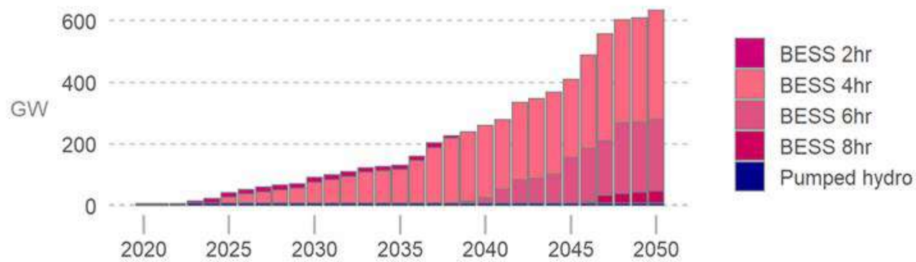

Figure 8. Energy storage investments to 2050, Reference Case

By 2050, we see a large concentration of battery storage in Northern and Western Region states, particularly in Rajasthan and Gujarat. These states have the highest total battery storage deployment, with 1,060 GWh and 680 GWh of battery energy capacity, respectively. Figure 9 shows the state-wise buildout of battery storage technologies to 2050.

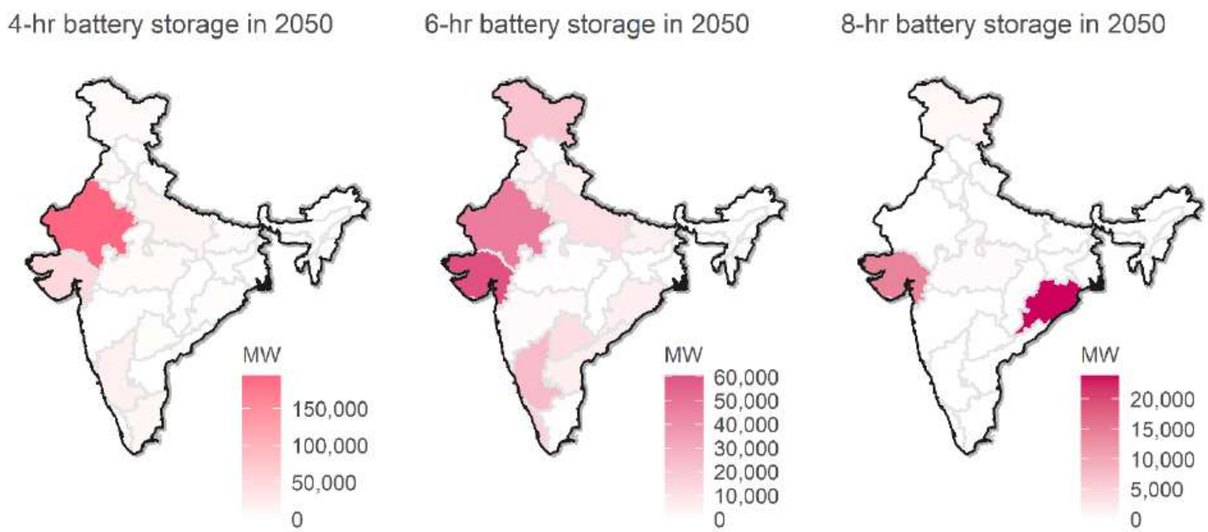

Figure 9. State-wise energy storage deployment to 2050, Reference Case

In the long term, states with the largest investments in battery storage also have high concentrations of solar PV deployment. Rajasthan and Gujarat have the highest battery capacity as well as the highest capacity of solar PV in India, with 450 GW and 270 GW installed by 2050, respectively. Odisha stands out with 24 GW of 8-hour BESS deployed by 2050. Although Odisha is not currently considered a high-solar state, by 2050 we see 37 GW of economic solar PV deployment in the state. The results also show a high value for 8-hour BESS to provide capacity in Odisha (see Section 3.1.3 for a detailed discussion of energy storage value streams).

Furthermore, of the top 10 states for solar PV capacity, seven of them are in the top 10 for battery storage deployment in 2050. Overall, battery storage and solar PV deployment across all states in India has a correlation coefficient of 97%. Excluding Rajasthan and Gujarat, which may be outliers due to those states' high concentrations of solar PV deployment, the correlation coefficient is 66%. While a combination of factors affects the deployment of solar PV and battery storage, the presence of a positive correlation indicates that there is a positive relationship between balancing areas with high-quality solar PV resources and cost-effective battery storage investments. While it may be natural to interpret that more energy storage "enables" higher levels of cost-effective solar PV, the opposite is also true—more solar PV can create more opportunities for energy arbitrage *and* shifts the timing of peak demand to enable a higher capacity credit for shorter-duration storage devices. This trend is well documented in the U.S. context (Denholm et al. 2019; A. W. Frazier et al. 2020; Denholm and Mai 2017; Denholm and Margolis 2018).

