Table 10. Capacity of Generation Technologies in India for Select Years, Reference Case

	2020		2030		2040		2050	
Technology	**GW**	**Share of Installed Capacity**	**GW**	**Share of Installed Capacity**	**GW**	**Share of Installed Capacity**	**GW**	**Share of Installed Capacity**
Solar PV	37	11%	250	31%	590	47%	1,400	51%
Wind	37	11%	200	24%	330	22%	330	12%
Hydro	43	12%	54	6.5%	54	3.5%	54	1.9%
Nuclear	8.1	2.3%	11	1.4%	11	<1%	11	<1%
Gas	24	7%	49	5.9%	49	6.1%	150	5.5%
Coal	190	55%	170	21%	180	12%	160	5.7%

Finally, we see several major expansions of interstate transmission capacity by 2050. Figure 19 depicts the transmission investments between 2020 and 2050 in the Reference Case.

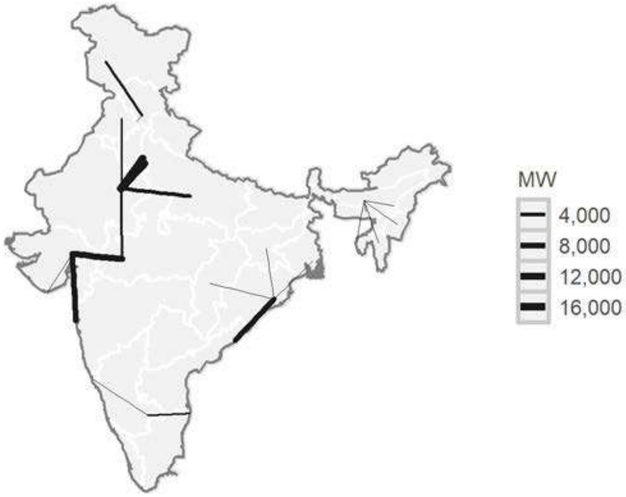

Figure 19. Transmission capacity investments through 2050, Reference Case

The bulk of new transmission investments are in the Northern region. Rajasthan and Gujarat see the most investments in new transfer capacity with neighboring states, which is needed to evacuate solar energy. Jammu and Kashmir also has increased transfer capacity with Himachal Pradesh to evacuate solar energy to high-demand states. We also see substantial investments in transmission between the Southern region and Northern region via the Gujarat-to-Maharashtra corridor, and the Southern region and Eastern region via the Andhra Pradesh-to-Odisha corridor.

3.2 How Will System Operators Utilize Energy Storage?

Storage operations change over time as the generation mix evolves and energy storage proliferates. To understand how storage resources will be optimally utilized in operations (i.e., commitment and dispatch) we used the hourly operations from the PLEXOS operations model. Results for 2030 showed that energy storage charges during the middle of the day and discharges primarily during morning and evening peaks. The energy storage utilization becomes more consistent in 2050 where storage again charges during the middle of the day but discharges through the peaks and into the nighttime hours. In both model years, energy storage followed a seasonal pattern of charging during earlier daylight hours in the summer months.

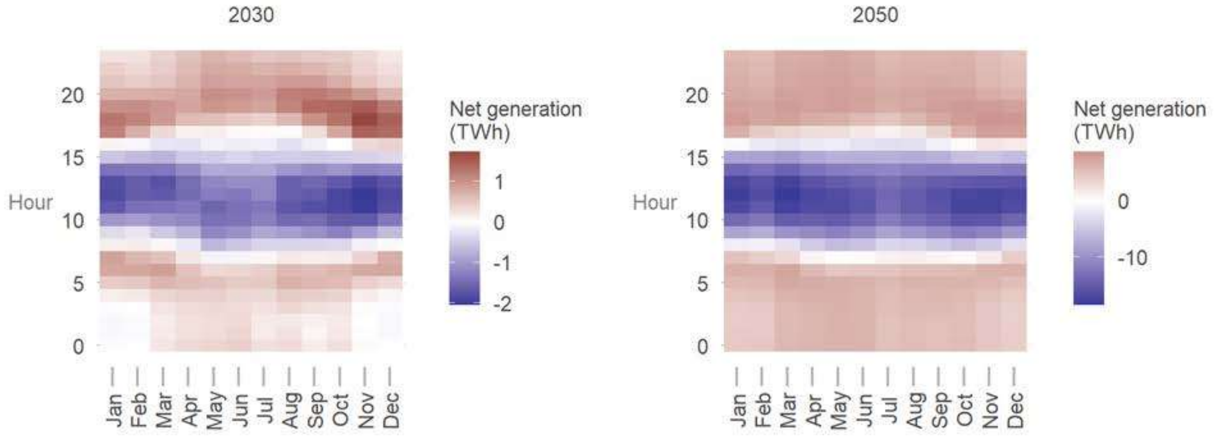

Figure 20. Diurnal monthly charging and discharging pattern for storage in 2030 and 2050, Reference Case

Note: Cells represents average net generation for the combined storage capacity (charging-discharging).

