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Developing a roadmap to a flexible, low-carbon Indian electricity system

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February 2020

ENERGY TRANSITIONS COMMISSION INDIA

A CPI Energy Finance report

Acknowledgements

This paper has been produced by the Energy Finance team at Climate Policy Initiative (CPI EF) as part of the first year of a programme run by the Energy Transitions Commission (ETC) India undertaken in collaboration with The Energy and Resources Institute (TERI) and the National Renewable Energy Lab (NREL).

Insights contained in this paper represent CPI EF's findings based on demand and supply scenarios published last year by TERI Analysing and Projecting Indian Electricity Demand to 2030 and Exploring Electricity Capacity Scenarios to 2030: Scenario Framework.

We are grateful for the support of our sponsors and partners, ETC India, Hewlett Foundation, Children's Investment Fund Foundation, TERI and NREL. We would also like to acknowledge the support from multiple stakeholders we engaged with throughout the development of the analysis and who took part in the meetings and workshops, including the Ministry of Power, Ministry of New and Renewable Energy, Central Electricity Authority, Central Electricity Regulatory Commission, Power System Operation Corporation, NTPC, Tata Power, Siemens and BSES.

The findings in this paper reflect the analysis conducted by CPI Energy Finance. An interim version of this paper was published in February 2019. Special thanks goes to Brendan Pierpont, formerly a principal at CPI Energy Finance.

Descriptors

Keywords Renewable energy, flexibility, solar, wind, thermal, demand response, energy storage

Region India

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About CPI

Climate Policy Initiative works to improve the most important energy and land use policies around the world, with a particular focus on finance. An independent organization supported in part by foundation funding, CPI works in places that provide the most potential for policy impact including Brazil, China, Europe, India, Indonesia, and the United States. Our work helps nations grow while addressing increasingly scarce resources and climate risk. This is a complex challenge in which policy plays a crucial role.

CPI's Energy Finance practice is a multidisciplinary team of economists, analysts and financial and energy industry professionals focused on developing innovative finance and market solutions that accelerate the energy transition.

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Executive summary

Decarbonisation of electricity and significant expansion of it as an energy resource are two of the most important tasks in mitigating climate change and meeting international greenhouse gas emission reduction targets[1]. In our analysis for the Energy Transitions Commission[2] in 2017, we demonstrated the feasibility and critical importance of improving electricity system flexibility in order to decarbonise electricity supply systems at a reasonable cost. The need for additional flexibility, the mix of available options, and their relative cost is highly dependent upon regional circumstances including weather, energy resources and demand patterns. Thus, the conclusions of the 2017 report, and the policies and incentives to deliver the options, need refinement at the national and regional level.

In India, increasing flexibility resources from its powerplants, energy storage and demand response has strong potential to help build low-carbon electricity systems. In fact, our analysis suggests that flexibility in India could reduce total system electricity supply costs by up to 5% on average, while improving the quality of supply. Further, if India achieves higher levels of flexibility, it will significantly increase the rate of deployment of renewable energy at little or no extra cost.

In other words, a low-carbon Indian electricity system with higher flexibility levels is significantly less expensive than the existing energy mix with current levels of flexibility.

Additionally, this report finds that flexibility needs will grow much faster than energy demand in India under any probable renewable energy deployment path. A shortage of flexibility could soon impede energy system growth and put at risk recent progress India has made to reduce involuntary load shedding and improve power quality. However, the report also finds that India has many potential flexibility options that could meet these growing needs, but electricity markets, infrastructure, technology and business models need to adapt and develop to access these options effectively. This development needs to start now to ensure that the options are available as the need arises.

Finding 1: In India, flexibility needs are growing much faster than energy demand

Electricity system flexibility is not a single resource, but rather, a collection of actions across different time frames. In our work, we define four main categories of flexibility, with locational flexibility as a fifth category:

- **Short-term reserves and load following**. Electricity systems need access to standby

What is electricity system flexibility and why is it important?

Electricity supply and demand must be matched instantaneously at each moment of each hour, every day of the year. Failure to do so causes more than just flickering lights. Spikes in electricity supply voltage and frequency damage equipment, close factories, and can cause electricity transmission systems to become unstable and fail, leading to blackouts and damage to infrastructure, and industrial and consumer equipment.

Historically, most electricity systems have been managed by increasing or decreasing output from hydro or thermal generators in response to changing demand. When a greater share of electricity demand was from continuous loads such as industry, this process was relatively easy. As the share of demand from residential and commercial consumers has grown, overall demand has become more variable. As a result, thermal powerplants have had to work harder, ramping output up and down, to match demand. Meanwhile, many of the low carbon energy supply options, including wind, solar, run-of-river hydro, and even nuclear, create more system challenges as their output varies with wind, rain or sunshine. In India, thermal plants have already reached limits on how fast they can ramp up or down, or how much electricity they can shift from one part of the day to another within current contractual agreements and operational practices, leading system operators to curtail excess supply.

Yet with the right incentives, power plants can make investments and change operating practices to become more flexible, demand can begin to respond to energy supply availability, and storage can be built to optimise this matching process.

1 Better Energy, Greater Prosperity, Energy Transitions Commission (2017) http://www.energy-transitions.org/better-energy-greater-prosperity

2 Flexibility: the path to low-carbon, low-cost electricity grids, Climate Policy Initiative Energy Finance (2017) https://climatepolicyinitiative.org/publication/flexibility-path-low-carbon-low-cost-electricity-grids

capacity that is ready to increase or come on-line instantaneously if there is a sudden powerplant or transmission outage, or demand surge. The increase in variable renewable energy has the least impact on this type of reserve, since needs are driven by the largest potential failures on a system, which are often large thermal powerplants or transmission lines or demand events.

- **Ramping** is the speed at which supply resources can increase or decrease to meet changes in demand from one minute to the next. Declining solar energy production in the evening, the very time that Indian households turn on the lights, cooking appliances and air conditioners, leads to significant increases in ramping needs at the evening peak.
- **Daily balancing** is the requirement to shift energy production (or demand) from one part of the day to another. Increased solar production during the day combined with increased air conditioning demand in the evening increases the need to shift energy from the day to the evening.
- **Seasonal balancing** is the requirement to shift energy (or demand) from one time of the year to another. In many countries seasonal balancing is related to winter heating demand or summer air conditioning demand or the seasonality of solar production. In India, the variation in solar production and even air conditioning (or heating demand) is relatively smaller than in many other countries. However, the variability of both demand and production from wind generation during the monsoon season creates a large monsoon driven seasonality in many regions of India.

Figure ES-1: Growth in flexibility needs

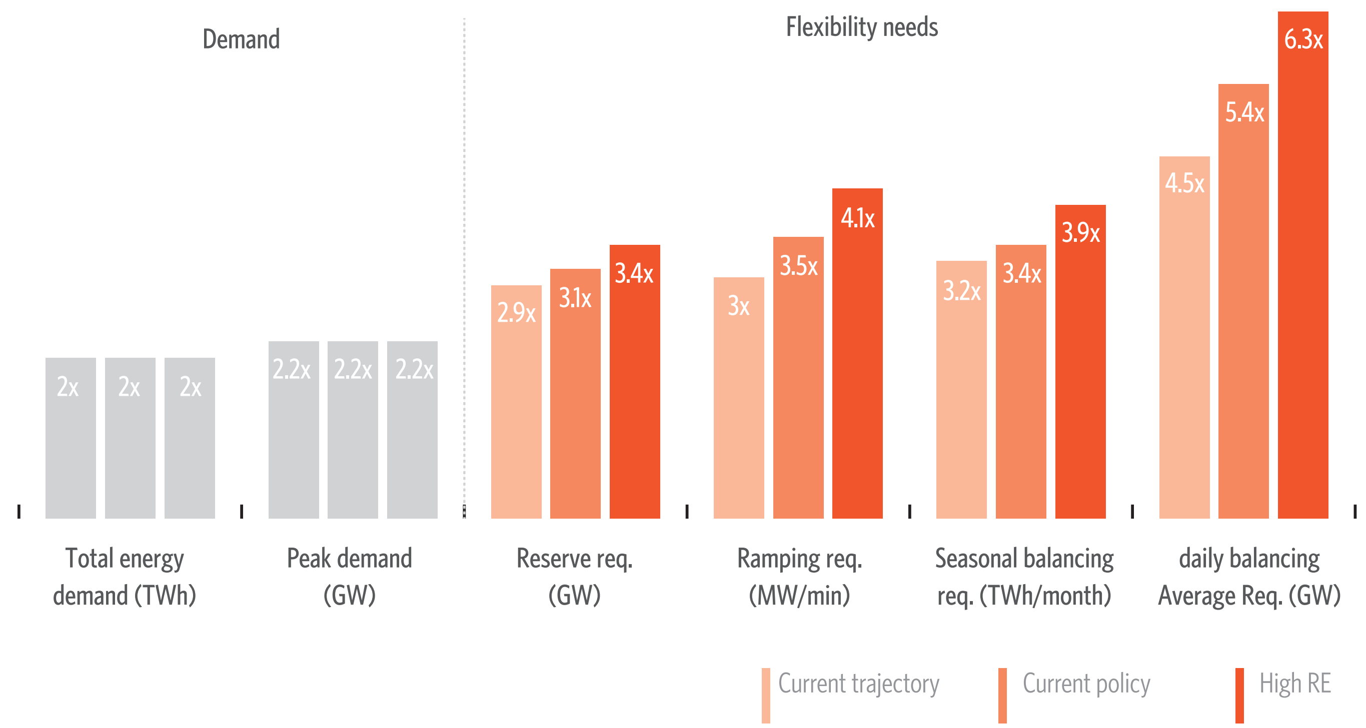
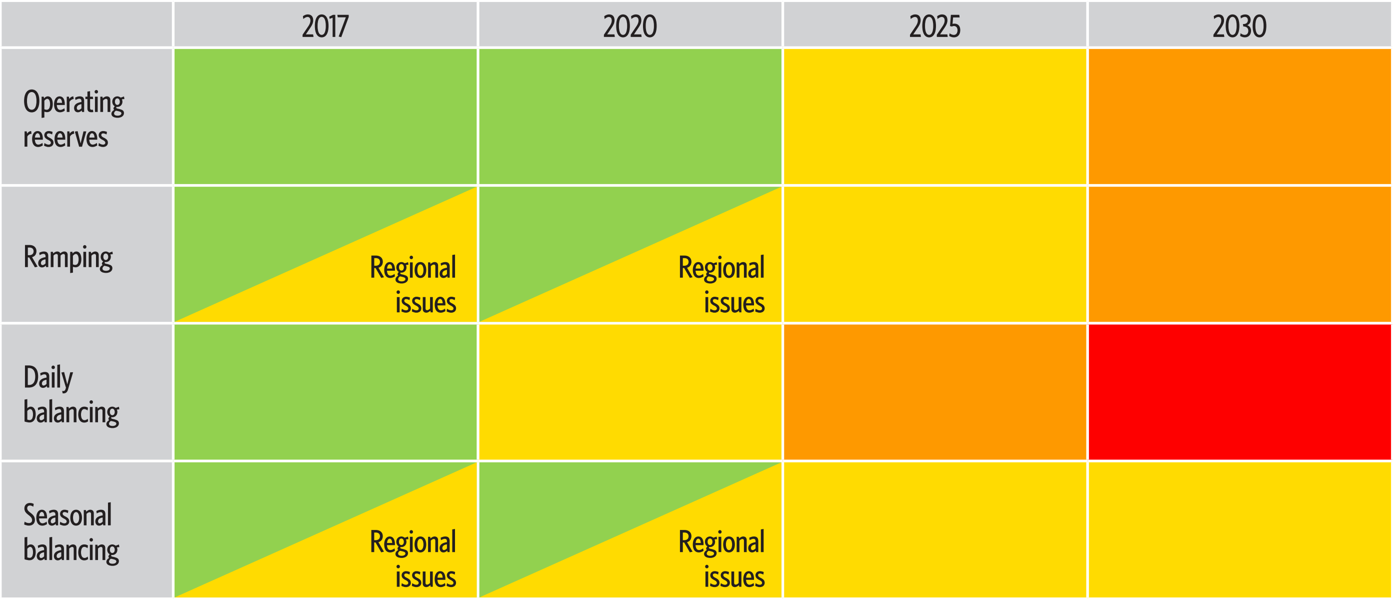


Figure ES-1 shows how each of these four categories of flexibility needs will increase in India under different renewable energy scenarios between now and 2030. The **current trajectory scenario** maintains current renewable energy growth rates, the **current policy scenario** assumes that India meets current policy targets, while the **high renewable energy scenario** assumes that India accelerates renewable energy deployment in line with increased climate mitigation objectives. In the latter scenario, many of the flexibility needs grow two to three times faster than electricity demand.

Figure ES-2: Without additional resources, flexibility will become a serious constraint in the near future under a high renewable scenario



Finding 2: Without additional resources, flexibility will become a serious constraint in the near future

Building on demand growth and load shape forecasts, and matching against existing flexibility resources, our modelling indicates, as in Figure ES-2 above, that India needs more of all types of flexibility by 2025, that under the high renewable energy scenario, India needs more of all types of flexibility by 2025, with daily balancing becoming critical by 2030. Today, India is beginning to experience challenges at a regional level, including fast increasing ramping needs in states like Karnataka due to high solar energy penetration, and significant seasonal flexibility needs in Tamil Nadu due to monsoons and large wind energy capacity.

Finding 3: India has many potential flexibility options that can be developed in time to meet these future needs

Our analysis addresses three main categories of flexibility option:

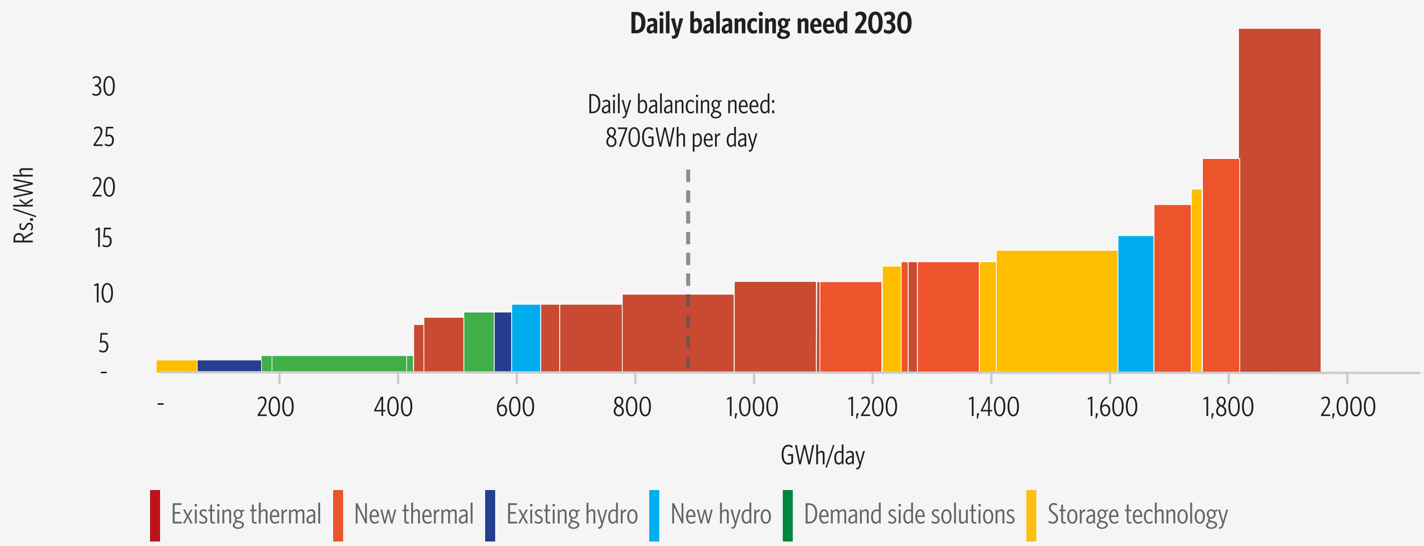
- **Demand side flexibility:** Improving the ability of consumers to modify their demand in ways that could help the system match electricity supply to demand;
- **Powerplant flexibility:** Technical, economic, and contractual solutions to improve the responsiveness of powerplants to variations in demand and renewable energy output;
- **Storage:** Including battery and other storage options to shift demand or supply in ways that could help match supply and demand.

For each flexibility option we have estimated the national potential and per unit (GWh/day, etc) cost to create a supply curve. We have estimated how these costs could evolve between now and 2030. Figure ES-3 on the following page shows how the mix of flexibility options could compete with each other given potential cost reduction through to 2030 for one type of daily balancing need (6 hours a day). Lowest cost options are on the left, with increasingly expensive options as we move to the right. Note that demand for daily shifting in a high renewable energy case is about 870GWh/day. With nearly 2,000GWh/day available, this need, like all others, is potentially well supplied even with the accelerated deployment of wind and solar.

Finding 4: Integration of higher levels of flexibility will significantly reduce total costs, particularly if India can develop a portfolio of demand, powerplant and storage options

Understanding how flexibility will affect the cost and reliability of the Indian electricity system requires modelling of the range of portfolio options available to simultaneously meet all electricity demand and flexibility needs, keeping the system in balance. We modelled different sets of demand, storage and powerplant flexibility options against current and

Figure ES-3: Supply and demand for daily balancing – high RE scenario 2030



future load shapes. Figure ES-4 shows how the mix of generation and flexibility resources would fit together in a single week in 2030. The left chart includes demand and storage flexibility options, while the right chart includes only powerplant based flexibility options. The black line represents the pre-flexibility load that needs to be met across the week. Note how in the right hand (powerplant only graph) coal fired powerplants (in black and grey shades) need to vary their production across the day and in some cases will need to be upgraded to turn on and off each day. Note also that there is a considerable amount of solar energy above the black line that will be curtailed. That is wasted. On the left hand side powerplants operate more continuously and with less variation, while most of the excess energy from solar production is either stored or used by demand shifted from other times of the day.

Figure ES-4: Demand flexibility and storage reduce curtailment and allow thermal plant to operate more efficiently

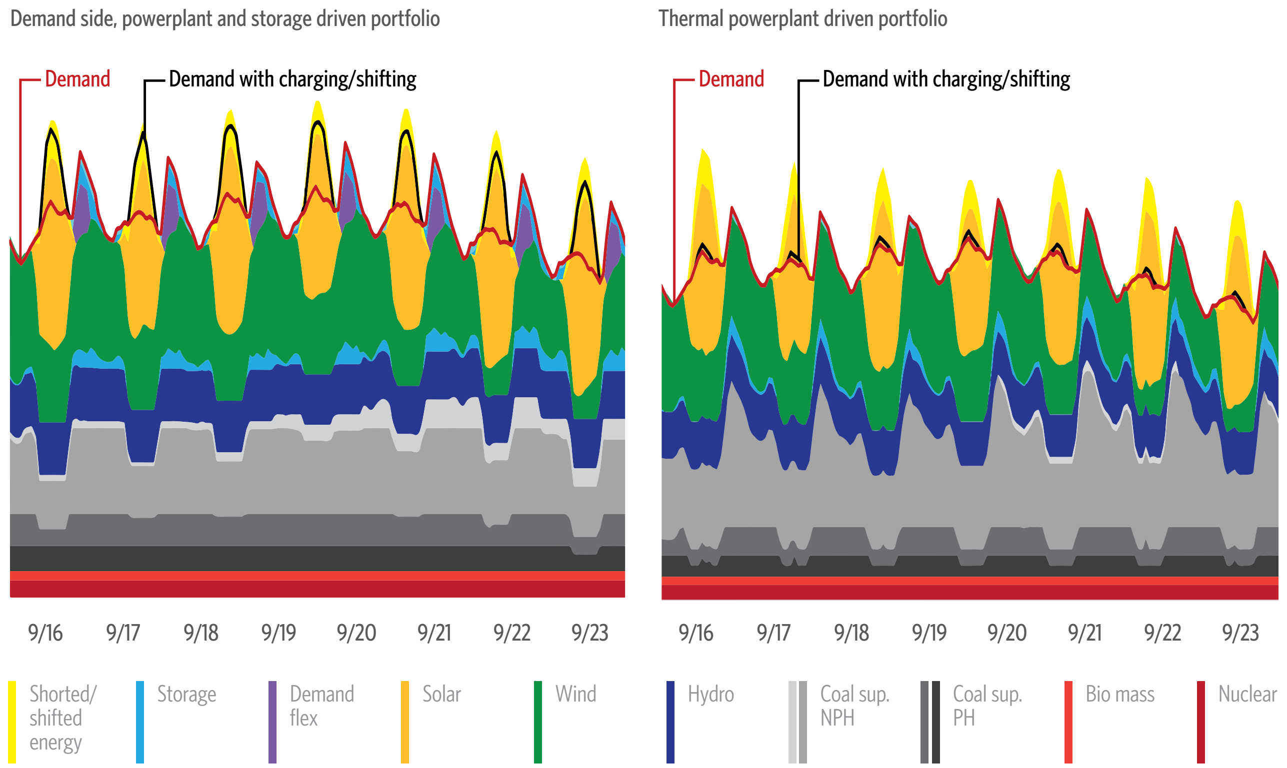
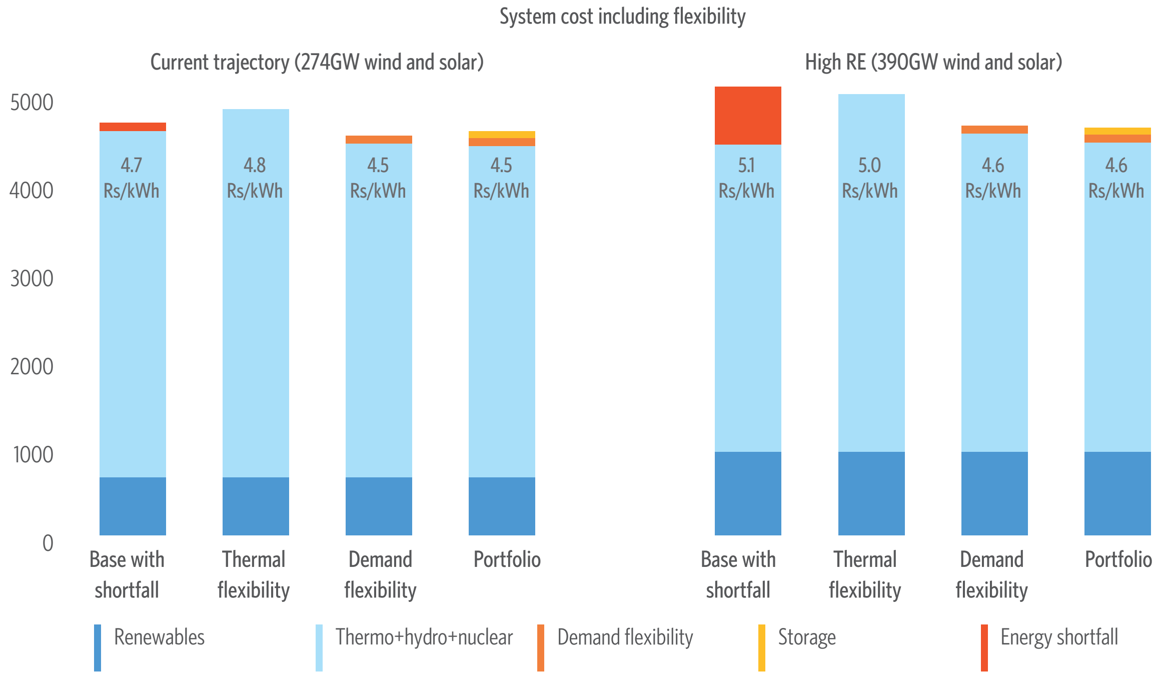


Figure ES-5: Impact of flexibility on total Indian electricity system costs



Additional flexibility from different resources will deliver an efficient and reliable electricity system, but the question is whether these improvements justify the investment and operating costs of the flexibility options. Our analysis, summarised in Figure ES-5, shows unequivocally that it does.

Figure ES-5 compares the average system price for all electricity supply in India including the total costs of new flexibility options under the current trajectory and high renewable energy scenarios. Figure ES-5 compares four sets of flexibility portfolios, existing flexibility, improvements in flexibility from powerplants only, increase in demand flexibility only, and a portfolio of flexibility options including demand flexibility, powerplant flexibility and storage that optimizes total system cost.

In the base case, the system will continue to have significant energy shortfalls at different times of the year. We have included the cost of meeting this shortfall with generator backups as a proxy for the economic impact of the shortages. Note how increasing powerplant flexibility only will eliminate energy shortfalls, but will increase overall system cost. Using the full portfolio of options is 5% cheaper than the base case at current renewable energy deployment rates and 8% cheaper in the high renewable energy case. In summary we find:

1. Balanced and demand flexibility portfolios significantly reduce carbon, costs and curtailment, even at low RE ambitions.
2. Combinations of flexibility options can have significant impact on system efficiency, for example deployment of demand flexibility and storage enable thermal powerplants to operate more steadily and efficiently in a balanced flexible portfolio.
3. Costs of integrating renewables can be kept low by optimising the utilisation of flexibility resources to meet particular flexibility needs, for example, energy storage from batteries is most suited to daily balancing, rather than meeting seasonal needs.
4. Our analysis shows that the mixed portfolio has 5% to 8% lower system costs, 8% to 12% lower carbon emissions and requires between 82% and 97% less curtailment.

Figure ES-6: Curtailment is dramatically reduced as are costs and carbon under a balanced portfolio

Portfolio performance (2030) - current trajectory

Scenario	Excess energy	Total cost	Carbon emissions
Power-plant driven	10%	4.8 (Rs/kWh)	4.8 (t/MWh)
Demand flex driven	-83%	-6%	-6%
Storage driven	-95%	-4%	-6%
Balanced portfolio	-97%	-5%	-8%

Portfolio performance (2030) - high RE scenario

Scenario	Excess energy	Total cost	Carbon emissions
Power-plant driven	13.8%	5.0 (Rs/kWh)	0.5 (t/MWh)
Demand flex driven	-63%	-7%	-9%
Storage driven	-80%	-5%	-10%
Balanced portfolio	-82%	-8%	-12%

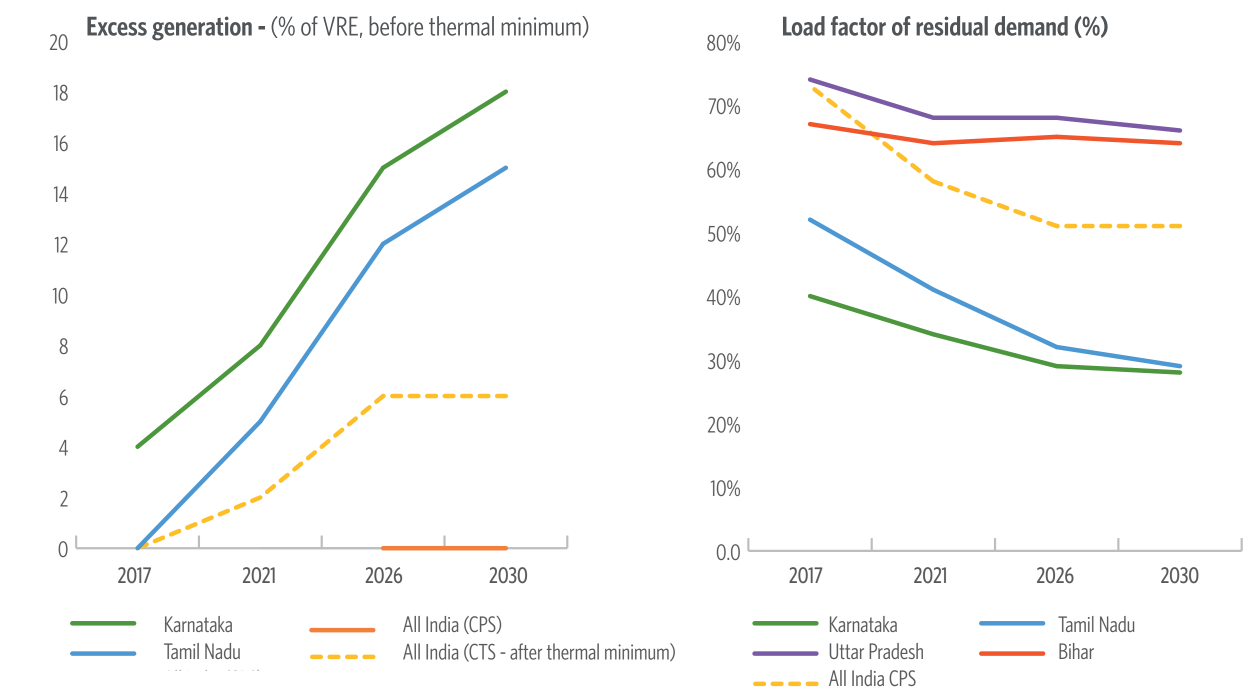
Figure ES-6 compares the average system price, the carbon impact and curtailment across four sets of flexibility options, starting with maximising flexibility from power plants, and comparing that to increases in demand flexibility only, and a balanced portfolio of flexibility options including demand flexibility, powerplant flexibility and storage that optimises total system cost.

