Using the capacity expansion results from ReEDS-India, we created a production cost model (PCM) in PLEXOS® for select years to evaluate how energy storage is operated on an hourly timescale. [2] Several assumptions were necessary to translate the CEM scenarios from ReEDS-India into the PCM. First, we "broke up" state-wise capacity investments from the CEM into unit-wise representations using a state-wise average size of existing generating units. This enabled detailed simulation of unit constraints and operational constraints, including ramp rates, minimum generation level, start-up and shut-down times, and minimum up/down time. Operational characteristics for new fossil-fueled units are based on average state-wise values of generators built between 2015 and 2020. Next, we added transmission investments by duplicating existing lines until total interstate transmission capacity matched the CEM buildout. We also updated regional transfer capacities to capture new state-to-state transmission capacity that crossed regional boundaries. Finally, we translated wind and solar buildout for each resource region into site-wise hourly generation profiles using NREL's reV tool (Rossol, Buster, and Spencer 2021). The resulting site-wise profiles were aggregated to the state level to create hourly state-wise wind and solar generation profiles for the PCM dispatch simulation. This process ensured that the geographic diversity of wind and solar resources was preserved when modeling system operations at the state level.

Box 1. Treatment of Energy Storage in the PCM

The PCM optimizes the operation of storage to achieve least-cost operations at the system level in each day of the year. The decision to charge, discharge, or provide reserves is based on the least-cost strategy for the day. The storage would generally charge during hours when the prices are relatively low and discharge during high-price periods. The decision is calculated by co-optimizing the provision of energy and ancillary services. Operations of storage devices are constrained by the storage duration and the maximum capacity. All storage technologies are assumed to be half-charged at the start of year. Constraints that are routinely discussed as being enforced in reality, such as depth-of-discharge and number of cycles, are not modeled to allow for insight about whether these constraints are necessary, given optimal system operations (Smith et al. 2012).

2.2 Scenario Design

Scenarios for this study are designed to understand the drivers for energy storage investment and assess the potential role for energy storage on the South Asia power system. Table 1 describes each scenario evaluated in this study. The Reference Case formed the basis for all the scenarios. All other scenarios were formed by making a change to the Reference Case. We used the Reference Case result from the ReEDS-India CEM to create the South Asia PCM for 2030 and 2050. We used the South Asia PCM to evaluate several scenarios of energy storage in Bhutan, Nepal, and Bangladesh. The methodology and results for South Asia scenarios are discussed in Section 3.6.

[2] We used PLEXOS version 7.4 using the Xpress-MP solver in this study. Operating reserves, represented as 5% of load on a regional basis, are co-optimized with energy.

Table 1. Scenarios Evaluated

Scenario Name(s)	Description	Scenario Category
Reference Case	The Reference Case represents standard assumptions about technology costs, policies, and regulations for energy storage through 2050.	Reference scenario
No ES Operating Reserves	Energy storage does not provide spinning reserves.	Regulatory scenarios
No ES Capacity Credit	Energy storage is not valued or compensated for its contribution to resource adequacy.	
No ES Time-Shifting	Energy storage is not valued or compensated for shifting energy supply to different times of day.	
No New Gas	No new investments in gas-fired capacity above what is currently planned.	Fossil-fuel policy scenarios
No New Fossil	No new investments in fossil-fueled capacity above what is currently planned.	
Low Battery Cost	Installed costs for BESS start lower and decline faster compared to the Reference Case.	Cost scenarios
High Battery Cost	Installed costs for BESS start higher and decline slower compared to the Reference Case.	
Low Solar PV Cost	Installed costs for solar PV decline faster compared to the Reference Case.	
Low Solar and Battery Cost	Combined Low Solar PV Costs and Low Battery Cost scenario	
Low PSH Cost	Installed costs for PSH are 50% lower than in the Reference Case.	
Nepal, Bhutan, and Bangladesh Operational Simulations	PCM scenarios for Nepal, Bhutan, and Bangladesh with incrementally increasing amounts of energy storage capacity.	South Asia regional scenarios

2.2.1 Reference Case

The Reference Case is not designed to forecast what is most likely to happen in the future. Rather, the Reference Case is designed as a launching point to examine the key drivers for energy storage deployment and allow us to examine these drivers through additional scenarios. Cost projections and performance characteristics for storage technologies are middle of the road based on several projections analyzed (see Section 2.3). Additionally, the regulatory environment created for the Reference Case is somewhat optimistic, allowing storage to receive credit for capacity and to participate in energy markets as both a source of electricity demand and generation, which is not currently allowed, but for which there is regulatory momentum to make these changes (Rose, Wayner, et al. 2020).