The shifting patterns of utilization between 2030 and 2050 are enabled by longer-duration energy storage that becomes economic in the late 2030s. In 2030, besides the 6.2 GW of PSH, the largest source of storage is 4-hour BESS. By 2050, PSH still has 6.2 GW, but there are now 275 GW of battery storages with 6 hours or more. This shift to longer durations allows energy storage to discharge longer into the nighttime hours and play more of a load-following role in 2050 as opposed to the peaking resource seen in 2030.

Another indicator about the operational requirements from storage is the number of operational cycles and starts per day. Cycles are related to degradation of energy storage; therefore, it is expected that metrics of cycling will be of interest to developers and operators going forward (Smith et al. 2012). We found that, on average, storage devices performed less than one full operational energy cycle per day in all months, both in 2030 and 2050. One full operational cycle means storage is providing generation corresponding to its total energy storage capacity.

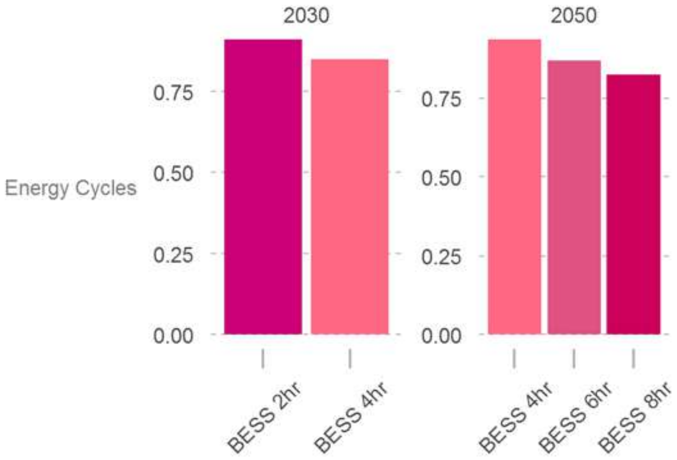

Figure 21. Average energy cycles per day for storage in the Reference Case

We observe that the average daily starts of storage devices (excluding PSH) increases from 3 in 2030 to 4 in 2050. Although additional constraints can be included in the model to limit the number of starts, it is important to understand the unconstrained needs of the system. This will provide useful indications for development of storage devices in the future.

3.2.1 What Role Does Energy Storage Play in Day-to-Day Operations in 2030?

Energy storage supports the system by providing balancing services and helping integrate more RE generation by avoiding curtailment through energy time-shifting. It does this in part by bolstering ramping capabilities to meet net load ramp requirements. Figure 22 shows the dispatch on one of the highest net load ramp days in 2030. The maximum net load ramp of around 60 GW occurs at 1700 hrs. The BESS and PSH is charging during the middle of the day and discharging mostly during the evening peak time, but also during the morning ramp up in load.