Finding 5: Development needs for flexibility will vary significantly by region

Just as there are variations internationally, there are significant variations within India. States such as Karnataka and Tamil Nadu that have experienced significant economic growth as well as renewable energy deployment have seen greater increases in flexibility needs.

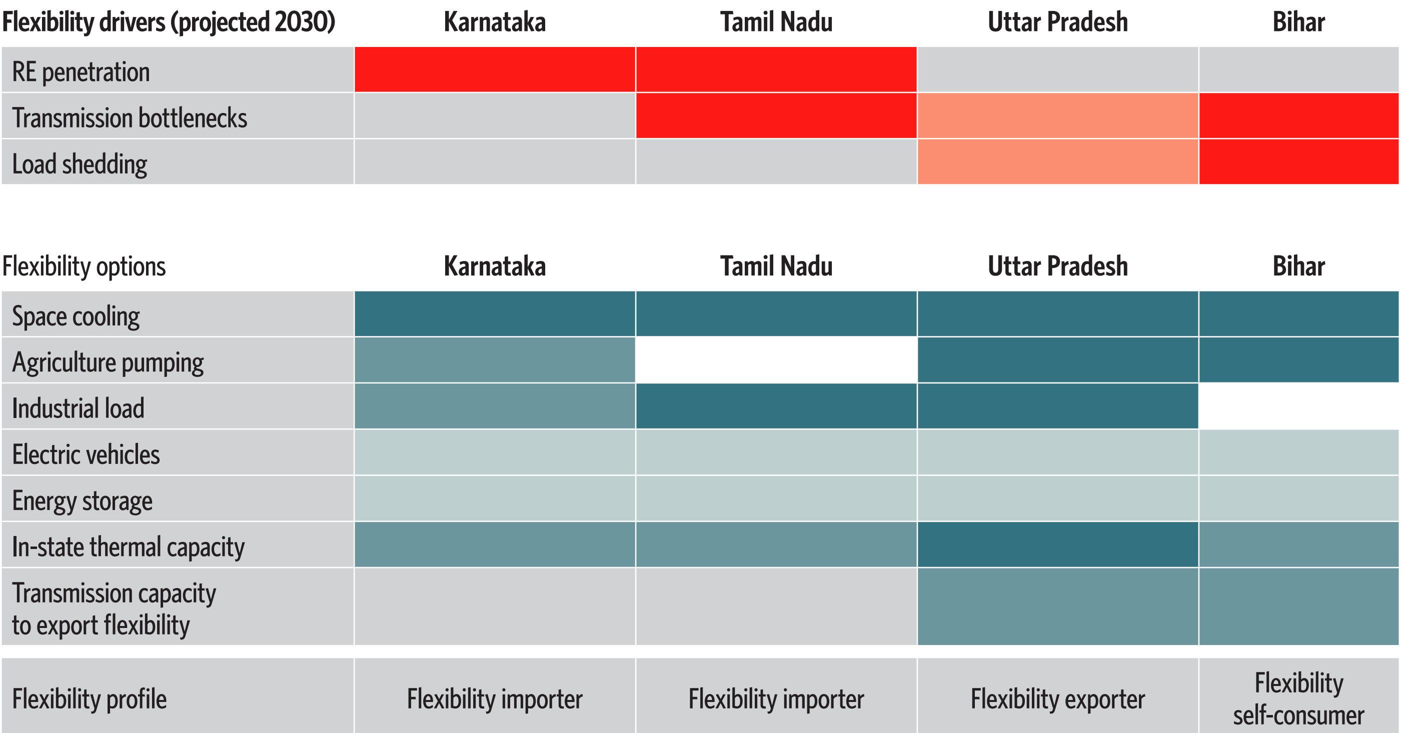
Figure ES-7 shows how the needs in those two states will grow in the high renewable energy scenario by 2030 versus the India average and the impact on two states with lower deployment (Bihar and Uttar Pradesh). Without interstate transfers and flexibility improvements, by 2030 Karnataka and Tamil Nadu could see up to 15%-20% of their renewable energy generation curtailed, versus 6% as an average across India. One measure of flexibility needs is the load factor required of thermal generation in the state. In Tamil Nadu and Karnataka, without interstate transfers, thermal generation load factors could fall to 30%. In states like Uttar Pradesh or Bihar capacity factors fall only slightly to around 70% over the same period.

Figure ES-7: Forecast growth of renewable electricity generation in the state vs India overall



Renewable energy penetration is only one of many factors that will affect flexibility needs and supply going forward. Figure ES-8 summarises some of the key factors affecting state supply and demand of flexibility and shows that if India can improve national markets for flexibility supply, states like Uttar Pradesh can benefit from exporting its flexibility capacity to states like Karnataka and Tamil Nadu. States like Bihar, meanwhile, should be able to improve its flexibility to reduce load shedding and improve power quality.

Figure ES-8: Key factors affecting state flexibility supply and demand



Finding 6: India will need to adjust elements of its electricity system, including data, technology, infrastructure, business models, incentives and market design, if it is to achieve its flexibility goals

Finally, developing demand flexibility, storage, increasing the flexibility of thermal and hydro powerplants, planning the integration of transmission to enable and enhance flexibility all require different types of policies and markets that will help integrate these options once they are developed. India needs to develop:

- **Data,** for example, to understand which consumers could change their electricity consumption patterns and at what costs;
- **Technology,** for example, to reduce the costs of storage and to create different types of storage systems that meet the needs of the various segments of the Indian electricity market (industrial, renewable energy plus storage, transport, household and commercial energy back up/back up generator replacement, etc);
- **Infrastructure,** such as transmission, to deliver flexibility, or the IT and metering systems to schedule and integrate flexibility;
- **Awareness,** from consumers, potential storage investors and powerplant operators as to the potential and value of flexibility from their assets;
- **Business models,** that enable investors, consumers and others to monetise and benefit from providing their flexibility;
- **Incentives,** that align flexibility providers with overall system needs.

Once all of these are in place and the flexibility options are deployed at reasonable costs, the technical market design can integrate the flexibility. Figure ES-9 summarises some of the critical needs that India needs to address for each of the flexibility options and integration of those options. CPI is working with states and national regulators to identify market design and policy solutions to address each of these issues.

Figure ES-9: Factors that increase flexibility resources must be integrated by market design

	Data Develop, improve, disseminate	**Technology** Develop, deploy, cost reduction	**Infrastructure** Plan, finance, build	**Awareness** Build and drive behaviour	**Business models** Facilitate development	**Incentives** Provide and harmonise	**Market design** Improve and integrate
Demand flexibility Develop, test, and roll out options	• Demand statistics • Potential • Cost	• IT and control systems	• IT and control systems	• Opportunities • Consumers	• Models for aggregators	• Investment • Dispatch	Integrate all options cost effectively
Storage Develop and install	• Potential • Cost	• Cost reduction • Local application • Indian manufacture	• Deploy, integrate, finance	• Opportunities	• Aggregators • Producers • Suppliers	• Capital investment • Dispatch	
Powerplants Encourage operation and regulatory changes and investment	• Integrated assessment of system plant • Value • Potential	• Test and deploy upgrades	• Test and deploy	• Overcoming entrenched practices • Operating and regulatory	• Plant owners • Upgrades	• Capital investment • Dispatch	
Transmission Continue expanding with flexibility needs under consideration	• Regional data • Cost compare • Flexibility in planning	• Use state of art as deployed in India	• Finance • Integrate	• Tradeoffs with flexibility	• Local, regional and national	• Regulation trading markets	
Integrate Each of the options to minimize cost	• Central clearinghouse for planning	• IT for systems integration and markets	• Financial capacity and planning		• Build aggregators • Help players work together		

For policymakers, this report should provide the reassurance that both renewable ambitions are realistic and the costs of renewables and their integration do not present a barrier to decarbonise and modernise India's power system. In fact, a lack of ambition would be more expensive for India as the energy transition represents an opportunity to create a more efficient system that is not only low-carbon, but also lower cost. The report should also serve to highlight the importance of thinking broadly about the range of issues, activities, policies, market design and investment issues India needs to address to continue to reduce the cost of electricity in India, while improving its reliability and quality and reducing its carbon footprint.

Introduction

India's growing population and fast-developing economy are fuelling an energy transition that is unprecedented in its history and shaped by characteristics particular to the country's legacy electricity system and ambitions for economic growth. While the government has addressed the need for a modern power system to meet the needs of its large population and developing economy partly by setting ambitious renewables targets (175GW by 2022), the existing electricity infrastructure and regulatory environment requires updating in order to provide India with a reliable, affordable and low carbon electricity system.

Increasing the flexibility of the electricity system is an important first step in improving electricity supply and reducing its costs, as it enables a reliable and continuous match of supply and demand to provide robust and high-quality power supply. In 2017, our work with the Energy Transitions Commission showed that if electricity system flexibility were not improved, India could face significant challenges in maintaining a reliable power supply and integrating high levels of variable output from ever growing shares of renewable energy could become technically difficult and costly. The regions covered in that report were able to absorb up to 30% variable renewable energy without the need for new investment. Beyond that level, challenges for the decarbonisation of India's electricity system will be intensified by the increase in variable renewable energy and changing demand patterns of growing consumer demand.

Dramatic declines in the cost of renewables have helped provide India with economic new sources of generation to meet electricity demand growth and changing patterns of demand. In 2019, India chalked up the lowest renewable energy costs in Asia Pacific, with the levelised cost of electricity for solar PV falling to $38/MWh, 14% cheaper than coal fired power.[3]

Without improvements in market design, integrating further renewable energy capacity could slow down India's ability to transform its power system to a more sustainable basis. Curtailment already threatens the economics of solar and wind projects. Meanwhile, thermal plants have seen their load factors fall during high renewable generation periods, hurting economics across the electricity sector and creating resistance to further renewable energy deployment. India has been working to improve electricity system reliability, which has further increased the need for additional system flexibility.

As a concept, electricity flexibility might seem to be a single resource, but in reality, flexibility is a range of technologies, incentives, behaviours and actions to meet different needs. The ability to turn a powerplant up or down is different from a household turning on the air conditioning an hour early, a factory shifting production schedules, or a batteries being installed by a generator or a distribution company, but all are forms of flexibility. Likewise, whether the flexibility is instantaneous, where control is given to a system operator, or planned and paid for months in advance, is also very different. Yet these activities and options must be planned and paid for, but how?

This paper explores the various options for flexibility in India and how much they will cost and what they will be worth to the overall development and operation of a low carbon system. The paper then looks at how India could integrate these options for maximum benefit at the lowest cost.

[3] India leads with lowest renewable cost in Asia Pacific, Wood Mackenzie https://www.woodmac.com/press-releases/india-leads-with-lowest-renewable-cost-in-asia-pacific/

Specifically, this report is divided into six sections:

- In the first section we summarize the methodology we applied in our analysis;
- We then examine India's flexibility needs as they will evolve between now and 2030 (section 2),
- In section 3 we investigate the potential and cost of flexibility options in the three main categories of flexibility options: a) Improving the flexibility of demand to respond to changing electricity supply needs, b) Increasing the flexibility of conventional thermal and hydroelectric power plants, and c) assessing the cost and potential of using storage technology as a flexibility option, particularly as the costs of storage falls over the next decade.
- Section 4 integrates these various flexibility options against the increasing demand for flexibility, modelling portfolios of options to identify the relative economics of different portfolios and assess the impact of flexibility on total system costs.
- Next, we take a close look at four regions – Tamil Nadu, Karnataka, Uttar Pradesh and Bihar (section 5) – each of which have different economies, weather, electricity demand, resources and electricity generation mixes. With this diversity, we explore how regional differences will affect flexibility needs, costs and plans, and what implications this could have for India as a whole and for the potential to trade energy and flexibility across regions.

In the final section we turn to what will be needed to develop, build, and integrate this flexibility into the Indian electricity system. For each of the flexibility options (demand, storage, powerplants) we describe what would be needed to ensure that these options develop in time and then can be used cost-effectively. Removing barriers such as the lack of data or infrastructure, providing incentives to reduce costs and develop technologies, and creating market places to optimise usage and facilitate investment are all important steps in developing and integrating flexibility. This final section highlights the need for changes to the electricity system frameworks, including the importance of electricity market design and reform, but the topic and needs are much greater and broader than described here. Following on from this work, Climate Policy Initiative Energy Finance is in the midst of a two-year project to develop plans for this market and industry reform to help India achieve its flexibility and electricity system objectives.

1 Framework and methodology

Our findings are based on the cost and resource potential of the various electricity system flexibility options in India, including the integration of these options within the context of the country as a whole and within the regions. The cost and resource potential of flexibility depends on how demand and generation capabilities evolve. Therefore, our approach assesses the impact of potential flexibility options against realistic scenarios to estimate the value of flexibility, as well as the priority flexibility options to be pursued.

We begin with future scenarios of possible energy mixes in the Indian power system. Each of the scenarios is based upon the work of The Energy Resources Institute India (TERI) and the Energy Transitions Commission India (ETC India) in evaluating the changes to Indian electricity supply and demand between now and 2030. In addition to a base scenario, these scenarios include different proportions of energy supplied by variable renewable energy and thermal powerplants, as these are the two most important determinants of how much flexibility the system will need.

Specifically, the following three scenarios have been considered:

1. A ***current trajectory*** scenario based on forecasts of future renewable energy deployment following current trends;
2. A ***current policy*** scenario where India meets the government's current renewable energy targets; and
3. A ***high renewable energy*** scenario that follows the ETC India high RE scenario, maximising renewable energy by 2030 with no new coal additions beyond the current pipeline.

Although current trends fall short of existing targets, meeting today's policy targets should be considered a "base case" as there is a strong potential for India to increase its renewable energy targets, as outlined in TERI/ETC India's demand work. Using the three scenarios, we undertook several steps which are outlined in the following section of this chapter.

1.1 Analysis of flexibility requirements.

For each of the three scenarios, we assess the development of different types of flexibility needs, namely operating reserves, ramping, daily balancing and seasonal balancing. The flexibility requirements were analysed on a timeline based between now and 2030. The assessment is based on ETC India's supply and demand modelling, analysis of the Indian load shape in a typical year and how it will be affected by changing usage patterns, analysis of system modelling, and application of Indian system operation guidelines. The flexibility requirements we have assessed include:

- **Short-term reserves** to meet sudden, unexpected changes in either supply or demand due to errors in scheduling, forecasting or forced outages.
- **Ramping** requirements where the limiting factor is not how much energy can be provided, but how fast the system can react to increasing (or decreasing) demand or decreasing supply (for example from solar PV) over a period of 15 minutes to three hours. In many electricity systems, the number of plants that need to be brought online over the course of the day can depend on the maximum system ramp, rather than peak capacity. That is, in some cases more plants that are needed for peak need to be online to provide sufficient system ramp rate.
- **Daily balancing** to match excess production with higher demand at a different time in a 24-hour period. It analyses the mismatch between the peaks and troughs of the demand curve against generation and the need to shift demand or generation resources to match the two. For example, when excess solar energy produced during the day needs to be shifted to the night, or when baseload plant needs to be turned down at night and replaced by daytime peaking plant.
- **Seasonal balancing** matches seasonal generation and demand and the flexibility to shift supply or demand across seasons and the year. In India, the most significant need results from the monsoon, when wind generation is high and the resulting excess generation needs to be shifted to months when demand outstrips supply. Solar generation is less variable across the year compared with countries that are further away from the equator, but these differences also contribute somewhat to seasonal variation.

1.2 Analysis of India flexibility options.

As a second step, we look at the potential and cost of flexibility options within three main categories:

- **Demand flexibility.** The biggest opportunity and uncertainty is the amount of demand flexibility India can harness. The lack of comprehensive data on the amount of energy consumed by different end uses, the appliances owned by different types of consumers, the load patterns of the different consumers and end uses, price sensitivity, customer attitudes, and other data needs hampers a complete analysis of demand potential. We have focused on developing preliminary estimates that can help determine the role and potential importance of demand side flexibility as an input to decision-making on the level of prioritisation India should set for demand flexibility. To this end, we focused our analysis on a subset of end uses (**commercial and residential air conditioning, agricultural pumping, electric vehicle charging, and industrial demand response**) where data is available and where consumers are most likely to be receptive to demand side opportunities. Capacities and growth have been calculated based on existing capacities, market data, current and projected growth. For the end-use/consumer combinations, we estimate potential and use these as proxies to identify potential barriers and requirements for implementation. Aplying conservative estimates to potential penetration rates, these end uses provide enough flexibility to the system to have a major impact on costs, reliability, and ease of integrating higher levels of variable renewable energy.
- **Powerplant flexibility.** Most flexibility today is provided by thermal and hydroelectric powerplants. These plants are capable of delivering all types of flexibility, although there limits and costs associated with these resources. At the basic level, operating thermal plants flexibly reduces plant efficiency, increases fuel costs and can increase operating costs. To provide reserve, extra plant capacity needs to be built and kept online, again increasing costs. We compare these costs for each type of flexibility using incremental costs to deliver the service. Additionally, we have found that most plants on the Indian system can deliver significantly more flexibility than they are currently offering. Without modification, experts suggest that the plants can offer more flexibility by changing operational practices. Investments into suitable retrofits can also significantly increase the amount of flexibility each plant can offer. We worked with Siemens, an ETC India member, to evaluate the cost and potential of retrofits and to include those options in our system modelling.
- **Energy storage.** Battery prices are falling dramatically across the world, and these cost reductions will help India lower costs. Batteries and other storage options like pumped storage hydro can provide most of the flexibility service, but the cost of doing so is highly dependent on the capital cost of the batteries systems (including balance of system, EPC and operation costs), the full cycle efficiency and the life of the batteries. We used estimates of each of these variables, and the investment return required, to calculate the cost of providing flexibility services through storage options at today's costs, and at costs and operating characteristics we forecast for 2030.

We should note that from a flexibility perspective, exploring potential options has not been exhaustive, but rather intended to identify important categories of options that are then used as proxies for cost and potential and integration within India. As such, we expect that with proper incentives and market design, many more flexibility options could develop, particularly on the demand side. From that perspective, the analysis on benefits and potential for flexibility are conservative, provided India can implement programmes to develop the needed flexibility options.

1.3 Modelling and evaluation of integrated flexibility option portfolios

Once we have estimated the demand for flexibility and the potential availability and cost for each of the flexibility needs, we can model how these various flexibility options would work together to meet India's electricity supply needs. By ranking these flexibility resources, we have created supply curves to show which flexibility resources would be dispatched at what cost to serve each flexibility need. Then, using these supply curves and forecasts for annual hourly load shapes for India, we evaluate the "dispatch" of different sets of flexibility options to meet the various flexibility needs of the system. The aim is to both assess the cost of integrating various levels of renewable energy into the system, as well as to evaluate how the availability of different supply side options affects cost and overall dispatch.

Thus, we have used our model to understand the costs and dispatch of the Indian system for each of the three energy mix scenarios outlined above, with the following mixes of flexibility resources:

- **A base case:** Only existing sources of flexibility are used.
- **Powerplant driven:** Flexibility in this portfolio is provided entirely by thermal and hydroelectric powerplants. Where it is economic, these plants are upgraded to increase their flexibility and new plant are added to the system if it is economic to do so.
- **Demand side driven:** This portfolio uses existing sources of flexibility combined with only demand side options at the scale and cost from the demand side flexibility analysis.
- **Storage driven:** Similar to the demand driven option, but using storage instead of demand with existing options.
- **Combined portfolio:** Our final portfolio combines all flexibility resources to determine which options would be used and at what scale, and to assess what lowest cost if all flexibility programmes were successful.

1.4 Case studies of regional differences

Much of our analysis takes India as a single unit. The underlying assumption would be that there are no transmission constraints or costs and that flexibility resources can be used to supply flexibility across India. This is a high level assumption and it is far from the reality we have now or could expect by 2030. Transmission constraints between states and regions create differences in pricing and dispatch, which are exacerbated by differences in weather, economies and as a result, demand patterns, energy supply and resources, including both renewable energy and conventional energy. To understand how these constraints and regional differences could affect flexibility costs and resource requirements, we have studied four states, with distinct energy needs and resources. We evaluated these regions on their own, and then in the context of how each state/region could benefit from or be affected by the trading of flexibility resources. The state differences provide initial indications of the needs for interregional/ multi-regional trading and national level policy. The regions we studied in detail are:

- **Tamil Nadu:** A strong economy with ambitious renewable energy goals driven initially by a need for energy sufficiency and reliability. As at December 2018, installed wind capacity in Tamil Nadu was 8.4GW, more than any other state. The strong seasonal variation of wind production, combined with seasonal patterns in neighbouring states and limited national transmission options, could lead Tamil Nadu to experience a seasonal flexibility problem, including excess production during the monsoon season.
- **Karnataka:** At over 5.2GW of installed solar capacity, Karnataka leads the country in solar deployment and plans to add more, including through roof top installations. The state combines a strong, growing and reasonably wealthy economy with high renewable energy ambitions and ample resources of both solar and wind. Karnataka could therefore experience some of the biggest ramping needs in the country, as well as potential excess generation during the day.

- **Uttar Pradesh:** Uttar Pradesh is also a developing economy, but one that is characterised by a large share of industrial consumption, large agricultural consumption and a good supply of contracted conventional thermal powerplants (within and outside the state) to meet demand. Uttar Pradesh is an example of a state that potentially has more flexibility resources than it will need, and therefore could have an opportunity to export its flexibility.
- **Bihar:** Bihar is one of the less developed states, with many areas in need of greater electrification and power supply. The state faces high instances of load shedding affecting large parts of the population. Bihar enables us to study the impact of energy access and initial electricity system growth on flexibility needs.

1.5 Assessment of finance, technology, strategy, planning and market design needs

Finally, based on the portfolio analysis and the regional analyses, we identify the key factors and policy areas that will be needed to drive a more flexible, lower cost, and potentially lower carbon system for India's future.

2 India's growing flexibility needs

Key findings

- While total demand is projected to roughly double by 2030, the need for flexibility will increase much more quickly, for example daily balancing is projected to grow six-fold by 2030.
- The need for daily balancing is likely to be the most pressing flexibility need facing India's electricity system through 2030, but other flexibility needs also require attention.
- At a regional level, ramping needs are already a concern, especially in states with high shares of solar, such as Karnataka.

All modern electricity systems must balance electricity demand and supply at every instant, and at every location, to avoid outages and damaging swings in voltage and frequency. India has been working hard to improve power quality and reduce involuntary and unscheduled power outages. However, India has improved power quality partly through planned and scheduled load shedding and renewable energy curtailment, both of which have significant costs to the economy. The cost of outages or poor power quality drives consumers and producers to install expensive backup generation and power conditioning equipment, or to bear the costs and consequences of unreliable supply.

More recently, as more wind and solar resources have been added to the system, matching output with load becomes more challenging and will be further complicated by the growing demands of an increasingly prosperous population.

Changing patterns of consumer demand make this matching process more complex and difficult. Demand is shifting in India, as it has elsewhere, from a larger share of industrial consumers who tend to have more continuous and stable demand to an increasing share of households and commercial consumers, whose heating and air conditioning demands tend to vary with the weather, and whose lifestyle can often include an evening demand peak when lights and appliances are turned on. Wind and solar, whose output depends on the weather rather than system operators, add to the difficulty of continuously matching supply and demand.

The key to making this match is to increase the flexibility of both energy supply and demand, so that each can be adjusted to meet the other at the lowest cost. This section outlines how we have defined and measured the needs for flexibility in India and how they will change under different scenarios. This measurement serves as a critical input in determining how much and what combination of flexibility resources (section 3) will be required by a low cost portfolio of flexibility resources (section 4) to meet India's future needs under different scenarios.

2.1 Defining different types of flexibility

While electricity system operators need to match supply and demand at each instant, to do so they need to make decisions across many time frames. Thermal powerplants take time to start up, so decisions about which plant will be running at various times need to be made hours or a day in advance. Demand varies across the year, so decisions about scheduled plant maintenance and fuel procurement to match these variations need to take place months in advance. New plant or storage systems can take years to build, so some decisions must be made years in advance. At the same time, a large transmission line or powerplant can suddenly go down, or a commercial break in a popular television programme can prompt a sudden surge of demand, so system operators need to make decisions instantaneously, and over the course of a few minutes, to restore the balance.

Different types of flexibility, that is different responses from the system operator, and electricity suppliers and consumers, are needed across these timeframes shown in Figure 2.1. For our analysis we have modelled four main types of flexibility needs:

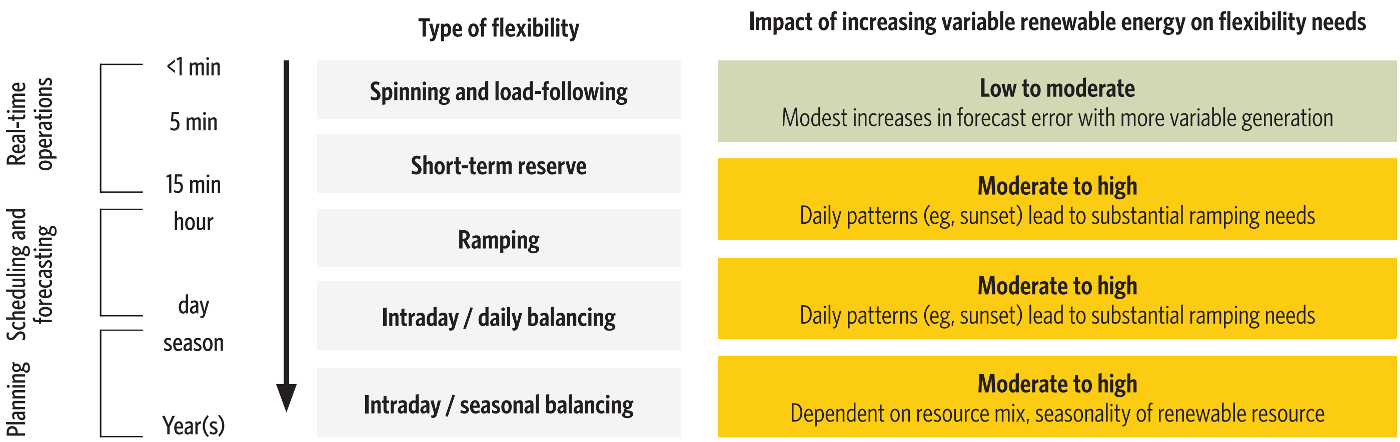
1. **Short-term** reserve is the capacity to replace energy if a powerplant or transmission line suddenly fails, or to meet a surge in demand. We have grouped the short-term flexibility needs, including spinning reserve, load following, frequency response, short-term reserve, into a single category, as these are the areas that are most well-equipped to meet growing flexibility needs.
2. **Ramping** addresses the need to increase (or decrease) output (or demand) fast enough to maintain a balance of supply and demand when

demand is expected to increase at its fastest rate. For example, when the sun sets and consumers turn their lights on at once – particularly if solar generation falls off at the same time – the limiting constraint to an electricity system may not be the capacity to meet the daily peak, but rather having enough capacity that can ramp up (increase capacity) fast enough to maintain a continuous match of supply and demand. It is not uncommon for a system to require extra powerplants to be dispatched beyond what is needed to meet peak demand, just to have enough ramping capacity to meet the day's maximum ramp rate. Finding demand or storage solutions to meet ramping can decrease the number of powerplants that need to be online, and increase the overall efficiency of the powerplants that are dispatched.

3 **Daily (intraday) balancing** matches demand and supply across the entire day. For example, adjusting for lower demand in the middle of the night when using baseload generation, or shifting higher solar energy production in the middle of a sunny day to meet lighting needs in the evening or night time.

4 **Seasonal (interday) balancing** matches supply and demand to meet annual cycles, for instance, when cold winters or hot summers drive up electricity demand, or rainy, sunny or windy days drive up energy supply.