2.2.2 Data and Assumptions

This study followed the same input data and set of assumptions presented by (Rose, Chernyakhovskiy, et al. 2020) for the ReEDS-India CEM, with several key modeling advances noted in this section. The PCM used the same input data and assumptions presented by (J. D. Palchak et al. 2019). Input data and assumptions were updated in three categories:

- Energy storage technologies
- Projections for electricity demand growth considering the 2020–21 global COVID-19 pandemic
- CBET among Bangladesh, Bhutan, India, and Nepal.

Additionally, we added a target for India to reach 450 GW of installed RE capacity by 2030. Detailed inputs for the CEM and PCMs are presented in Appendix A and Appendix B, respectfully. The remainder of this section summarizes inputs and assumptions that were uniquely developed for this study.

2.3 Battery Storage Technologies

The estimates for current and future costs for BESS vary widely. Figure 3 shows cost projections for 4-hour lithium-ion BESS from various published sources, with 2020 costs ranging from $812/kW to $1,455/kW ($203/kWh to $364/kWh). BESS technologies based on other chemistries such as sodium-sulfur were not evaluated in this study. We used the BloombergNEF 1H 2020 cost projection for 4-hour lithium-ion BESS for the Reference Case. The BloombergNEF 1H 2020 cost is selected as a reasonable mid-range projection among the various published sources. Notably, the BNEF 1H 2020 projection is lower than NREL's 2020 Annual Technology Baseline (ATB)–Low scenario for BESS costs in the United States.

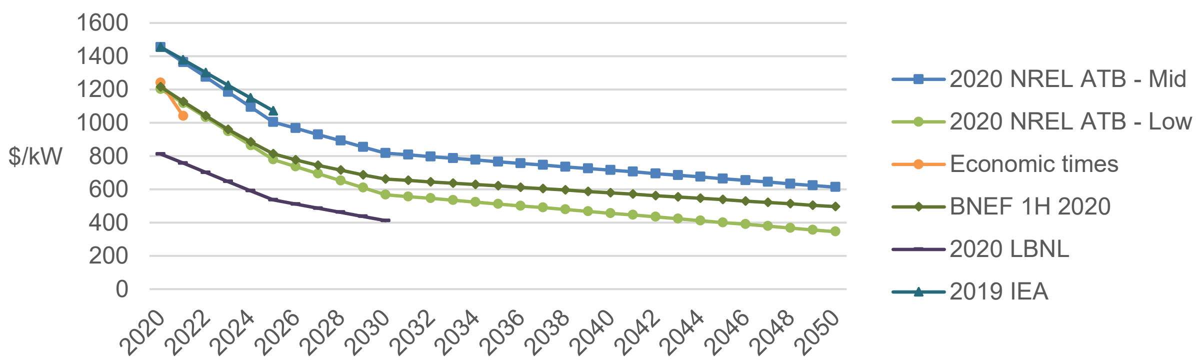

Figure 3. Select published projections for the installed costs of 4-hr BESS

Sources: 2020 NREL ATB: (NREL 2020); Economic times: (The Economic Times 2020); BNEF 1H 2020: (BloombergNEF 2020); 2020 LBNL: (Deorah et al. 2020); 2019 IEA: (IEA 2019)

For other duration BESS, there are fewer cost projections available. Therefore, we scaled the cost for different BESS durations from the 4-hour BESS cost using scaling factors derived from (Cole and Frazier 2020). We also followed (Cole and Frazier 2020) for assumptions about BESS lifetime, O&M costs, and efficiency (see Table 2).