3.1.3 What Are the Drivers for Energy Storage in the Reference Case?

Like conventional resources, energy storage projects can provide multiple services to the power system. The same battery storage facility, for example, can help reduce operational costs by performing energy time-shifting, provide reliable capacity for long-term capacity adequacy, and *also* provide essential grid services (i.e., ancillary services) to help maintain grid reliability. We refer to these services as the **value streams** for energy storage investments. Table 7 shows three major categories of value streams from energy storage evaluated in this study.[5] In the Reference Case, we assumed that energy storage operations are fully coordinated to maximize the total value that they provide to the grid. This means that the state of charge is managed in such a way that energy storage devices are available when they are cost-effective to charge and dispatch energy for grid needs. It also means that, in the Reference Case, we assumed that energy storage projects can receive full compensation for the multiple services they provide to the grid. These assumptions are explored in Section 4.5.

Table 7. Value Streams for Energy Storage Evaluated in This Study

Energy Storage Service	Description
Capacity adequacy	Energy storage provides a reliable source of peaking capacity.
Energy time-shifting	Energy storage is used to shift energy between low-value and high-value periods.[6]
Operating reserves	Energy storage is used to provide operating reserves (i.e., spinning reserves).

By looking at the value provided to the system for different services, we can learn about the drivers for energy storage investments. Figure 10 shows the average value streams provided by different types of energy storage projects in the CEM.

[5] Transmission and distribution network upgrade deferral and congestion management are other potential categories of energy storage value. However, assessing opportunities for energy storage to defer or avoid transmission equipment upgrades or help alleviate distribution network issues requires detailed power flow modeling that is outside the scope of this study.

[6] Another common term for this service is energy arbitrage.

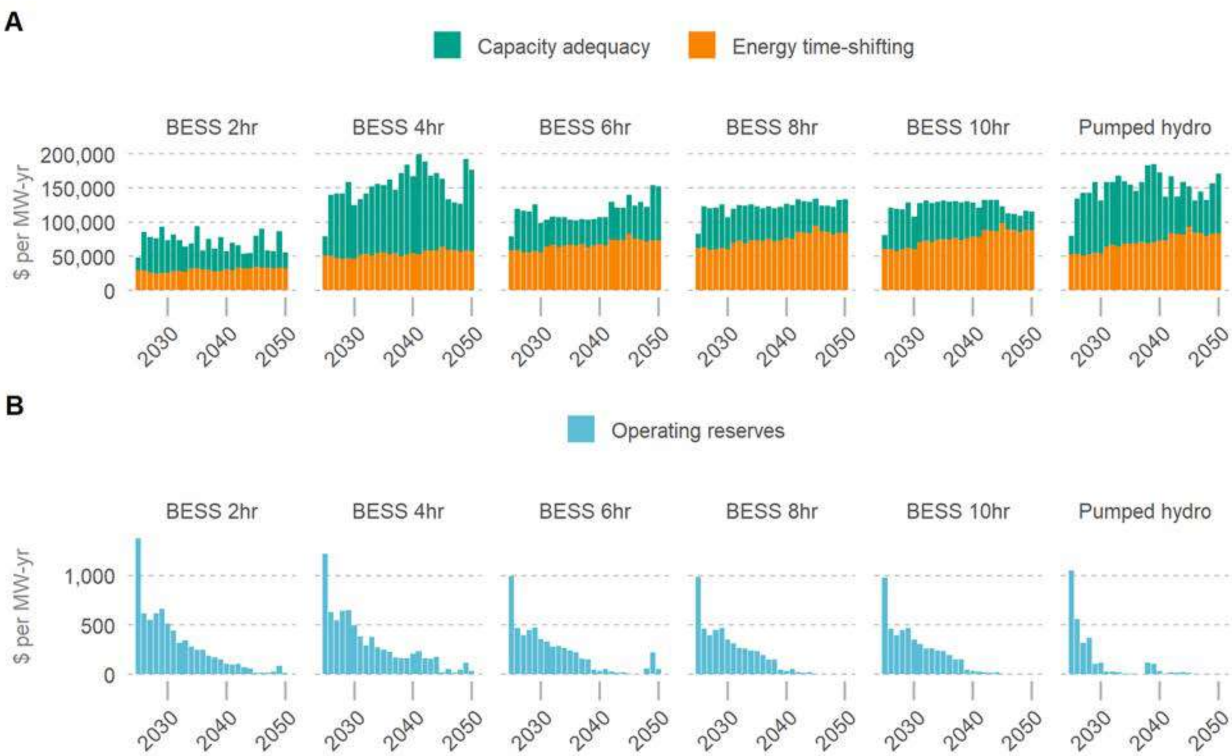

Figure 10. Average value streams for energy storage in the Reference Case

Note: Y-axis scales differ between categories.