Figure 2.1: Different types of flexibility needs



Calculating net demand

Net demand analysis determines the difference between load and variable renewable generation to enable efficient scheduling of other capacity, such as conventional generation. In our work in India, we followed these steps:

Net demand analysis

- Calculate hourly renewable energy production, plus baseload nuclear assuming constant generation when online
- Calculate hourly demand
- Calculate difference between demand and variable renewable energy supply for each hour
- Extract key flexibility metrics and visualize profiles

Demand

- Demand shape based on 2013-14 year, escalated to 2030 using total energy and peak load requirement for 2030 based on TERI demand analysis and the 19th EPS

Supply

- Renewable energy capacities based on TERI current policy scenario
- Wind and solar profiles based on NREL Greening the Grid data – India-wide average weighted by "high RE scenario" state-level capacities
- Minimum hydro by day from the Ministry of Power's Large Scale Integration study, smoothed using a seven-day moving average
- Nuclear baseload production assumes constant output at expected load factor of 66% (2017) to 75% (2030)

Sources: 19th Electric Power Survey – Central Electricity Authority http://www.cea.nic.in/reports/others/planning/pslf/summary_19th_eps.pdf
NREL Greening the Grid (2017) https://www.nrel.gov/docs/fy17osti/68530.pdf
Ministry of Power's Large Scale Integration study (2016) https://powermin.nic.in/sites/default/files/uploads/Final_Consolidated_Report_RE_Technical_Committee.pdf

2.2 Assessing flexibility needs

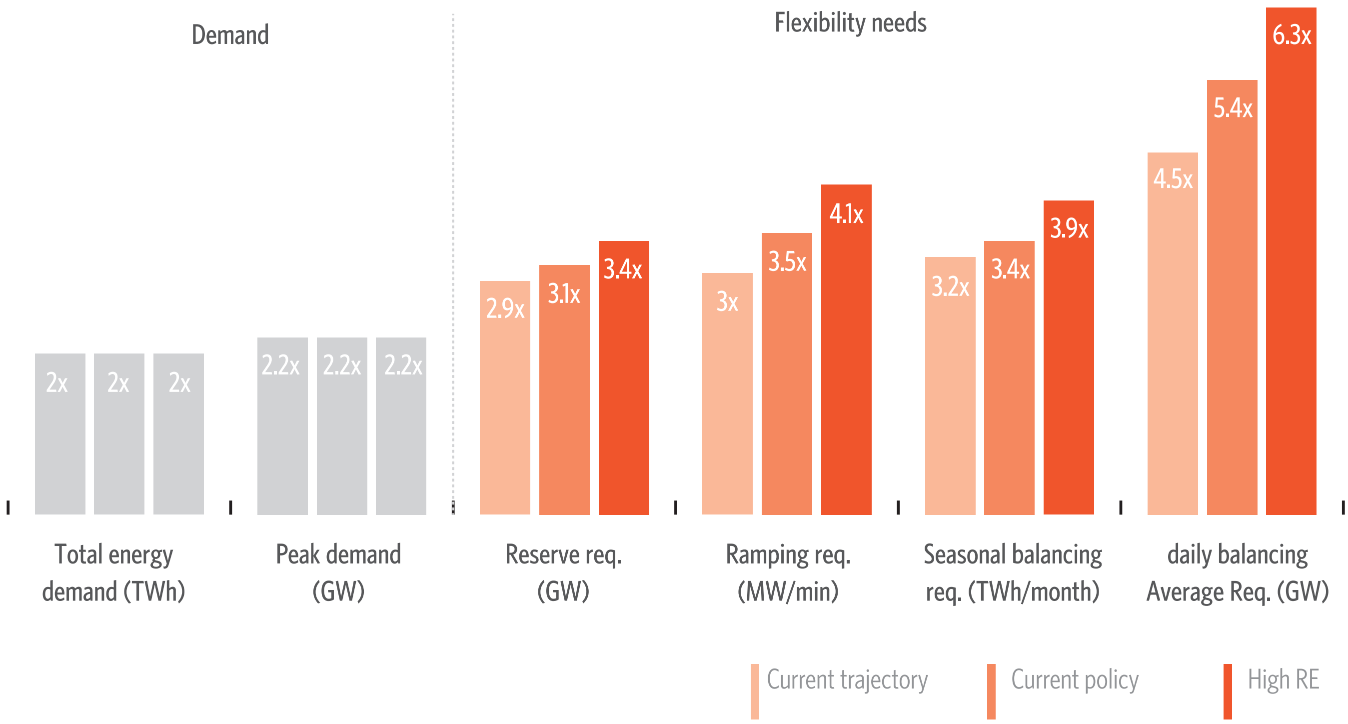
To assess these needs under each scenario we examined supply and demand on an hourly basis (and sometimes less) over the course of 2017 and future years. To address the effects of changing demand profiles and higher renewable energy production, we use a net load, or net demand, approach (see box on previous page). In this analysis, we forecast future hourly load profiles based upon the TERI/ETC India demand models, and then net off the must run, or undispatchable generation from all sources, including wind, solar, nuclear, must run hydro. The resulting net demand is the load that must be met by dispatchable generation or altered through storage and demand flexibility.

In our analysis we treat demand flexibility as an energy supply option akin to flexible generation.

At the broadest level, our analysis indicates that the demand for flexible resources will intensify in the push to meet the government's target of 175GW installed capacity for wind and solar by 2022. But even as demand doubles over the timeframe of our analysis (2017-2030), flexibility needs such as daily balancing could increase by 6.3 times under a high renewable scenario, and even 4.5 times under a conservative scenario (current trajectory).

While this analysis shows the challenge of increasing flexibility needs, for our portfolio and option modelling, we required more detailed analysis, as we set out in the rest of this chapter.

Figure 2.2: Growth in key flexibility needs – 2017-2030



Source: CPI Analysis

2.2.1 Short term reserves

Indian system operators manage several different levels of reserves across different timeframes, yet these are the least affected by changing demand and rising renewable energy capacity mainly because the sizing of these reserves is often based on the largest single point of failure, such as a large powerplant or transmission line. Since renewable energy assets tend to be smaller in MW size, simultaneous failure of generation assets is unlikely. Exceptions are either transmission line failure when delivering significant renewable energy, or sudden output variations due to weather (eg, wind gusts or lulls, or cloud cover). Nevertheless, the scale of these events is likely to be small compared to major powerplant outages. Furthermore, system operators have invested significantly in resolving the short-term reserve problem. Our estimates of reserve requirements are based on national standards and include the larger of a single plant or transmission failure, or 3% of peak demand (to address simultaneous unexpected demand shocks and forecast errors) plus 5% of peak renewable energy production (to address weather and forecast errors).

Table 2.1: Operating reserve needs may see some growth

	Drivers	Current need	Implementation	Growth
Primary reserve (sec - 5 min)	Largest system contingencies (failure of large power plant or transmission line)	~ 4GW	Partial • Per 2010 Grid Code, thermal generators over 200MW equipped with governor control to independently respond to frequency changes	Minimal growth
Secondary reserve (< 1 min - 15 min)	Contingencies, load forecast error, wind and solar forecast error, congestion management	~ 4GW	Partial • Requires automatic generation control • Currently being tested at some generators and LCDs	Proportional or slower growth than peak demand
Tertiary reserve (5 min - 60 min)	Contingencies, load forecast error, wind and solar forecast error, congestion management	~4-5GW	Implemented • Reserve Regulation Ancillary Services program started operation in 2016 with inter-state generating stations • 55GW of participating generators • Dispatches available (undispatched) capacity based on merit order	Proportional or slower growth than peak demand

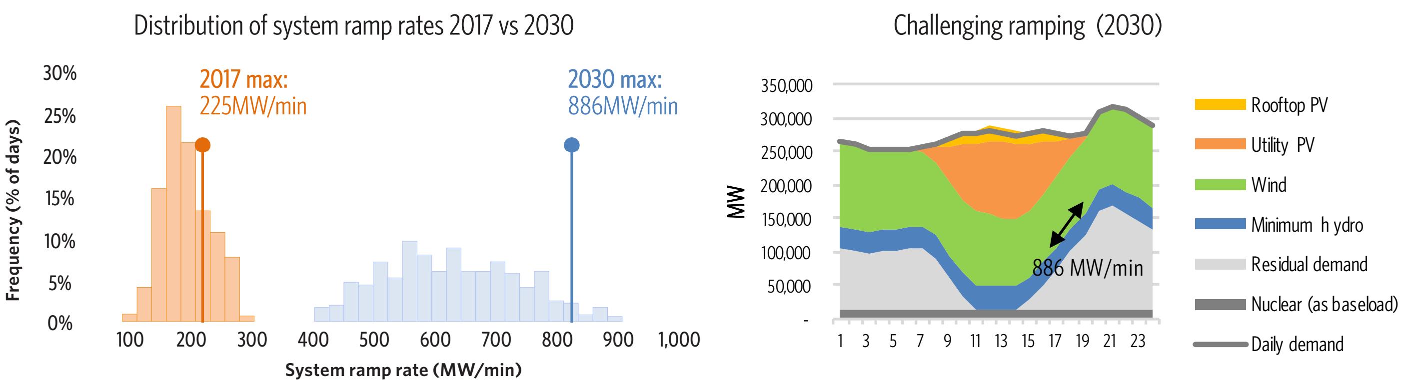
Note: Overlap with National Electricity Policy (NEP) target of 5% spinning reserve
Sources: CERC, Explanatory Memorandum on Introduction of Ancillary Services in India, 2015; POSOCO, Power System Operation and Ancillary Services, Presentation, Dec 2017, CPI analysis

2.2.2 Ramping

Ramping requirements increase as demand becomes more variable and as solar energy output drops in the evening. In fact, growth in solar energy is expected to shift (and in some case has already shifted) maximum ramping requirements from the morning to the evening.

Our analysis, which is based on the evaluation of net load profiles to identify the highest likely ramp rates within a year shows that even under current renewable energy targets (current policy scenario), maximum ramp rates will not only increase by more than threefold between 2017 and 2030, but that there will be a much wider spread of maximum ramp rates across the year.

Figure 2.3: Growth and distribution in ramping rates – current policy scenario



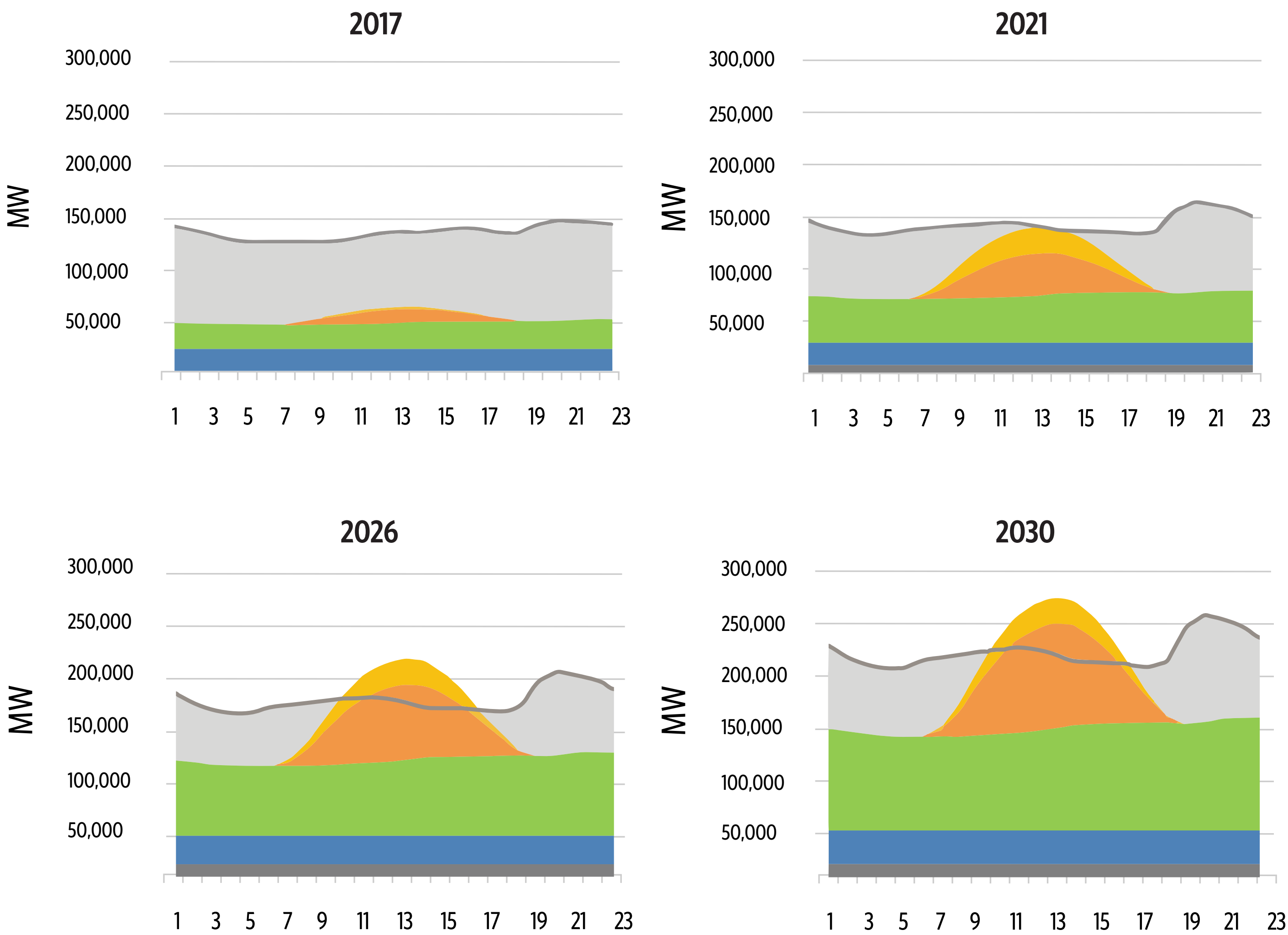
2.2.3 Daily balancing

A reliable electricity system requires matching the patterns of electricity supply and demand across the course of a day. In extreme cases, there is the need to shift excess energy generated in one hour to hours where more energy is needed. Often, daily balancing means shifting energy across the day to smooth the residual load that must be met by thermal powerplant to improve the efficiency of these plants and reduce the costs of starting up powerplants for a few hours. But there are multiple dimensions to daily balancing – the amount of energy needed to be shifted could all arrive in one hour, but be needed over several hours later in the day. To illustrate the point, you may have 1,000MWh of excess that needs to be shifted occurring all in one hour, 100MWh per hour over 10 hours, or 1MWh per hour over 10 hours over 100 days. Although each of those shift the same amount of energy, each has very different consequences on generation costs and the cost of flexibility options. The 1,000MWh in one hour, for example, benefits from a lower capital cost solution, while for the 1MWh over 1,000 hours, it would be more cost effective to invest capital to shift the 10MWh/day 100 times.

As such, our portfolio analysis is based on net load profiles, rather than daily balancing metrics, to incorporate the mix of high capital costs/low variable cost and high variable cost/low capital cost options that would optimize the portfolio for a lowest cost.

Despite the intricacies, figure 2.4 shows clearly how daily balancing needs will increase as the variability over the day, and the eventual excess energy production in the middle of the day, increase over time.

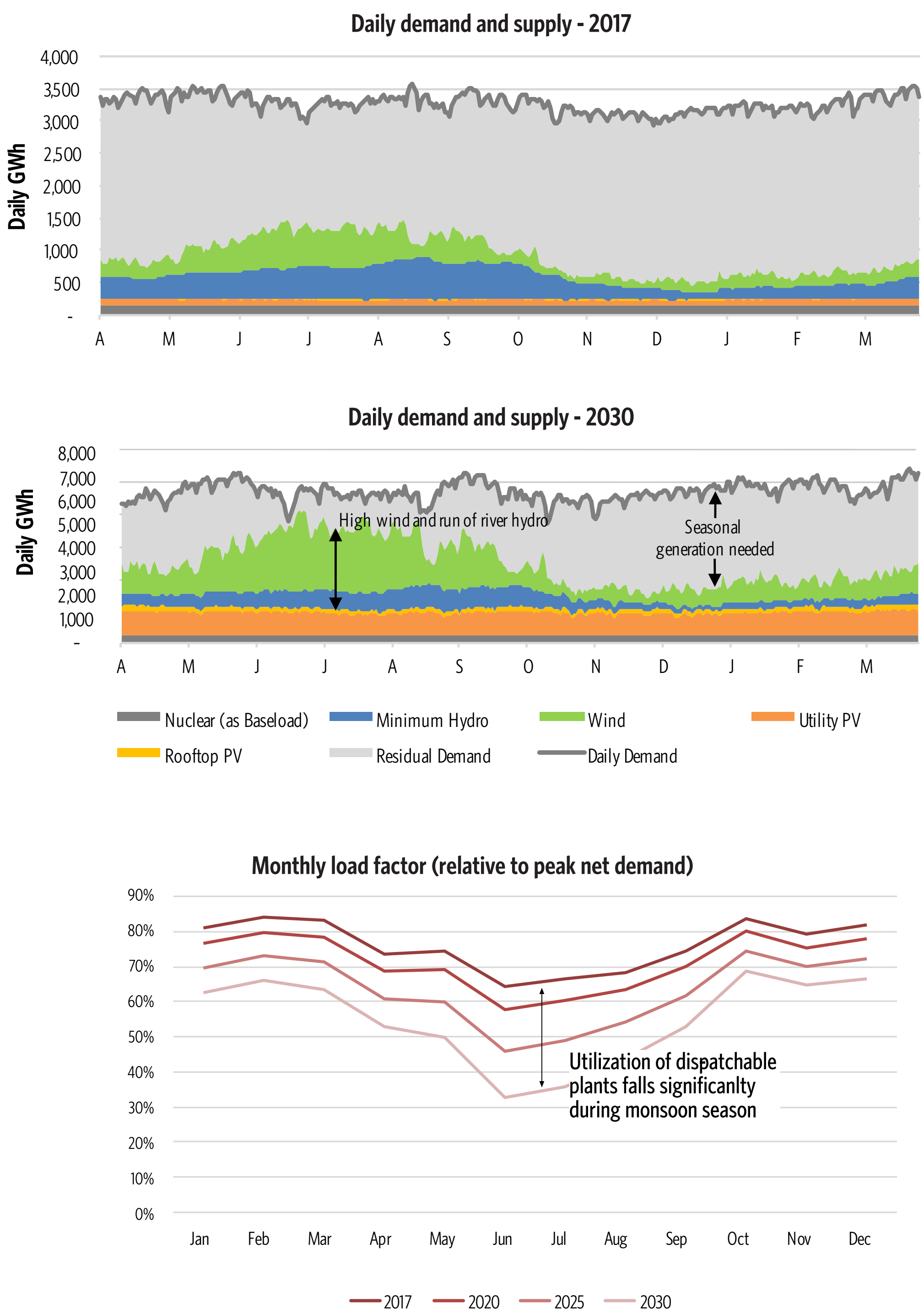
Figure 2.4: Growth of daily balancing needs – current policy scenario (mid-June)



2.2.4 Seasonal flexibility

In India, demand varies less over the course of the year than in countries with colder winters. The largest seasonal variation in India is wind that blows more strongly during the monsoon than in other parts of the year and variations in must run generation from hydro. Figure 2.5 shows how changes in wind, solar and hydro production, combined with changes in demand, lead to variations in the amount of load that needs to be met from more flexible and dispatchable generation sources. The final chart in figure 2.5 shows how the load factor of net load relative to net peak demand for the lowest month will fall from 65% today, to close to 30% by 2030. Powerplants will need to be more flexible in these months and may need to shut down for part of the time.

Figure 2.5: Growth in seasonal demand and supply – current policy scenario



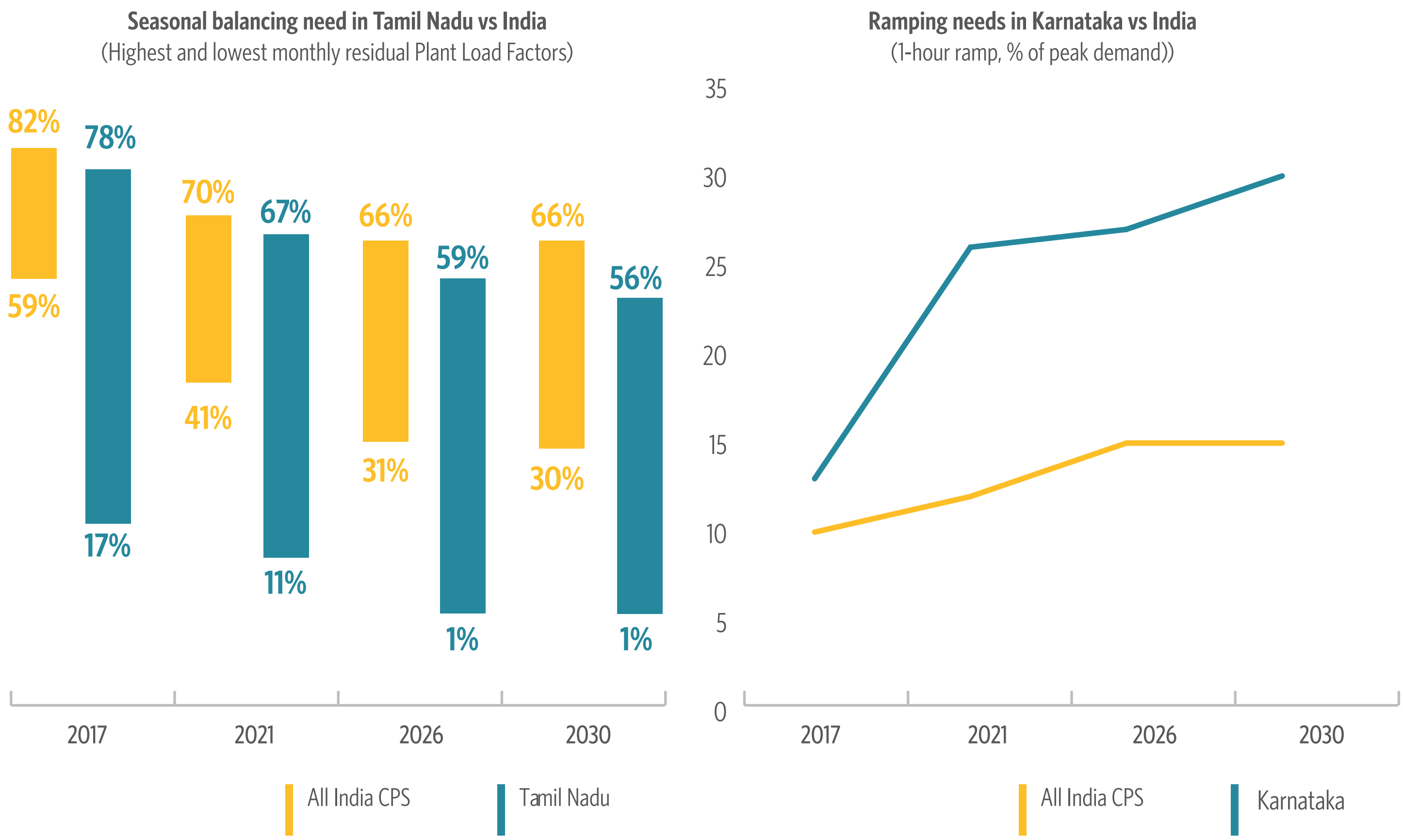
Like daily balancing, the challenges of meeting seasonal balancing depend upon the specific shape of seasonal needs, rather than a single metric, and therefore must be assessed through a broader portfolio modelling approach. Additionally, variations in how daily balancing is met will reduce seasonal balancing needs. For example, during months with a supply deficit, a greater share of daily balancing needs will be met by peak generation, where added generation will fill both daily and seasonal balancing needs. Conversely, daily balancing needs during the months of surplus supply may be met more by demand flexibility and storage.

Our analysis indicates that with a moderate amount of daily balancing, seasonal variation alone will not lead to excess energy production on a nation-wide basis until well after 2030. However, this may not be the case in regions with high shares of wind generation and limited transmission capacity to export surplus wind power to neighbouring regions. Critically, wind generation is likely to drive greater need for seasonal flexibility while solar primarily drives the need for daily balancing capacity.

2.3 Geographical differences

In a country as geographically vast and diverse as India, there are some extreme variations in the need for flexible capacity, and flexibility needs may intensify sooner than in some other regions. These differences are particularly profound in those states that have the highest shares of renewable energy generation. Solar mainly affects ramping and daily balancing, so we can see that by 2030 Karnataka will have ramping needs that are double that of India on average see figure 2.6. Either transmission will need to import flexibility to Karnataka, or energy will be spilled on some days. Wind mainly affects seasonal balancing. Tamil Nadu, which has a large share of wind generation in its mix, already sees load factors of 17% for net load during the highest RE generation month, compared to 59% for India as a whole. This figure will fall to 1% by 2026.

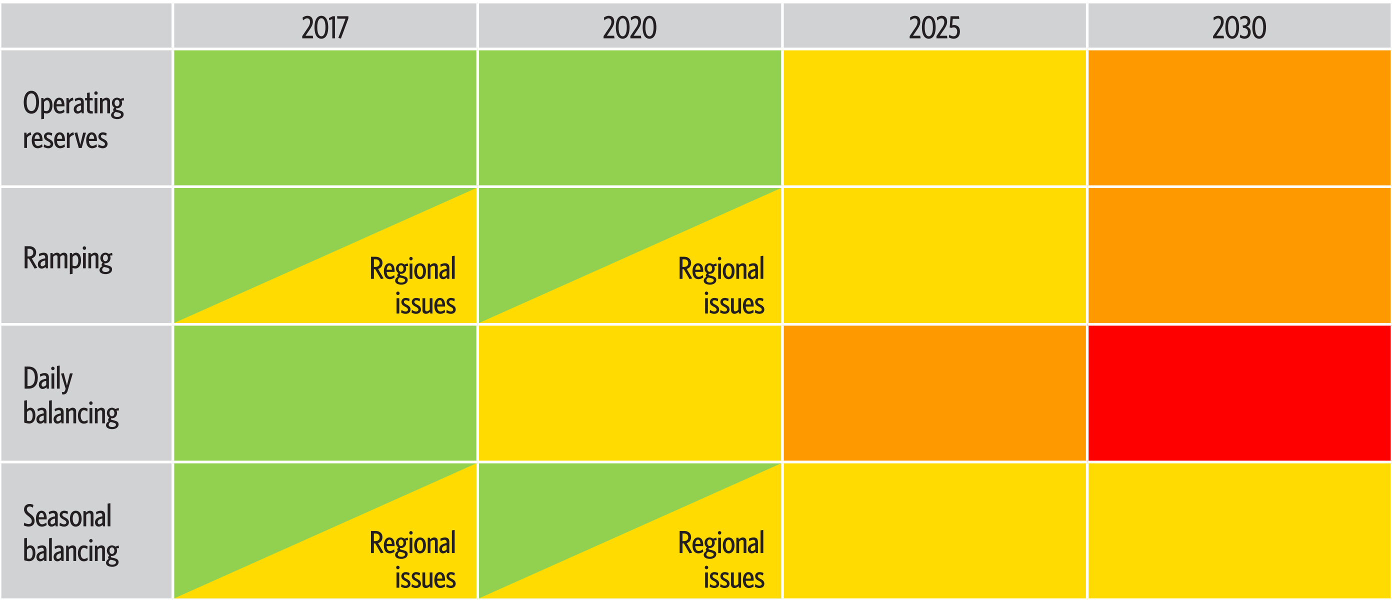
Figure 2.6: Ramping and seasonal needs differ by region and vs India as a whole



2.4 Summary of flexibility needs over time

Figure 2.7 summarises the coverage of Indiawide flexibility needs as they would evolve if no additional resources are developed. By the early to mid 2020s India will need to add significant amounts of flexibility to the system, with the need becoming critical for daily balancing by 2025. By 2030, all flexibility needs will become critical in the absence of active measures to address flexibility needs. Ramping and seasonal balancing are already starting to present challenges at the regional level.

Figure 2.7: India electricity system's ability to deliver key types of flexibility – high RE scenario



3 Flexibility resource options

Key findings

- India's future flexibility capacity requires the development of three main resources – demand flexibility, energy storage and power plant flexibility.
- By 2030, demand flexibility from different sources like agricultural loads, EV charging, industrial flexibility and cooling can provide most of the flexibility needed for daily balancing and ramping.
- We estimate a total potential load of ~600GW by 2030 in sectors that could operate flexibly, such as industry and agriculture; of this, between 40GW to 180GW would be able to operate flexibly.
- This potential load could supply 30% of operating reserve, 42% of ramping need and 18% of daily shifting.
- Increased powerplant flexibility could provide lower cost options, but incentives and investment are required.
- Storage costs need to come down if it is to pkay a role alongside with demand and powerplant flexibility, although storage has many advantages including locational flexibility and the ability to deliver multiple types of flexibility.

India can achieve its renewable ambitions by optimising existing flexibility capacity and developing three new resources:

- demand side response from energy consumers represents a highly cost-effective resource;
- access to India's vast thermal fleet will make the most of flexibility in the electricity system;
- energy storage from emerging technologies such as lithium ion batteries will reach sufficient scale as costs decline.

Historically, India has relied on thermal and hydro powerplants to balance supply with demand, turning these plants up or down in response to varying demand. When flexibility demands were too high for powerplants to cover, power quality dipped and outages were forced across the system. In recent years, India has reduced unplanned outages through scheduled load shedding for groups of customers in order to improve power quality. Planned service interruptions are also less costly to consumers than unexpected interruptions. Meanwhile, consumers have assumed that supply would adapt to their consumption patterns.