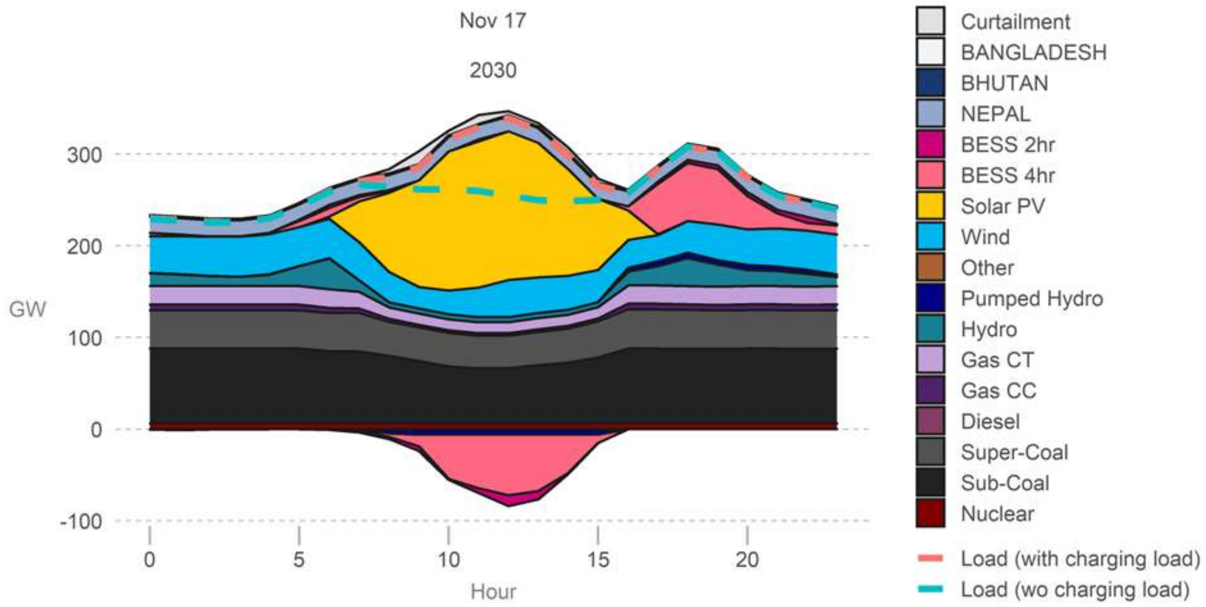

Figure 22. Dispatch stack for one day with the highest net load ramp in 2030

Note: Generation below zero indicates that energy storage is charging. Load (with charging load) includes the charging of energy storage from the grid as a load. Load (without charging load) only includes the demand from electricity customers.

Ramp rate analysis of the same day revealed that storage provided a majority of the ramping requirements throughout the day (see Figure 23).

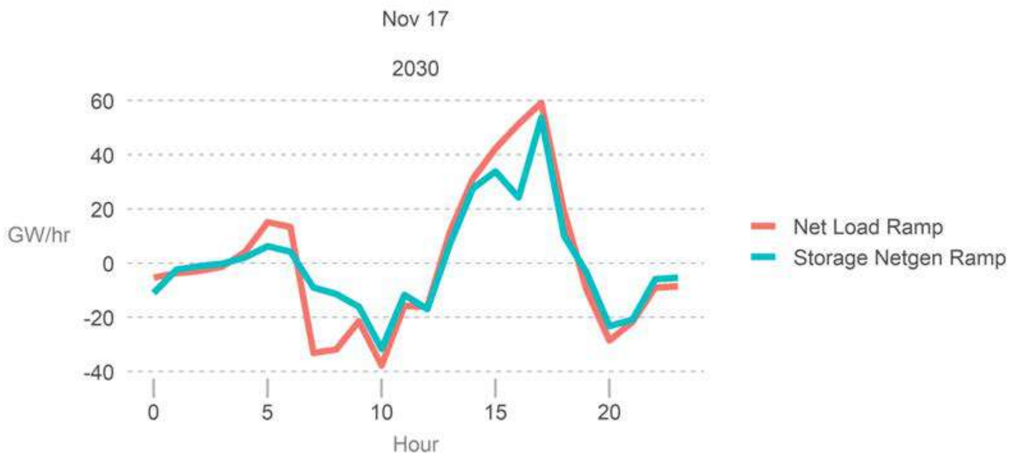

Figure 23. Comparison of net load ramp and storage net generation ramp during the day with highest net load ramp in 2030 Reference scenario

The correlation between the hourly net load ramp and storage net generation ramp was also consistent throughout the year (Figure 24) with an annual correlation of 0.95.

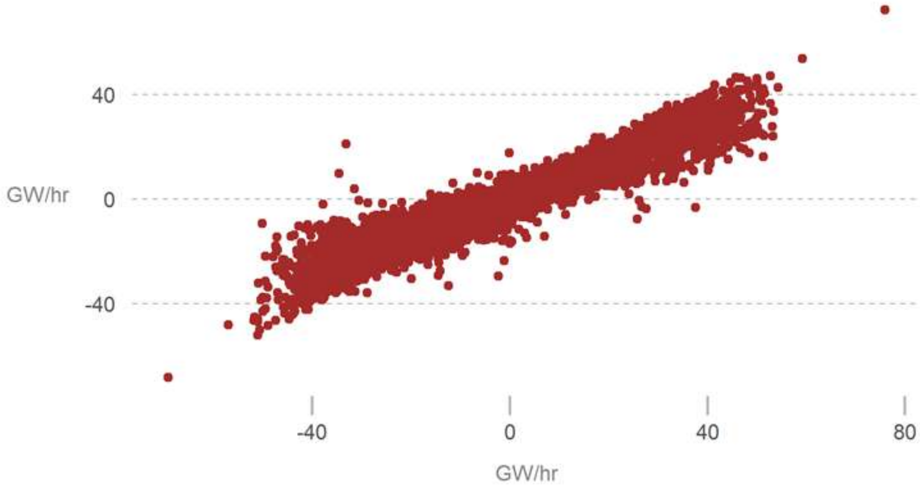

Figure 24. Daily correlation between net load ramp (x-axis) and storage discharge ramp (y-axis) in 2030 Reference scenario

