RE (FDRE) tenders in India and positioned ESS as a central feature of future tender design. This policy prioritizes RE and ESS integration, aligning project objectives with grid needs.

Another 2023 initiative, **Mission on Advance and High-Impact Research (MAHIR),** established by MoP and MNRE on June 7, aims to advance emerging energy technologies. This five-year mission (2023-28) seeks to identify relevant innovations, foster domestic technology development, and support Indian startups through collective brainstorming, pilot projects, and technology transfers.

The **MoP Framework Promoting ESS**, introduced in August 2023, established a National Framework for ESS, which includes transmission waivers, ESO, production-linked incentives for Advanced Chemistry Cells (ACC), and concessional green finance for ESS projects. This framework provides a structured approach to scaling ESS across the country.

The **Ancillary Services from ESS under Central Electricity Regulatory Commission (CERC) Regulations** were introduced on January 31, 2022. These regulations allow ESS to participate in providing Secondary and Tertiary Reserve Ancillary Services, creating additional revenue streams for ESS operators and promoting investment. The system rewards providers based on performance, with incentive rates scaling from 0 to 50 paise per kWh for performance thresholds from 20% up to 95% and above.

The **Approach Paper on CERC Multi-Year Tariff (MYT) Regulations for 2024-2029** proposes increased incentives for dam/reservoir-based PSPs, which are seen as pivotal for peak load management. The draft suggests rewarding these plants for energy supplied during peak periods, acknowledging their critical role in balancing demand and stabilizing the grid.

The **Central Electricity Regulatory Commission (CERC)**, on May 16, 2024, issued an order under Petition No. 249/MP/2023, **setting a procedural framework for the scheduling, metering, accounting, and settlement of a pilot BESS project**. SECI had conducted bidding for this 500 MW/1000 MWh BESS at the Fatehgarh-III Sub-Station in Rajasthan, with JSW Renew Energy Five Limited (JSREFL) emerging as the winning bidder. The monthly capacity charges were set at ₹10.83 lakh per MW at the delivery point. Notably, 150 MW/300 MWh (30%) of the BESS capacity is allocated for grid ancillary services. The National Load Dispatch Centre (NLDC) developed procedures specific to scheduling, metering, and settlement for this portion, intended for frequency control services under CERC's Ancillary Services Regulations, 2022. This order sets a precedent for integrating BESS into grid operations and providing essential ancillary services. On July 17, 2024, CERC published a gazette notification under petition no. RA-14026(11)/1/2023-CERC, outlining the tariff determination for energy storage. It highlights that the tariff for renewable energy projects integrated with storage will be structured either as a composite tariff or a time-of-day-based differential tariff.

The Ministry of Power has a **discussion paper addressing the use of connectivity for solar projects by BESS during non-solar hours**. This paper explores how BESS can play a crucial role in optimizing energy distribution and improving grid stability, particularly during periods when renewable energy generation is low or unavailable, such as after sunset or during cloudy days. The key points highlighted in the paper include: (a) **Leveraging Storage for Off-Peak Hours**: BESS can store excess energy generated during solar hours and discharge it during non-solar hours, effectively filling the gap between demand and renewable energy generation. This improves grid reliability by balancing the intermittent nature of solar power and ensuring a continuous and stable energy supply, even during periods without sunlight. (b) **Enhanced Grid Flexibility and Reliability**: By enabling the use of stored energy during non-solar hours, BESS enhances grid flexibility and reduces the reliance on fossil fuel-based peaking plants. This not only supports decarbonization efforts but also ensures that energy supply remains uninterrupted, supporting grid operators in maintaining voltage and frequency stability. (c) **Facilitating Energy Trading**: The paper emphasizes that BESS can support energy trading during non-solar hours by storing excess energy generated during peak solar periods and releasing it when electricity demand rises, allowing utilities and grid operators to optimize energy flows and market participation. (d) **Regulatory and Technical Support**: The paper suggests that regulatory frameworks should be adjusted to facilitate the integration of BESS for non-solar hours, including ensuring that storage systems are adequately credited for their contributions during these times. It also advocates for the development of technical standards that enable efficient and reliable operation of BESS in conjunction with grid systems, particularly focusing on its use during non-solar hours.

8.1.5. VIABILITY GAP FUNDING

In September 2023, the Union Cabinet approved **Viability Gap Funding (VGF) for BESS**, addressing initial cost barriers by covering up to 40% of project capital costs for 4000 MWh of BESS projects across the country. The program is expected to run through FY 2025-26 with an annual budgetary support of Rs 37.6 billion ($450 million). The program requires the project awards to follow tariff-based competitive bidding with a contract period of 10-12 years and commissioning timelines between 18 to 24 months. The number of cycles are expected to be 572 per year, implying double cycle operation for about 180-200 days and single cycle operation for the remaining days. In October 2024, NTPC Vidyut Vyapar Nigam (NVVN) Ltd conducted the first successful bidding under the VGF program for a standalone battery energy storage capacity of 500 MW/ 1000 MWh, with average winning bid of INR 2.37 lakh/MW/month, which is 35-40% reduction over GUVNL and SECI bids on standalone storage just a few months ago.

8.1.6. STATE LEVEL INITIATIVES

In December 2022, Andhra Pradesh implemented a **PSP Promotion Policy** to exploit the state's 33 GW PSP potential. This policy supports national Renewable Purchase Obligations (RPOs), encourages private investment, and promotes PSP projects for peak power management and economic growth.

In December 2023, the Maharashtra government introduced the **Policy for Development of Pumped Storage Projects (PSPs)**, aiming to drive large-scale energy storage in the state for grid reliability and safety. This policy seeks to develop a Mega Watt (MW)-level ESS through PSPs, enhance grid operation, and support the co-location of Pumped Hydro-Solar Hybrid Power Projects, optimizing land use with Integrated Development Centers (IDCs) and power evacuation infrastructure. Additionally, it promotes PSP projects that facilitate inter-basin water transfers, aiming to create a favorable environment for private investment in PSPs. The policy provides a comprehensive framework to guide effective implementation, fostering growth and investment in Maharashtra's storage landscape.

The **Maharashtra Electricity Regulatory Commission (MERC) Renewable Energy Tariff Regulations 2024**, published on August 19, 2024, introduced a multi-year framework that, for the first time, establishes a methodology for calculating tariffs for ESS. This regulation, with a control period from April 1, 2025, to March 31, 2030, outlines detailed guidelines for determining tariffs for Battery Energy Storage Systems (BESS) and Pumped Storage Hydro Plants, covering capital costs and operations and maintenance expenses. The regulations mandate a minimum round-trip efficiency of 75% per monthly operating period and a normative annual availability of 95% for BESS, with a Return on Equity (RoE) of 18% post-tax for standalone BESS.

In Delhi, the **Delhi Electricity Regulatory Commission (DERC)** approved a 20 MW/40 MWh standalone BESS project on May 1, 2024, following an initial in-principle approval granted on July 26, 2023. This project, to be installed at the BRPL Grid Sub-Station, will serve as an energy arbitrage asset. DERC adopted a single-part tariff structure, setting capacity charges at ₹57,59,610 per MW per year. Importantly, any financial gains from BESS operations will directly benefit Delhi consumers through reduced Power Purchase Costs, marking a consumer-friendly approach to energy storage investment.