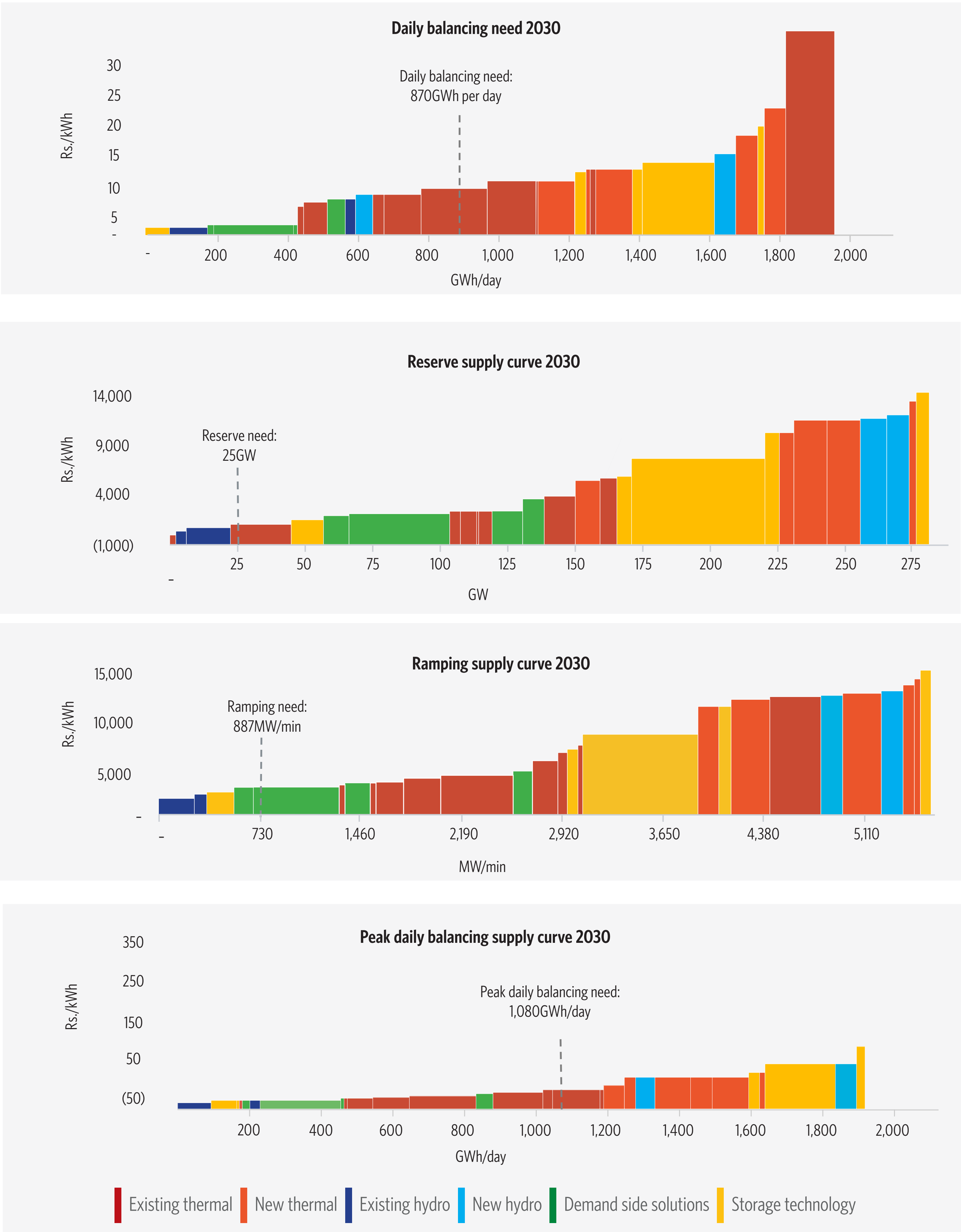
Even though small changes in consumption patterns could significantly reduce system costs, consumers have been given little or no information on how to shift demand nor have incentives to vary their demand. Powerplants have options that could significantly increase flexible resource contributions to the system, but they also lack incentives to cover capital costs and higher operating costs of providing this flexibility, even though the lower system costs would more than make up for higher costs. Meanwhile, the cost of energy storage, including batteries, is falling rapidly.

As part of our analysis, we created supply curves to help understand the cost competitiveness of different resources in providing various kinds of flexibility. For each of the flexibility options we have modelled potential supply (reflected in the width) and its cost (height) for each of the flexibility needs. Costs include variable costs, such as incentives to cover higher operating costs or higher fuel demand, as well as capital costs to cover equipment, upgrades and investments. By ranking these options costs from the lowest to highest costs, we created supply curves showing how different levels of flexibility needs could be met at different costs.

Figure 3.1 shows the supply curves for different flexibility needs throughout the day. The first of these curves shows the stacking of these options to provide daily balancing. With a potential supply of over 1,900GWh/day, and demand of 870GWh/day, demand appears to be well covered. Although in the case of daily balancing, demand flexibility solutions are the cheapest options, most existing thermal and hydro resources would also emerge as cost competitive and viable options. However, if demand flexibility resources are not developed in time, even greater volumes of the existing coal fleet become a viable solution as flexibility providers along with some new highly efficient pithead coal-based power plants.

By 2030, flexibility needs for reserve capacity would remain significantly low (~25 GW) and existing hydro assets can be used to provide for most of the reserve capacity needs along with some demand side options. With the growth in share of renewables, especially solar in the energy mix by 2030, ramping requirements would rise and would need flexibility resources with fast response times.

Figure 3.1: 2030 supply and demand for daily balancing - high RE scenario



Our supply curves show that existing hydro assets are the most cost-effective solutions for ramping, but they are insufficient in meeting ramping needs. Demand flexibility options can offer another low-cost solution to meeting ramping needs. But without demand flexibility options, the cost of existing captive diesel based gensets becomes a viable option.

If all three of these options are adequately developed, India should be well positioned to meet its flexibility needs. Developing all three enables the lowest total system cost and offers backup in case one or another of them develops slower than forecast. Integrating these options to achieve the lowest cost and most reliable supply is an important task both in balancing the development effort between the options, and in developing systems that incentivise and dispatch these resources.

3.1 Options for flexibility from demand and consumers

Incentivising consumers to adjust their consumption patterns can be a source of low-cost flexibility, depending on the cost to consumers and the requirements to meter, control and incentivise the shift. While these demand options are potentially low cost, developing, measuring and relying upon their availability can be more difficult than other options as consumer requirements and behaviour are less well understood than flexibility from power plants and storage solutions. Building a useful share of low cost demand flexibility will take time, and the potential scale of demand flexibility is significantly more uncertain than flexibility from powerplants or storage. Nevertheless, achieving large-scale demand flexibility could be transformational in terms of reducing India's electricity costs, improving electricity supply quality, and enabling the integration of even higher levels of variable renewable energy.

By 2030, demand flexibility from different sources like agricultural loads, cooling load, EV charging and industrial flexibility could provide most of the flexibility needed for daily balancing and ramping. Incorporating demand flexibility into a future system requires an understanding of how it can meet system needs, the experience that India has had so far with demand flexibility, the sources of flexibility and their costs, and how these sources fit within the overall portfolio of electricity flexibility.

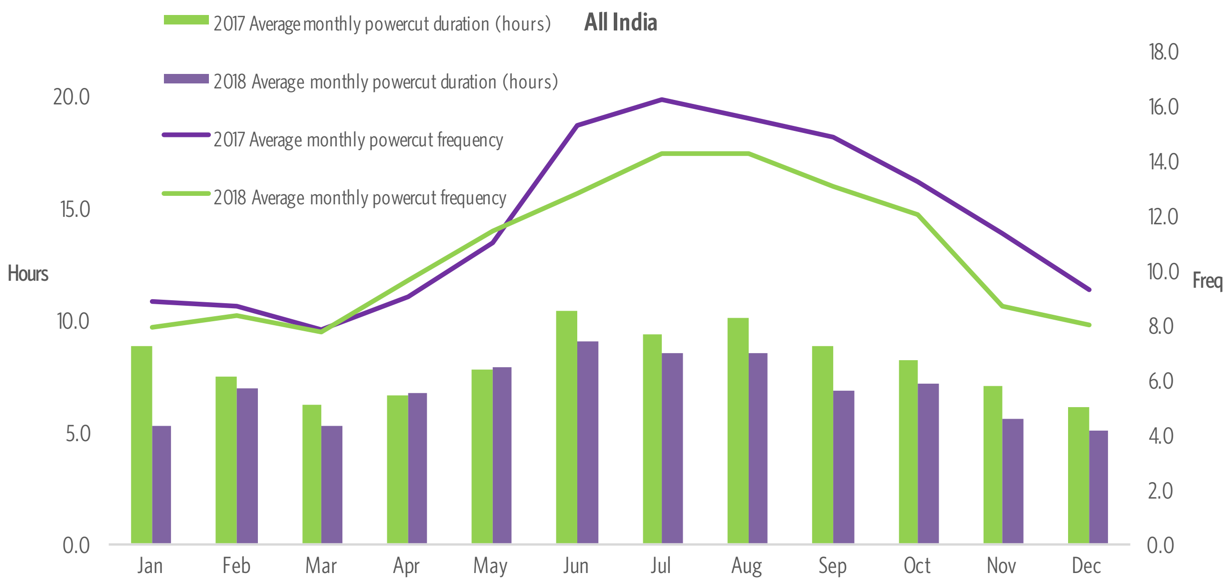
The starting point in India, as elsewhere, is that the supply system will adjust to demand rather than vice versa. This expectation is reflected in tariff structures, metering equipment design and behaviour. Demand flexibility currently presents a missed opportunity which can be developed in many ways such as passive structures like time of day pricing or through active real-time pricing of tariffs, awareness campaigns or other incentives. Costs include incentives to consumers, communication equipment, relevant IT monitoring systems and customer management. It may also prompt customers to invest in *smart* equipment which can communicate with the electricity system and change own consumption according to price signals.

3.1.1 Involuntary demand response or load shedding

In the past couple of years, access to electricity has become universal in India, but the system is yet to achieve the reliability of 24x7 supply. The country has faced frequent outages despite having more than adequate installed generation capacity. Some of the challenges faced by the electricity systems are based on the fact that as demand grows, it becomes difficult to manage and maintain the stability of the grid, which leads to outages and load shedding. Rising demand puts an added burden on the aging distribution infrastructure leading to outages and the high costs of power during high demand periods makes the procurement of peaking power uneconomical for discoms, which triggers load shedding. In figure 3.2, we see that when the demand rises across the country in summer, the frequency and duration of the power cuts rise to its peak.

The mechanism of cutting off supplies at times of shortages (load shedding) has been utilized in India for many years in order to manage the needs of the grid. Although such load shedding can be counted as a form of externally administered demand response, it comes at a very high cost to consumers. Consumers often had to invest in expensive back-up systems and operate in ways that would reduce the impact of load shedding. In recent years, with the advent of better communication systems and more stringent regulations around load shedding, the country is gradually moving towards a more planned approach where in urban centres like Delhi, consumers are warned in advance so that they can manage and schedule their activities to minimise disruption. The next step would be to design incentives and encourage voluntary load reduction which would ensure that customers are able to run their essential appliances while also helping the electricity supply companies and grid operators manage the load. The first steps towards achieving this would be to invest in IT and communication systems, with costs easily recovered from the earnings/savings from active demand response.

Figure 3.2: India has been using involuntary load shedding to balance demand



3.1.2 Pilots

Taking their cue from the learnings and success of demand response programmes in other regions, India has started experimenting with demand response pilots. However, the slow pace of their roll out has indicated the need for an intervention to accelerate the adoption of the successful pilots. Some of the major demand response pilots that have been undertaken in the country are listed below.

Table 3.1: Demand response pilot programmes in India

Tata Power - Delhi	354 consumers participated, 17 events
BSES - Delhi	Ran pilot for largest 500 customers
Tata Power - Mumbai	27 customers participated, 18 events
JVVNL - Jaipur	17 participating customers across 3 Industrial areas, 4
Thermal Energy storage - Tata Power Mumbai	Thermal storage capacity of 15K Tons enrolled

During the various pilots, the distribution companies like Tata Power were able to demonstrate effective load reduction through the use of different demand response options such as temporarily shutting down space cooling units at large commercial premises, shifting activities like municipal pumping away from peak demand periods.

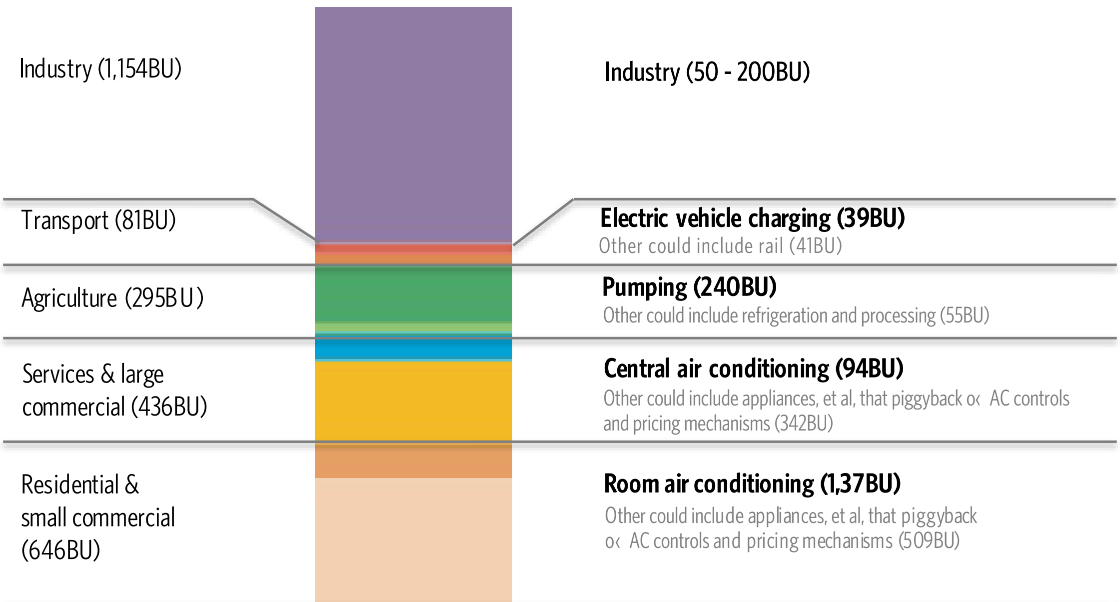
3.1.3 Flexibility potential from demand response

The potential for flexibility depends on the consumer and what economic value the electricity supply delivers at any time. Therefore, the key to unlocking demand flexibility is identifying the significant energy costs while providing convenient systems to develop the flexibility. The major areas which hold the potential to provide flexibility are industries, e-mobility, agricultural pumping and space cooling. It is important to understand that not all consumption could provide flexibility. In fact, the share of consumption that may be available for flexibility may be quite limited and vary significantly between different sources. In figure 3.3, we project the capacity that may be available by 2030 from the key flexibility options.

Often, opening a first avenue of demand response reduces the cost and inconvenience of subsequent end uses but considering that demand response systems are in their infancy in India, in our 2030-time frame we have conservatively chosen to focus on the first end uses. For example, industrial demand response potential would vary from industry to industry and even between plants of the same industry depending on the production processes adopted, raw materials used, storage available, market structures, etc. Therefore, in our analysis we have chosen to estimate industrial demand response at the sectoral level in order to reduce error rates.

Cumulatively, the key sectors considered in our analysis present a peak load of ~600 GW by the year 2030. It is estimated that out of this capacity, depending on the scenario considered (low, mid and high), between 40GW to 180GW would be able to operate flexibly. The potential of demand flexibility can be assessed on the basis that these end uses contribute to each of the flexibility needs representing nearly 30% of the total operating reserve, 42% of the ramping need and 18% of the daily shifting requirement. Also, industrial flexibility is expected to be a key contributor towards seasonal flexibility along with the possible mothballing of thermal assets for a few months.

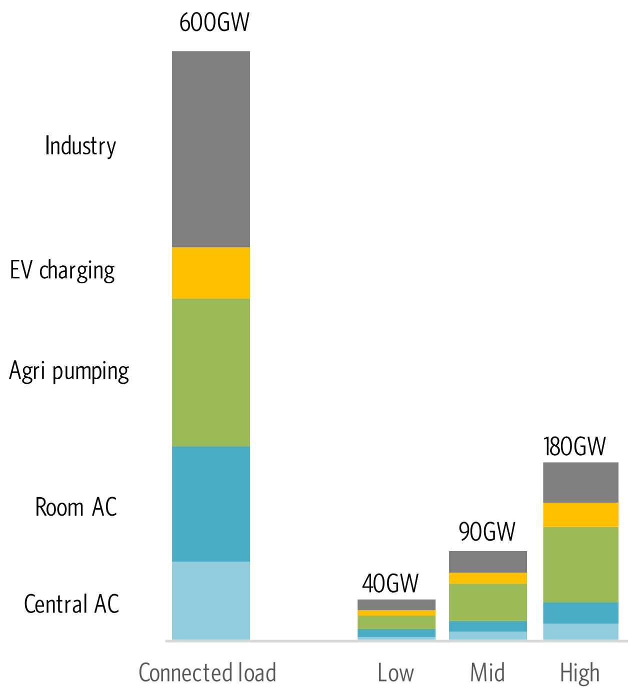
Figure 3.3: Energy available for daily demand shifting by sector



Source: TERI (baseline scenario) and CPI analysis

* BU = billion units (kWh)

Figure 3.4: Sources of low cost demand flexibility



2030 Flexibility	Operating reserve	Ramping flexibility	Daily flexibility	Seasonal flexibility
Industry	20GW	20GW/hr	20-120 GWh/day	Possible, not quantified
EV charging	12.5GW	12.5GW/hr	75.0 GWh/day	-
Agricultural pumping	37.7GW	37.7GW/hr	226.3 GWh/day	-
Space cooling	19.8GW	19.8GW/hr	27.8 GWh/day	-

In our analysis we estimated the cost per unit of flexibility offered by each end use option as well as the potential scale under different scenarios. It is evident from figure 3.4 that significant low-cost potential for flexibility supply is available through the demand side options but leveraging it may be a challenge without considerable planning and investment.

In order to arrive at the estimates in fig 3.4, each of the resource options were analysed quantitatively as well as qualitatively to understand the potential of the resource option and the systems needed to utilize the same. These options are discussed in detail in the forthcoming sections.

3.1.4 Agricultural pumping

Agricultural pumping represents a major share of electricity demand in India accounting for nearly 20% of consumption, or 90TWh annually. Most of this supply is either free of charge or highly subsidised to support farming, which accounts for 14% of India's GDP and employs around 42% of the country's workforce.[4] Our analysis found that at the current rate of growth, the number of pumps used in the country for agriculture would rise by close to 50% in the coming decade. And despite improvement in energy efficiency of the pumps, the electricity consumption by agriculture could see an increase of over 40% by 2030. This represents a significant proportion of India's electricity demand and a significant opportunity for flexibility. Agriculture pumping load does not necessarily need to be provided at any particular time of the day, and can be aligned closer to periods of generation peak to provide flexibility to the system.

Table 3.2: Potential for flexiblity from agricultural pumping

	2017	2030
Number of grid connected pump sets	20m	28.4m
Energy consumed by pump sets (BU) [running for 3.4 hrs daily]	92	131
Annual electricity consumption per pump (kWh)	4,617	4,072
Annual cost of electricity per pump (INR)	18,466	30,712

India has nearly 30 million irrigation pumps, of which nearly two-thirds are grid connected while the remaining one-third run on diesel. In order to improve irrigation and reduce dependence on monsoons, more than 500,000 pumps are added each year. A programme has been initiated to install more efficient pump sets, which has an energy saving potential of 37TWh, and a cost saving of INR 150 Billion and a short payback period of around four years.

3.1.5 Feeder segregation

However, only the consumption of the pump sets should be shifted so that supply to rural households and industries is not disrupted. To accomplish this, agricultural pumps would need to be connected to a separate feeder that can be turned off during periods of high demand and turned on during periods of excess renewable generation each day. In order to allow this freedom and to minimise T&D losses, a feeder segregation programme is currently underway that will:

- Increase revenues to the utility arising from loss reduction and/or change in sales mix in the project area;
- Shift load to off peak hours providing flexibility and also reducing the cost of peak power procurement;
- Improve quality of supply in non-agricultural segments.

The cost of setting up an additional feeder is typically between INR 0.20 to 0.25 million per kilometre at a cost of around INR 65,000 per connection. A total amount of Rs 430 billion, along with budgetary support of Rs 335 billion from the central government, has been approved under the scheme for feeder separation and strengthening of the sub-transmission and distribution infrastructure in rural areas. Feeder separation programmes have been successfully completed in Gujarat, Andhra Pradesh, Punjab, Rajasthan, Haryana and Madhya Pradesh, among other states.

Analysis of the data from Gujarat where the feeder separation program has been completed suggests that load curves from the state have flattened with the discoms being able to shift the pumping load to off peak hours. Gujarat registered a growth of 10.39%, in energy input, from FY 2007-08 to FY 2009-10. However, peak demand grew by only 1.93% during the same period along with marked reduction in the power outages and voltage related issues.

The segregation of the feeders, also allowed the disaggregation of the agricultural power consumption from broader rural load, drastically reducing the load attributed to agriculture.

A solarization programme of agricultural pump sets (KUSUM) has also been initiated, but the impacts and outcomes of it have not been evaluated as a part of this study as off-grid solar pumps while reducing the load on the grid also reduce the availability of the related capacity for flexibility.

[4] Trading Economics https://tradingeconomics.com/india/gdp-from-agriculture

3.1.6 Air conditioning

India has very large potential for a space cooling market driven by current low penetration of air conditioning (~5%) which is expected to rise to 70% by 2040, coupled with more frequent cooling degree days and greater affordability thanks to increases in household income. In parts of India where AC penetration is already high, such as Delhi, cooling already accounts for 40%-60% of summer peak load. Rise in power demand for cooling is expected to add 140GW of peak demand by 2030 and energy efficiency measures aim to limit it to 90GW.

Shifting AC cooling by a few minutes for room ACs or precooling using the chiller for central ACs would provide flexibility to the electricity system. Changing the target temperatures on the thermostat also reduces pressure from cooling load providing additional sources of flexibility from both residential and commercial consumers.

3.1.7 Residential air conditioning

Our research showed that room ACs account for almost 60% of all cooling capacity and their share in the cooling mix has increased in recent years. Currently there are 30 million room air conditioners installed in India. Nearly half a million room air conditioners are sold in India each year and the sales have been growing at a CAGR of 13%. Of these, nearly 50% of the AC sales go towards new installations. By 2030, the number of installed room air conditioners is expected to reach 124 million units with a combined cooling capacity of 177 million tons[2]. Energy efficiency is also improving – our analysis shows that electricity consumption by an average air conditioner is expected to halve by 2030. Even factoring in this energy efficiency benefit, the load from Room ACs is expected to more than quadruple to 2030.

Table 3.3: Potential for flexibility from residential air conditioning projections

Room AC	2017	2030
Number of units	30,000,000	124,000,000
Total installed capacity (million tons)	43	177
National room air conditioning load (GW)	42	117
Annual electricity consumption per AC of 1.35 ton (kWh)	2,286	1,044
Annual electricity expense per AC (INR) [With average tariff across consumer categories rising 5% annually]	13,715	11,809

Even if a small percentage of this load can be harnessed for flexibility, it would add significantly to flexibility potential from demand response. For our analysis we have considered a conservative 10% of the total as capacity that participates in providing flexibility services.

To tap into the flexibility potential of the residential cooling load, air conditioners would need to be connected to smart systems which could temporarily reduce their electricity consumption during peak periods. Smart air conditioners which can connect to home automation devices have been launched in the Indian market, but currently these are not the most energy efficient and can cost up to 50% more than the existing options. Smart Plugs are also available at an average price of ~Rs 4,000 per plug which can be used with non-smart ACs for switching the devices on/off remotely through mobile apps based on DR signals. This can integrate large volumes of the room AC load for flexibility.

[2] A ton is the cooling capacity of an air conditioning system. One ton is equal to the amount of heat required (288,000 Btu) to melt one ton of ice in a 24-hour period. The cooling capacity of an AC is based on its rating.

3.1.8 Commercial (central) air conditioning

Our research shows that total installed capacity of central air conditioners in India is currently 33 million tons. With rapid urbanisation, central air conditioning capacity is expected to reach an installed capacity of 122 million tons by 2030. The energy consumption by central ACs by 2030 is expected to grow over 3.5 times from the current 25TWh to nearly 90TWh a year by 2030. Office complexes are expected to be the largest consumers of central air conditioning capacity. It is easier to implement flexibility options such as thermal storage with central ACs as a substantial load is controlled from a single point.

Table 3.4: Potential for flexiblity from commercial air conditioners

Central AC	Current	2030
Installed capacity (million tons)	33	122
Annual power consumption (BU)	55	94
National central air conditioning load (GW)	32	81

Central air conditioners can help provide flexibility by reducing the cooling load for a short duration during peak demand or by using precooled thermal energy storage systems which allow the cooling systems to be switched off during high demand/peak periods.

Our analysis revealed that although there is a high cost of retrofitting thermal storage systems in an existing central cooling system, the cost of greenfield installation of a cooling system with thermal storage is the same as a conventional central cooling system. This is achieved through dual use of the chilling equipment under sizing of the chillers themselves because they no longer need to be designed for peak cooling need as the peak can be served through the thermal storage.

3.1.9 EV charging

India's ambition to switch to 100% EVs by 2030 will significantly increase demand on the electricity system, but the batteries from this electric fleet could also provide a potentially significant grid resource for flexibility to support renewable generation, balance electricity supply and demand and alleviate strain on the network at a local and national level.
There is a wide range of uncertainty in EV adoption scenarios for India. LBNL analysis (2017) indicates that sales of new 2-wheeler, 3-wheeler and car sales would lead to EVs making up 100 million 2-3 wheelers and 40 million cars, adding 82TWh (103TWh without efficiency gains) of new electricity demand and 23GW of peak charging load. TERI's more modest forecasts leads to roughly 77TWh per year of new demand, but also incorporates fleet vehicles such as buses and taxis.

Table 3.4: Electricity demand growth from electric vehicles

Vehicle type	Share of EVs in new vehicle sales (%)	Total electricity demand from EVs - existing and new sales - (GWh)
Four-wheelers	10%	7,626
Two- and three-wheelers	25%	11,152
Buses	15%	12,630
Light-duty freight vehicles	10%	9,726
Total	Source: TERI (baseline scenario)	**41,134**

Assuming four hours per day of charging, TERI's figure translates into roughly 50GW of controllable demand. However, this demand is not always available when needed for flexibility so we have assumed that only 25% or 12.5GW of this capacity will be available for flexibility.

3.1.10 Industrial demand response

Industrial demand in India has great potential for large scale demand side flexibility. With the right incentives, reserves can be tapped by managing demand, eg by changing production schedules to non-peak periods to provide daily shifting. Changing production to months of high wind and hydro generation seasons (monsoons) can also help offer seasonal flexibility.

Electricity consumption by the industrial sector in India has grown at a rate of over 7% pa[5] since 2000 and currently consumes 4,68,825 GWh, around 42% of total electricity demand. The electricity demand from industry is expected to continue to grow at ~6% a year with the demand from energy-intensive industries growing at 5% - 6.5% a year until 2030. The growth in electricity consumption is fuelled by economic growth which is expected to rise to over 7.5% a year[6] in the mid-2020s. The projected growth in power demand lags the economic growth rate because GDP increases are largely expected to come from less energy intensive service sectors.

Table 3.5: Industrial sector demand growth to 2030

	2001	2015	2030
Total industrial electricity demand (GWh)	159,507	4,3,523	1,153,916
- Supplied through grid (GWh)	107,296	2,5,696	796,897
- Met through captive generation (GWh)	52,211	1,7,827	357,019

Different industries have the potential to provide different types of flexibility, but the flexibility potential that can be tapped into depends on a number of factors:

- **Energy intensity –** Industries with high energy intensity can offer flexibility as even small changes in the timing of energy consumption can have a significant impact on both electricity demand as well as the cost for the consumer.
- **Production type –** Industries with batch manufacturing processes would be more suited to providing daily balancing flexibility by shifting processes / shifts closer to peak generation blocks. Process industries on the other hand may have better potential to offer ramping capabilities by shutting off their energy intensive processes temporarily and letting them briefly run on process inertia during periods of high ramp demand.
- **Product type –** Industries whose products have seasonal demand with the final or intermediate product having storage possibility can be incentivised to increase production during high renewable generation months (monsoons) and store the goods while reducing production during the lean periods to offer seasonal flexibility.

Multiple strategies can be employed for implementing industrial demand side flexibility, such as:

- **Load priority systems:** This is a flexible load technique which makes a priority system of the specific industry's different electric loads. The aim is to identify which loads can be turned off and for how long, and which loads are crucial to productivity. The same can also be implemented for commercial entities like business parks and the system can be modelled on the same principle that is used currently in designing backup for essential services like hospitals
- **Rescheduling processes or parts of processes:** One technique is to adjust the labour hours for electricity intensive processes into times with lower electricity cost. This could reduce electricity costs, if it is possible to reschedule parts of, or whole processes. Incentives can be designed to promote the shifting and covering the cost of storage.

5 Source: Brookings Institution

6 Source: Standard Chartered

- **Heat, cool or media storage:** For some industries it could be beneficial to implement storage of heat, cool or process media when the electricity price is low. Depending on the type of industry and production processes this could be used in different ways.
- **Heat and power co-generation:** In industries with large demands for heat or other energy consuming processes, steam production is often necessary to sustain parts of the production processes. With a co-generation unit this steam could, in addition to heat, produce electricity by using turbines and heat exchangers, instead of only producing heat. The electricity generated from part of the steam can be used to reduce consumption from the grid during periods of peak demand or during periods with high ramping needs.
- **Direct load control:** Direct load control systems can be connected to non-critical production and offers the possibility of regulating different electricity loads with the objective to shave peaks and shift loads to desired hours of demand.