Storage can also help system operators in absorbing more RE to lower the costs of operations. Figure 25 shows the dispatch stack for May 5, 2030. Typically, storage is charged during the daytime and helps to shift energy to the evening hours when it is needed. This impacts the whole generation stack, while at the same time allowing a greater absorption of solar energy, decreasing the backdown requirements of coal, and reducing the potential need for more thermal peaking resources. Additionally, on this day, some energy storage continues charging during the evening peak time to accommodate more wind in the system.

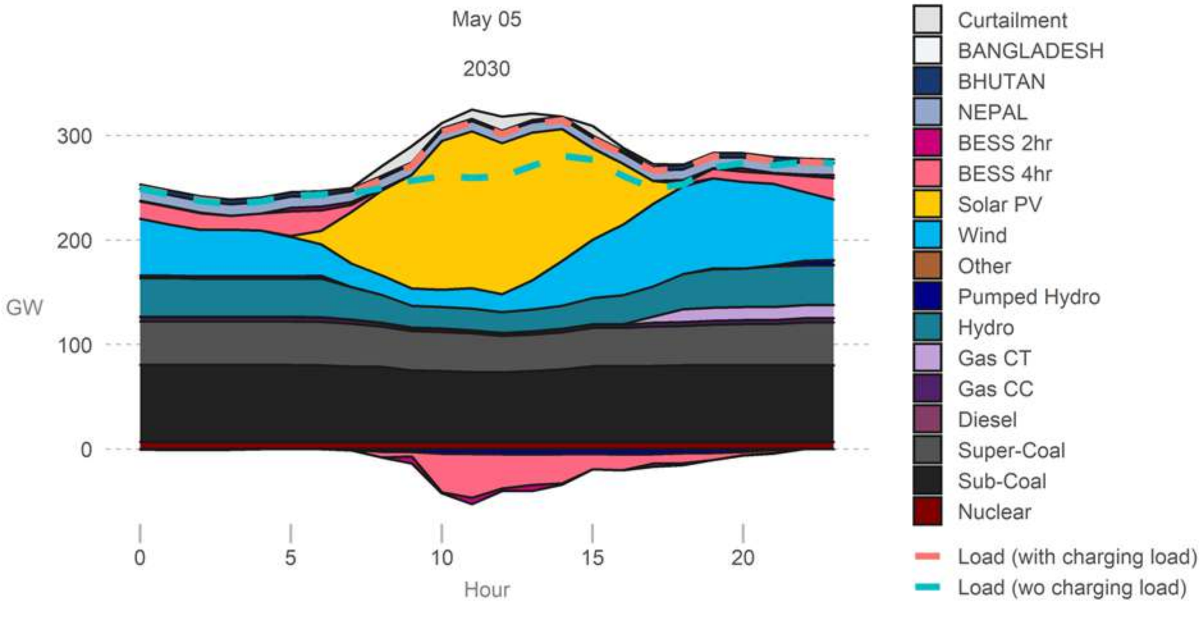

Figure 25. Dispatch stack of one day in 2030 when storage helps absorb more RE

Energy storage can also support balancing the RE variability. In Figure 26, storage devices continue discharging in the morning hours, after the start of solar generation, to compensate for the variability of wind generation. At 0800 hrs, wind generation reduces by 28 GW, which is partially compensated by storage devices helping the system mitigate this supply-side variability.