On September 26, 2024, the **Maharashtra Electricity Regulatory Commission (MERC)** approved the procurement of 1000 MW of energy storage from pumped hydro storage (PHS) projects in Maharashtra, with an additional greenshoe option of 2000 MW, allowing for potential expansion. The bid results, as outlined in MERC's order, provide a benchmark for competitive energy storage costs in the region. For projects designed to discharge up to 8 hours daily, with a maximum continuous discharge of 5 hours—enabling two cycles per day—the levelized cost of storage is estimated at ₹3.2 per kWh. This pricing is competitive when compared with recent Battery Energy Storage System (BESS) auction results, offering a cost-effective solution for long-term storage over a PHS project lifespan of 40 years.

8.2. KEY STRATEGIC RECOMMENDATIONS

As described in the previous section, recent national and state government policies have begun to lay a foundation that will support ESS deployment and its integration into RA planning and procurement, electricity markets, and system operations. Building on that foundation, this section recommends key next steps for ESS policies across six areas, including: (1) solar and co-located storage initiatives, (2) RA planning and procurement strategies, (3) markets and value stacking, (4) long-term policy frameworks and ESO implementation, (5) interconnection streamlining and data sharing, and (6) domestic manufacturing policy. Together, these strategies can foster a robust energy storage ecosystem that can support India's renewable energy ambitions, strengthen energy security, and advance the country's transition to a low-carbon grid.

8.2.1. LARGE-SCALE SOLAR + STORAGE INITIATIVES, INCLUDING CO-LOCATION MANDATES

As highlighted in this and our previous study, developing 15–20 GW of energy storage capacity within the next 2–3 years will be essential for India to prevent peak power shortages by 2026–27. A cost-effective approach to rapidly adding this storage capacity is through co-location with both existing and new solar projects. Co-locating ESS with solar installations can generate significant balance-of-system (BOS) cost savings, reducing storage capital costs by 15–20%. An effective strategy to facilitate this would be to include a co-located storage requirement in certain upcoming solar auctions.

- **Adding ESS to Existing Solar Projects**

Integrating energy storage systems (ESS) with existing grid-connected renewable energy (RE) projects, particularly solar, would significantly enhance the utilization of interconnection and transmission infrastructure. With over 90 GW of installed solar capacity and nearly 50 GW under construction, MOP and MNRE should prioritize adding 15-20 GW of energy storage at these solar sites without the need for additional transmission infrastructure. Recent SECI auctions for co-located solar and storage projects have demonstrated that this integration can be achieved with a storage adder of approximately Rs 0.8/kWh. Co-locating ESS at existing solar sites would also allow for additional solar capacity to be deployed at the same locations, maximizing grid infrastructure efficiency.

However, to fully capture these benefits, regulatory challenges around dispatch, operations, and existing Power Purchase Agreements (PPAs) must be addressed. The Ministry of Power (MoP) has initiated discussions on regulatory adjustments, indicating potential support for ESS integration with existing solar assets.

The "must-run" status of RE can pose operational challenges for effectively utilizing co-located storage assets. This issue could be addressed by adopting conditional "must-run" policies, for example by treating dispatch during non-solar hours differently. Additionally, if storage enables more RE capacity at the same interconnection point, limited RE curtailment could be allowed during periods of congestion or oversupply, accompanied by compensation mechanisms to incentivize balanced operations. Such an approach would promote optimal ESS co-location, prioritizing storage to absorb surplus generation and ensuring efficient resource utilization during peak generation periods.

- **Mandate New Solar Auctions to Include 20% Co-located Energy Storage for Peak Supply**

To meet evening peak demand effectively, India could launch annual auctions targeting 15–20 GW of solar power paired with 5–10 GW (or 20–40 GWh) of storage each year, with a cost target of Rs 3/kWh by 2027. To ensure this storage capacity is built, MNRE / MOP should mandate new solar auctions over the next 3 years to include co-located ESS, covering approximately 20% of daily solar generation. For instance, a 100 MW solar project could pair with a 30-50 MW, 4-hour ESS, providing affordable peak power at Rs 3 – 3.5/kWh, as demonstrated by SECI's recent solar + storage auctions.

- **Expanding Viability Gap Funding (VGF) to Accelerate Solar + Storage Projects**

Expanding the Viability Gap Funding (VGF) scheme to solar + storage projects would accelerate RE and storage deployment, potentially enabling an additional 50–100 GW of solar and 16–32 GW of storage capacity by 2027. By broadening VGF support, India could facilitate large-scale solar + storage projects to ensure grid reliability, particularly during evening peak demand.

8.2.2. RA PLANNING AND PROCUREMENT STRATEGIES

Standalone and co-located ESS can play an important role in meeting RA requirements under India's emerging RA framework. Going forward, state-level RA frameworks need to be closely aligned with long-term planning and resource procurement processes to support cohesive implementation.

To support a robust RA framework that fully integrates ESS, regulators should prioritize establishing clear methodologies for evaluating storage value streams, determining capacity contributions, and creating frameworks for hybrid RE and storage project planning. Key recommendations for RA planning and procurement for ESS can be summarized as follows:

- **Define Methodologies for Storage Value Streams**: Regulators should create clear methodologies to assess the full range of ESS value streams, including frequency regulation, load shifting, peak demand support, and backup power. Standardized evaluation methods can help quantify and prioritize these benefits, ensuring a consistent approach for planning and investment in storage technologies. Such standardized evaluation also aids in capturing the strategic value that ESS brings to grid stability and peak demand management.

- **Comprehensive Guidelines for Storage Capacity Requirements and RA Credits**: Building on guidance from CEA, regulators need to develop comprehensive guidelines to determine ESS capacity requirements that align with RA obligations. This would involve a structured methodology to calculate capacity contribution (CC) and assign RA credits, optimizing ESS for peak demand and grid reliability. Recommendations emphasize using effective load carrying capability (ELCC) as a primary metric to quantify ESS's reliability benefits. ELCC reflects an ESS's ability to meet peak demand by accounting for variables like discharge duration, availability probability during peak periods, and cycling capacity.

- **Duration-Based Capacity Credits**: Duration-specific capacity credits are crucial, recognizing that ESS with longer discharge durations offers more substantial reliability benefits. For instance, a 4-hour battery would receive a higher RA credit than a 2-hour battery, directly reflecting its extended availability during peak load periods and providing regulators with a simple, duration-based crediting approach.

- **Hybrid Project Crediting Framework**: Considering the synergies between renewable energy and storage, regulators should establish frameworks that support hybrid project development. Hybrid crediting frameworks can enable these projects to earn combined RA credits, factoring in the intermittent nature of renewable sources and the firming capability provided by storage. This approach maximizes RA contributions and encourages integrated project planning for both renewables and storage.