3.1.11 Different processes in the following industries offer potential for flexibility:

- **Cold storage:** Emergency generators, refrigeration systems (the cold storage part of the process) and thermal storage can be used for flexibility. Most farm produce stored in cold storage requires the temperature and relative humidity to be maintained over a relatively narrow range – therefore the temperature of cold storage systems cannot be raised to curtail energy demand during peak hours. The chillers on cold storage systems run nearly 20 hours each day with some degree of seasonal variability. The most promising gains could be in the case of emergency generators providing system services.
- **Ferrous plants:** In iron and steel plants, an induction furnace could be a significant source of flexibility. Load shifting to cheaper times of supply can save an estimated 3-4% of process energy costs or just below 1% of the total energy costs of the plant. (Source: IndustRE)
- **Non-ferrous plants:** The flexibility source in non-ferrous plant can be tapped by shifting the discontinuous (batch) process of alloy melting or grinding (cement) or stentors, diggers, humidifiers and centrifuges (textile). The process could provide flexibility by partially shifting the batch production from peak electricity cost periods to lower power costs periods.
- **Paper & pulp:** Demand flexibility can be accessed by adding product storage capacity after mechanical pulping but before use in paper mills. Also, a possible mechanism for providing flexibility could be the use of an electricity boiler next to the gas boilers to produce heat when the imbalance price is beneficial compared to the gas price (valley filling).

Table 3.6: Flexibility potential by industry

Industry	Share of consumption	Processes offering flexibility
Textile	8%-12%	Stentor, jiggers, humidifiers and centrifuges
Iron & steel	5%-7%	Material preparation, waste metal recovery, sand reclamation unit
Paper & pulp	3%-4%	Chip plant, ETP, pulp preparation
Cement	2%-3%	Grinding

Table 3.7: Barriers and potential solutions

	Barriers	Potential business models	Incentives needed
Agricultural pumping	- Existing structure of common feeders for rural domestic consumption and agricultural demand - Political sensitivities around charging agricultural customers - Lack of discom incentives to invest in feeder separation to isolate agricultural demand	- Separation of all agricultural feeders which can provide load shifting opportunities - Metered and billed usage for non -agricultural rural consumption	- Continued push for completion of feeder separation programme - Direct benefit transfer schemes
Space	- Fleet of existing fixed speed room air conditioners with no 'smart' features - Poor building insulation limits inherent thermal storage in buildings - Lack of data on regional AC penetration or usage profile to predict available flexible loads - High cost of efficiency retrofits in central ACs - Behavioural barriers to changing temperatures - Fragmented control over AC investment and operational decisions	- Aggregation and dispatch of fleet of AC systems by discom or third party - Shift to high efficiency ACs with pay back through savings - Use of thermal energy storage in greenfield central AC installation to lower opex and provide load shifting - Smart controls for savings linked to demand response through marginal temperature changes - Unlocking demand response value through smart AC or Smart Plugs - Thermal storage systems to replace diesel gen-sets as backup during outages	- Time of day tariffs for residential and commercial customers - Prioritisation of high efficiency smart ACs (NCAP) - Building guidelines for central ACs to include thermal storage - Sharing of DR linked saving between discom and market participants
EV charging	- Prediction of charging profiles and available charging load - Lack of ubiquitous, standardised charging infrastructure - Charging patterns likely to be driven by consumer needs and convenience, not electricity pricing - Uncertainty around EV market potential	- Aggregation of EV charging demand participating in electricity markets - EV charging subscription plans with discounts for greater flexibility	- Location-based and time of use pricing for EV charging
Industry	- High cost impact of halting supply line based or process-based industries - Fragmented nature of industry demand (over 2/3 consumers outside electro-intensive sectors)	- Earning through sharing of discoms saving by shifting planned maintenance to high electricity demand season - Unlocking demand response through local targeting of non-process industries with high technical potential	- Regulatory mechanism to facilitate sharing of savings

Summary

		Air conditioning	Agricultural pumping	Electric vehicles	Industry*
Potential connected load**	2018	75GW	106GW	N/A	86GW
	2030	198GW	152GW	50GW	200GW
Spinning and load following		Central cooling solutions can offer limited spinning and load following capabilities by turning off equipment chillers for a few minutes through automated demand response	Upon separation, the agricultural feeders can be temporarily turned off to reduce immediate load and therefore reduce requirement of spinning capacity	Can provide limited spinning capacity through v2g operations for charger connected vehicles. Real world use cases currently in testing phases	Potential for providing load following capabilities using automated demand response for certain equipment (pumps, compressors, etc)
Short-term reserve		Smart air-conditioners and smart plugs through demand response can shut down the compressor to free up MW. But installing smart systems currently bear a significant cost		May provide short-term reserve capability by temporarily interrupting charging with appropriate price incentives to the vehicle owner/operator	Turning off some of the non-essential equipment temporarily can help free up energy for short term balancing
Ramping		Central AC load may be shifted to off peak hours using thermal storage or temperature raising in a central AC fleet (only part of the fleet's temp raised for a time block). Room ACs may not offer flexibility to reduce ramping	Supplying agricultural feeders during the peak generation or low demand periods can reduce ramping needs	Charging cars during high generation and off peak consumption hours can reduce additional ramping needs	Non-process industries, (running morning to evening) may exaggerate the ramping need. However, future ramping need driven by solar could be partially covered by backing down some of the batch operations
Intraday balancing		Central air-conditioners through thermal energy storage can shift peak cooling load to off peak durations creating a flatter load curve	Through the segregation of feeders, agri pumping operations can be shifted to off-peak hours thereby flattening the load curve	Charging of batteries during off peak hours can help flatten the load curve	By shifting some of the batch manufacturing activities to off peak times, industries can provide intraday balancing
Seasonal flexibility		May contribute to local needs for seasonal flexibility	Contributes to the need for seasonal flexibility	PHEVs have some potential to provide seasonal flexibility by shifting to gasoline based operations during high peak months	Can help meet seasonal flexibility need by scheduling planned outages and maintenance during periods of high demand/low generation

*Including captive capacity; ** non-coincident capacity of equipment

	Costs	Areas needing investment
Agricultural pumping	12,200 INR / kW (derived from cost per connection)	• Dedicated agricultural feeders • Distribution monitoring and automation
Space cooling	5,000-15,000 INR/kW up front additional cost Ongoing cost of < 700 INR/kW-yr	• Smart AC controls • Fleet control, optimisation and dispatch software • Thermal energy storage systems
EV charging	5,000-10,000 INR/kW up-front cost Ongoing cost of < 700 INR/kW-yr	• Additional batteries to enable battery swapping for 2- and 3- wheelers • Additional charging points for cars • Fleet control, optimisation and dispatch software
Industry	Costs are industry dependent ranging from very low for batch manufacturing industries with high technical potential, eg packaging to very high for even partial; back down of process based industries, eg steel	Control systems for isolating and shifting loads Fleet control, optimisation and dispatch software Equipment R&M for sustaining flexible operation

3.2 Meeting flexibility needs with thermal and hydro powerplants

Key findings

- Thermal and hydroelectric powerplants, along with load shedding, provide most of the flexibility needed by India's electricity system today.
- We find that India's coal fleet could provide more flexibility than it does currently – up to 107GW – of which about 20GW would require significant plant upgrades and investment.
- While hydro can provide a lot of low-cost flexibility, however, it is highly seasonal and its contribution to flexibility is unlikely to be expanded significantly.

Thermal and hydroelectric powerplants, along with load shedding, provide most of the flexibility needed by India's electricity system today. With a large fleet of existing powerplants that will remain in commission for years to comte, coal plants can be an important source of medium-term flexibility that can be increased in several ways. Greater ramping and load shifting capacity can be procured through a mixture of operational and technical interventions such as reducing the technical minimum, two-shifting at certain plant and designating powerplants for increased ramping capacity. Plants past their PPA contract periods could also be considered for seasonal flexibility.

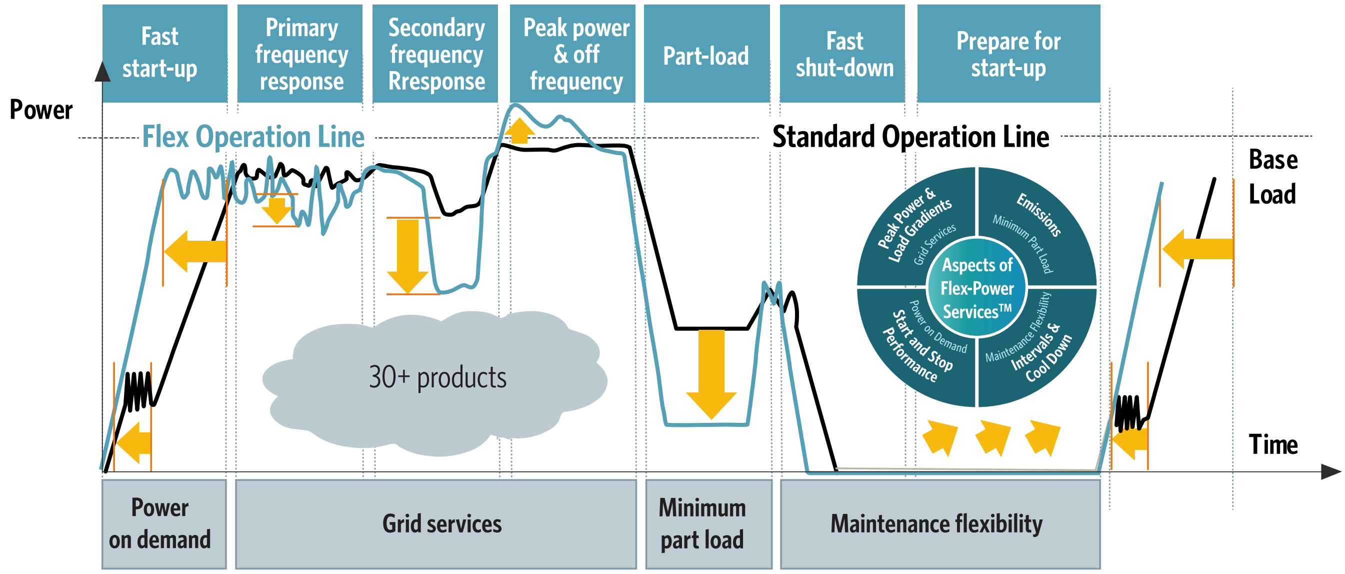
However, there are limits to how much flexibility they can provide and there are costs associated with it. India's electricity system will need this flexibility and to achieve the lowest cost and most robust system, it will need to integrate powerplant flexibility with demand and storage options. To assess integration opportunities, we need to start with how powerplants provide flexibility, and the limitations and costs.

3.2.1 Limits to flexibility from thermal plant

Within limits, powerplants are dispatchable. That is, system operators can turn plants on or off, up or down. But the limits are significant.

- **Minimum generation –** Powerplants cannot operate stably below a certain level of peak capacity. Below that level, output will become unsteady and the equipment cannot handle the operating parameters. The level of minimum generation is a function of the plant itself, as well as the control equipment and system or plant owner operating policy (designed to maintain a stable electricity system). Flexibility from ramping or daily balancing, is limited to the "flexible range". For example, a 200MW plant with a 55% minimum operating level could offer 90MW of ramping or, in many cases, daily balancing.
- **Ramp speed –** Just as an automobile requires time to accelerate, powerplants require time to it odraise temperatures to provide steam and increase output. To meet increasing, or ramping, demand as factories start up or lights are turned on (or solar PV output decreases) a system will bring on as many powerplants needed to address two constraints: how much total ramp will be needed and how fast that ramp will be needed. A single powerplant can contribute the difference between its minimum and maximum as its total ramping, and contribute its rate of acceleration (MW/min) to the peak ramp. Often the number of powerplants dispatched in a system will depend upon the maximum acceleration required (adding up all of the maximum ramp rates of the available plants), rather than the number of plants required to meet peak load.
- **Start-up time –** Depending on how long a powerplant has been idle, it takes time to get up and running, even to a minimum output. Startup times generally last for several hours, requiring notification to the operator of when the plant will be needed well in advance. More often, plants need to be left at minimum generation so that they are available later in the day for peak times or peak ramping needs.
- **Minimum down time –** Likewise, most plants cannot be shut down for a few minutes or an hour and then re-started. Minimum down times also lead to plants running at minimum or less than maximum output for parts of days.
- **Load following/frequency response/other –** Finally, powerplants can be asked to make smaller adjustments on a real-time basis to help manage supply and demand balance. Providing these services requires more sophisticated control systems and sometimes plant modification.

Figure 3.5: How coal-fired power plants contribute to flexibility services



ST stress controller	Advanced fast loading	HP turbine with last MS-valve	Fast preservation
SPP hot start on the fly	Primary frequency response	Partial bypass concept	Fast cooling
HP internal bypass cooling	Condensate throttling	Part load optimization package	ST hot standby
Advanced fast loading	Dispatch control	Minimum load reduction	FMS
ST EOH counter 4.0	Maximum load plus	Top feedwater heater	
Low loss start			
Fast start / hot start			

Source: Siemens

Figure 3.5 above, provided by ETC India member Siemens, shows how a typical powerplant could offer various flexibility services to the system. The black line represents the potential flexibility offered from a typical powerplant before it is made more flexible through investment, changes to operating practices, renegotiation of contracts that limit flexible operation or provide disincentives to do so, and enhanced control systems.

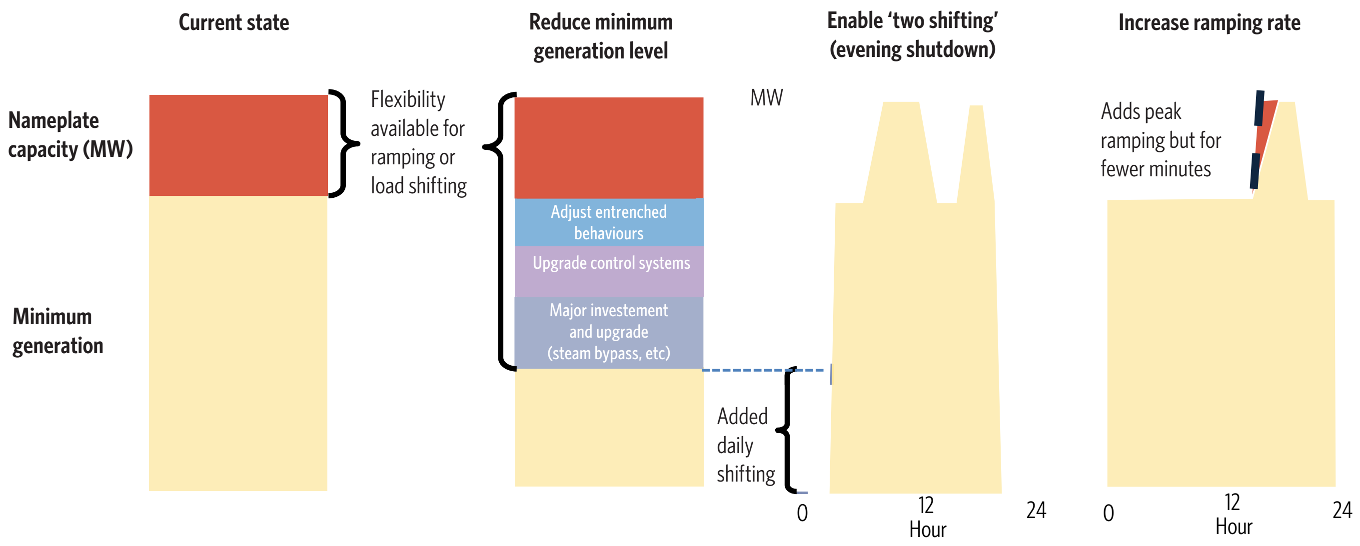
3.2.2 Options to increase flexibility from thermal powerplants

Figure 3.6 on the following page highlights three main options for increasing the flexibility of thermal powerplants.

- **Reducing minimum generation levels.** There are several options for increasing powerplant flexibility by reducing minimum stable generation levels. First, while we understand that most powerplants in India are technically capable of operating at 55% of nameplate capacity, many of the plant operators and dispatchers set 70% capacity as the dispatch minimum. Several factors contribute to this common practice including operator fear that lower generation levels will cause technical problems, or contracts or markets that penalize operators for lower output or do not pay for the higher per unit costs of operating at lower, less efficient, levels. Next, we understand that with varying levels of investment, particularly in control systems, many Indian powerplants have the potential to operate at 40% of nameplate capacity or even lower. In addition to the uncertainty about operations and higher per unit costs, there are not currently no mechanisms to pay for and incentivise the investment required for this additional flexibility.

- **Enabling "two-shifting" for evening or daytime shutdown.** Powerplants in India generally require a significant time to shut down and start up in order to avoid damaging the equipment. The result is that many plants need to continue operating at minimum generation even at times when there is excess generation on the system so that these powerplants will be available to generate at full capacity when demand increases later in the day. Experience outside of India has shown that

Figure 3.6: Coal plants provide an important source of medium-term flexibility



investment to enable short – 6-12 hour daily – shutdowns can more than pay for itself through the value of flexibility that the shutdowns provide and can do so with little impact on reliability and maintenance costs. However, to our knowledge, two shifting has not been tried in India, so the feasibility, cost and impact is unknown. There are also no mechanisms or incentives currently to pay for the investment cost.

- **Increasing ramp rate.** A third potential improvement is to increase the ramping rate of powerplants so that they can provide more ramping services when needed. Again, investment in control systems and other equipment is required and will need to be incentivized. Note that increasing the ramp rate flexibility will be limited by minimum generation requirements.

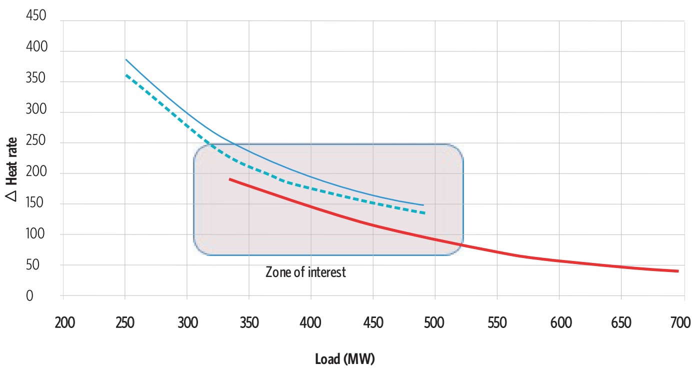
Each of these options will provide more flexibility, but each also come at a cost in at least five ways that we describe on the page opposite.

3.2.3 Costs of providing flexibility from thermal powerplants

Although the powerplants that provide flexibility are already running, there are at least five ways that offering flexibility could increase the costs to the powerplant and to the system:

1. **Efficiency penalty.** Thermal powerplants are less efficient when they operate below their maximum rated capacity. Figure 3.7, provided by Siemens, shows how the heat rate of a 500MW coal-fired powerplant would decline at lower load factors. This plant could operate at a minimum load of 50% or 250MW. We factor in 10% efficiency loss at part load.

Figure 3.7: Impact of part-load operations on efficiency (courtesy of Siemens)



Source: Siemens

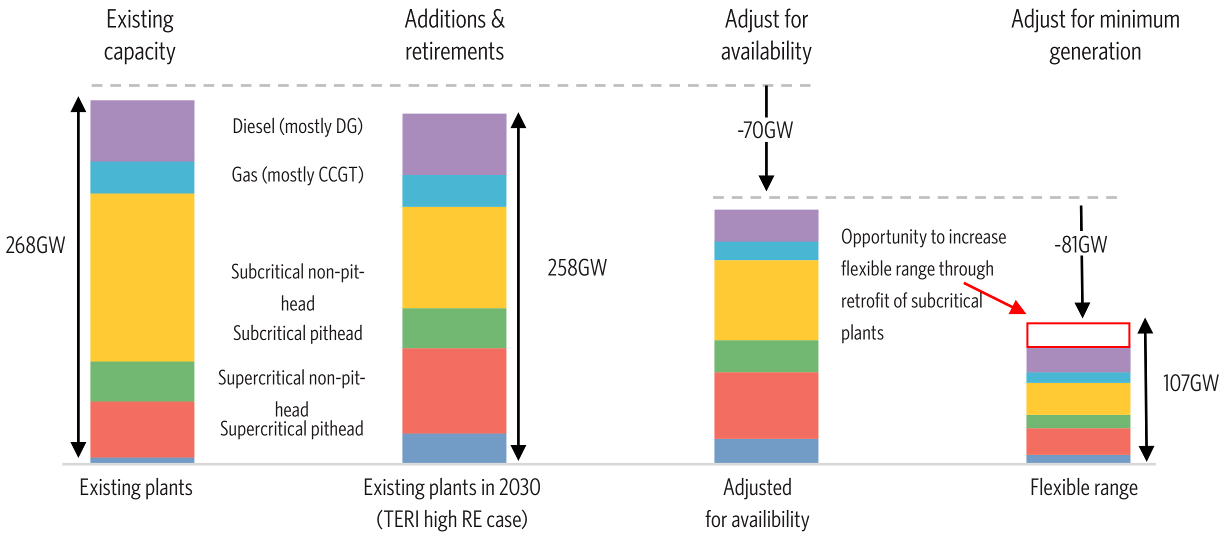
2. **Operating costs.** Operating plants more flexibly requires changes in temperature and starting and stopping equipment, all of which puts strain on the equipment, requires increased maintenance and monitoring. Additionally, plant failures and mor frequent repairs may be more likely. How much costs, maintenance and failures increase is controversial, as is how much investment and changed operating procedures can reduce these costs. We have not factored in any increase in operating costs, separate to the penalty already factored in through efficiency losses above.

3. **Capacity.** Providing some flexibility services, such as short-term reserve, requires powerplants to operate at less than maximum capacity so that they can increase output quickly in response to sudden surges in net demand. Not only does operating below the maximum increase fuel costs, system-wide additional plants may be needed.

4. **Start-up costs.** While fuel is saved by shutting a plant down, restarting a plant and bringing it back online incurs extra costs including fuel, operating costs, etc.

5. **Upgrade costs.** Many plants are not operating as flexibly as they could. Increasing flexibility for these plants requires changes in operating practices, guidelines and incentives. More flexibility can be added to the system through investment. Based on inputs provided by Siemens, a retrofit and modernization of a 210MW unit could increase the flexible range by lowering minimum generation levels from 65-70% to as low as 40% while decreasing the fuel cost penalty, lowering ongoing operations and maintenance costs, and extending the life of the plant. Such a retrofit may cost 110 crore INR for a 210MW unit, but 170 crore INR for a much larger 500MW unit. However, India's coal fleet is relatively young and only a portion of plants are old enough to be good candidates for economically viable retrofits over the next 10 years.

Figure 3.8: Potential flexible capacity from existing thermal power plants



3.2.4 Estimating available thermal powerplant flexibility

We estimate how much flexibility is available by identifying which plants could provide flexibility, adjusting these numbers over time for additions and retirements, then adjusting for availability (that is, maintenance and repair down time), and then adjusting for minimum generation, as in figure 3.8.

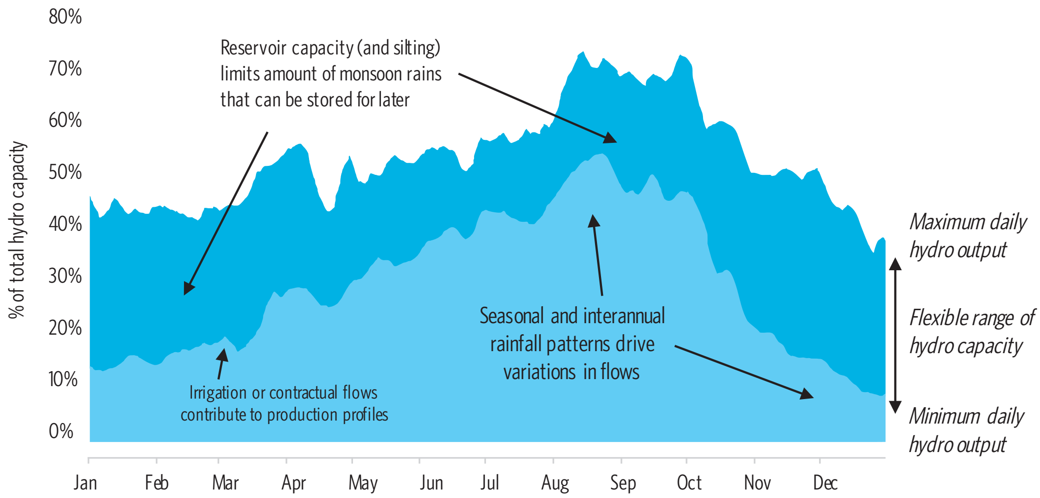
After these adjustments, powerplants can provide 107GW of flexibility capacity to the system, of which about 20GW would require significant plant upgrades and investment.

3.2.5 Hydroelectric powerplant flexibility

Hydroelectric powerplants with large reservoirs are often much more flexible than thermal powerplants. They can start up almost instantaneously, with little startup costs; they have almost no minimum generation limits and can operate at almost any level of output with little efficiency loss. Running below maximum output saves energy for later use, and these plants can easily follow load. For these reasons, hydro powerplants are often the first source of flexibility.

However, there are certain complications. Rainfall drives potential output, so output and flexibility provision are seasonal. At times, plants must operate at high output to avoid water spillage, at others they must operate at least enough to ensure that rivers flow to supply irrigation and keep wildlife alive. Seasonal flexibility is limited by the size of the reservoirs and rainfall patterns. At the same time, there are many hydroelectric generators that have limited or no reservoirs and therefore offer only limited levels of flexibility. Figure 3.9 on the next page shows how hydro flexibility in India varied in 2014.

Figure 3.9: India-wide minimum and maximum daily hydro production, 2014 (CEA)

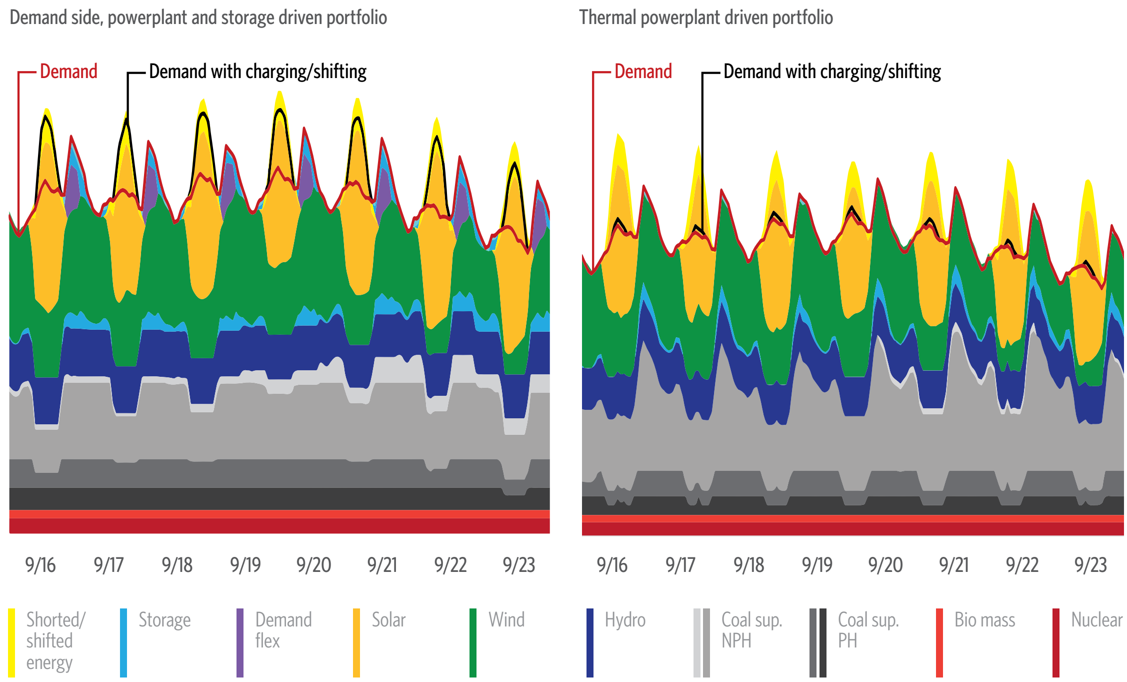


3.2.6 Meeting specific flexibility needs

Each flexibility need incurs different costs for the powerplants and different capacity availabilities. Figure 3.10 shows where thermal and hydro powerplant fit within the flexibility supply options. Hydro is among the lowest cost options for all flexibility needs, but only for reserves is there usually enough existing hydro capacity to come close to fulfilling India's needs. Thermal power plants will play an increasing role in daily balancing, ramping and seasonal balancing, providing almost all of the latter at a reasonable cost. Existing captive diesel gensets, owned by consumers, will also be able to contribute to meeting the peak daily balancing needs, if adequate controls and incentives can be built to harness their capacity at the right time.