Energy time-shifting and capacity services are the largest source of value for energy storage, both in the near and long term. The value of energy storage to provide operating reserves, on the other hand, is relatively small and declines over time. While operating reserves are an essential grid service, the total requirement is relatively small when compared to requirements for energy and capacity services. In the near term, new energy storage devices can capture much of the operating reserves requirement and reduce the overall cost of providing operating reserves by displacing fossil-fueled generation, which is required to start up and maintain headroom to contribute to operating reserves. However, as new energy storage is added to the grid over time, the value for a unit of energy storage to provide operating reserves declines rapidly as the requirement is satisfied by existing resources.

In general, differences in value streams between different years and storage durations are driven by several interrelated factors, including the penetration of RE in the generation mix, the shape of the demand curve, planned retirements of conventional generators, and the amount of energy storage deployed in any given year.

The remainder of this section will explore each category of value streams in further detail.

Capacity Adequacy

The contribution of generation resources to long-term capacity adequacy, often referred to as a generator's "firm capacity" (measured in MW), can also be expressed as a **capacity credit.** The capacity credit is the percentage of a generator's installed capacity that can reliably provide energy to meet peak demand.

Box 2. Capacity Credit for Energy Storage

Peak demand is often defined with a length of time that a regulator or utility decides that they need reliable capacity. Being able to reliably provide power for this amount of time is what determines a resource's capacity credit. For energy storage resources, the capacity credit depends on the duration of the storage and the duration of the peak demand that must be met. In a hypothetical example depicted in Figure 11, up to 200 MW of a 2-hour storage device can serve peak demand with a capacity credit of 100%. In this example, the 2-hour storage discharges 100 MWh at 2 p.m.–3 p.m., 200 MWh at 3 p.m.–4 p.m., and 100 MWh at 4 p.m.–5 p.m. to reduce the net peak demand by 200 MW. The new peak demand after accounting for the storage discharge is now 200 MW over a 5-hour period. A longer duration storage device would be needed to reduce the peak further, as seen in Panel B. This example shows how the capacity credit of energy storage declines as more storage devices are added to the grid. This is because each additional unit of energy storage "flattens" the demand curve, requiring a longer duration of energy discharge. See (Frazier et al. 2020) for a detailed demonstration and analysis of the relationship between energy storage capacity credit, the shape of the net demand curve, and energy storage deployment.

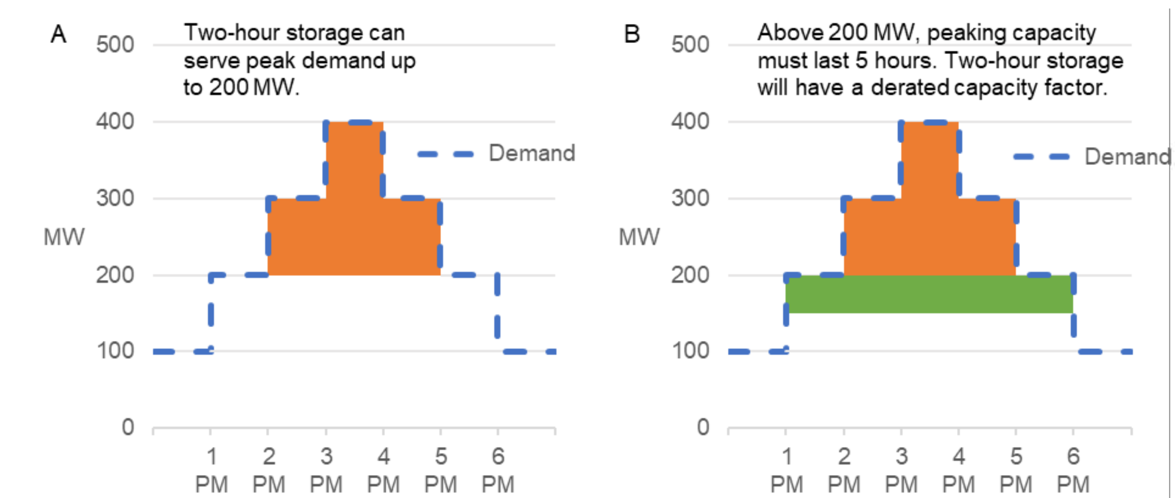

Figure 11. Illustrative example of energy storage capacity credit

Note: Figure adapted from Frazier et al. 2020.