- **Seasonal and Regional Adjustments**: RA guidelines should recommend adjustments in capacity credits based on seasonal variations, particularly in regions with high variability in demand. Seasonal adjustments ensure that ESS is credited appropriately during critical reliability periods, reflecting its ability to support grid demands in line with seasonal peaks.

- **Performance-Based and Probabilistic Adjustments**: Incorporating a performance-based adjustment mechanism helps maintain alignment between assigned RA credits and real-world ESS performance. This could include periodic reviews of capacity credits based on availability during peak hours, response times, and performance data. Probabilistic modeling, which considers the likelihood of ESS being available during peak or critical events, offers a nuanced calculation of its RA contribution, reflecting the real-world reliability ESS can provide to the grid.

In summary, these recommendations provide a structured pathway to fully integrate ESS into the RA framework, enhancing grid stability and resilience alongside growing renewable deployment. By adopting these guidelines, regulators can unlock the full potential of ESS, supporting RA while aligning with long-term energy transition goals.

8.2.3. MARKETS AND VALUE STACKING

To fully capitalize on the potential of energy storage, adjustments to electricity market structures are needed. These modifications should allow energy storage to participate broadly and receive fair compensation for its range of services, including energy arbitrage, RA capacity provision, and ancillary services (AS). Such adjustments will ensure that storage can compete on an equitable basis with other resources in the wholesale electricity market.

Allowing storage to “stack” revenues from different services – energy arbitrage revenues, RA payments, and AS revenues – requires rules or contracts that clarify when an ESS must provide AS or be available to provide RA instead of earning revenues through energy arbitrage.

Continuing to develop efficient AS markets and markets for managing congestion is also important for realizing the potential of energy storage. Because of storage’s fast response and flexibility, it is well-suited to supply frequency regulation reserves and for managing real-time imbalances, for instance in managing DSM charges. Because BESS can be flexibly located on the transmission system, it is well-suited for reducing transmission congestion as well.

With the full adoption of Market-Based Economic Dispatch (MBED), interstate transmission demands are expected to rise significantly, necessitating close coordination among system operations, dispatch, and market settlement processes. ESS, particularly when directly dispatched by the National Load Dispatch Center, will play a critical role in supporting this transition and enhancing MBED implementation.

8.2.4. TECHNOLOGY-NEUTRAL ENERGY STORAGE OBLIGATIONS

Uncertain regulatory environments and shifting policies can deter long-term investment in ESS and RE. A stable, long-term policy framework, incorporating clear targets and performance-based incentives, would provide the investor confidence needed for ESS and RE growth. In 2022, the Ministry of Power has already issued a technology-neutral Energy Storage Obligation (ESO) aimed at enhancing grid reliability and supporting clean energy integration. Many states – Assam, Bihar, Chhattisgarh, Haryana, Himachal Pradesh, Madhya Pradesh, Maharashtra, Mizoram, Rajasthan and Tamil Nadu – have issued their respective ESO targets, which align with the ESO targets issued by MoP. This mandate requires that 1% of total electricity consumption in FY 2023-24 be sourced from storage resources, with a planned increase to 4% by FY 2030, translating to a national storage requirement of

200-250 GWh, assuming daily cycling. To maximize the effectiveness and impact of this mandate, it is recommended that all state regulators expedite the adoption of the ESO into their regulations, with monitoring and compliance oversight by CERC in conjunction with FOR and the SERCs in order to ensure a coordinated and unified approach.

To meet the ESO requirements effectively, it is recommended that states consider a mix of storage solutions, each tailored to their unique operational needs. Potential approaches include:

- **Storage installations to assist system operation**: Deploy storage systems in alignment with CERC grid code regulations. This approach allows system operators to directly manage grid stability and support real-time balancing, which is essential for integrating variable renewable energy sources.

- **Standalone storage solutions procured by utilities directly or through SECI**: Encouraging utilities or SECI to procure standalone storage resources offers flexibility. These resources can be optimized to address peak demand, manage load fluctuations, and ensure a reliable power supply during off-peak hours.

- **Storage co-located with renewable generation**: As explained previously, prioritizing co-locating storage with renewable energy installations enables a cost-effective and efficient storage solution and is particularly advantageous for solar installations.

These diverse solutions provide pathways for states to meet the ESO while adapting to regional demand patterns, renewable resource availability, and infrastructure capacities.

8.2.5. STREAMLINING INTERCONNECTION AND DATA SHARING STANDARDS FOR EFFICIENT STORAGE DEPLOYMENT

Outdated interconnection standards often delay ESS and RE projects, creating obstacles to timely integration. Simplifying interconnection processes and supporting distributed ESS aggregation, especially for smaller installations, would improve grid access. Virtual power plants (VPPs), which pool distributed RE and storage assets, could further optimize grid reliability, enabling seamless coordination of smaller, distributed systems.

Finally, real-time data sharing on resource availability and grid conditions is crucial for effective ESS deployment, yet current regulatory frameworks lack data-sharing mandates. Standardized communication protocols, coupled with investments in Advanced Metering Infrastructure (AMI), would enhance situational awareness and improve decision-making capabilities across the grid.

8.2.6. DOMESTIC MANUFACTURING AND SUPPLY CHAINS

Developing sustainable supply chains and competitive domestic manufacturing for energy storage is critical for achieving India's renewable energy and energy security goals. It also presents an opportunity for the Indian industry to develop as a key manufacturing hub and create jobs for the future in order to maintain global competitiveness. The expansion of existing schemes, such as the Production-Linked Incentive (PLI) program, specifically targeted at advanced chemistry cells (ACC) as well as R&D, will encourage domestic production of lithium-ion batteries, solid-state batteries, and other emerging storage technologies. Moreover, making strategic investments to secure key supply chains (such as strategic lithium or rare earth reserves with partner countries) would be critical for scaling India's clean manufacturing industry. Additionally, establishing manufacturing hubs in key regions with access to raw materials, skilled labor, and robust infrastructure can create a well-integrated supply chain.

While India has made significant progress in the domestic manufacturing of clean technologies, there are concerns about the availability and supply security of lithium and other critical minerals used in them, especially in batteries. To reduce dependence on imported materials, policies promoting indigenous sourcing and processing of key minerals—such as lithium —are essential. India has already made significant lithium discoveries in several states such as Jammu and Kashmir, Karnataka, Rajasthan etc. Incentives to develop these sustainable and domestic raw material supply chains will help build resilience against global supply fluctuations and drive cost efficiencies in domestic battery production. Studies have shown that large portions (up to 95%) of lithium in spent batteries can be recycled and reused. This implies that if the lithium in retiring EV and grid batteries in India is recycled up to its full potential (95%), it could meet between a quarter and a half of the annual lithium demand by 2040 or so. Therefore, the creation of a national battery recycling program is essential for supporting a sustainable supply chain as well as a circular economy. This program should provide guidelines for battery lifecycle management, from collection to recycling, to address end-of-life concerns and recover valuable materials. By repurposing materials from used batteries, India can not only minimize raw material imports but also reduce waste.