To meet these requirements, thermal powerplant will need to operate more flexibly, with lower minimum generation and more frequent start-ups, variations in generation across the day, and seasonal shutdowns when less thermal capacity is needed. However, given the availability of many lower cost demand and storage flexibility options, the operation of thermal powerplants will depend upon how much of these sources develop. Figure 3.10 shows how thermal powerplant of different types will operate differently in a system with fully developed demand flexibility and storage, compared to a system where powerplants are the only source of flexibility. We explore different portolio combinations in section 4.

Figure 3.10: Thermal power plant contribution to flexibility depends on interactions with other system resources



3.3 Meeting India's flexibility needs with energy storage and batteries

Key findings

- By 2030, the cost of stationary energy storage systems using lithium-ion batteries in India may decline by as much as 75%.
- We forecast a global decline in total costs for stationary storage systems (inclusive of all balance of systems costs) from $587/kWh in 2017 to $142kWh in 2030
- By 2030, global EV sales of over 20 million cars per year implies annual battery need of at least 1,000GWh per year – which will drive down the costs further for other applications, such as daily balancing.
- Grid applications are expected to reach 300+GWh of cumulative energy storage deployment by 2030 globally, of which around 25GWh is expected in India.
- Central Electricity Authority estimates 63 sites with over 96GW of potential capacity for pumped hydro, of which only around 5GW has been developed to date.

The difficulty and cost of storing AC electricity is the reason there is a flexibility issue for electricity systems. Inexpensive, instantaneously accessible storage could provide reserve capacity, it could smooth out demand ramps, follow load variations, balance demand over the course of the day and, if the capital cost of the storage were nearly free, it could store energy from one season to use in the next.

Until recently, storing energy in the form of water behind dams in hydro powerplants, and pumped storage hydro powerplants, was the only widespread, cost-effective method of storing electricity. Even hydro storage is usually expensive when capital costs are included, and its potential is limited by geography and water availability. India has good existing reserves of hydro capacity, but in spite of its potential, significant growth from 41GW is hampered by the complex approvals process, social, development and environmental factors and construction timelines.

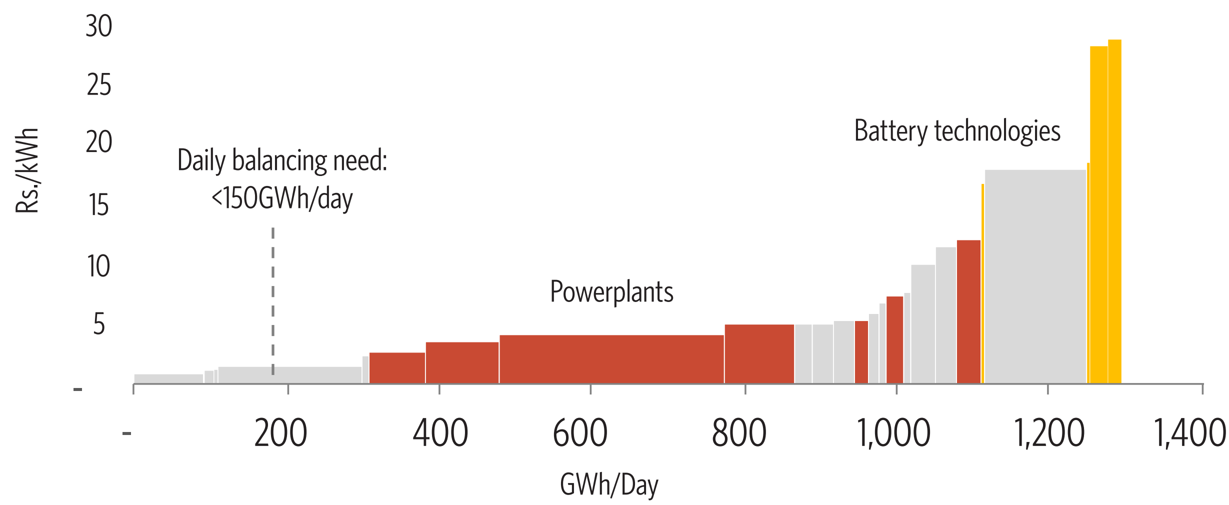
Recently, however, lithium ion batteries and inverters have been developing in capability and falling in cost to the point where they may soon contribute substantially to AC power system flexibility. Low-cost batteries could provide benefits beyond even those provided by pumped storage hydro, as batteries are scalable at almost any level, they could be located where needed to reduce transmission and distribution costs and constraints, they could be integrated into equipment, and they could be used for multiple purposes, such as balancing and transport.

Whether pumped storage, li-ion batteries, or other technologies are used for storage, they will need different cost and operating characteristics that depend on the flexibility need.

Table 3.18: Storage requirements by flexibility need

	Reserves and frequency response	Ramping	Daily balancing	Seasonal balancing	EV / Transport	Distributed/ household
Long storage duration			✓	✓		
Long life under frequent cycles	✓	✓	✓		✓	
High round-trip efficiency	✓		✓	✓	✓	✓
Low capital cost	✓	✓	✓	✓	✓	✓
High energy density					✓	✓

Figure 3.11: The position of li-ion batteries in the daily balancing supply curve (2017 costs)



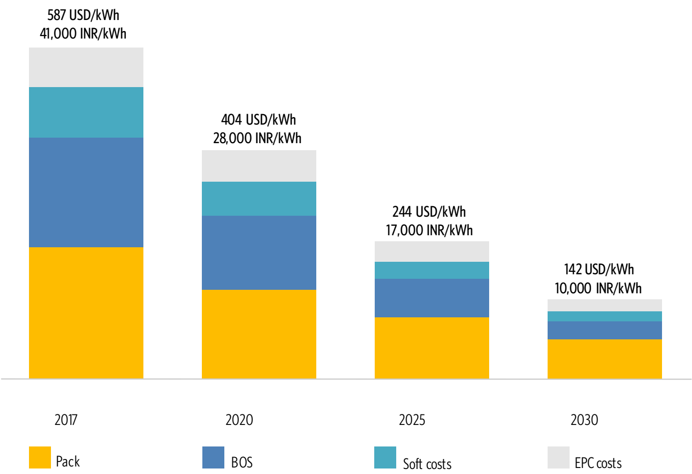
As we have seen, powerplants and demand flexibility can also provide these services at a cost. Today, those costs are much lower than the cost of batteries for many of the flexibility needs as shown by the example in figure 3.11.

The key, then, to the storage revolution for India is to develop a package of lower costs, efficiency, life and operating characteristics, and business models with incentives, that delivers these services more cost effectively than powerplants or demand management. The evidence that this can be done for at least some of the flexibility needs is positive, but work on developing the manufacturing, technology, business models and incentives needs to start now to deliver the capacity when it will be needed.

3.3.1 Declining costs of energy storage

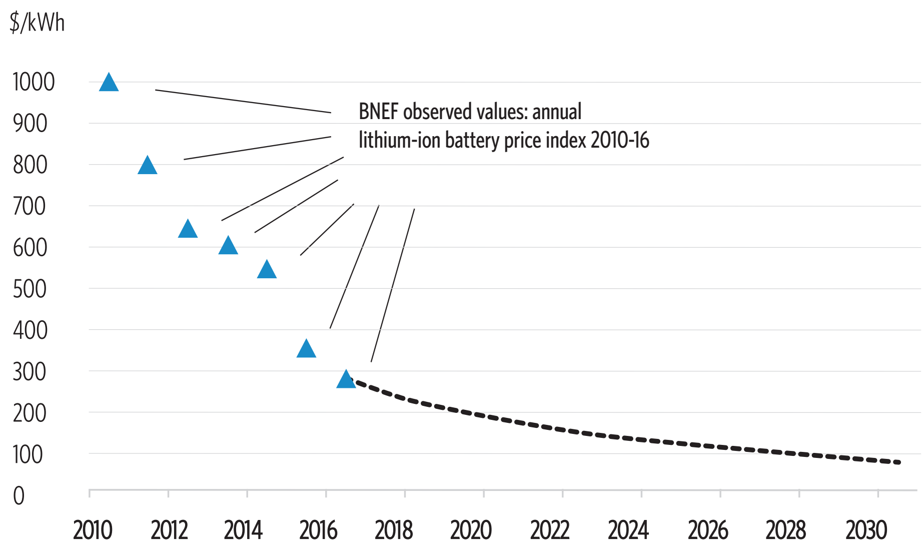
By 2030, the cost of stationary energy storage systems using lithium-ion batteries in India may decline by as much as 75%. Lithium ion batteries are versatile in the flexibility services they provide – they are most cost effective for short-term, fast-response and daily flexibility needs. There are other battery storage technologies such as flow batteries, power to hydrogen and sodium sulphur, but they are currently less mature.

Figure 3.12: Battery cost projections for the India market



Based on McKinsey figures, assuming India BOS discount of 25% by 2030, increasing from no discount in 2017. 2030 extended based on 2017-2025 CAGR. Exchange rate - 70 INR/USD.

Figure 3.13: Battery cost projections for the India market



Source: Bloomberg New Energy Finance

While other technologies may emerge as cost effective grid storage, lithium ion battery costs themselves continue to decline dramatically, driven by global development focused on electric vehicles. By 2030, forecasted global EV sales of over 20 million cars per year implies annual battery need of at least 1,000GWh per year. Indian EV demand is highly uncertain, but might contribute to falling battery costs in India and determine how India's energy storage industry develops.

Simultaneously, the cost of the balance of system (BOS), including foundations, installation, connections and soft costs like financing and project development, are also falling. Taken together, we forecast a global decline in total costs for stationary storage systems to fall from $587/kWh in 2017 to $142kWh in 2030.

Unlike battery packs, where much of the cost trajectory is determined by global factors, BOS and soft costs depend more strongly on the local market. In general, BOS costs typically fall as local developers and installers learn how to optimize these costs as the local industry develops. In India, the BOS and soft costs are typically lower, but will only stay lower if India begins a substantial programme of developing and installing stationary battery systems.

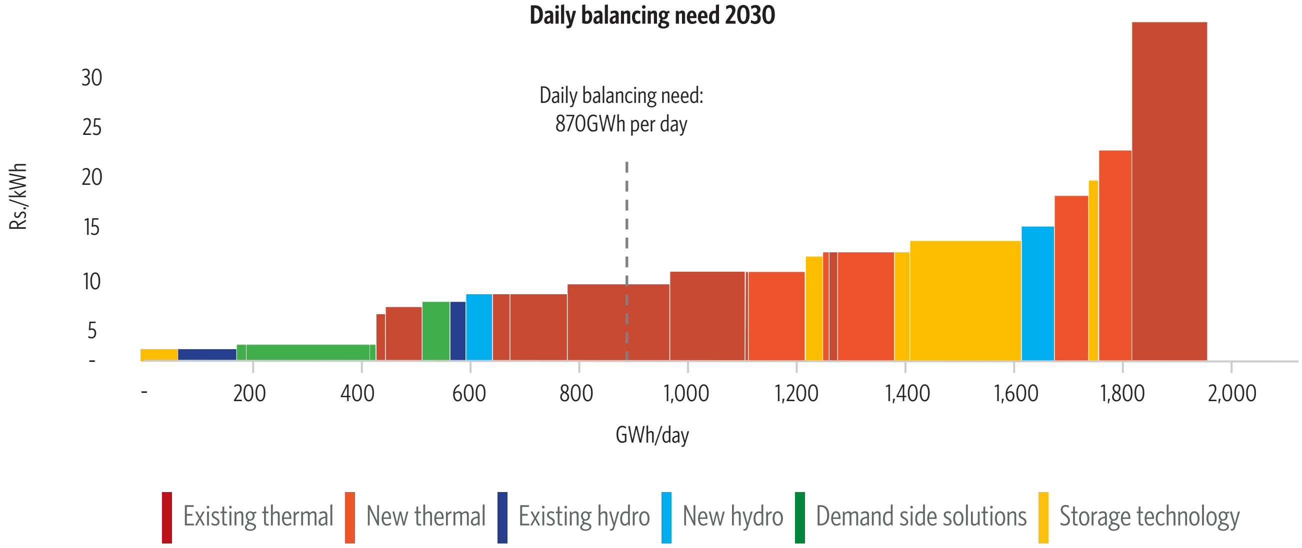
In figure 3.13, Bloomberg New Energy Finance forecastss that battery production costs will decline from $162/kWh in 2017, to $74/kWh by 2030. Balance of system costs and soft costs for engineering, production and construction (EPC) currently make up as much as 70% of the total system cost. But these costs are expected to decline rapidly to 50% by 2030. We estimate system costs at c.INR 10,000/kW dropping to c.INR 7,000/kW by 2030.

3.3.2 The role of lithium ion batteries in the power system

Even with those levels of cost reductions, batteries will remain uncompetitive with powerplants and demand flexibility for many flexibility requirements, if the batteries are built exclusively to address that one flexibility need alone. However, the costs are much closer in figure 3.14.

In this scenario, daily balancing needs are easily covered by powerplant and demand side options without batteries. Even if no demand flexibility enters the picture (the shift of the balancing need line) there are still less expensive options to deliver flexibility.

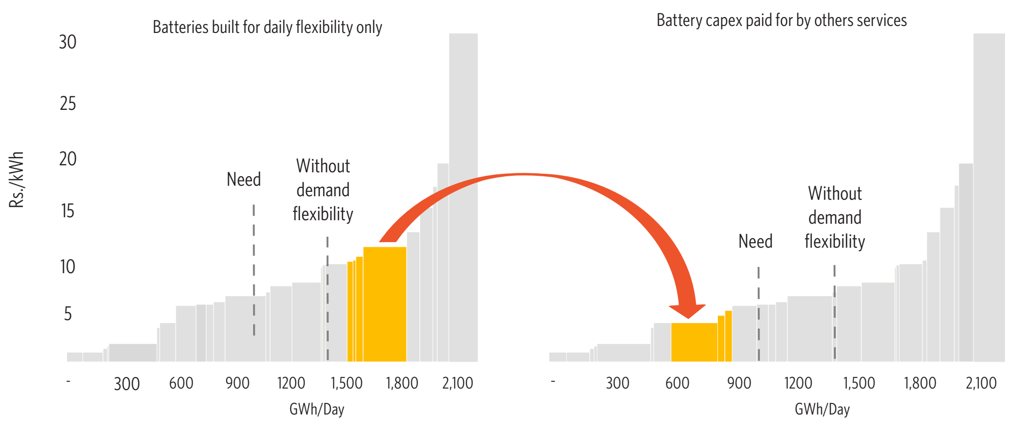
Figure 3.14: The positioning of batteries in the daily balancing supply curve at 2030 costs



This picture underestimates the potential for batteries in three important ways:

1. Battery storage, using li-ion or other technologies, is expected to continue to decline in relative costs well beyond 2030, and there is reason to expect that 2030 prices may be lower than those assumed here.
2. As thermal powerplants retire, their ability to offer more flexibility will decline, while batteries provide a scalable source of flexibility that can increase with needs.
3. Most significantly, battery storage is much better equipped to provide multiple sources of flexibility. For instance, locating batteries behind transmission constraints can eliminate that constraint, batteries can be used to develop new electricity and service delivery models, and batteries are controllable to the extent that it is easier to mix reserves, ramping and daily balancing in one asset.

Figure 3.15: The impact of multiple services on battery flexibility costs (2030 costs)



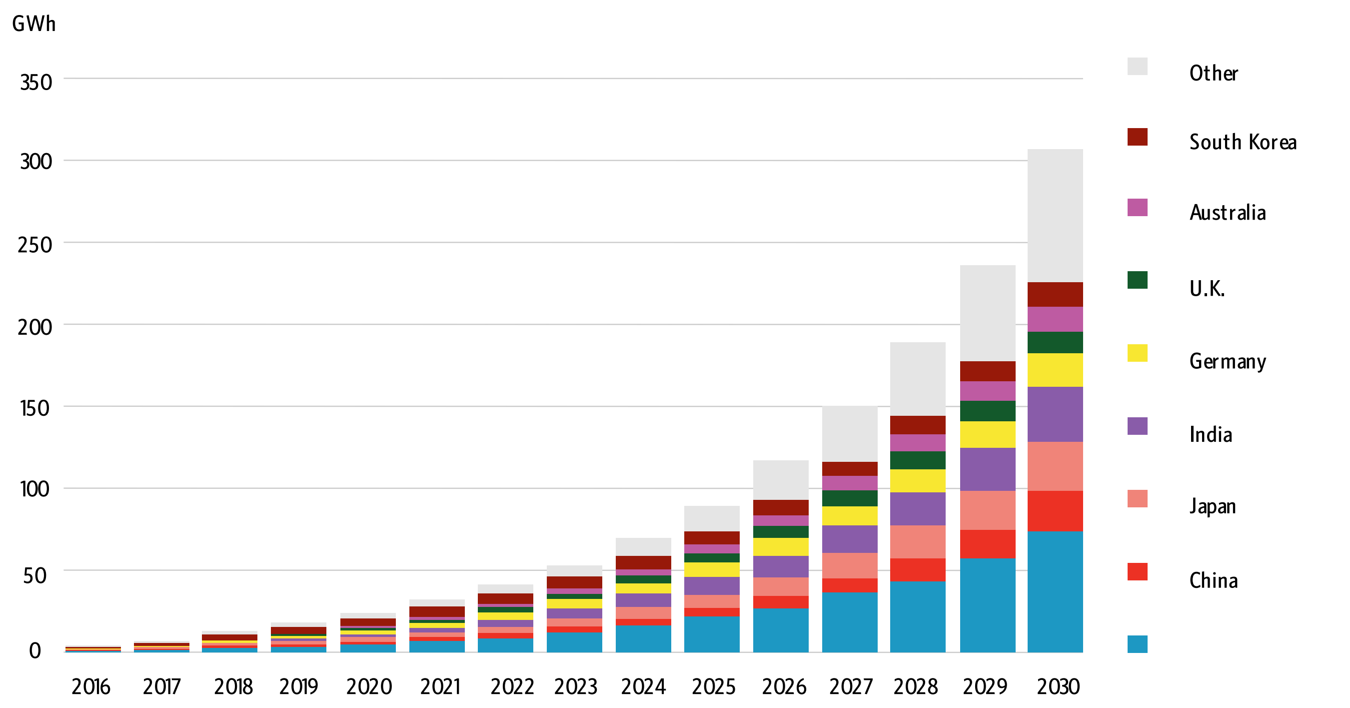
The last of these three will make batteries competitive much sooner. The cost curve on the left in figure 3.15 assumes that the entire capital cost of the battery is allocated to daily balancing. However, if the battery is already needed, say to provide local system security or to reduce distribution system costs, then the capital cost will not need to be covered by daily balancing, as the battery has already been built and paid for (just as existing powerplants have been paid for and new powerplants would cost more to deliver flexibility if they are built solely for that purpose). The impact is to improve the competitiveness of batteries dramatically, as on the right in figure 3.15, where batteries provide a significant share of daily balancing needs.

A similar picture plays out in all the flexibility needs except seasonal storage, where batteries become more cost-effective as multiple uses are considered. Providing seasonal storage can be expensive as a battery might be used only one or two cycles a year. However, even here we see a role for batteries, as we expect that batteries would provide more flexibility services such as ramping and daily balancing when renewable energy and demand are more closely in balance, while powerplants will provide more flexibility during those seasons where additional energy is needed.

Understanding and modelling all the potential interplays between the different uses of batteries requires analysis of transmission, distribution, and consumer needs beyond the capability of our model. Furthermore, much of the potential will depend on market design, incentive programmes, and technology and control system development. Thus, our modelling is likely to significantly underestimate the potential of battery storage and over estimate the cost. To access these future benefits, India will need to develop the battery market and the market incentives that will enable the technology to flourish and provide the value it can to the system.

Globally, grid applications are expected to reach 300+GWh of cumulative deployment by 2030, of which around 25 GWh is expected in India (BNEF). Our expectation is that if India can solve the incentive, market, and flexibility service integration issues, storage can provide even greater levels of cost savings well into the 2030s and 2040s.

Figure 3.16: Cumulative grid energy storage deployment



Source: Bloomberg New Energy Finance

3.3.3 New pumped hydro

Batteries are not the only energy storage option. There is significant potential for pumped hydro in India – the Central Electricity Authority estimates 63 sites with over 96GW of potential capacity, of which only around 5GW has been developed to date. But pumped hydro can be challenging and costly to develop, due to complexity of project approvals, development and construction, and the pipeline of projects that could be delivered by 2030 (given long development and construction timelines) is relatively modest. For our analysis, we based our models on a forecast of 10GW additional pumped hydro by 2030.

Table 3.8: Pumped hydro storage potential in India (CEA 2017)

Region	Potential capacity (MW)	Capacity developed (MW)	Capacity under construction (MW)
Northern	13,065 (7 sites)	0	1,000 (1 site)
Western	39,684 (29 sites)	1,840 (4 sites)	80 (1 site)
Southern	17,750 (10 sites)	2,006 (3 sites)	0
Eastern	9,125 (7 sites)	940 (2 sites)	0
North Eastern	16,900 (10 sites)	0	0
Total	**96,524 (63 sites)**	**4,786 (9 sites)***	**1,080 (2 sites)**

4 Integrated flexibility portfolios

Key findings

- Demand flexibility is important in high renewable scenarios because portfolios that include more of this resource in combination with powerplant and storage, are significantly less expensive than those that rely on powerplants only.
- Balanced and demand flexibility portfolios significantly reduce costs even at low levels of renewables – and demand flexibility should be pursued under all renewable policy scenarios.
- Once all flexibility options are optimised in a balanced portfolio, we would expect a flexible system to be more cost-effective than a system with little flexible or renewable capacity.
- Using the full portfolio of options is 5% cheaper than the base case at current renewable energy deployment rates, and 8% cheaper in the high renewable energy case.

Our supply curves indicate how cost competitive each flexibility option is in providing each flexibility need. Putting all of these components together, as in figure 4-1 demonstrates that the lowest cost mix of options is likely to include demand, powerplant and storage options. In this daily balancing example, existing hydro, new hydro, existing powerplants and demand measures would all constitute low cost options to meet the average daily 6-hour balancing need of 870GWh. If the capital costs of battery storage are amortised for another need, storage too would be among the low-cost options.

But an electricity system's flexibility needs are not a series of independent markets, rather they are linked together to meet the overall system requirements.

Thus to understand which options will be used, and how procuring these options will impact total system cost, we have built different portfolio of flexibility options, using the supply curves as a guide, and used these options to calculate total system cost over the course of a full year's hourly demand profile. While these are not complete system optimisation models, these models should provide results that are accurate within the constraints of the assumptions around load, costs, interest rates, resource potential, renewable energy supply, weather conditions, and so forth for 2030. Our model fits the various assumptions from the flexibility supply curves, resource potential, and load shapes for demand and renewable energy supply together in one model as depicted in the figure below.

Figure 4.1: Demand flexibility and storage allow thermal plant to operate more efficiently

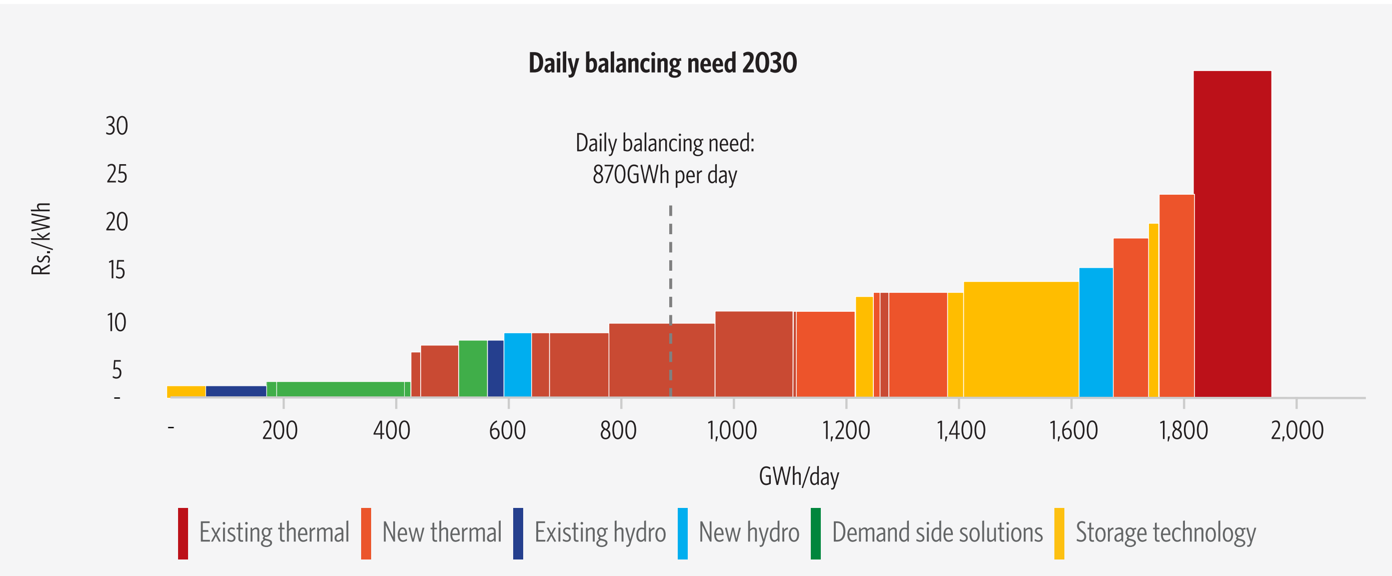
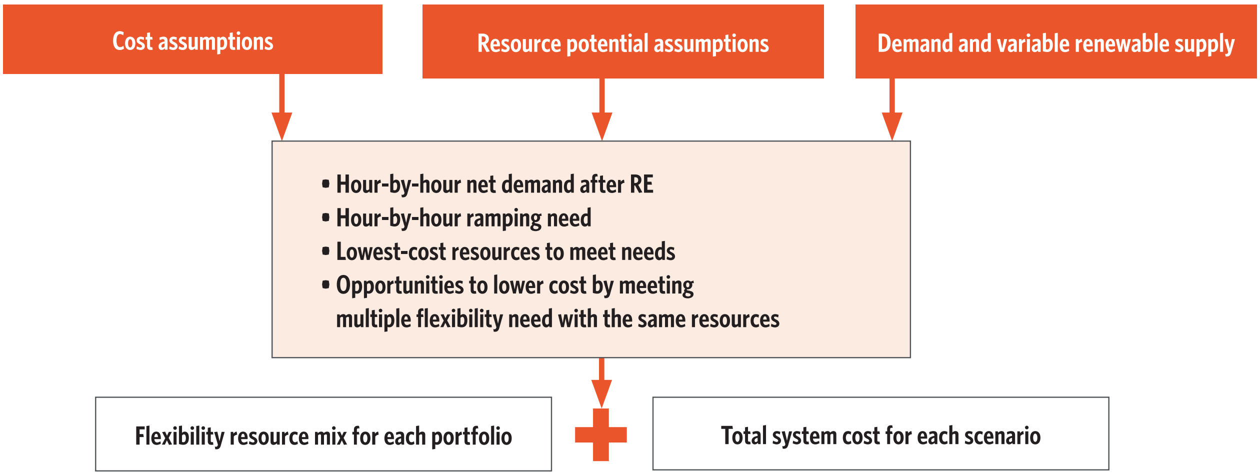


Figure 4.2: Integrating assumptions into a flexibility portfolio model



4.1 Flexibility portfolios

This flexibility analysis should provide answers to three questions that policymakers should be asking as India transitions to a cleaner electricity system with higher levels of variable renewable energy:

- How much variable renewable energy can India integrate into its electricity system?
- How much should consumer driven demand flexibility contribute to meeting flexibility needs?
- How much will flexibility add to the system costs under high renewable energy scenarios?

To some degree, both the amount of renewable energy and demand flexibility are variables that policymakers can influence. Since these two variables are also key determinants of system costs and the cost and source of flexibility, our portfolios have been designed to test how each of these two variables will affect flexibility options and cost.

Our portfolios fall into four different types, dependent upon RE ambition and demand flexibility.