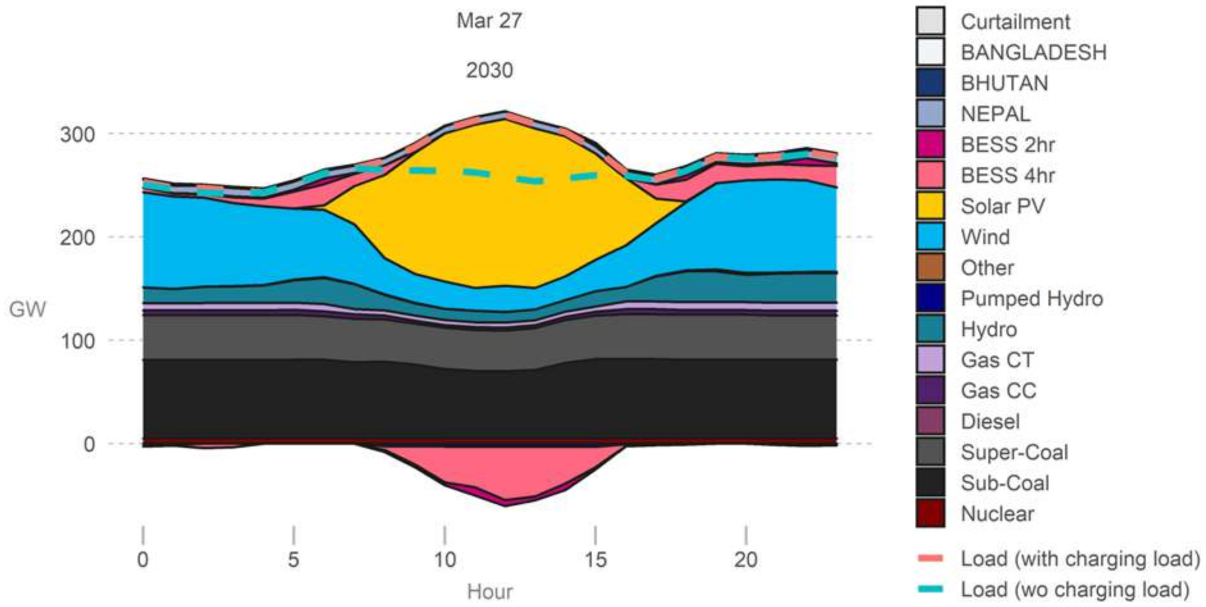

Figure 26. Dispatch stack of one day in 2030 when energy storage helps manage variability of RE

3.2.2 What Role Does Energy Storage Play in Day-to-Day Operations in 2050?

Energy storage, along with other non-fossil fuel energy resources (solar, wind, hydro and nuclear), can meet the bulk of energy requirements in 2050, supplying more than 80% of the total generation annually.[9] For 10% of the days in the year, the penetration of non-fossil fuel energy resources is greater than 90%. And on some days, these resources can provide almost 100% of energy requirements, as seen during a week of September (Figure 27). Ramping support from energy storage is especially critical in 2050, providing the bulk of ramping needs for the system.

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[9] This study did not evaluate the inertia requirements and the impact of high penetration of inverter-based resources on the dynamic stability of the transmission system, which is an area for further research.

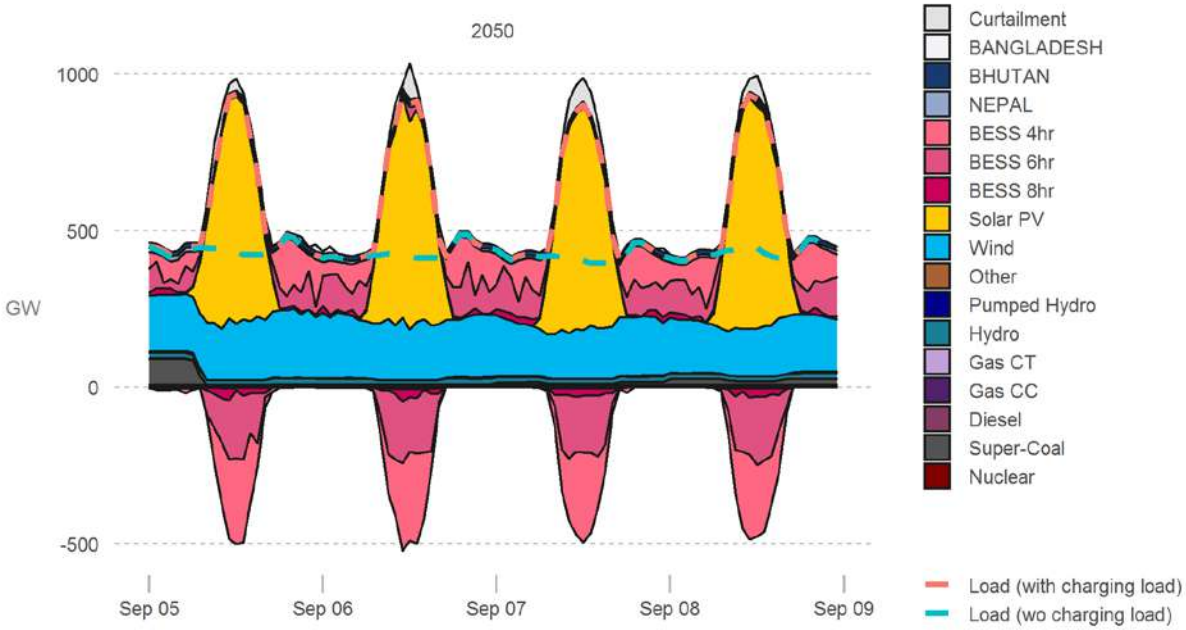

Figure 27. Dispatch stack of four days in 2050 when non-fossil fuel sources provide close to 100% of energy requirements, Reference Case