By addressing planning, market adjustments, storage value chains, large-scale solar + storage initiatives, and domestic manufacturing, these initiatives would continue to build an enabling environment for energy storage. Together, they support system reliability, reinforce India's renewable energy goals, and accelerate the transition to an economical, clean, and resilient energy grid. Through this multi-faceted approach, India is laying the foundation for a robust energy storage ecosystem capable of supporting renewable integration and meeting future energy demands.

9. KEY CAVEATS

Although we assess an operationally feasible least-cost pathway for India's power system using weather-synchronized load and generation data, further work is needed to advance our understanding of other facets of a power system with high RE penetration.

First, this report primarily focuses on renewable-specific technology pathways and does not explore the full portfolio of clean technologies that could contribute to the future electricity supply. Also, the RPO fulfillment by utilities has been assumed to be met by resources located within the same state, except in states that do not have enough RE potential such as Delhi. Second, issues such as loss of load probability, system inertia, and alternating-current transmission flows need further assessment. Options to address these issues have been identified elsewhere (for example, Denholm, 2020). Third, our assessment does not fully address the operational impacts of day-ahead / intra-day forecast errors in RE and load. However, several studies have shown that with state of the art forecasting techniques, the impact of such forecast errors appears to be small (for example, Hodge, 2015; Martinez-Anido, 2016).

Although this analysis does not attempt a full power-system reliability assessment, we perform scenario and sensitivity analysis to ensure that demand is met in all periods, including during extreme weather events and periods of low renewable energy generation. This modeling approach provides confidence that integrating over 500GW of clean power into the grid is technically feasible and economically desirable by FY 2030. This is critical, because power sector decarbonization can be the catalyst for decarbonization across all economic sectors via electrification of vehicles, buildings, and industry. Owing to the global nature of renewable energy and battery markets, our study indicates the possibility that cost-effective decarbonization can be a near-term reality.

Finally, although this report describes the system characteristics needed to accommodate high levels of renewable generation, it does not address the institutional, market, and regulatory changes that are needed to facilitate such a transformation. Further details on the key assumptions and results can be found in the appendices.

APPENDIX 1: DETAILED MODELING ASSUMPTIONS

We conducted optimal capacity expansion and power plant level hourly economic dispatch using PLEXOS, with transmission network represented at the interstate level as shown in the following figures.

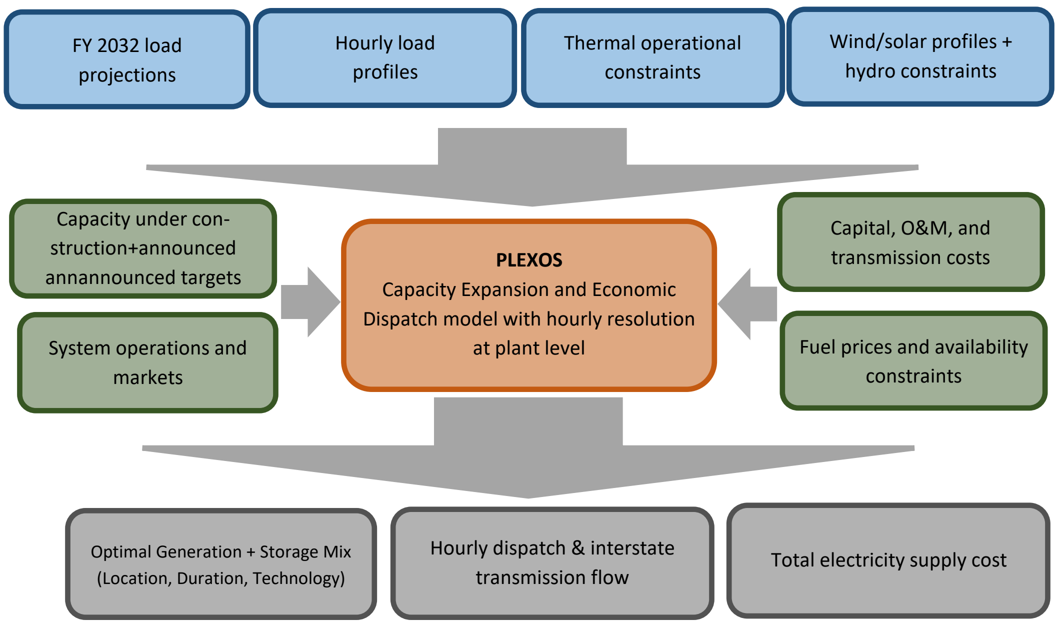


FIGURE 36: Overview of the modeling framework

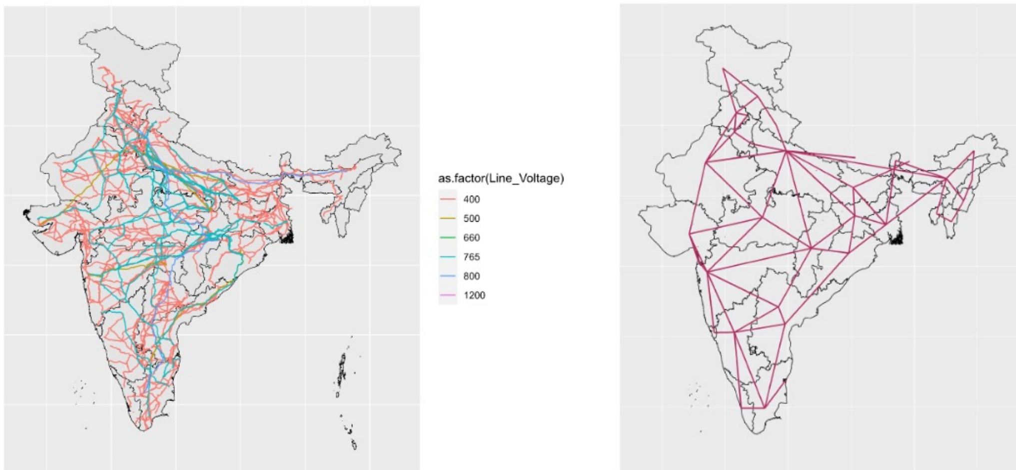


FIGURE 37: Actual transmission network and representation with a simplified interstate network (36 nodes)

CAPACITY UNDER CONSTRUCTION

51 GW of under-construction firm capacity, including 25 GW of coal, 17 GW of hydro and ~8.7 GW of nuclear is included in the model as shown in the following table.

This capacity is actively under construction and does not include capacity that is only in the planning phase.

	Coal	Hydro	Nuclear	Total
FY 2025	14040	5228	0	**19268**
FY 2026	2400	4550	1400	**8350**
FY 2027	2780	2530	1400	**6710**
FY 2028	2260	510	4000	**6770**
FY 2029	2400	300	500	**3200**
FY 2030	1600	0	1400	**3000**
FY 2031	0	0	0	**0**
FY 2032	0	3780	0	**3780**
Total	**25480**	**16898**	**8700**	**51078**

RPO TRAJECTORY AND NATIONAL STORAGE GOAL

Renewable Purchase Obligation is shown in the following table. They are expressed as % National of the total energy demand. In states that have passed RPO regulations, their RPO targets have also been modeled.