As part of the modeling for this study, we identified the total amount of energy storage with different durations that can provide peaking capacity with a 100% capacity credit. The result of this analysis for select years is depicted in the left panel of Figure 12. The left panel shows the total potential (i.e., upper bound) for energy storage with 100% capacity credit, in GW, based on the load curve in each of India's balancing areas in 2030, 2040, and 2050. Intervening years are not shown to allow easier visual comparisons. The right panel shows the total energy storage capacity that is optimally built in the Reference Case. Comparing results from the left panel with the Reference case buildout provides insights into the value of different storage durations for resource adequacy. When the bar in the left panel is higher than the buildout, this indicates that additional storage capacity at 100% capacity credit could be built but is not cost-effective in the

Reference Case. When the bar in the left panel is lower than the buildout, this indicates that energy storage is cost-effective and is receiving a derated capacity credit in the Reference Case.

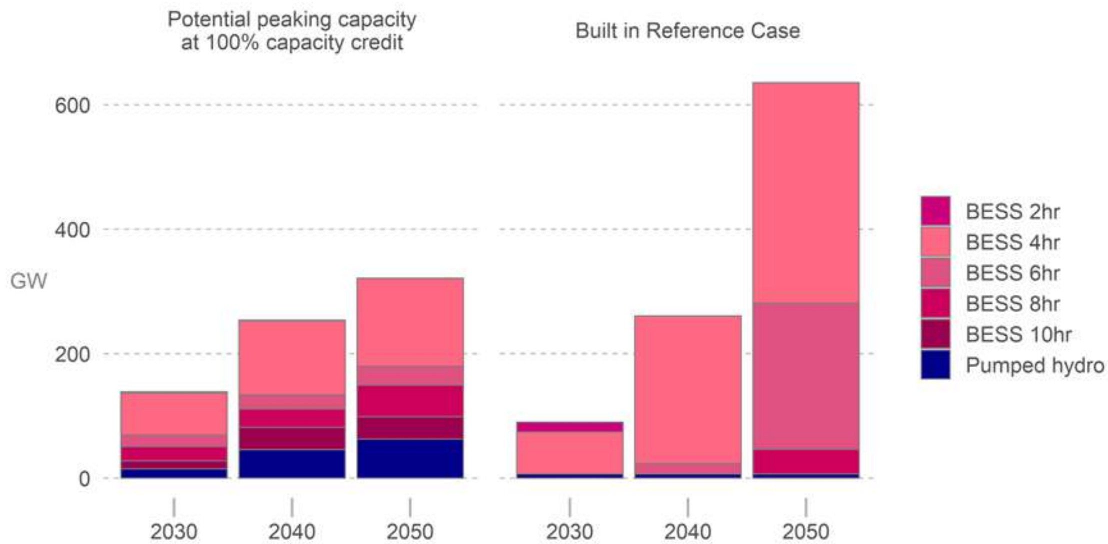

Figure 12. Peaking potential and built capacity for energy storage in the Reference Case

Note: Selected years displayed for ease of visual comparison.

Four-hour BESS has the largest potential to provide peaking capacity with a 100% capacity credit across the entire model horizon. Notably, as shown in the right panel of Figure 12, more 4-hour BESS is built in the model than the peaking potential at 100% capacity credit. This indicates that other factors, including energy-time shifting and operating reserves value, make it economic to deploy 4-hour BESS for purposes other than resource adequacy. The same is true for 6-hour BESS in 2050. Other technologies, including 10-hr BESS and pumped hydro, also have significant peaking potential in the long-term. However, as shown in the right panel of Figure 12, no new l0-hour BESS or pumped hydro is built in the model. This indicates that the value of 10-hour BESS and pumped hydro to provide capacity adequacy does not outweigh other factors such as the cost of investment and availability of other, lower-cost resources that can provide peaking capacity.