Energy storage provides most of the balancing for the 2050 Reference Case. Solar energy is largely coincident with ramping requirements; however, the flexibility gained from energy storage during ramping periods in the morning and evening plays a critical role. Additionally, the longer duration storage from PSH, BESS 6- and 8-hour is providing the energy requirement through the night. Four-hour storage also continues to discharge through the night. The typical operations scheme for storage is to charge for 8–10 hours in the middle of the day and then discharge for 12–14 hours until the morning ramp up in load. Figure 28 shows the operations of different durations of BESS for two states, Gujarat and Odisha.

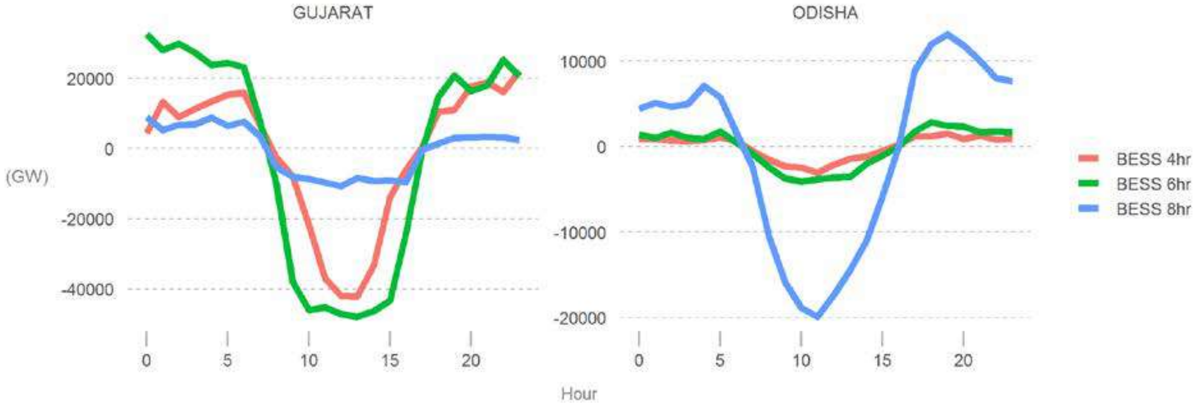

Figure 28. Average storage operations for Gujarat and Odisha during April–June in 2050

3.2.3 Storage Helps in Balancing RE Forecast Errors

Energy storage can play a key role in balancing RE forecast errors. We study this aspect by running a day-ahead and real-time operational scenario. The day-ahead scenario is run with hourly RE forecast values. The results from the day-ahead scenario are passed to real time with actual 15-minute RE profiles. The mean absolute error between day-ahead forecast and real-time generation for utility solar PV, distributed PV, and wind in the model was 1.73%, 1.83%, and 5.71%, respectively. In our PCM, the commitment of coal, combined cycle gas, and hydro unit commitment was fixed in the real-time model based on the day-ahead optimization. There are three primary modes of flexibility to manage balancing in the real time: (1) storage redispatch, (2) thermal unit redispatch, (3) quick-start unit (e.g., gas combustion turbines) commitment and dispatch, and (4) curtailment of RE.

A sample day shown in Figure 29 indicates the role of energy storage in balancing RE forecast errors. During the morning hours when there is a negative forecast error in real time, storage increases its discharge to balance the deficit. Similarly, during the afternoon, storage charges to manage overgeneration. A similar pattern is observed during the evening when storage discharges to compensate for reduced RE generation. The role of energy storage in balancing RE forecast errors was found to be consistent throughout the year.