Table 2. BESS Inputs and Assumptions

Reference Case Assumption	BESS 1-hr	BESS 2-hr	BESS 4-hr	BESS 6-hr	BESS 8-hr	BESS 10-hr
Power Capacity Cost in 2020 (Crore ₹/MW)	2.9	4.9	8.5	12	15	19
Energy Capacity Cost in 2020 (Crore ₹/MWh)	2.9	2.5	2.1	2.0	1.9	1.9
Fixed O&M Cost in 2020 (Crore ₹/MW-year)	0.21					
Lifetime	15 years					
AC-AC Round-Trip Efficiency	85%					

We developed two additional BESS cost curves for the scenario analysis presented in Section 3.5. Costs for the High Battery Cost scenario are based on the 2020 NREL ATB Mid Case. The Low Battery Cost scenario is based on the 2020 LBNL projection for BESS costs in 2030, extended to 2050 using the same year-over-year cost decline as the Reference Case. Figure 4 presents the cost curves across different BESS durations and scenarios. The large range of costs across different scenarios, both in the near-term and through 2050, reflects current uncertainty about battery costs for grid-scale applications in South Asia.

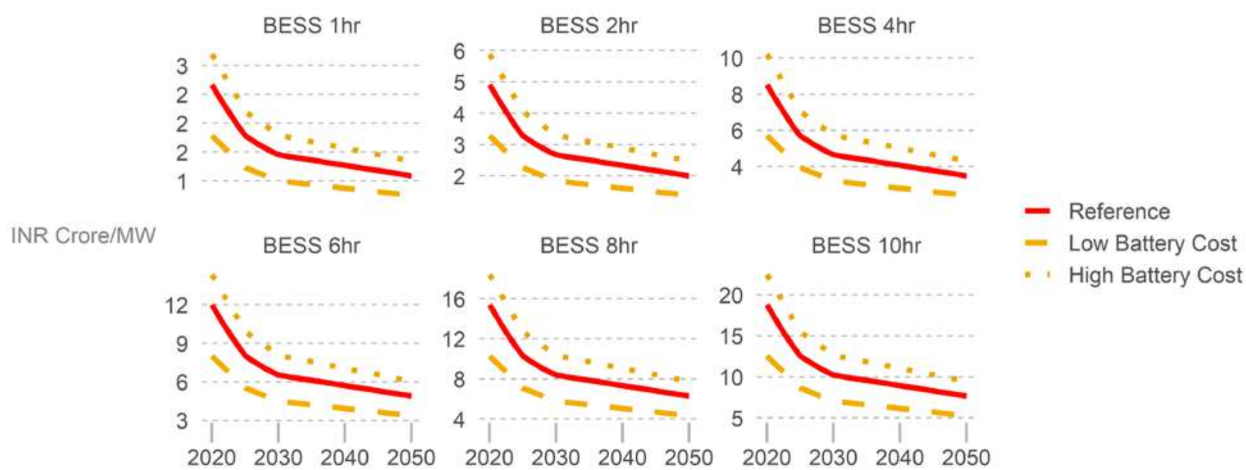

Figure 4. Cost scenarios for battery storage

2.4 PSH Potential

Special considerations are needed when implementing PSH in CEM because the feasibility of such projects is limited by geographic conditions and land-use constraints. Therefore, we limited the state-wise potential for PSH deployment based on a hydro-electric potential study carried out by CEA (P. K. SHUKLA 2017). According to the CEA report, total PSH potential in India is 96.5 GW. For existing PSH capacity, we included commissioned and planned PSH plants from the latest CEA report *Pumped Storage Development in India* as of this writing (CEA 2021).

Additionally, several simplifying assumptions are made to represent investment opportunities for PSH in the CEM. Table 3 presents the key assumptions for new investments in PSH plants. We assumed a uniform cost for the construction of a PSH plant across all Indian states.[3] We also assumed that all potential new PSH plants have a 12-hour duration (i.e., 12 hours of energy at full power output). Finally, we made a simplifying assumption that potential new PSH plants are closed loop, have no natural inflows, and can store energy from grid power only.