Over time, energy storage plays an increasing role in meeting India's capacity reserve margin requirements.[7] Compared to 2020, by 2030, coal-fired capacity still provides the bulk of the capacity reserve margin, but there are growing and significant contributions from diverse resources, including hydro, gas-fired capacity, wind, and solar PV, as well as energy storage, as seen in Figure 13. Energy storage, almost exclusively 4-hour battery storage, provides 15% of the capacity reserve margin in 2030 in the Reference Case. In the longer term, the share of coal in the capacity reserve margin declines as more gas-fired capacity, energy storage, and RE resources are deployed. While the total share of energy storage in the capacity reserve margin increases over time, reaching 31% in 2050, the average capacity credit declines as more storage is deployed, as shown in Table 8. The same trend of declining capacity credits is true for wind

[7] The capacity reserve margin requirement is assumed to be 15% above peak demand in each season.

and solar resources, which provide small additions to the capacity reserve margin despite large growth in total capacity.

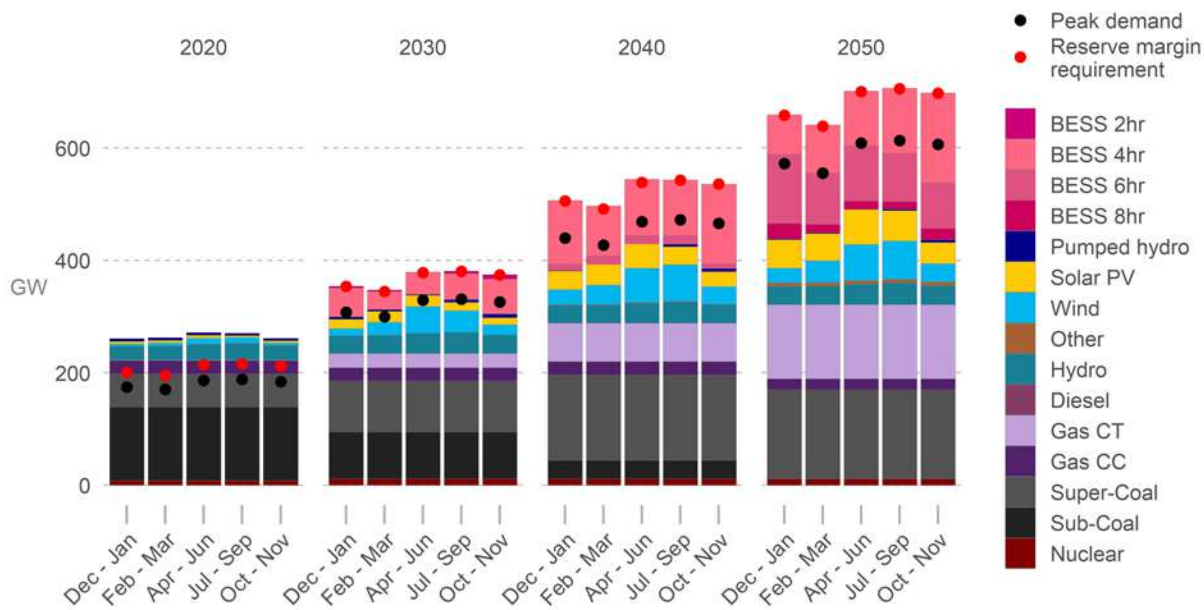

Figure 13. Contribution of different technologies to India's reserve margin by season for select years in the Reference Case

Table 8. Contribution of Energy Storage to the Reserve Margin Requirement

	2030	**2040**	**2050**
Proportion of Reserve Margin Requirement Met by Storage	15%	22%	31%
Total Energy Storage Capacity (GW)	90	260	640
Energy Storage Capacity Contributing to Capacity Reserve Margin (GW)	56	120	220
Average Capacity Credit of Energy Storage	62%	46%	34%

The declining capacity credit of energy storage is an important factor that contributes to the cost-effectiveness of nonstorage capacity resources in the long term. In the Reference Case, nonstorage capacity is primarily provided by new gas-fired capacity. The potential impacts of energy storage capacity credit are explored further in the No ES Capacity Credit scenario in Section 3.3.

Energy Time-Shifting

Energy time-shifting refers to moving low-value energy to high-value periods (otherwise known as energy arbitrage). This can help in reducing RE curtailment, reducing the number of thermal unit starts, and ensuring greater utilization of low-cost generation resources.

To get a detailed view of the opportunities for energy time-shifting in the operational timeframes, we employed the PLEXOS operational model, which allowed for hourly comparisons of energy prices. We calculated energy time-shifting revenue of energy storage as the difference between per-unit revenue received for discharging and per-unit price paid for charging. We found that the energy time-shifting revenue is around $31/MWh in 2030. Figure 14 shows the average daily price differential in each month and the resultant energy time-shifting revenue of energy storage in 2030.