FY	Wind *	Other RE (including Solar)	Large Hydro **
2022-23	0.8%	23.4%	0.4%
2023-24	1.6%	24.8%	0.7%
2024-25	2.5%	26.4%	1.1%
2025-26	3.4%	28.2%	1.5%
2026-27	4.3%	29.9%	1.8%
2027-28	5.2%	31.4%	2.2%
2028-29	6.2%	32.7%	2.5%
2029-30	6.9%	33.6%	2.8%

* From projects commissioned after March 31, 2022
** from projects commissioned after March 31, 2019
Source: https://powermin.gov.in/sites/default/files/Notification_Regarding_Renewable_Purchase_Obligation_RPO

National Energy Storage Goals are shown in the following table. They are expressed as % of total energy demand. In states that have set state level storage goals/targets, their storage targets have also been modeled.

FY	Energy Storage as % of demand (technology agnostic)
2022-23	
2023-24	1.0%
2024-25	1.5%
2025-26	2.0%
2026-27	2.5%
2027-28	3.0%
2028-29	3.5%
2029-30	4.0%

Source: https://powermin.gov.in/sites/default/files/Renewable_Purchase_Obligation_and_Energy_Storage_Obligation_Trajectory_till_2029_30

VARIABLE COST OF EXISTING COAL POWER PLANTS IN INDIA

Each point in the following figure shows the variable cost of an existing coal power plant in the country (210 GW, 250 power plants).

138 GW of coal capacity (177 power plants) has a variable cost of more than Rs. 2.5/kWh.

44 GW of coal capacity (70 power plants) has a variable cost of more than Rs. 4/kWh.

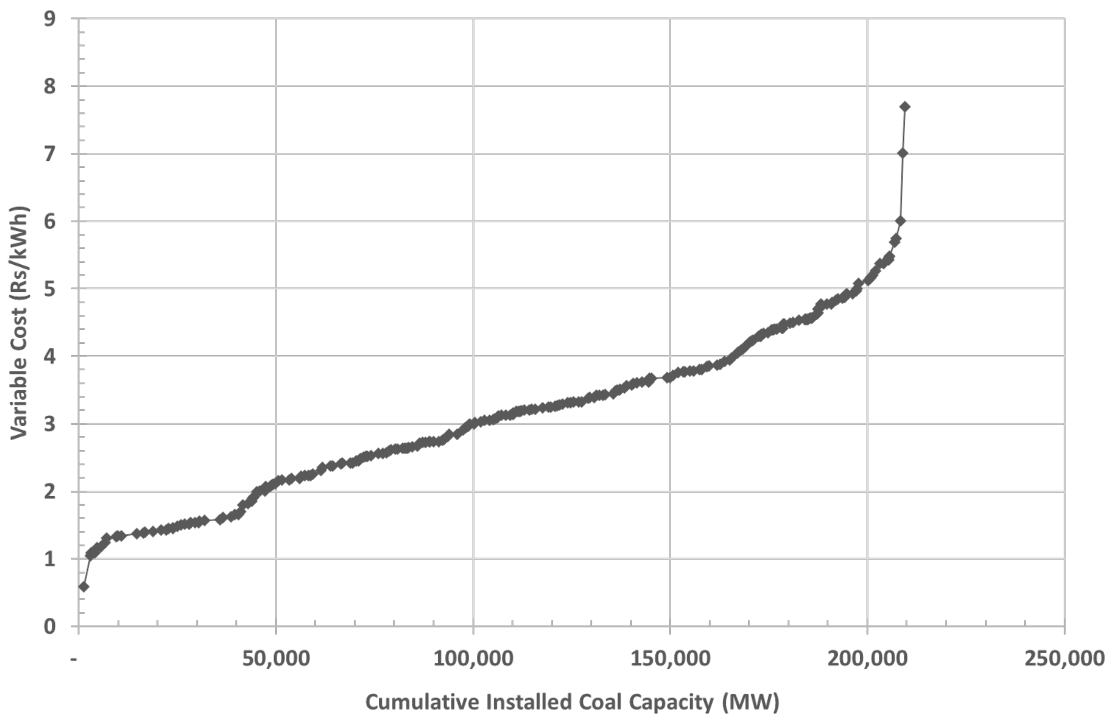


FIGURE 38: Variable Cost of Existing Coal Power Plants in India

KEY COST ASSUMPTIONS: ENERGY STORAGE

We develop three scenarios for battery storage capex and two scenarios for pumped hydro capex

Battery Storage Capex

	4-hour Standalone ($/kWh, 2023 real)*		
	Base	**High**	**NEP**
2024	225	257	244
2027	181	241	201
2030	145	227	169
2032	135	201	169

*Includes cost of battery pack replacement in year 13

Roundtrip efficiency = 90%
Depth of Discharge = 90%
Availability = 95%
Project economic life = 25 years
Battery pack life = 5,000 cycles / 12 years, whichever is shorter

Pumped Hydro Storage Capex

	Pumped Storage (Rs. Cr./MW, 2023 real)	
	Low	**Base**
2024	4.1	6.6
2027	4.1	6.6
2030	4.1	6.6
2032	4.1	6.6

Roundtrip efficiency = 80%
Depth of Discharge = 95%
Availability = 95%
Project economic life = 25 years

Pumped hydro is a mature technology and therefore its cost is not assumed to change over time in real terms. Also, pumped hydro capital costs are highly site-specific.

BUILDUP OF BATTERY STORAGE CAPITAL COST (25-YR EQUIVALENT)

Base case BESS capital cost

	Unit	Standalone 2023					
		2-hrs	4-hrs	6-hrs	8-hrs	12-hrs	24-hrs
Battery Pack Cost	$/kWh	139	139	139	139	139	139
Structural BOS	$/kWh	3	3	3	3	3	3
Electrical BOS	$/kW	150	150	150	150	150	150
EPC	$/kWh	20	20	20	20	20	20
Battery Pack Replacement in year 13 (discounted NPV)	$/kWh	22	22	22	22	22	22
Total Capex	$/kWh	259	222	209	203	197	191
Depth of Discharge	%	90%	90%	90%	90%	90%	90%
Total Capex (adjusted for DoD)	**$/kWh**	**280**	**242**	**230**	**224**	**217**	**211**

	Standalone 2030					
	2-hrs	4-hrs	6-hrs	8-hrs	12-hrs	24-hrs
Battery Pack Cost	64	64	64	64	64	64
Structural BOS	3	3	3	3	3	3
Electrical BOS	126	126	126	126	126	126
EPC	17	17	17	17	17	17
Battery Pack Replacement in year 13 (discounted NPV)	18	18	18	18	18	18
Total Capex	165	134	123	118	113	107
Depth of Discharge	90%	90%	90%	90%	90%	90%
Total Capex (adjusted for DoD)	**176**	**145**	**134**	**129**	**124**	**119**