Table 3. PSH Assumptions

Input	Value
Installed Cost	9.9 Crore ₹/MW
Fixed O&M Cost	0.29 Crore ₹/MW
AC-AC Round-Trip Efficiency	80%
Duration	12 hours

We explored five alternative scenarios for PSH investment costs (see Table 4). One option to develop PSH in India is to upgrade existing reservoir storage plants. Upgrading existing plants is estimated to be a lower-cost option compared to building a new PSH facility. Therefore, we evaluate a range of PSH cost scenarios that are lower than the reference. These scenarios are designed to discover the cost at which PSH is cost-competitive with other resources, including battery storage. Results for PSH cost scenarios are presented in Section 3.5.

Table 4. PSH Cost Scenarios

Scenario	Installed Cost Relative to Reference Case
PSH Cost (10%)	10% lower
PSH Cost (20%)	20% lower
PSH Cost (30%)	30% lower
PSH Cost (40%)	40% lower
Low PSH Cost	50% lower

2.5 Electricity Demand Growth

Our assumptions for state-wise electricity demand growth were based on the 19th Electric Power Survey, with several important adjustments (CEA 2018a). First, due to the 2020 global pandemic, we assumed both energy and peak demand in 2020 remained at the same level as 2019 for all states. After 2020, we assumed that demand growth rates will return to pre-pandemic levels after 2025. Between 2020 and 2025, we used the Energy And Resources Institute's forecasts for electricity sector demand growth recovery under a V-shaped scenario (Spencer

[3] Site-specific cost assessment for new PSH plants is outside the scope of this study.

2020). Second, because the 19th Electric Power Survey was published several years ago, we updated historic state-wise electricity demand with actual energy and peak demand observed from January 2016 to December 2019 using annual reports published by CEA (CEA 2016b; 2017b; 2018c; 2019b; 2016a; 2017a; 2018b; 2019a). Finally, we extended the Electric Power Survey state-wise demand projections for all years between 2025 and 2050. After 2026, the 19th Electric Power Survey provides demand projections in 5-year increments until 2036. We assumed linear growth in annual energy and peak demand in the intervening years. For 2036–2050, we assume the same rate of demand growth as the previous 5 years. Table 5 presents the assumptions for all-India energy and peak demand in 2020, 2030, 2040, and 2050.

Table 5. Projections of Annual Energy and Peak Demand in India for Select Years

Year	National Energy Demand (TWh)	National Peak Demand (GW)	National Load Factor (%)
2020	1,300	180	82.9%
2030	2,300	310	82.5%
2040	3,200	450	81.9%
2050	4,200	580	81.5%

Demand growth projections were used to create hourly state-wise load profiles for each from 2020 to 2050, using the actual hourly state-wise load from 2014 as the base year.

2.6 Future Power System Buildout for South Asia

Because development of a CEM for Bangladesh, Bhutan, and Nepal is beyond the scope of this study, alternate methods are used to evaluate opportunities for energy storage in these countries and account for changing patterns of CBET in the ReEDS-India model. We used the national plans for generation and cross-border transmission capacity additions in each country and interpolated intermediate values for years that are not available. Projections for demand growth beyond the timeframe in official plans were based on the average growth rate from the previous 3 years. No new generation or cross-border interconnection was added beyond the official plans.

Bhutan: Bhutan's power system almost exclusively comprises run-of-river (ROR) type hydropower plants. As a result, the country's generation supply is highly seasonal with limited flexibility. Bhutan has cross-border links with India, and all surplus generation in the existing and planned system is exported to India. The load, generation, and cross-border interconnection projections for Bhutan through 2040 are based on the National Transmission Grid Master Plan, 2018 (Department of Hydropower & Power Systems 2018). We assumed all hydropower capacity additions were ROR and used hourly profiles of hydropower generation and load to calculate the hourly CBET to India in every year to 2050. Power transfers are modeled as fixed flows and proportionally distributed to the states that are connected with Bhutan based on the ratio of expected transmission capacity.