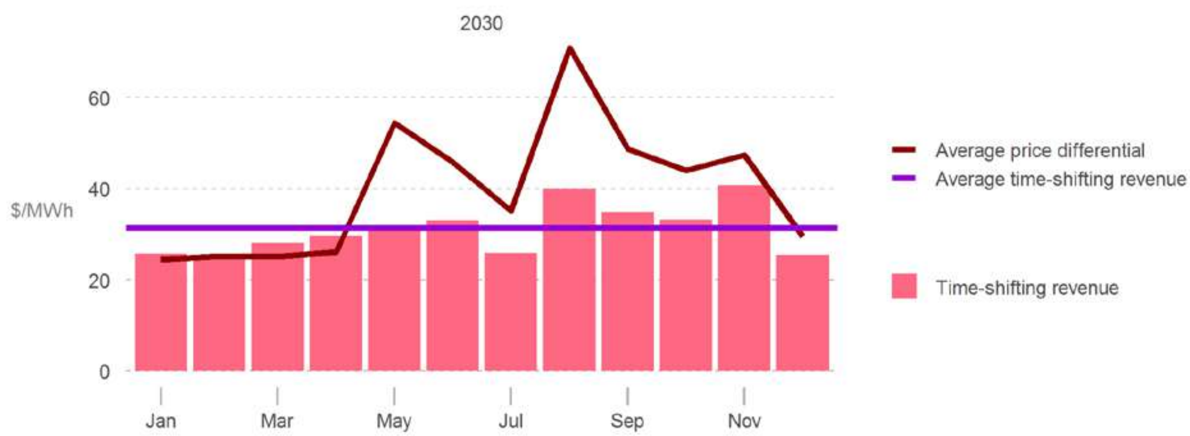

Figure 14. Average energy-shifting revenue for energy storage and monthly average price differential in 2030, Reference Case

We see more energy time-shifting opportunities during June to November in 2030. This seasonal trend is due to higher price differential in these months caused by dispatch of costly gas generation and transmission congestion. This trend also correlates with the actual price differential observed during these months in power exchange prices in 2018 and 2019 (Rose, Wayner, et al. 2020).

We also calculated the energy time-shifting value of energy storage in 2050. We found that the energy time-shifting value varies from $14/MWh to $99/MWh, depending upon whether the transmission constraints were enforced or not. It is important to understand here that the energy time-shifting value is dependent upon the daily price differential. This price differential during any day varies with the level of transmission constraints, variable charges of the costliest marginal generator, and penetration of zero variable charge generation such as solar, wind and hydro. Because a lot of uncertainties are involved in these factors, the numbers presented here should be taken as a possible future scenario that may vary.

Operating Reserves

Another role for energy storage in the power system is to provide ancillary services in the form of operating reserves, which we assumed to be 5% of load procured at the regional level. Providing operating reserves has proven to be a key entry point for recent energy storage development in the United States, in part because of the ability for energy storage to respond rapidly to control signals (Bowen, Chernyakhovskiy, and Denholm 2019). Operations modeling of India showed that energy storage technologies will provide up to 81% of total reserve requirements in 2030, increasing to 97% in 2050 in the Reference Case (see Figure 15). Six-hour storage provides 49% of the total reserve requirements in 2050, whereas 4-hour storage provides a significant share of reserve requirements in both 2030 (70%) and 2050 (39%).

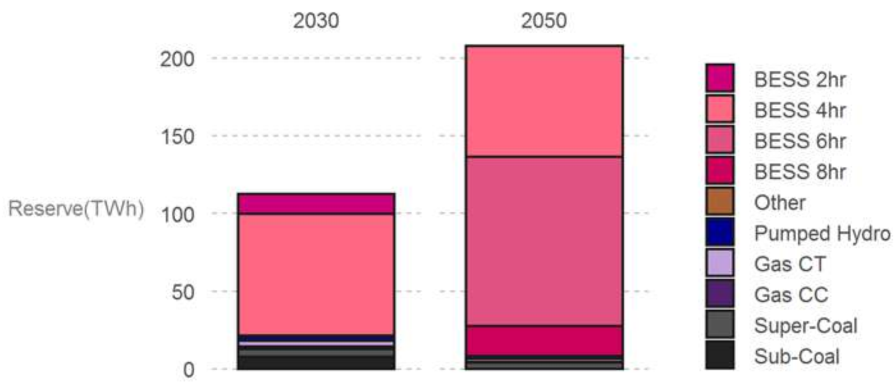

Figure 15. Generation technologies contributing to operating reserves in 2030 and 2050 in the Reference Case

On some days in 2050, energy storage can provide all reserve requirements. Figure 16 shows the reserve provision of one such day when energy storage provides 100% of reserve requirements. Overall, in 2050, energy storage provides more than 85% of reserves in all days and more than 95% of reserve requirements for 63% of the days in the year.