	Standalone 2035					
	2-hrs	4-hrs	6-hrs	8-hrs	12-hrs	24-hrs
Battery Pack Cost	50	50	50	50	50	50
Structural BOS	3	3	3	3	3	3
Electrical BOS	105	105	105	105	105	105
EPC	14	14	14	14	14	14
Battery Pack Replacement in year 13 (discounted NPV)	18	18	18	18	18	18
Total Capex	138	112	103	99	94	90
Depth of Discharge	90%	90%	90%	90%	90%	90%
Total Capex (adjusted for DoD)	**148**	**121**	**112**	**108**	**104**	**99**

All cost numbers in real 2023 currency

High case BESS capital cost

	Unit	Standalone 2023					
		2-hrs	4-hrs	6-hrs	8-hrs	12-hrs	24-hrs
Battery Pack Cost	$/kWh	139	139	139	139	139	139
Structural BOS	$/kWh	3	3	3	3	3	3
Electrical BOS	$/kW	180	180	180	180	180	180
EPC	$/kWh	25	25	25	25	25	25
Battery Pack Replacement in year 13 (discounted NPV)	$/kWh	28	28	28	28	28	28
Total Capex	$/kWh	285	240	225	218	210	203
Depth of Discharge	%	90%	90%	90%	90%	90%	90%
Total Capex (adjusted for DoD)	$/kWh	307	262	247	239	232	224

	Standalone 2030					
	2-hrs	4-hrs	6-hrs	8-hrs	12-hrs	24-hrs
Battery Pack Cost	116	116	116	116	116	116
Structural BOS	3	3	3	3	3	3
Electrical BOS	180	180	180	180	180	180
EPC	25	25	25	25	25	25
Battery Pack Replacement in year 13 (discounted NPV)	20	20	20	20	20	20
Total Capex	254	209	194	186	179	171
Depth of Discharge	90%	90%	90%	90%	90%	90%
Total Capex (adjusted for DoD)	272	227	212	205	197	190

	Standalone 2035					
	2-hrs	4-hrs	6-hrs	8-hrs	12-hrs	24-hrs
Battery Pack Cost	64	64	64	64	64	64
Structural BOS	3	3	3	3	3	3
Electrical BOS	180	180	180	180	180	180
EPC	25	25	25	25	25	25
Battery Pack Replacement in year 13 (discounted NPV)	18	18	18	18	18	18
Total Capex	200	155	140	133	125	118
Depth of Discharge	90%	90%	90%	90%	90%	90%
Total Capex (adjusted for DoD)	213	168	153	145	138	130

KEY COST ASSUMPTIONS: GENERATION

Solar and Wind

	LCOE (Rs./kWh, 2023 real)	
	Solar (@ AC capacity factor = 23%, Inverter loading ratio = 1.3)	**Wind (@ capacity factor = 30%, Class 3 Turbine @ 100m)**
2024	2.4	3.2
2027	2.2	3.1
2030	2	3
2032	1.9	2.9

Coal and Gas

	Capital Cost (Rs. Cr/MW, 2023 real)	
	Coal	**Gas**
2024	9.8	7.4
2030	9.8	7.4

	Fixed O&M Cost (Rs Lakh/MW-yr, 2023 real)	
	Coal	**Gas**
2024	18.8	11.3
2030	18.8	11.3

Note that these are real costs, which implies that in nominal terms these costs would be largely flat or slightly increasing.

WIND AND SOLAR RESOURCE POTENTIAL AND HOURLY GENERATION PROFILE

We deploy three interdependent algorithms (see figure) for assessing the solar and wind resource potential and hourly generation profile in India:

1. **Resource potential assessment**

2. **Clustering**

3. **Hourly generation profiles**

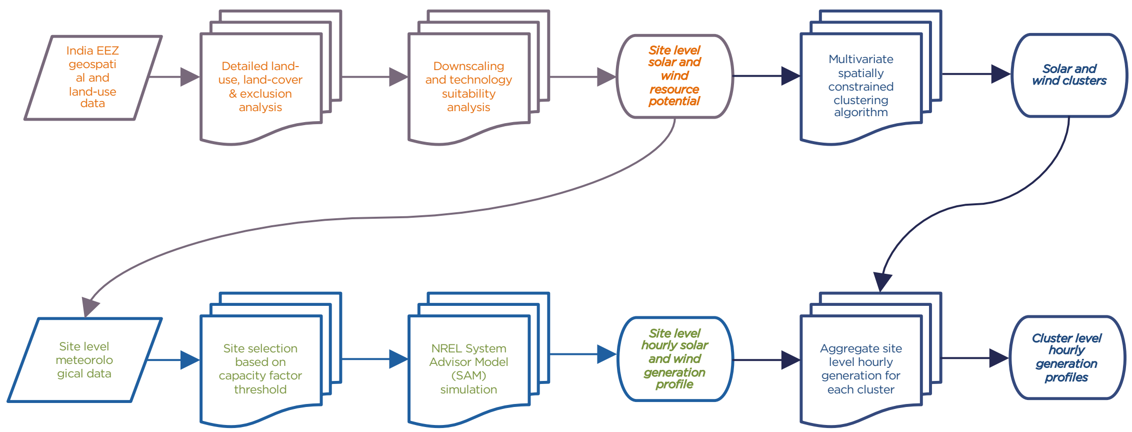


FIGURE 39: Overview of Methodology for Assessing Solar and Wind Potential and Hourly Generation Profile

OPERATIONAL ASSUMPTIONS

- **Reserves**

For capacity expansion, we assume a 5% planning reserve margin and 3% spinning reserves.

For dispatch, we model three categories of reserves (regulation, spinning, and load following). Reserve requirement quantities are functions of load and VRE share and vary by product. Requirement levels are calculated based on methods from the Sergi et al (2021) and Lew et al (2013). Reserves are effectively modeled as "up" reserves.

	Load (% of Load)	Wind (% of Generation)	Solar	Response Time (minutes)
Spinning	3%			10
Regulation (only modeled in dispatch)	1%	0.50%	0.30%	5
Load Following (only modeled in dispatch)		10%	4%	60

- **Power plant operational parameters**

	Coal (new)	Coal (existing)	Gas CCGT	Gas CT	Hydro (Reservoir type)	Hydro (Run-of-River)	Nuclear	Biomass	Wind	Solar	Battery	Pumped Hydro
Planned Outage rate	5%	Actual based on CEA Thermal Performance Review	5%	5%	5%	5%	10%	10% (Availability is seasonal)	1%	1%	1%	5%
Forced Outage rate	5%	Actual based on CEA Thermal Performance Review	5%	5%	5%	5%	10%	10%	1%	1%	1%	5%
Technical Minimum Level %	55%	CS + IPP = 55%; State = 70%	40%	20%	0	0%	90%	70%	0	0	0%	0%
Cold-start time (hours)	24	24	12	1	0	0	96	24	0	0	0	0
Minimum up-time (hours)	12	12	6	1	0	0	96	12	0	0	0	0
Minimum down-time (hours)	6	6	3	1	0	0	96	6	0	0	0	0
Cold-start Cost ($/MW)	100	100	30	1	0	0	0	0	0	0	0	0
Ramping (% of IC per minute)	1%	0.50%	2%	10%	25%	0	0	1%	0	0	100%	100%
Auxiliary Consumption	7%	7-8%	5%	2%	1%	1%	10%	10%	0.50%	0.50%	0.50%	1%
Roundtrip Efficiency	0	0	0	0	0	0	0	0	0	0	90%	80%
Heat Rate GJ/MWh	9.5	9.3-11	7.6	12	0	0	0	12.6	0	0	0	0

HYDRO GENERATION CONSTRAINTS

We assess plant-level monthly hydro dispatch constraints using historical generation data (for the load synchronized 2018 weather year), as summarized in the table below.