Nepal: Most of the existing hydropower plants in Nepal are ROR with a few reservoir hydropower plants as well. These hydropower plants are seasonal in nature with limited flexibility. The present CBET between India and Nepal is limited to contracted quantum between the two countries. Although Nepal imports from India at present to meet daily and seasonal balancing needs, it is expected that Nepal's planned expansion of its domestic hydropower resources will enable it to become a net exporter to India in the future. The future generation capacity in Nepal till 2028 is considered based on the Ministry of Energy's white paper (Ministry of Energy, Water Resources and Irrigation 2018) and the generation capacity for 2040 is based on Transmission System Development Plan of Nepal (Rastriya Prasaran Grid Company Limited 2018). The total reservoir hydropower capacity for 2040 was calculated based on individual proposed plants mentioned in the transmission system development plan. All other hydropower capacity was assumed to be ROR type. For intermediate years until 2040, a linear growth was assumed for ROR and reservoir hydropower based on existing and 2040 projected capacity. Projections for electricity demand from 2015 to 2040 was based on the reference scenario published in (Water and Energy Commission Secretariat 2017). CBET between India and Nepal is represented by two components: (a) fixed flow generators; and (b) generators with monthly energy limits. We used hourly profiles of ROR hydropower generation and load to calculate the hourly fixed flow component of CBET to India in every year to 2050. Fixed flows are proportionally distributed to the Indian states, which are connected with Nepal based on the ratio of planned interconnection capacity. For the second component, we used monthly energy limits of reservoir hydropower generation.

Bangladesh: The existing generation mix in Bangladesh is comprised of gas, fuel oil, coal, hydropower, and diesel-based generation. Although the system has some level of flexibility, costly fuel oil and diesel generators are a substantial part of the generation mix, which contributes significantly towards production costs and emissions. We assumed future generation buildouts follow the latest power system master plan, low case of revisiting Power Sector Master Plan 2016 of Bangladesh, which includes coal generation, nuclear generation, gas generation, and imports from other South Asian countries (Ministry of Power, Energy & Mineral Resources 2016). Concerns about domestic gas availability in the future are incorporated in the modeling (see further details in Appendix B). Projections for electricity demand to 2040 and cross border interconnections were also based on the Power Sector Master Plan report. To represent CBET, we used the Power Sector Master Plan to calculate the total transfer capacity between India and Bangladesh for every year through 2041 and assumed no additional transfer capacity from 2042 to 2050. Monthly available transfer capacity was moderated using the monthly ratio of actual transfers and maximum possible transfer based on actual monthly power transfer for 2019 (Power System Operation Corporation Limited 2019). The moderated hourly transfer capacity for each year through 2050 is proportionally distributed to the Indian states where these interconnections are planned based on the ratio of expected transmission capacity.

Notably, there are no utility-scale energy storage projects operating in any of these countries. However, changes in technology costs and system needs are prompting increased interest in energy storage technologies. In Nepal, the government is supporting the development of a PSH pilot project to meet peak demand needs and increase the flexibility of the country's power system, and the Nepal Electricity Authority is undertaking an economic feasibility study on the potential for utility-scale battery storage in the country (NEA 2016a; 2016b; Water and Energy Commission Secretariat 2017). In Bangladesh, the draft National Solar Energy Action Plan recommends a policy for industrial storage systems for peak shifting, load management, and balancing for variable RE generation (Chowdhury 2020).

See Appendix B for further details about modeling assumptions.

3 Results: Opportunities for Energy Storage

Across all scenarios, energy storage technologies are expected to play an increasing role in India's power system. Figure 5 shows that power capacity of storage technologies reaches between 180 GW and 800 GW, representing between 10% and 25% of total installed power capacity in 2050. Energy capacity of storage reaches between 750 GWh and 4,800 GWh in 2050.

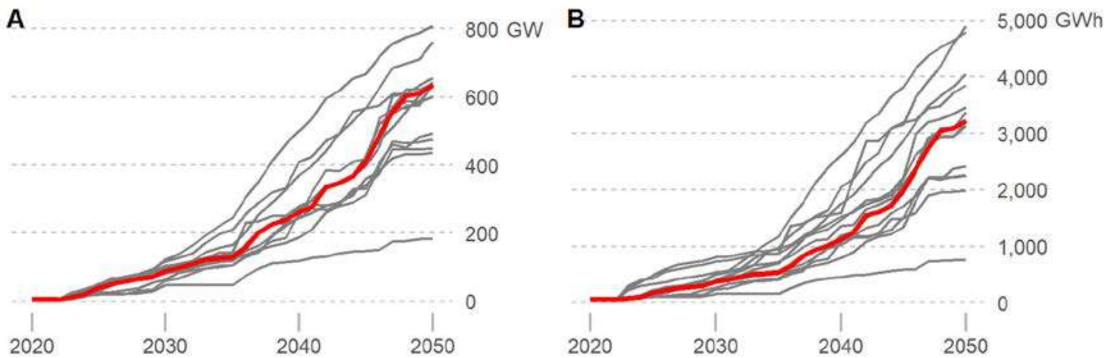

Figure 5. Energy storage power (A) and energy (B) capacity deployment in India to 2050