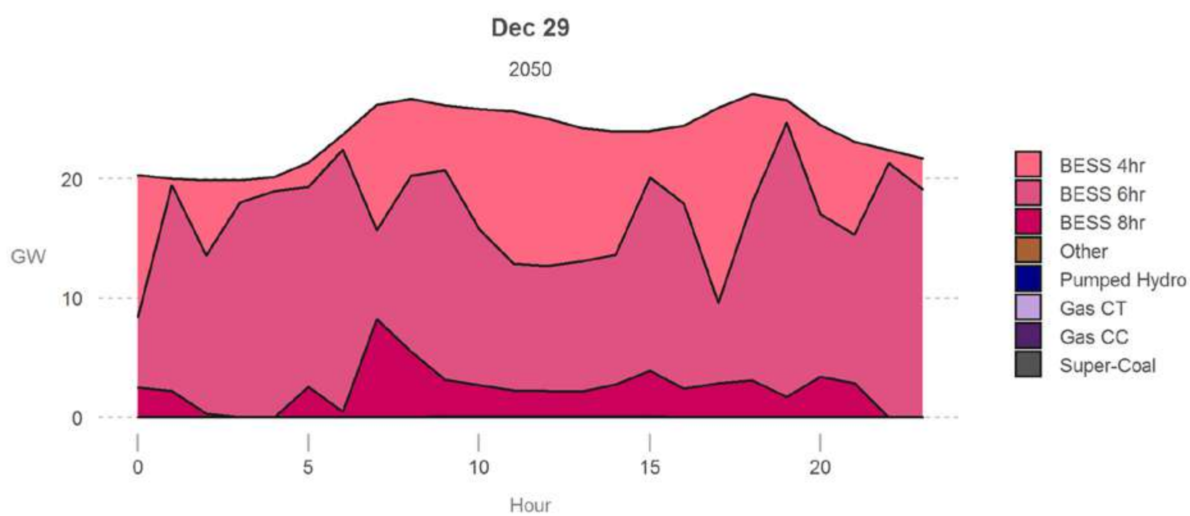

Figure 16. Generation technologies contributing to operating reserves on a day when storage provides 100% of reserve requirements in 2050, Reference Case

Although energy storage provides over 90% of operating reserve requirements in 2050, this service represents a small portion of the overall storage capacity. It can be seen from Table 9 that the capacity factor, or utilization factor, of energy storage for operating reserves goes down from 13% in 2030 to 4% in 2050. The capacity factor for reserve provision is calculated as the ratio of total reserve energy provision and maximum energy it can generate, assuming total capacity generating around the clock. Although energy storage cannot provide generation around the clock at full capacity, this number gives a good indication regarding energy storage capacity utilization for providing reserves.

Table 9. Reserve Provision Capacity Factor (%) for Energy Storage in 2030 and 2050, Reference Case

Type	2030	2050
BESS 2-hr	9.1	-
BESS 4-hr	13	2.3
BESS 6-hr	-	5.3
BESS 8-hr	-	5.7
Pumped Hydro	22	13

3.1.4 How Does the Generation Mix in India Change as Storage Is Deployed?

Solar PV and wind power have the highest growth in installed capacity among generating technologies over the next several decades, with a combined year-over-year growth rate of 40% between 2022 and 2050. Figure 17 shows the deployment of generation capacity through 2050 in the Reference Case.[8] Solar PV sees particularly high growth from the mid-2030s to the late 2040s. Wind grows rapidly from the mid-2020s to the mid-2030s, after which deployment levels off around 330 GW. There is a dip in wind capacity in the 2040s when many existing wind power plants are retired at the end of their economic life, although new deployments make up for retirements by 2050. There are no economic investments in hydropower or nuclear capacity beyond planned additions, reaching 54 GW and 11 GW in 2023, respectively. We also see relatively small increases in biomass and waste heat recovery capacity in later years, reaching a combined 6.5 GW in 2050 (not shown in Figure 17).

Reference Case results show gas-fired plant capacity growing significantly, both in the near term and long term. All new gas-fired capacity is simple cycle combustion turbine technology. These are peaking units that are designed to run for a small percentage of the year. There is also 24 GW of existing combined cycle gas that begins to retire in the 2030s, falling to less than 20 GW by 2050.

[8] The Reference Case includes RE capacity targets of 175 GW by 2022 and 450 GW by 2030.