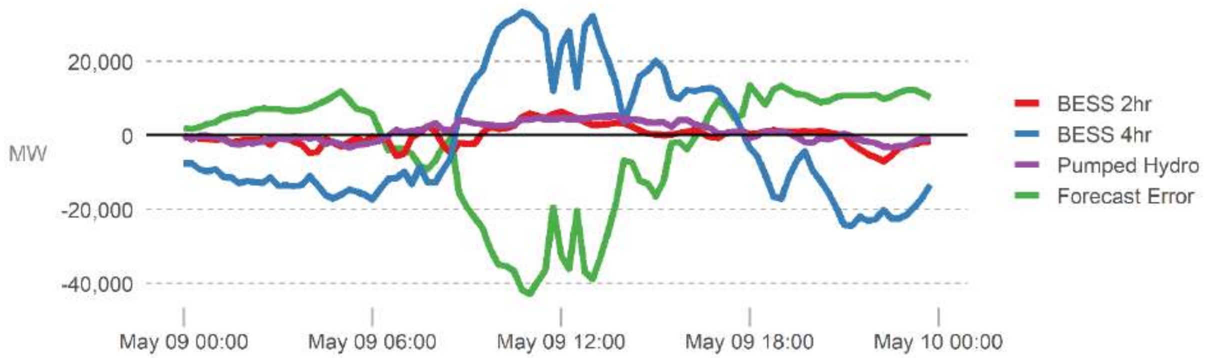

Figure 29. Change in storage dispatch to balance RE forecast error during one day in 2030

3.3 What Are the Regulatory Drivers for Energy Storage Opportunities?

We used scenario analysis to understand how regulations that enable energy storage to provide various grid services impact energy storage investment potential. Figure 30 shows the evolution of energy storage capacity in India from 2020 to 2050 under the Reference Case and three scenarios that vary the regulatory environment.

Electricity sector regulations establish what types of electricity technologies can provide different grid services and receive compensation for those services. To determine an appropriate compensation scheme, utilities and regulators need agreed-upon methods to identify the value that technologies, including energy storage, will provide to the power system. Because energy storage is a novel technology, utilities and regulators may need to further develop tools and expertise to assess the full value that energy storage can provide. The goal of the regulatory scenarios is to indicate which regulations might be best suited for innovation to enable a fair environment for energy storage. In the case of a market-based electricity sector, utilities and independent power producers rely on market prices to reflect the value of different grid services. However, market regulations may exclude (either explicitly or by omission) energy storage from participating in certain markets. In practice, the electricity sector has a mix of cost-of-service tariffs and market-based products that may or may not reflect the full value that different technologies provide to the power system. In India, while most grid services are compensated through cost-of-service tariffs, there is increasing interest in moving toward market-based products (The Financial Times 2020).

The three scenarios discussed in this section provide insight into potential consequences of undervaluing energy storage for specific services and/or excluding energy storage from participating in markets for certain grid services (see Table 1 for scenario descriptions). By design, the scenarios represent extreme or “edge” cases in which energy storage does not receive any value or compensation for the service under consideration.

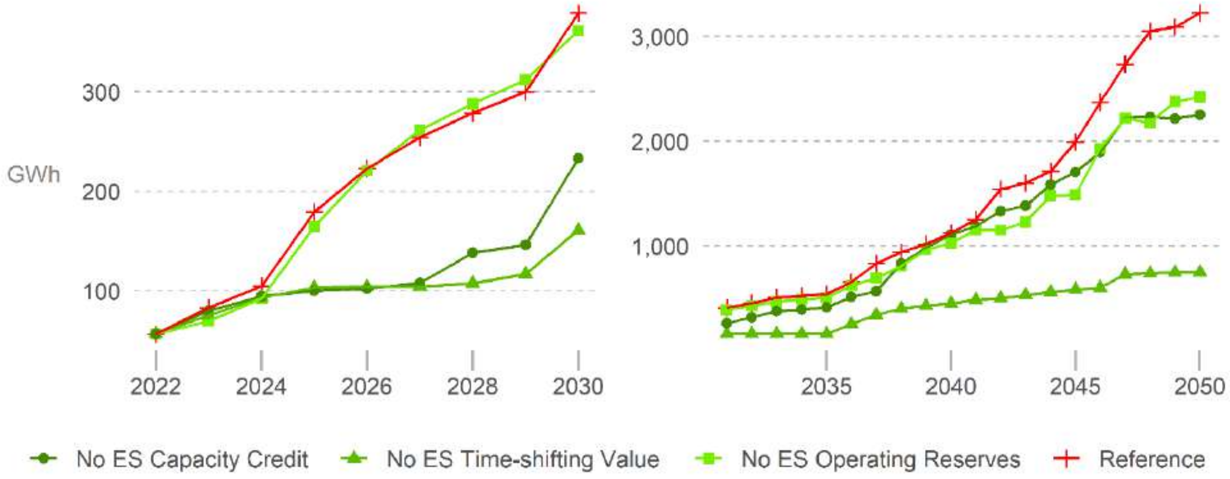

Figure 30. Energy storage capacity under regulatory scenarios through 2030 (left) and 2050 (right)

Note: Y-axis scale changes between left and right panels.