Each line represents one modeled scenario. The Reference Case is highlighted in red.

The remainder of this section will discuss: (1) the Reference Case results and key drivers for energy storage in India; (2) the role of energy storage in system operations; (3) scenario results; and (4) the regional South Asia result.

3.1 Reference Case Results

Energy storage has the potential to reach 23% of the installed power capacity in India by 2050. Table 6 provides the installed capacity and share of energy storage in total power capacity under the Reference Case in key years.

Table 6. Energy Storage Deployment in Reference Case for Select Years

	2020		2030		2040		2050	
Energy Storage Technology	**GW**	**Share of Installed Capacity**	**GW**	**Share of Installed Capacity**	**GW**	**Share of Installed Capacity**	**GW**	**Share of Installed Capacity**
PSH	4.8	1%	6.3	0.8%	6.3	0.4%	6.3	0.2%
BESS 2-hr	0	0%	16	2%	0	0%	0	0%
BESS 4-hr	0	0%	68	8%	240	16%	350	13%
BESS 6-hr	0	0%	0	0%	17	1%	240	9%
BESS 8-hr	0	0%	0	0%	0	0%	40	1%
Total	**4.8 (57 GWh)**	**0%**	**90 (380 GWh)**	**11%**	**260 (1,100 GWh)**	**17%**	**640 (3,200 GWh)**	**23%**

3.1.1 What Types of Energy Storage Are Cost-Effective in the Near Term?

Under Reference Case assumptions, energy storage deployment grows quickly with an average year-over-year growth rate of 42% between 2020 and 2030. Figure 6 shows deployment of different energy storage technologies from 2020 to 2030 in the Reference Case. Investments in large-scale battery storage are cost-effective beginning in 2023, the first year when economic investments are allowed in the model.[4] Initial investments are primarily 2-hour duration battery systems. Beginning in the mid-2020s, 4-hour battery storage dominates the energy storage landscape.

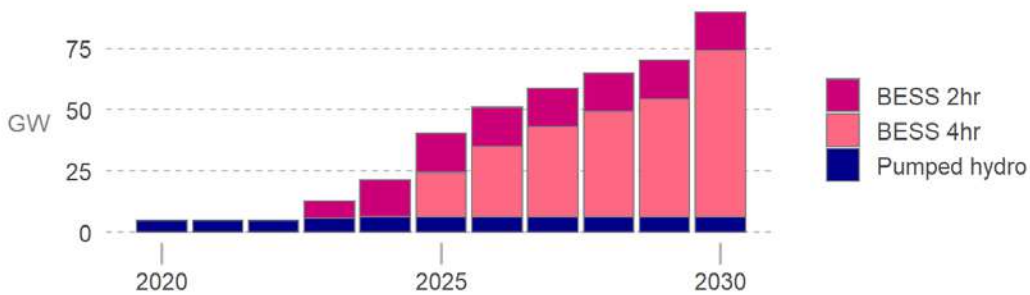

Figure 6. Energy storage investments to 2030, Reference Case

We see energy storage investments spread across all regions in India. Figure 7 shows the geographic distribution of energy storage deployed through 2030 in the Reference Case. Pumped-hydro deployment is limited to those projects that are currently under construction or planned, as per CEA (CEA 2021). Battery storage investments are found to be cost-effective in 26 states. Three states have over 10 GW of battery storage capacity by 2030: Jammu and Kashmir, Gujarat, and Karnataka.