Reservoir hydro plants are modeled using a monthly energy budget approach using the actual monthly generation/capacity factors in the weather year 2018 (last “normal” weather year). For run-of-river plants, hourly output is assumed to be constant throughout the week/month subject to the energy budget constraint.

	Average Capacity Factor (%)				
	Northern Region	Western Region	Eastern Region	Southern Region	North-Eastern Region
January	23.8	30.1	17.8	28.4	25
February	29	27.3	17.6	31.6	22.9
March	36.1	25.7	19.1	39.8	22.2
April	40.2	26.4	24.6	30.6	34.4
May	62.4	25.7	18.1	27.2	48.7
June	64.4	23.1	26.5	27.2	61.1
July	67.2	26.7	28	30.5	79.5
August	66.8	46.8	26.7	36.8	83.1
September	71.2	48.7	32.1	53.5	66.7
October	40.2	37.6	26.4	39.1	60.2
November	29	26.4	15.8	28.9	39.9
December	25.7	21.2	8.3	24.1	25.9

APPENDIX 2: INDIA'S RISING ELECTRICITY DEMAND

INDIA'S ELECTRICITY DEMAND IS DOUBLING EVERY DECADE

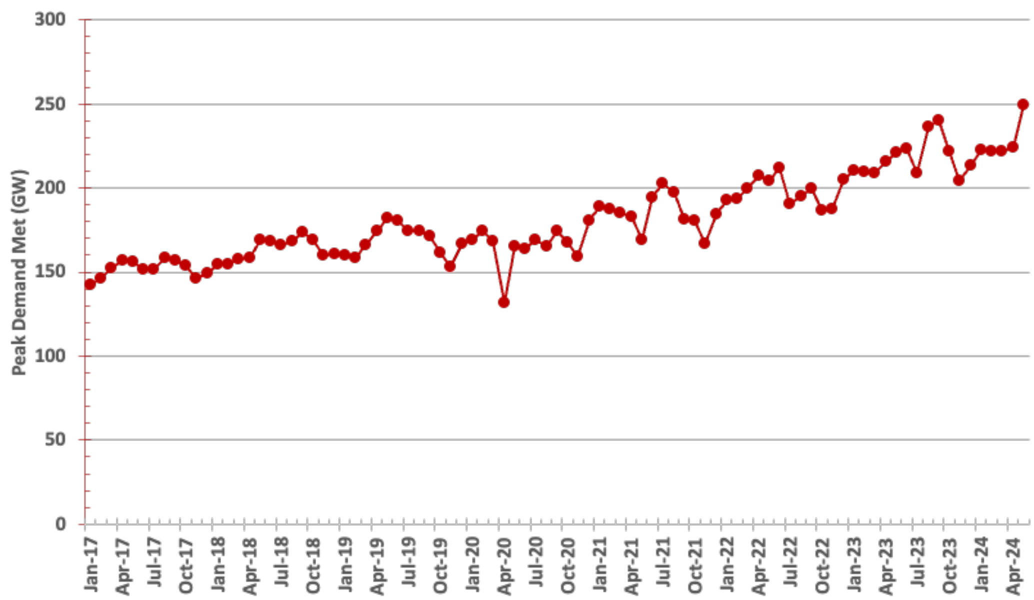
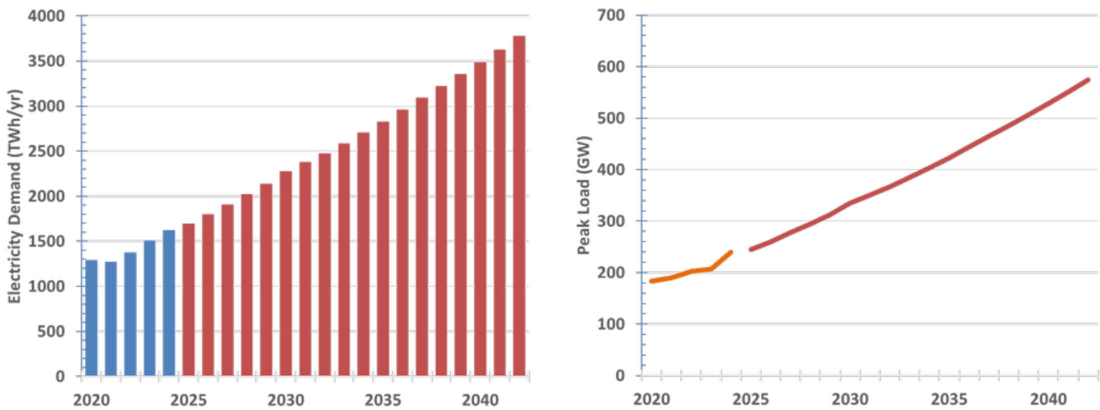


FIGURE 40: All-India monthly peak demand

India's electricity demand grew by 7% in 2023, compared to a global average of 2.2%. Between May 2019 and May 2024, India's peak electricity demand increased by a staggering 68 GW, from 182 GW to 250 GW, representing an annual growth rate of 6.5%. The post-COVID period has seen an even more dramatic increase, with peak demand shooting up by 46 GW in just two years, from 204 GW in May 2022 to 250 GW in May 2024.



Data sources: CEA Power Supply Reports and 20th EPS (2023)

FIGURE 41: India's electricity demand at busbar – actuals up to 2024 and projections thereafter

BETWEEN 2015 & 2024, INDIA ADDED 175 GW TO ITS POWER GENERATION CAPACITY WITH RE CONTRIBUTING ~65% OF THIS GROWTH

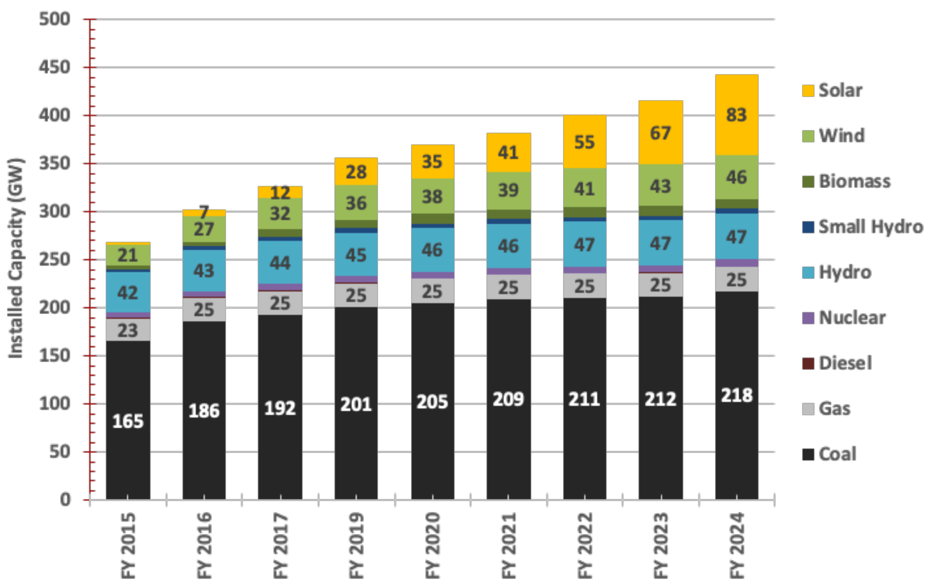


FIGURE 42: All-India Installed Capacity (GW)