The ability of energy storage to receive compensation for energy time-shifting (i.e., buy low, sell high) has the largest impact on both near-term and long-term storage deployment. By 2030, the energy capacity of storage technologies is 57% lower in the No ES Time-shifting Value scenario compared to the Reference Case and 76% lower by 2050. This scenario represents an environment in which energy storage projects are not able to monetize (i.e., receive revenue) for the time-shifting service that they provide to the grid. This scenario could happen in a contract structure in which a single tariff does not correctly account for the changing price of energy throughout the day.

When energy storage does not receive time-shifting revenue, the investment and operating costs of energy storage projects must be covered with other services to make the investment cost-effective. Because time-shifting is a significant source of value for energy storage in India (see Section 3.1.3), removing this value stream significantly limits the investment potential for storage technologies. Moreover, removing the energy time-shifting value stream for storage has significant impact on the long-term capacity and generation mix in India. Figure 36 shows the difference in capacity and generation in the No ES Time-shifting Value scenario relative to the Reference Case.

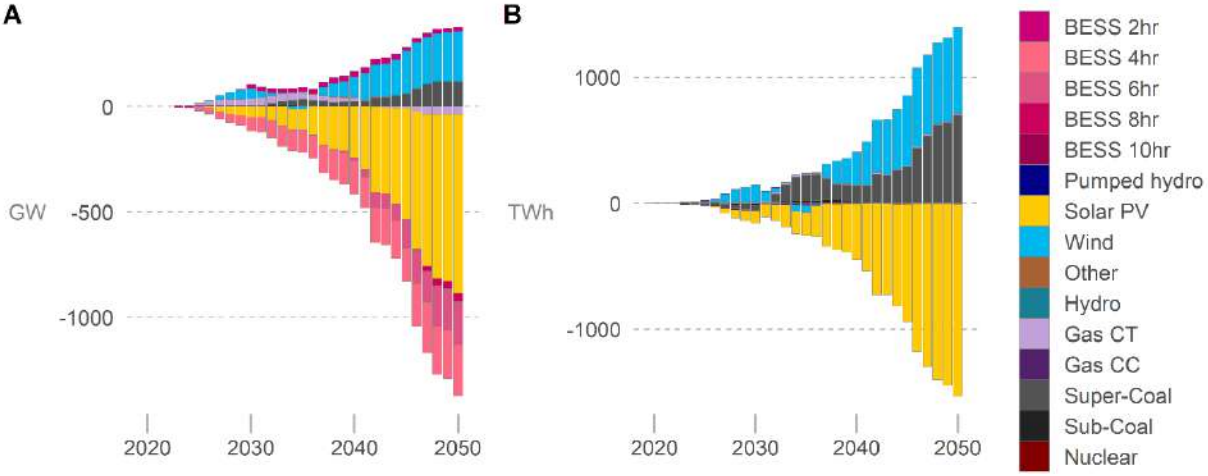

Figure 31. Difference in capacity (A) and generation (B) in the No ES Time-Shifting Value scenario relative to Reference Case

Solar PV deployment is substantially lower by 2050, decreasing 60% from 1,400 GW to 550 GW. In the long term, with less cost-effective energy storage and solar PV, a combination of wind and supercritical coal capacity are deployed to offset reduced generation from solar PV. Notably, new investments in coal increases the national coal capacity to 280 GW by 2050, up from 160 GW in the Reference Case, and generation from coal-fired capacity increases by 120% in 2050. This results in a 120% increase in CO_2 emissions in 2050, more than doubling relative to the Reference Case, and a 20% increase in total CO_2 emissions from the power sector between 2020 and 2050. Emissions in the regulatory scenarios are discussed in greater detail below.

The No ES Capacity Credit scenario also had a significant impact on the results, with 38% less energy storage deployed by 2030 and 30% less by 2050 compared to the Reference Case. Without a revenue stream for their contribution to capacity adequacy, the investment potential for energy storage is reduced. While energy storage is technically capable of providing reliable capacity, evaluating its contribution to the planning reserve margin requires a systems-level approach. This is because the capacity contribution of energy-limited storage depends on the shape of net demand during peak (or possibly other high stress times), which may change over time as new wind and solar resources are added to the grid as demand evolves. Other factors, including the availability of other peaking resources and the state of charge of the storage device, also impact the capacity contribution.

The No ES Capacity Credit scenario evaluated the impact of reducing the capacity credit of energy storage technologies to zero. When energy storage is not allowed to contribute toward the power system's capacity adequacy requirement, other resources are needed to meet the planning reserve requirement, as seen in Figure 32.