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[4] The model includes a mix of planned and economic investments in generation and transmission capacity. Planned investments are capacity additions from the 13th National Electricity Plan, including 175 GW of RE by 2022 (CEA 2018d), as well as 450 GW of RE by 2030. Due to the 2019–2020 global pandemic, we assumed that conventional capacity additions planned for 2020 would be delayed by 1 year to 2021. Economic investments are capacity additions chosen within the model optimization. We allowed the model to choose economic investments beginning in 2023.

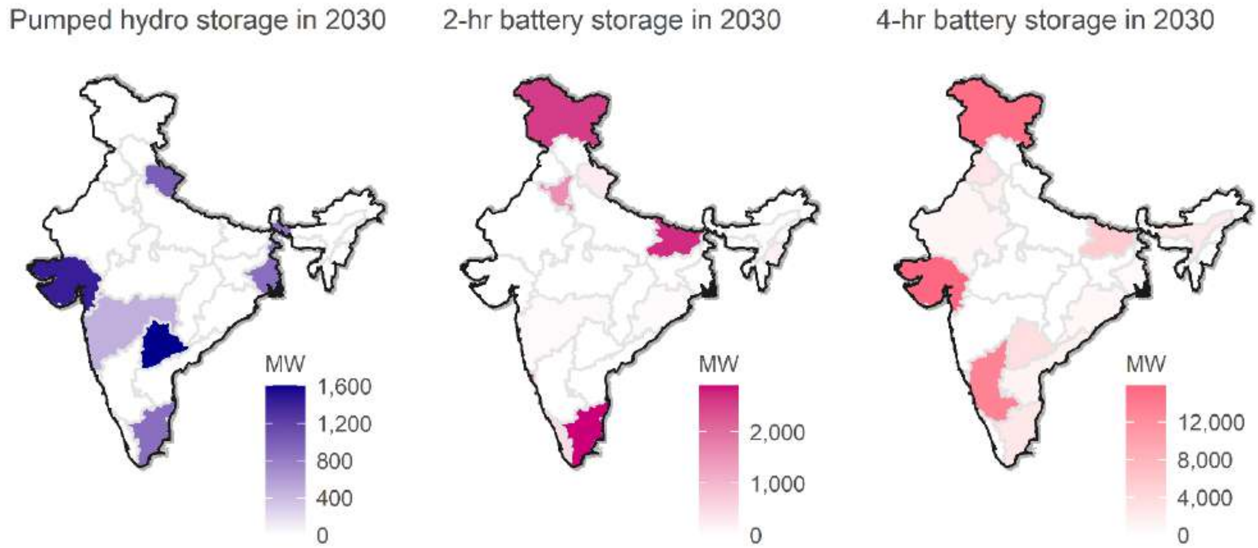

Figure 7. State-wise energy storage deployment to 2030, Reference Case

Energy storage opportunities at the state level are dependent on several interrelated factors. Existing flexible resources such as hydro, gas, and certain coal-burning units can diminish the cost-effectiveness for new battery systems in some states. Existing pumped-hydro facilities may also decrease the cost-effectiveness for longer-duration batteries. Interstate electricity transmission capacity and trade can also impact energy storage opportunities. For example, states like Karnataka and Jammu and Kashmir that have abundant RE resources and rely on out-of-state generation resources for supply-demand balancing show investments in battery storage to avoid costly upgrades in interstate transmission capacity.

3.1.2 How Much Energy Storage Is Cost-Effective in the Long Term?

In the longer term, energy storage investments continue to grow with every year. Figure 8 shows the investments in energy storage technologies through 2050 in the Reference Case. Total energy storage deployment reaches 635 GW. This represents 23% of total installed capacity in 2050. The total energy capacity of energy storage reaches 3,220 GWh, with an average storage duration of 5 hours across all devices. Four-hour battery storage is the only cost-effective storage technology from the mid-2020s through the late 2030s. All 2-hour storage devices are retired by 2039, having reached the end of their technical and financial life. There are no additional investments in 2-hour batteries after they are fully retired. Beginning in 2039, 6-hour batteries are cost-effective in certain locations. Beyond 2040, 6-hour batteries have the highest growth of any storage technology. Eight-hour batteries start to become cost-effective in the mid-2040s. Under Reference Case assumptions, we did not see additional investment in PSH beyond what is currently under construction or planned.