Over the past nine years (FY 2015-2024), India has added a substantial 175 GW to its power generation capacity. This growth includes approximately 52 GW from coal and over 113 GW from renewable energy (RE) sources. Notably, between FY 2020 and FY 2024, India saw the addition of 48 GW of solar capacity and over 8 GW of wind capacity. In FY 2024 alone, nearly 70 GW of new RE capacity (mostly solar) has been tendered.

APPENDIX 3: A BRIEF GLOBAL REVIEW OF ENERGY STORAGE POLICIES

STORAGE POLICY - 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 and plans to install an additional 30 GW of non-hydro energy storage in the next year.

- Government policy has focused on a combination of storage mandates at a central and province level, research and development of storage technologies, new financial models to install storage with renewables, and ancillary services for the energy storage market.

STORAGE POLICY – 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 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, for South Korea’s battery industry.

STORAGE POLICY - EU

- The European Battery Regulation requires 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 over time - 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 battery production.

STORAGE POLICY - US

- The passage of the Inflation Reduction Act in 2022 has mobilized investments, consumer subsidies and private sector mobilization in battery manufacturing.

- At least 50 new manufacturing projects have been announced across the EV supply chain, totaling over 500 billion dollars in investment.

- The Advanced Manufacturing Production Tax Credit provides a tax credit equal to 10% of the cost of production to the producer of critical minerals like lithium, cobalt, graphite, and nickel.

- Other recently passed pieces of legislation (Bipartisan Infrastructure Act and CHIPS Act) catalyze and provide large federal investments to develop the domestic battery supply chain.

APPENDIX 4: ECONOMICS OF FLAT-BLOCK SOLAR+STORAGE

In this section, we demonstrate the economics of a hypothetical 100 MW solar plus storage flat-block power plant in India using a simple hourly simulation.

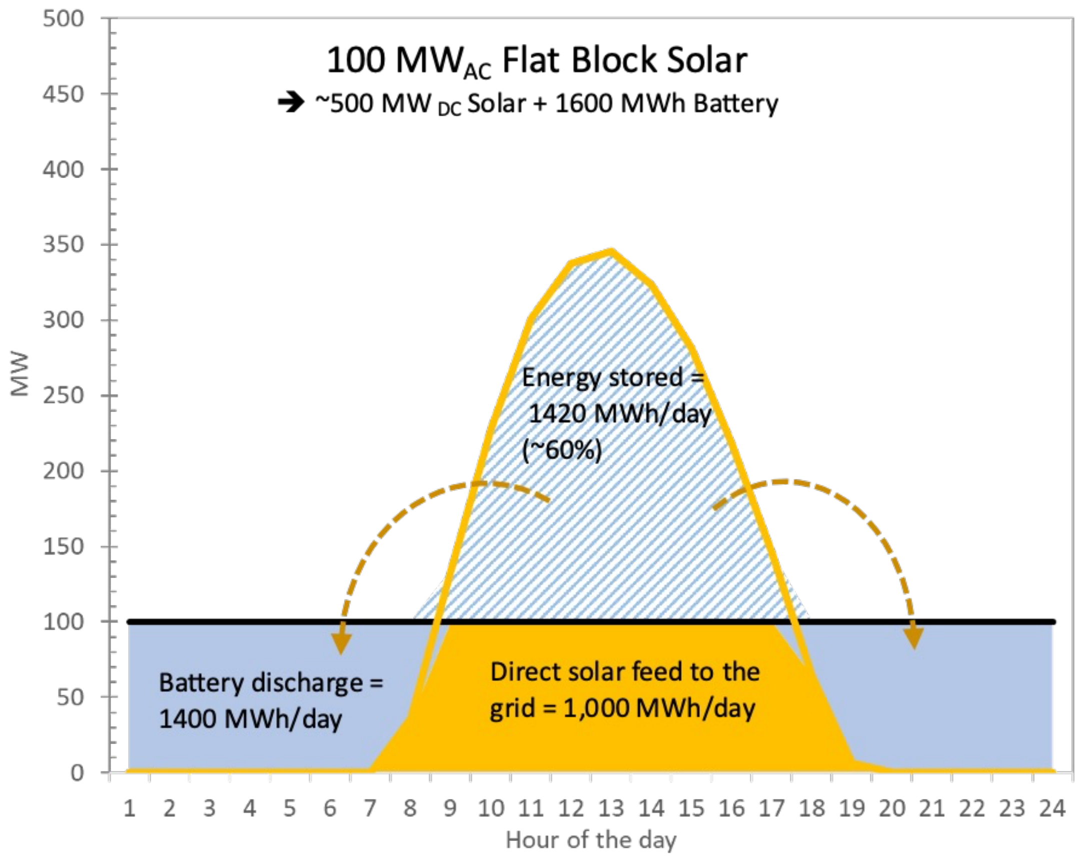


FIGURE 43: Operational simulation of a 100 MW flat-block solar + storage in India. Flat block solar + storage would need about 60% of DC solar energy to be stored in storage.

100 MW flat block power would imply 2400 MWh/day of total energy requirement (100 MW x 24 hours). For a typical DC capacity factor of 20%, solar capacity requirement would be ~500 MW$_{DC}$. For a 100 MW interconnection, direct solar feed to the grid would be about 1,000 MWh/day, requiring about 1400 MWh/day of energy to be stored. Assuming a 90% roundtrip efficiency, the system would need about 1,600 MWh of energy storage, or about ~66% of DC solar energy would need to be stored.

SECI auctions revealed a storage adder of about ₹ 1/kWh for 33% DC solar energy stored. So storage adder for 66% DC solar energy storage would be ~2 times or Rs 2/kWh. Assuming a solar LCOE of Rs 2.5/kWh, flat block solar + storage price would be 2.5 + 2 = ~₹ 4.5/kWh. Given the global trends in the batteries market, the storage adder may further reduce by 15-20% by 2030, solar + storage flat block cost could be under Rs. ~4.0/kWh. This is lower than the LCOE of most new coal power plants, implying the economic viability of any new thermal investments need to be seriously reassessed.

Contact for more information:

Dr. Nikit Abhyankar: nikit@berkeley.edu

Mr. Himanshu Chawla : himanshu.chawla@powerfoundation.org.in

Power Foundation of India

IECC INDIA ENERGY & CLIMATE CENTER

UC Berkeley
Goldman School of Public Policy