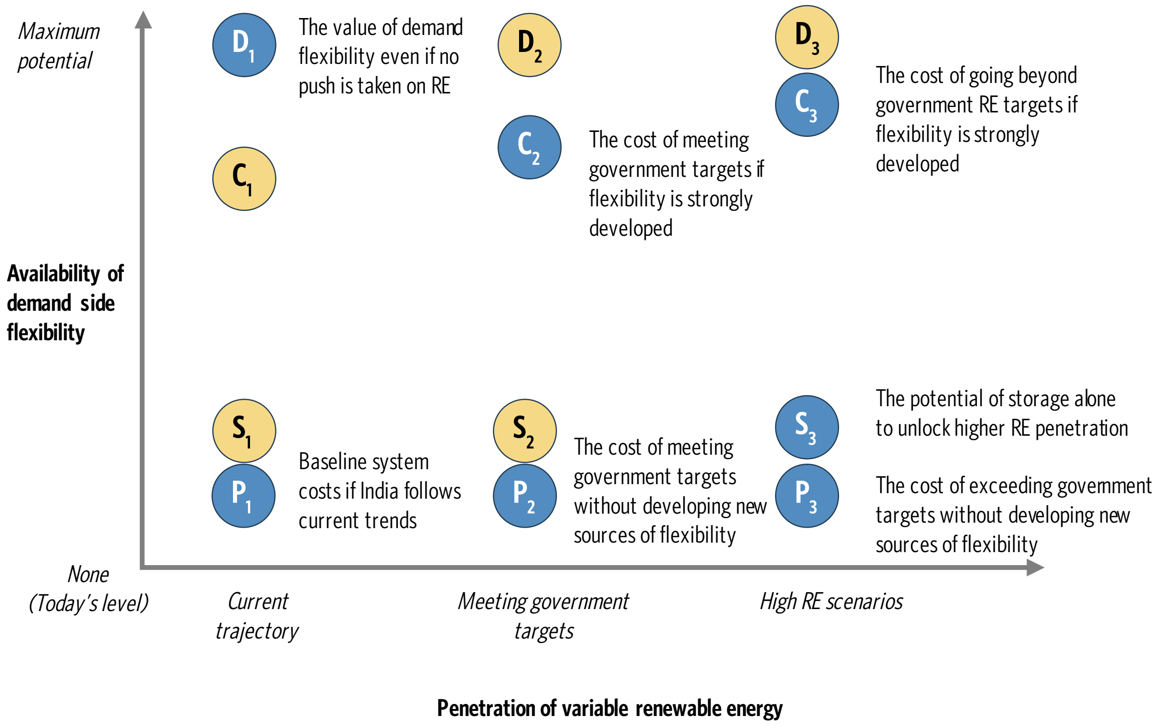
P. Powerplant driven portfolios – System flexibility is provided entirely by thermal and hydroelectric powerplants. Plants are upgraded and new plants added to the system if needed and economic to do so.

D. Demand side driven portfolios – System flexibility is provided by existing sources of flexibility and combined with demand flexibility options. Limited new thermal capacity may be added if needed and economic to do so.

S. Storage driven portfolios – System flexibility is provided by existing resources of flexibility combined with storage options. Limited new thermal capacity may be added if needed and economic to meet any balance demand.

C. Balanced portfolios of all options – System flexibility is met with a combination of all flexibility options to determine which options would be used and at what scale to meet the needs at the lowest cost if all flexibility programmes were successful.

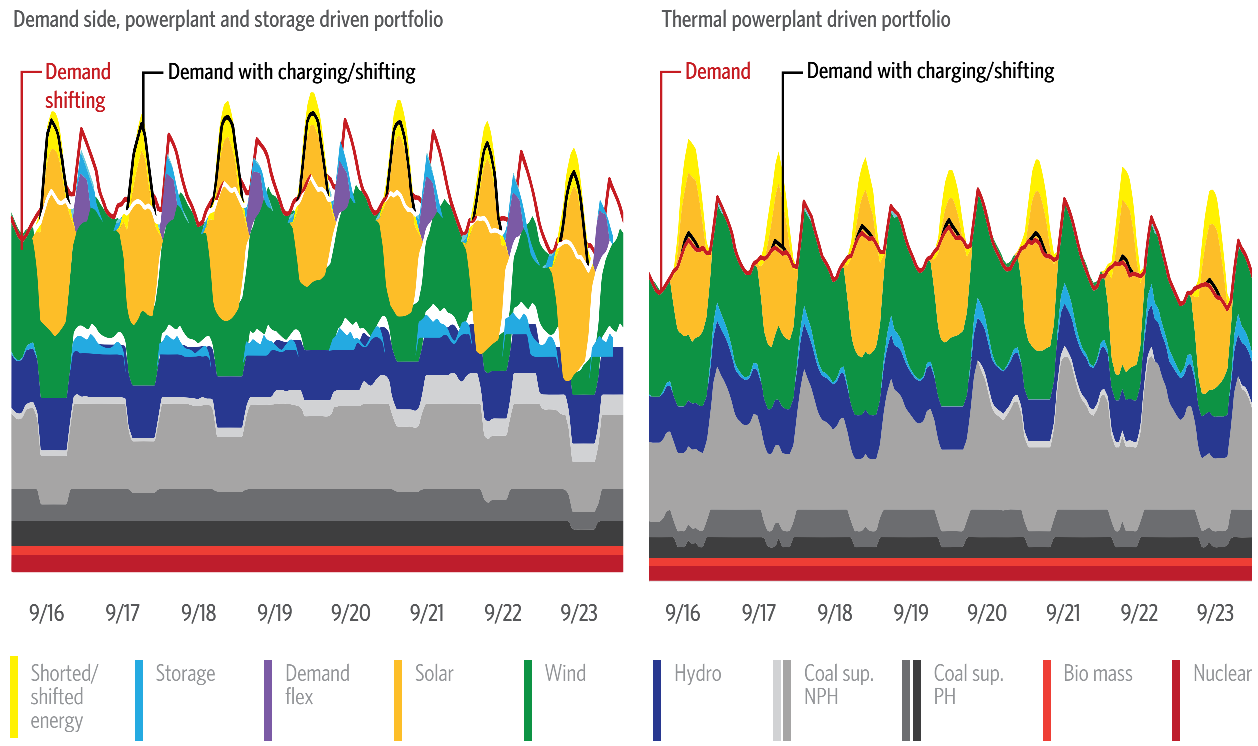
Figure 4.3: Portfolios built to assess the impact of demand flexibility and renewable energy ambition



In figure 4.3 above, the scenarios highlighted (D1, P1, P2, C2, C3, S3, and P3) each offer valuable insight into the three key questions for policymakers.

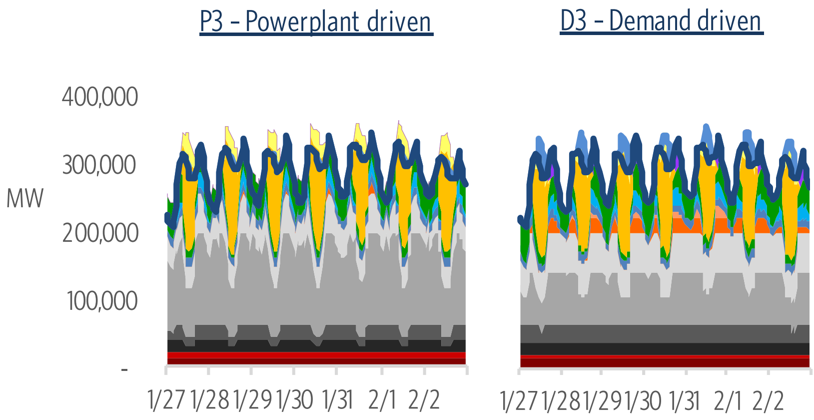
Figure 4.4 below shows outputs from the model of how the mix of flexibility options affects powerplant operation and curtailment. The red line near the top shows demand across a week. The thin blue line shows the adjusted demand after factoring in flexibility. On the left, where demand flexibility and storage are also included, thermal powerplants have a steadier generation profile, which increases their efficiency. On the right, without demand flexibility and storage, powerplants are more strained and more energy – the energy above the red and blue lines – is curtailed.

Figure 4.4: Demand flexibility and storage allow thermal powerplant to operate more efficiently



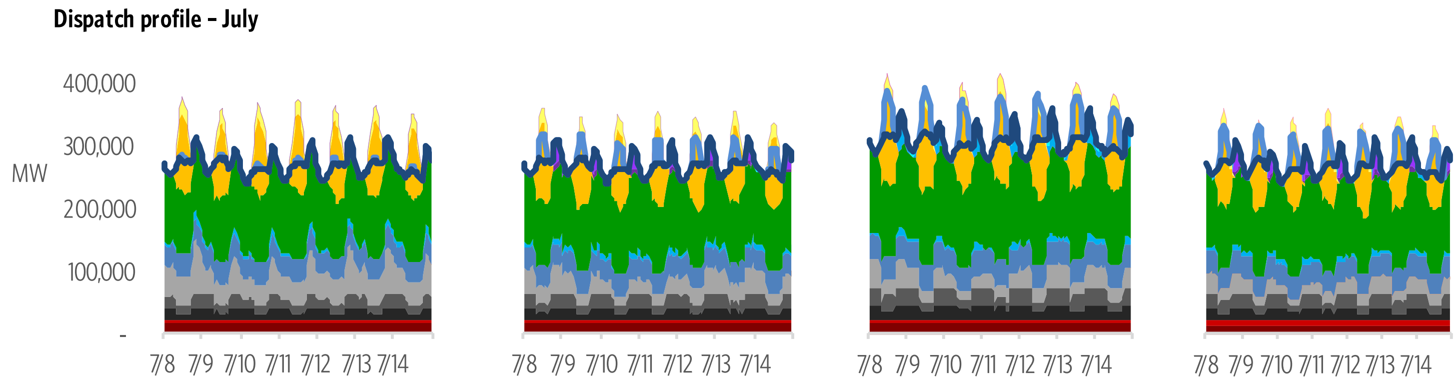
Below is another set of outputs from our model, which looks at the dispatch profile for each of the portfolios side-by-side. For the week in January, only the powerplant driven portfolio on the left sees the thermal plants strained and maximum curtailment of both solar and wind energy, while the rightmost balanced portfolio has the least constrained powerplant generation profile and almost no curtailment of renewable energy.

Figure 4.5: Dispatch profile for high RE scenario – late January



When we move on to a week in July, we see the same comparative impact, exaggerated by increased renewable generation. Power plants are constrained across all portfolios during this week but more variable in the far left power plant flexibility scenario and renewable curtailment is minimum for the balanced portfolio.

Figure 4.6: Dispatch profile for high RE scenario – July



The impact of these different portfolios can be seen clearly in the figures above, which compare current trajectory and high RE scenarios for each portfolio.

The balanced portfolio shows an overall lower curtailment in both the high RE (97%) and current trajectory (82%) scenarios.

In summary we find:

1. Employing a mix of demand, powerplant and storage flexibility results in an overall lower curtailment in both the high RE (97%) and current trajectory (82%) scenarios
2. The balanced portfolio could reduce total system electricity costs by as much as 5%, including the cost of the additional flexibility options, even if India does not increase its ambitions with respect to renewable energy.
3. It also delivers 8% to 12% lower carbon intensity than the base case.
4. Once additional flexibility is integrated into the system, India can increase its renewable energy options at almost no additional cost.
5. Taken together, an ambitious renewable energy system rollout combined with a mix of enhanced flexibility resources would continue to be significantly less expensive than continuing the existing less ambitious path with no increase in flexibility. At the same time the system would have higher power quality and reliability.

Figure 4.7: Balanced portfolio of demand, storage and powerplant flexibility perform best on most metrics and are least risky

Portfolio performance (2030) - Current trajectory

Scenario	Excess energy	Total cost	Carbon emissions
Power-plant driven	10%	4.8 (Rs/kWh)	0.6 (t/MWh)
Demand flex driven	-83%	-6%	-6%
Storage driven	-95%	-4%	-6%
Balanced portfolio	-97%	-5%	-8%

Portfolio performance (2030) - High RE

Scenario	Excess energy	Total cost	Carbon emissions
Power-plant driven	13.8%	5.0 (Rs/kWh)	0.5 (t/MWh)
Demand flex driven	-63%	-7%	-9%
Storage driven	-80%	-5%	-10%
Balanced portfolio	-82%	-8%	-12%

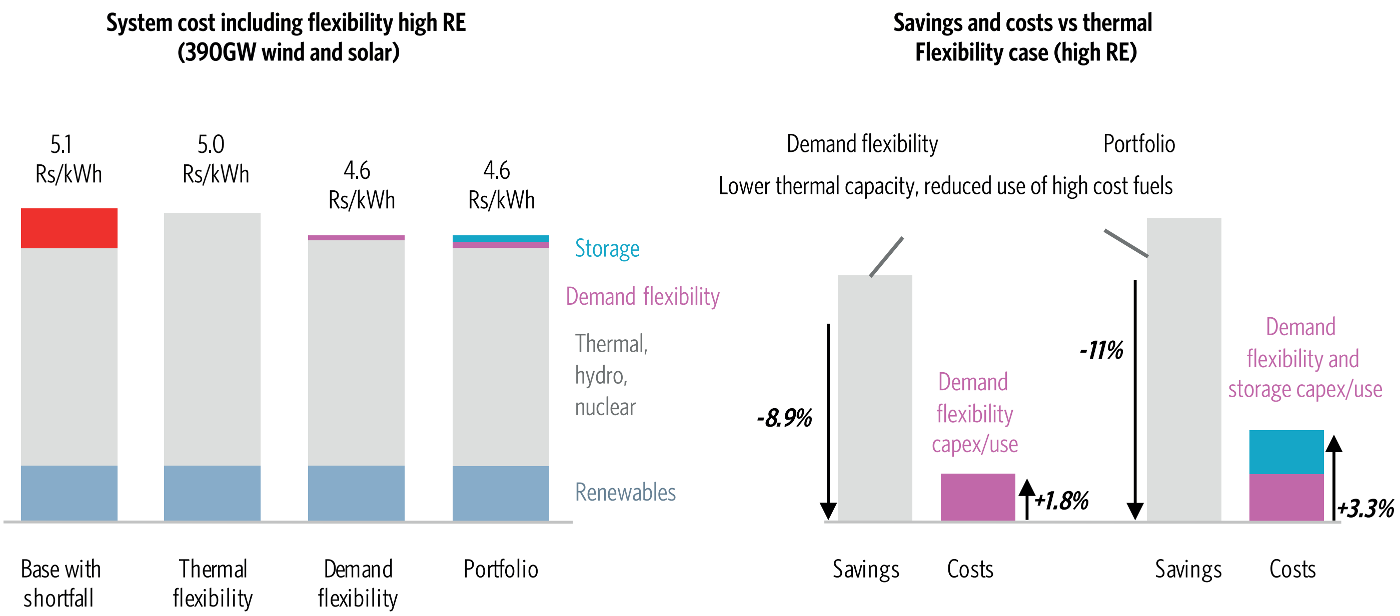
In the base case, the system will continue to have significant energy shortfalls at different times of the year. System cost analysis includes the cost of meeting this shortfall with generator backups as a proxy for the economic impact of the shortages.

The average total system cost (in today's money) is the lowest for the balanced portfolios for both the current trajectory and the high RE scenarios, with the high RE portfolio system cost (Rs 4.6/kWh) lower than the system cost for base case (Rs 4.7/kWh) or thermal portfolio (Rs 4.8/kWh) in the current trajectory scenario.

Figure 4.7 shows the system cost for different portfolios under the high RE scenario, and also the savings and cost advantage the demand flexibility portfolio and balanced portfolio provide compared with the powerplant option.

In the annex we present further detail on our model, providing further information on how each of the portfolios perform on different metrics under different scenarios and the portfolio composition across generation and flexibility resources.

Figure 4.8: System cost for different portfolios under the high RE scenario and savings from demand flexibility and balanced portfolio s



5 Flexibility needs and challenges will be different in different regions across India

Key findings

- As at December 2018, Tamil Nadu had the largest wind based installed capacity in India (8.4MW), and Karnataka had the highest solar installed capacity (5GW).
- These states will face significant excess of energy supply, almost triple that of India's by 2030.
- Seasonal flexibility in Tamil Nadu is expected to rise sharply by 2030 due to wind-based generation that peaks in the monsoon period and slumps in spring.
- In Karnataka, ramping is expected to rise to 30% of peak demand by 2030 from its current levels of 14%.
- Uttar Pradesh faces a 10% peak power deficit and electricity demand is expected to surge with the implementation of 24x7 power for all program
- Thermal storage systems in 25% of forecast central ACs could potentially shift 1GW of peak load to off-peak hours at no additional cost.

Much of this analysis treats India as a single entity for electricity generation, transmission and distribution. The reality is that India is a large and diverse country with significant transmission costs and constraints. An important consideration in developing a flexible Indian electricity system is a tradeoff between building additional local flexibility or building transmission to harness excess flexibility in one region to use in another. Local flexibility can involve building batteries or prioritising demand flexibility or powerplant options in one area, whereas pan-India flexibility might enable balancing loads between regions with disparate needs. For example, regions with excess generation during the monsoon season may balance those that have excess solar production at different times of the year.

A complete evaluation of transmission requirements would require detailed assessment of demand and powerplant options in each state and an India-wide transmission model to forecast costs and constraints. That analysis is beyond the scope of this study, but given the uncertainty in the estimates of the availability of different flexibility options in 2030, it is unlikely that detailed analysis would provide a great deal of valuable insight. Instead, we have investigated the flexibility needs of four individual states – with different electricity supply and consumption characteristics and flexibility needs – to ascertain how limiting the exchange of interstate flexibility might affect the results, and to evaluate how transmission planning and interstate exchanges and markets should be incorporated into a flexibility development policy.

In isolation, some Indian states will face greater flexibility needs than India as a whole, while others will face less. High renewable energy states will often face particular challenges, whereas thermal generation heavy states could have an opportunity to reduce their electricity costs by harnessing and exporting demand flexibility.

However, as India moves down the path of greater flexibility and renewable energy, there are at least four reasons why we should go beyond the India level analysis to look at regional constraints and differences.

1. **Transmission constraints** and costs restrict the exchange of energy, and therefore flexibility and excess renewable energy, between regions. The effect is that many states and regions are, at times, effectively separate systems for the purposes of balancing energy and meeting system reliability needs. For flexibility, the implication is that resources in one part of the country might not be useful to meet needs in another. In the longer term, the decision is one of transmission costs versus providing flexibility locally or nationally. However, in the shorter-term transmission might not be available, while even in the long term, there are likely to be many cases where it is cheaper to provide flexibility locally rather than investing in more transmission.
2. **The local economy, energy consumption** practices and equipment will lead to significant

differences in the availability of local demand side and supply side flexibility resources. Once transmission constraints take effect, the value and need of flexibility resources in one area may be higher than in another, but also the ability to deliver them might require different incentives.

3. **Weather** has a profound impact on flexibility needs as weather drives both the variability of demand – given temperature driving heating and air conditioning demand – as well as renewable energy output that can be driven by monsoons or sunshine. As long as there are transmission constraints, local climate and weather will have significant impacts on local and state level flexibility needs.

4. **Renewable energy output and ambitions –** While weather affects the output profile from RE, the ambitions are a function of local policy. Nevertheless, with transmission constraints the result of changing local flexibility needs is similar. Further, understanding how regions or states cope with high renewable energy today, can help us understand how India might cope when higher levels of RE are reached nationally. Of course, states with higher RE penetration tend to have better RE resources, so we could expect that they will continue to have a higher share of the total as India's RE increases.

To start evaluating the potential impact of transmission constraints and regional differences, we have evaluated the needs and potential in four geographically divserse states with different weather patterns, wind and solar capacity levels, susceptibility to power cuts (representing current power shortages), and agricultural and industrial capacity, which represent different types of demand, and demand flexibility potential.

Figure 5.1: States with maximum need and impact were selected for the analysis

Maximum installed solar capacity	Karnataka (5.2MW)	Telangana (3.3MW)	Andhra Pradesh (2.3MW)	Rajasthan (2.3MW)
Maximum installed wind capacity	Tamil Nadu (9.8MW)	Gujarat (5.7MW)	Karnataka (4.8MW)	Maharashtra (4.8MW)
Industry and agricultural irrigation	Tamil Nadu (37,400 factories)	Maharashtra (29,000 factories)	Gujarat (22,900 factories)	Uttar Pradesh (14,500 factories)
	1,61 million hectares of ground water irrigated land	3 million hectares of ground water irrigatead land	3 million hectares of ground water irrigatead land	10,64 Million Hectares of ground water irrigatead land
Annual powercut frequency and population	Jhakhand (718)	Uttaranchal (558)	Bihar (444)	Nagaland (347)
	33m Individuals	10m individuals affected	10m individuals affected	2m individuals affected

For our four case studies we chose states with largest wind based installed capacity (Tamil Nadu 8.4GW) and solar installed capacity (Karnataka 5GW). Uttar Pradesh has low levels of RE, but with the highest level of irrigated land and large industrial base. Finally, Bihar has the largest population affected by power cuts and thus represents states that are faced with inadequate supply, transmission and distribution shortages, or large number of power cuts affecting a substantial proportion of the population. For the purpose of this study, the states were considered in isolation and not as a part of a larger system to identify the flexibility challenge faced by each state.

The challenges are, indeed, very different. The two RE heavy states will face significant excess of energy supply, almost triple that of the India average by 2030 (see figure 5.2), if these states have no access to interstate transmission and if flexibility resources are not increased in the coming decade.

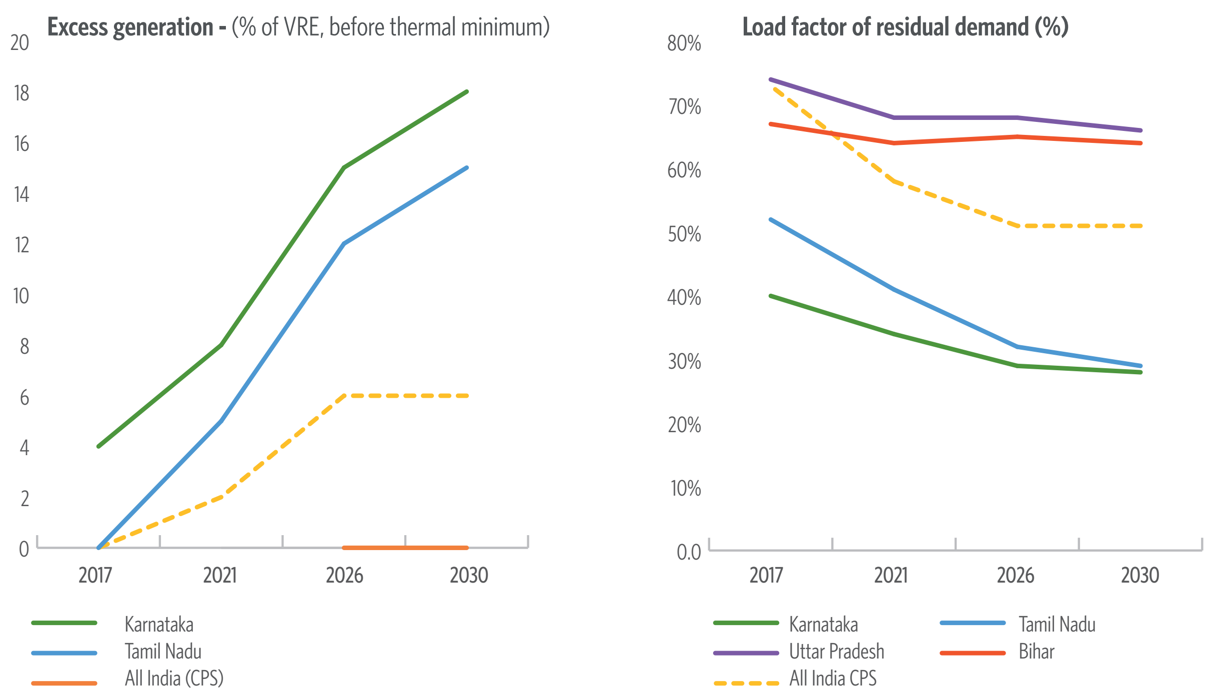
The chart on the right is even more telling, residual demand, that is the demand that must be met by flexible powerplants, falls to near 30% in the RE heavy states, while staying near current levels in Uttar Pradesh and Bihar. Without transmission constraints, the average load factor would stay somewhere in between across India.

5.1 Tamil Nadu

Tamil Nadu has the highest installed capacity of wind generation in India. Most of the renewable generation is through wind (8.4GW wind and 2.3GW solar as at December 2018). Tamil Nadu also large thermal generation capacity (13.5 GW) including lignite-based generation capacity. The state plans to add ~5 GW of thermal capacity by 2022 along with 500MW of pumped hydro capacity. Nuclear generation which is typically run as base load is also expected to increase for 1.5GW to 3.5GW in the next decade. Amidst all this, wind-based generation faces seasonality issues and is often treated as infirm power. The variation causes backdown of thermal assets to their technical minimum and increases forced outages. The state has seen some early cases of technical curtailment which have been successfully challenged in court by investors and operators.

The need for seasonal flexibility in Tamil Nadu is expected to rise sharply by 2030 due to the highly seasonal nature of wind-based generation that peaks in monsoon period and slumps during the months of spring. Currently the state uses banking arrangements with other states to manage its seasonality related challenges. But with changing demand profiles and growth in renewable generation within the state as well as in the neighbouring states coupled with potential transmission bottlenecks, Tamil Nadu might be facing a seasonal flexibility related challenge in the coming decade.

Figure 5.2: Flexibility needs would evolve sooner and be more significant in certain states



With renewables running as must run capacity, by 2030, residual PLFs at thermal powerplant are expected to drop to zero for three to four months of the year. Withouth interstate trading and/or additional seasonal flexibility, the financial viability of generating assets could be under pressure. We note that states neighbouring Tamil Nadu often face similar issues, so the issue is regional and national, rather than just a state level one.

5.2 Karnataka

Karnataka already has a large share of renewables in its generation mix (~47%). By 2030, over two thirds of its capacity is expected to come from renewable resources, with solar alone contributing 40% of the energy mix. High technical minimums and low ramp rates limit ramping potential. There is limited flexible capacity available from hydro powerplants due to agricultural demand and monsoon flows.

Daily ramping requirements are expected to rise significantly as solar energy increases from 5.GW (December 2018) within the state's energy mix. By 2030, ramping needs are expected to rise to 30% of peak demand from current levels of 14%.