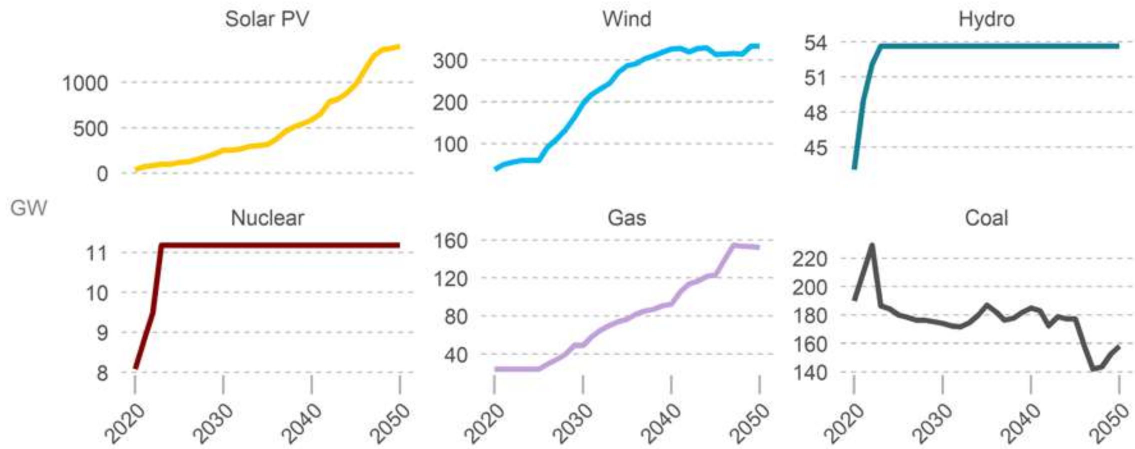

Figure 17. Deployment of generating technologies in India to 2050, Reference Case

Note difference in y-axis scales. Plot does not include biomass.

Total installed capacity in India reaches 2,700 GW by 2050. Figure 18 shows the installed capacity (Panel A) and the capacity mix (Panel B) by technology through 2050, and Table 10 provides numbers for select years. Solar PV represents the largest share of the capacity mix in the long term, with 1,400 GW found to be cost-effective by 2050 in the Reference Case.

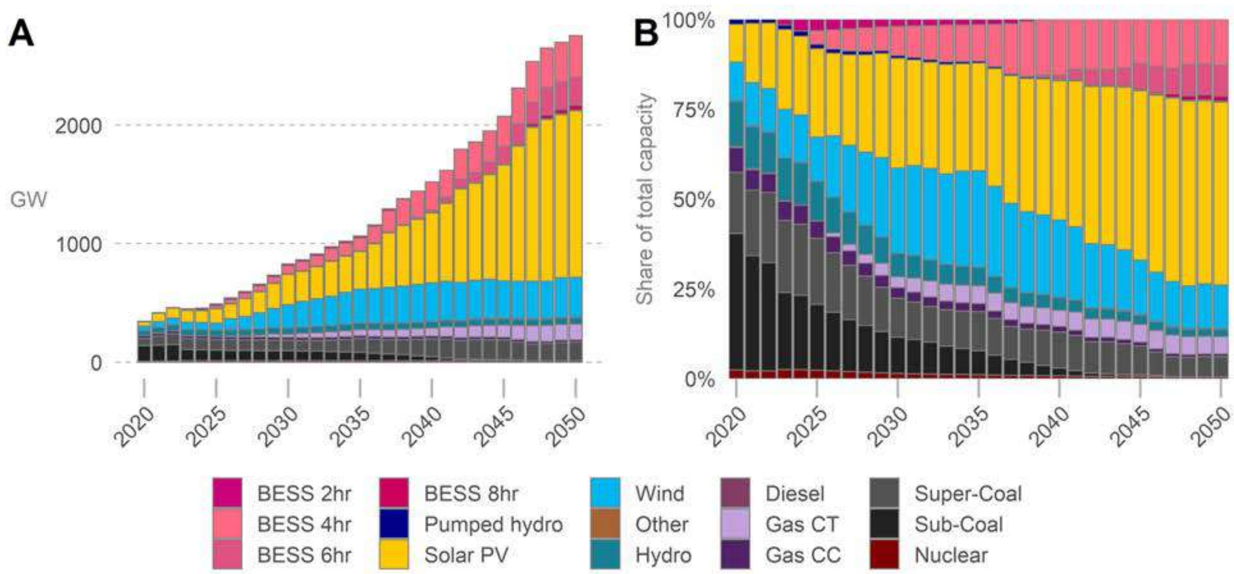

Figure 18. Reference Case installed capacity (A) and capacity mix (B)