Figure 5.3: Tamil Nadu will need seasonal balancing due to high wind generation variability and the decline of thermal power plants

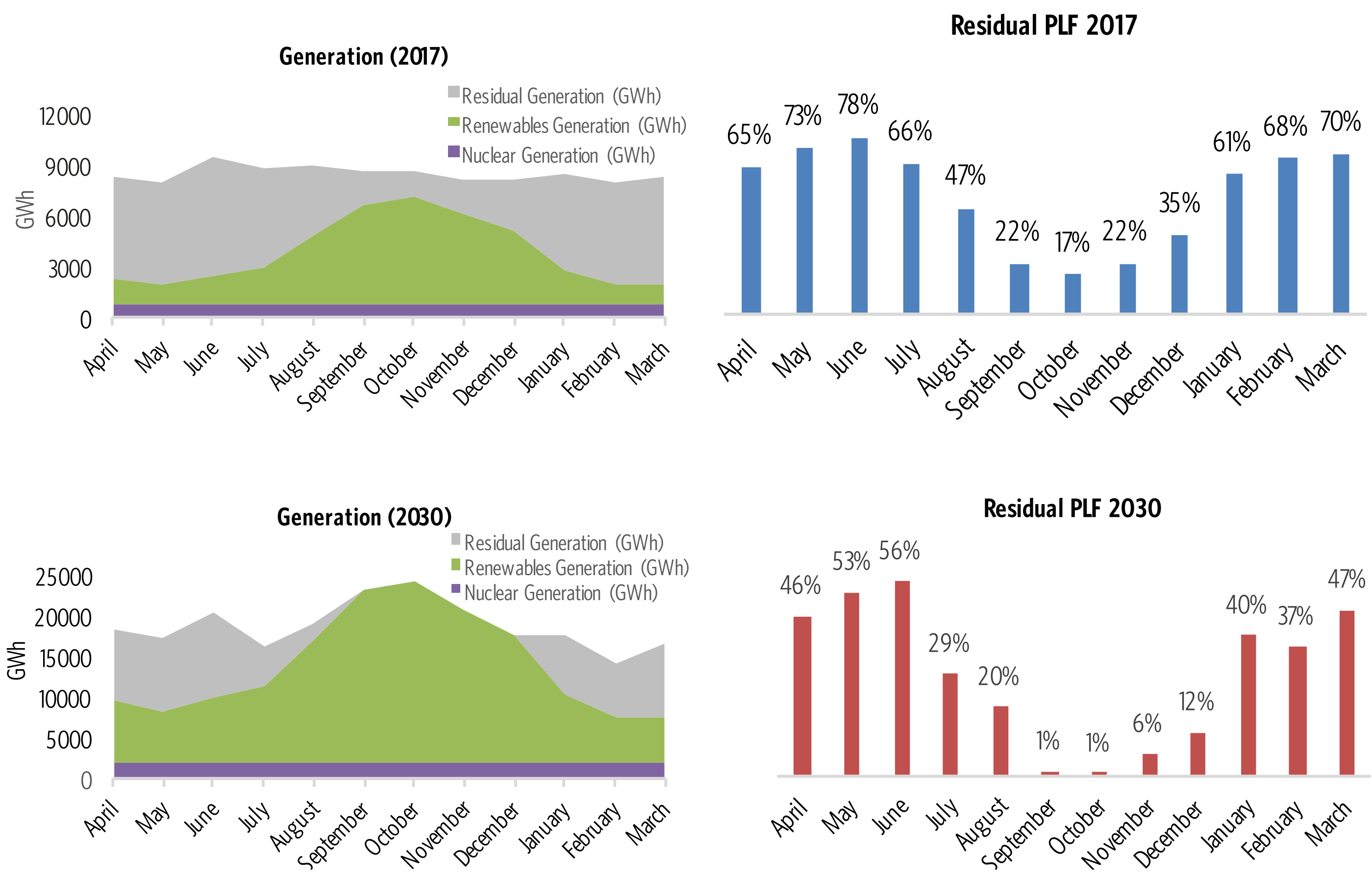
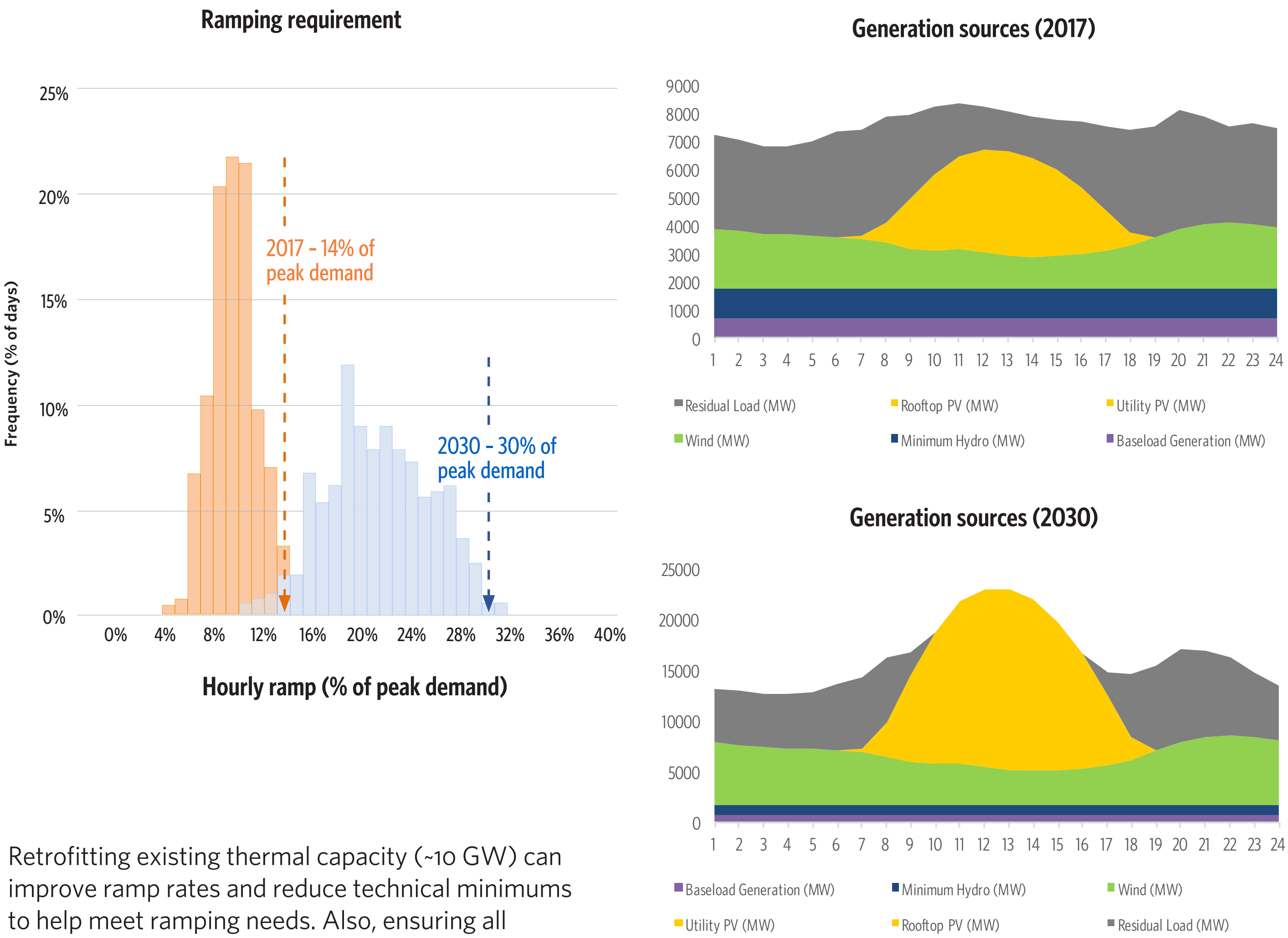


Figure 5.4: Karnataka's daily ramping need due to high solar generation could be balanced with new technology and by adjusting plant operations



Retrofitting existing thermal capacity (~10 GW) can improve ramp rates and reduce technical minimums to help meet ramping needs. Also, ensuring all upcoming thermal capacity (~3GW) can support two-shift operations would support the system in meeting flexibility needs. Storage systems are still expensive so they can be only selectively applied. Vehicle to grid initiatives can make storage solutions competitive on price which would help open the market in the early stages. Until these options develop, interstate exchange and additional flexibility resources are required. Improving interstate grid infrastructure would support the export of power during peak solar generation and reverse flows during monsoons.

5.3 Uttar Pradesh

Uttar Pradesh faces a 10% peak power deficit and the electricity demand is expected to surge with the implementation of 24x7 power for all program which may aggravate the peak shortage. State discoms are under financial stress and depend heavily on import of power from generators outside the state to meet the peak power needs. About a quarter of UP's contracted generation capacity lies outside state borders and this is likely to continue increasing to 2030.

Potential transmission bottlenecks can restrict imports that are currently used to meet flexibility needs, and the electricity board may not be able to afford the installation of additional peaking power capacity, which would aggravate the peak shortage. Despite these near-term issues, UP's large industrial base, agricultural energy use, and reliance on flexible thermal generation implies that if regulation, pricing, markets and incentives were fixed, UP could have significant levels of excess flexibility to cover all of its needs and those in other states.

Through feeder separation, combined agricultural consumption of ~25 BUs can be shifted to low demand hours by 2030. Building only 20% of new central AC capacity with thermal storage at no additional cost can help offset the peak demand by c~1.5 GW. Using demand response to shift only 10% of the heavy industrial load by a few time blocks can help shift 3 BU of power demand.

Appropriate markets supported by transmission infrastructure and trading mechanisms could enable a significant source of value for UP in selling its flexibility to other states and regions.

5.4 Bihar

At 228.8kWh per capita, power consumption is 75% less than the national average. However, in the past decade, demand for power in Bihar has surged more than 150%, and its electrification program is expected to accelerate it further.

But supply is repeatedly disrupted due to poor infrastructure which is unable to cope with peak demands and high levels of transmission losses leading to involuntary flexibility through load shedding which would need to be reduced to meet the 24x7 Power for All program energy access and reliability targets. Load shedding in the state has a positive correlation to demand and rises significantly during the high demand period of monsoon in this agricultural state.

Bihar faces near and medium-term challenges stabilising an adequate supply for its own needs. Poor metering and low rates of revenue collection (~40% AT&C losses) make it more economical for the discom to shed load than procure costly peaking power.

Moreover, poor infrastructure is unable to cope with load growth, and resulting in system failure during peak demand periods. While 20% of the state's electricity is consumed by agriculture, only ~5% of agriculture feeder segregation has been completed, limiting the ability to tap into the full scope of load shifting potential for agriculture, for improving flexibility and supply reliability.

Improving flexibility will help but is unlikely to lead to significant revenues from selling flexibility until internal supply is secured. Shifting 10% of industrial load can provide 183TWhs of flexible power demand, thereby reducing net peaking power required. Shifting agricultural load through separate feeders can help move ~300 MUs of consumption to off peak hours. Of the forecast additions of AC with thermal storage, around 25% could potentially shift 1GW of peak load to off-peak hours at no extra cost.

Figure 5.6: Demand will rise most strongly in the months where there are already power shortages

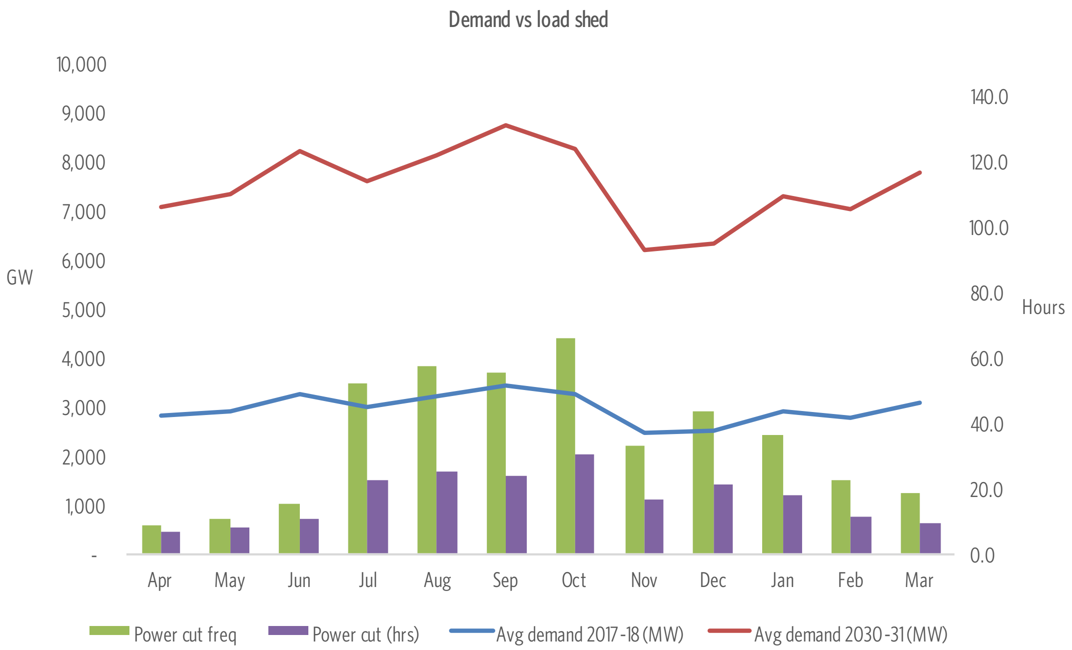
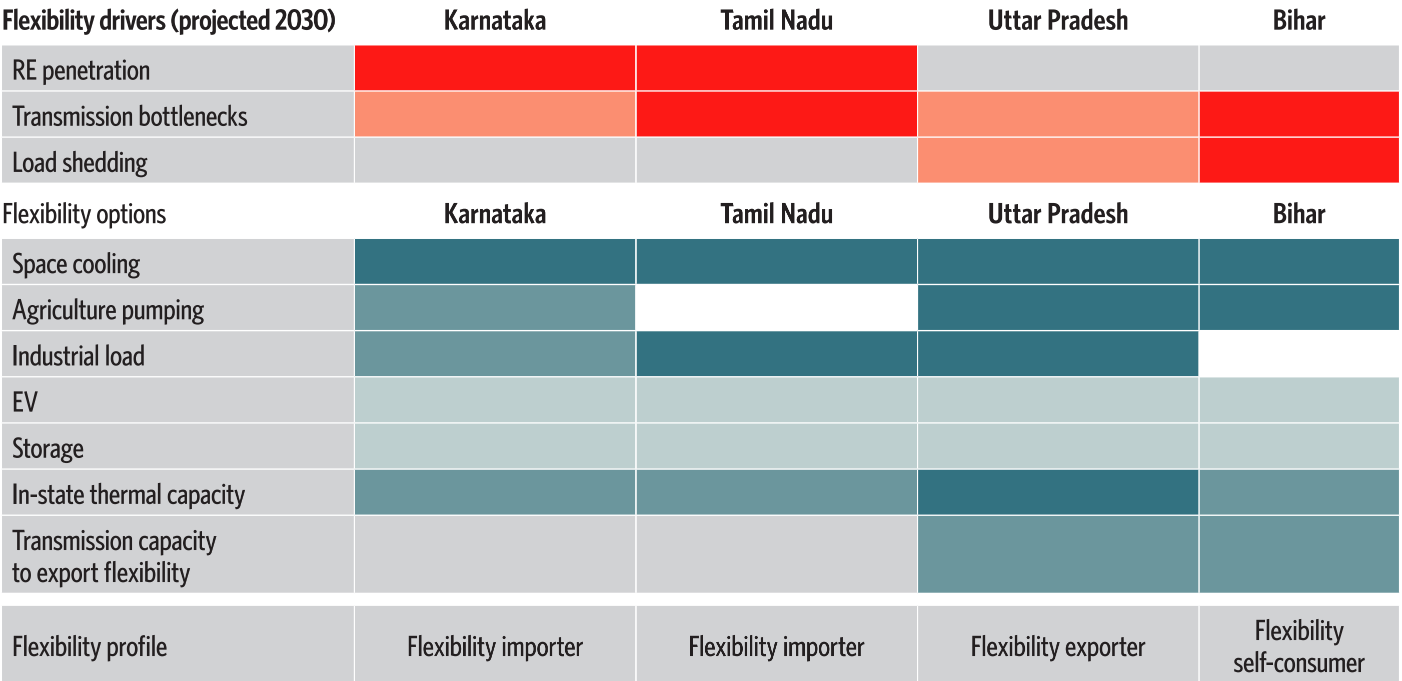


Figure 5.7: States may emerge as net importer or exporter of flexibility



5.5 Regional insights for India's flexibility

Figure 5.7 shows that in combination, transmission between states, RE ambitions, load shedding issues, and the availability of flexibility options should make Tamil Nadu and Karnataka importers of flexibility, while Uttar Pradesh could be an exporter, as Bihar develops more resources for its own use.

The regional analysis highlights at least five areas where flexibility needs and analysis should be incorporated into India's plans for electricity industry reform.

1. **Incorporating all flexibility needs into transmission planning and development**
   The large differences between states and regions in India highlight the value of transmission. A robust transmission system reduces the needs for flexibility by maximising the availaiblity of flexible resources and differences in consumption across the country.

   This flexibility can be available at lower cost compared with developing in-state resources. India has an ambitious transmission expansion and development programme underway already. While the programme focuses on reducing energy costs by enabling access to low-cost supply from across India, the programme also aims to improve the quality and security of supply across India.

   Beyond these objectives, our work indicates that flexibility represents an important value stream for transmission. In planning and further development of the transmission system, the growing importance of flexibility, including seasonal and daily balancing and ramping, suggests that transmission planners and developers need to incorporate flexibility benefits in decision making.

   For generators, demand and supply aggregators, energy consumers, or flexibility service providers, an important question will be whether to build or buy flexibility services locally or import them from other states. Clear transmission planning, pricing, and consideration of flexibility requirements is an important part of making this decision.

2. **Building and reforming interstate electricity markets and trading**
   Improving transmission systems will help reduce flexibility needs, but access to interstate flexibility resources is only possible if there are adequate price signals, incentives, and trading arrangements. Operators in UP, for example, will only develop significant industrial flexibility resources if they see, and can rely on, markets for their flexibility that they can access at a reasonable cost.
   Building this capability suggests not only more comprehensive markets with higher participation, and guaranteed third party access, but also better data provision, and the possibility of long term markets and longer term contracts to justify the investment in flexibility development.

3. **State level planning and regulation**
   As long as transmission has a cost or there are transmission losses, there will be differentiated needs between states and the need for developing local flexibility. Each state thus needs to include flexibility needs, development and procurement into planning and development of intrastate transmission and distribution, generation, storage, and demand flexibility development. In an ideal world, where there are reliable interstate markets, this planning should include buying and selling flexibility and generation into the markets.
   Even before developing local capabilities, there are actions that states can take to unlock flexibility that is currently inaccessible due to regulatory and commercial barriers. For example, must run levels for thermal power plants are higher than what is technically possible even without modification; contracts often give some thermal plants must run status, or higher priority, which prevents them from offering valuable flexibility to the system. Contracts and business practices prevent powerplants from even considering seasonal mothballing or two shift operation, which could help with local and national seasonal and daily balancing/ramping, respectively. Of course, without interstate trading and markets, there is currently little incentive to make these changes, unless the issues are in state.

4. **State level energy and flexibility markets**
   Efficient access to intrastate flexibility options also requires tradeoffs between differing resources and transmission or distribution. As at the national level, state level markets, that allow consumers, distributed generators, storage owners, and powerplants to each offer services to the market, is essential in accessing and integrating the widest range – and therefore lowest cost and most diverse – of flexibility options.

5. **State level flexibility programmes and beta testing**
   Finally, we have noted that costs, resources, and local practices will vary enough between states such that programmes from one state or region might not be applicable in another. The differences will be particularly acute in the demand side area, but storage and generation will also see marked differences. In order to develop programmes that address these differences, each state should begin developing and testing flexibility resources programmes that are tailored to each state's needs and resources.

6 Summary and next steps

India can pursue ambitious renewable energy targets, but concerted action on data, market design, development, investment, consumer behaviour and infrastructure is essential

Our analysis has shown that flexibility reduces system costs and makes integrating more clean energy cheaper. Thus, increasing flexibility is a no-regrets steps for India.

While developing more flexibility should be addressed urgently to reduce costs and improve the quality of electricity supply, the pathway is not as straightforward. India needs to develop new data and information, technology, behaviour, and market designs to develop flexibility efficiently and cost effectively. Figure 6.1 summarises some of the challenges in developing each of the flexibility options and then integrating them across India.

Developing and integrating each of the categories of flexibility options will require concerted action along the following lines:

- **Data and information.**

  Demand. One of the major difficulties in developing demand options is understanding how consumers could reliably shift their demand at reasonable cost with which incentives. The starting point is understanding end use demand levels and patterns. For example, what is the general load pattern across the day and year for lighting, air conditioning, appliances, or various industrial and commercial applications. Without knowing the pattern, it is very difficult to understand how that pattern can be changed. Regional and end use demand profiles then can feed into incentives and programmes that change the demand, but we cannot understand the effectiveness of these programmes if we cannot

Figure 6.1: Factors that increase flexibility resources must be integrated by market design

	Data Develop, improve, disseminate	**Technology** Develop, deploy, cost reduction	**Infrastructure** Plan, finance, build	**Awareness** Build and drive behaviour	**Business models** Facilitate development	**Incentives** Provide and harmonise	**Market design** Improve and integrate
Demand flexibility Develop, test, and roll out options	• Demand statistics • Potential • Cost	• IT and control systems	• IT and control systems	• Opportunities • Consumers	• Models for aggregators	• Investment • Dispatch	Integrate all options cost effectively
Storage Develop and install	• Potential • Cost	• Cost reduction • Local application • Indian manufacture	• Deploy, integrate, finance	• Opportunities	• Aggregators • Producers • Suppliers	• Capital investment • Dispatch	
Powerplants Encourage operation and regulatory changes and investment	• Integrated assessment of system plant • Value • Potential	• Test and deploy upgrades	• Test and deploy	• Overcoming entrenched practices • Operating and regulatory	• Plant owners • Upgrades	• Capital investment • Dispatch	
Transmission Continue expanding with flexibility needs under consideration	• Regional data • Cost compare • Flexibility in planning	• Use state of art as deployed in India	• Finance • Integrate	• Tradeoffs with flexibility	• Local, regional and national	• Regulation trading markets	
Integrate Each of the options to minimize cost	• Central clearinghouse for planning	• IT for systems integration and markets	• Financial capacity and planning		• Build aggregators • Help players work together		

measure what the starting point for energy consumption and timing was and then monitor the change and evaluate the cost effectiveness to improve the programme. Furthermore, without some sort of end use metering or analysis, delivery of incentives is almost impossible.

Powerplants. While information on the flexibility of powerplants can be more easily deduced from the vintage and design of the power stations, the data is difficult to access and we are not aware of a comprehensive database that covers all of the plants in India. Differences between nationally owned, state owned and private power plants inhibit data collection, while the picture is further complicated by contractual and tariff constraints on operation.

Other. Further data will be required on renewable energy generation profiles, transmission capacities, costs, and so forth. In many countries there are national research institutions or agencies that collect and manage this information and sometimes provide analysis for energy planners, such as the Energy Information Agency in the US.

- **Technology.** Advances or adoption of new technology will be of significant help to meeting flexibility goals.

  o ***Batteries and the cost of storage.*** The first area is reducing the cost of storage in India. While the generic costs of batteries are falling globally, a trend from which India can take advantage, storage technologies will need to be adapted, and reduced in cost, to address specific requirements in India. The entire storage system extends beyond a battery and could be significantly different when applied to large scale batteries at substations or powerplants, smaller systems to support distribution, transport related storage, or commercial or residential backup that could include connection to offer services back to the grid. Each of these options need to be developed cost effectively for India, and India may need to consider local manufacturing capabilities to improve its cost position.

  o ***Metering, measurement, communication and settlement.*** With more flexibility options, system operators will have more options to dispatch and control. Each of these will need to be monitored and controlled, not just for dispatch, but also for incentivisation and planning.

  o ***Powerplants.*** There are various technical solutions to improve the operation of powerplants. These options can increase the speed of ramping, allow for better control and efficiency at lower operating levels, or allow for quicker and shorter shutdowns and startups. Each of these need to be developed and tested across different plant models before deployment.

- **Infrastructure.** Increased flexibility, whether from flexible demand or powerplants, is not useful if it cannot be delivered to where it is needed, when it is needed. Systems and coordination to measure and develop the flexibility resource are key, but hard infrastructure will include developing assets, most of which should be in development in any case, but now with consideration of how these assets will also facilitate flexibility. Examples include:

  o ***Transmission and distribution*** are central elements of delivering and rationalizing flexibility resources. Planning and building these elements will likely increase and need to consider carefully the flexibility needs and resources.

  o ***Information technology and metering*** will drive markets, incentives, payments, and new programme development. Information is a key to balancing this system and creating the infrastructure to gather and use this data is an important step to minimizing costs.

- **Awareness and behaviour.** Many of the options presented here are new to Indian electricity consumers or producers. Before any action can be taken, consumers and producers need to become aware that these opportunities exist and that there is potential benefit from providing more flexibility. Beyond that, programmes need to help change entrenched practices that have developed over many years.

While incentives may provide an economic case, changing behaviour – for example to change the hours of agricultural pumping, to accept operating powerplants at lower minimum levels, or changing how a house is cooled – often requires different mechanisms than pure incentives including utility and customer education, development of new business models, creation of new market participants, political will and new policy frameworks.

- **New business models.** One issue for flexibility measures, including particularly demand measures, is that the size and value of any single action might not be material enough for a consumer to act on. The savings from shifting pumping from one agricultural pump is unlikely to justify the cost of understanding the markets, figuring out how to contract and bill for the flexibility services, and day-to-day involvement in trading markets, where necessary. The key may be the development of businesses like aggregators who can aggregate the flexibility potential of many individual sources, combine these options with other assets like storage or power generation, and create value by trading and dispatching the capacity. Developing these new business models can have a very important role in reducing the costs of flexibility options and making growth and scale more accessible.

- **Incentives and markets** need to operate at two levels:

  o ***Dispatch and optimization:*** As we have seen, each flexibility need will have a series of options that can serve that need, each of which may have a different cost or price. Providing a lowest cost mix of options requires selecting a mix of options optimized across all of the flexibility needs. Incentives are needed to encourage flexibility providers to offer the flexibility when it is needed, and markets are needed to determine the best mix of options given costs and constraints. For example, more liquid wholesale electricity markets that create a transparent price signal, more time-varying and dynamic retail prices would encourage demand flexibility, new contract structures with powerplants, demand flexibility aggregators, storage assets that value flexibility characteristics. Markets will need to operate at different time scales for planning, commitment (and to ensure availability when needed) and actual scheduling and dispatch.

  o ***Investment.*** While short term markets create incentives to provide flexibility, they often are not sufficient to provide incentives to develop or invest in new flexibility options or upgrades. Additional markets, such as capacity markets, may be necessary to encourage new developments and investment in new assets.

  Batteries, plant upgrades, information technology and metering for consumers, may be smaller individual investments than new, large powerplants, but collectively they will still represent significant investment for India. The investment patterns, time horizons, risks, and the investors themselves, will often be distinct from typical power sector investors. Likewise, investment during the development phase for these options will have different patterns and needs than once the options become mainstream. These differences need to be addressed early in order to accelerate development.

- **Market design, policy interventions and frameworks.** A number of the current market structures, incentives and the policy framework that underpin them are structured to support old generation supply and demand models. Transitioning into the new behaviours, new market models and incentivizing evolution of operational and financing models will require not just the creation of new pathways (eg, markets can find the right price for ancillary and balancing services, real-time markets, market aggregators and deployment of control and measurement infrastructure to facilitate demand side flexibility) but also assessment of approaches to integrate flexibility and flexible operation within the scope of existing contracts and arrangements (eg, adjustment of existing thermal generation contracts to compensate for financial and operational cost of flexible operations).

Regardless of how far India moves on its clean energy ambitions, additional flexibility in demand, powerplants and storage will lower the cost and increase the reliability of India's electricity supply. Building a programme to improve the capacity and cost competitiveness of storage options in India is an important step that requires development in the near term and deployment programmes in the longer term. Improving demand flexibility through further test programmes, development programmes and market reform and incentives is another step that can provide significant value to India under any circumstances, but they will need to start as soon as is practical to ensure that the flexible capacity is available for when it is needed in the future. With all three of these flexibility options developed, then flexibility will be the key enabler for reducing system costs, increasing power quality, and transitioning the India power sector into a low cost, low carbon, sustainable system which can support and facilitate increasing renewable energy and lower emissions.

Annex

Current trajectory: Thermal powerplant driven flexibility portfolio
Current trajectory: Demand flexibility portfolio
Current trajectory: Storage flexibility portfolio
Current trajectory: Balanced flexibility portfolio
High RE: Thermal flexibility portfolio
High RE: Demand flexibility portfolio
High RE: Storage flexibility portfolio
High RE: Balanced flexibility portfolio

Current trajectory: Thermal powerplant driven flexibility portfolio

Portfolio statistics

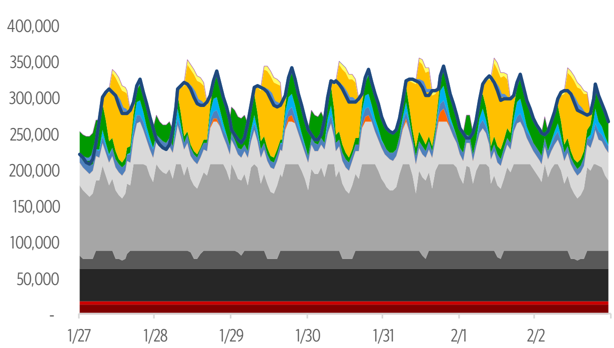
System cost (Rs/kWh)	4.8
Excess production (% of VRE)	10.0%
Emissions intensity (tonnes CO2/MWh)	0.60
Coal capacity (GW)	313
Coal capacity factor (%)	54%
Average coal loading when running (%)	71%
Demand flexibility capacity (GW)	N/A
Battery capacity (GW)	N/A
Pumped hydro capacity (GW)	5.8
Captive diesel generators capacity (GW)	N/A

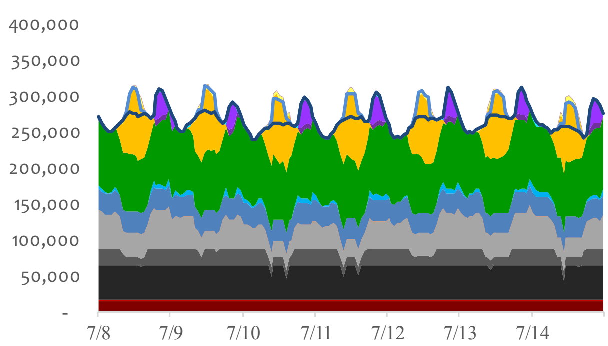
Key implementation risks

- High levels of excess energy production drive need to manage curtailment risk
- Coal fuel availability, allocation, and seasonal storage are critical to reliability
- Political / social appetite for coal-related pollution may be a challenge

Operational challenges

- Daily ramping, part-load operation, cycling of many coal plants
- Substantial excess production
- Infrequent, seasonal use of gas
- Seasonality of coal use requiring extended shut down periods





Current trajectory: Thermal flexibility portfolio (detailed data)

	Capacity (GW)	Energy share (%)	Capacity factor (%)	Fixed cost (Rs/ kW-yr)	Variable cost (Rs/kWh)
Wind	123	16.3%	36.6%	7,000	-
Solar PV	141.0	10.8%	21.3%	4,700	-
Rooftop PV	10.0	0.7%	20.4%	7,050	-
Hydro	68.0	8.5%	34.8%	11,062	0.26
Nuclear	16.9	4.9%	80.0%	25,000	0.50
Biomass	5.0	1.2%	65.0%	14,700	7.47
Super coal - pithead	58.3	16.2%	76.9%	10,503	1.90
Sub coal - pithead	29.6	7.5%	70.5%	9,771	2.27
Super coal - non-pithead	151.0	32.0%	58.8%	10,503	3.85
Sub coal - Non-pithead	74.0	5.4%	20.4%	9,771	4.66
Gas CCGT	22.1	0.0%	0.2%	9,256	5.32
Gas OCGT	-	0.0%		5,620	8.66
Diesel (grid)	-	0.0%		1,685	28.21
Air conditioning	-	0.0%		2,948	-
Agricultural pumping	-	0.0%		3,601	-
Industry	-	0.0%		-	5.00
EV charging	-	0.0%		1,849	-
Battery	-	0.0%		7,562	-
Pumped hydro	5.9	-0.1%	-3.6%	11,062	-
Captive diesel	-	0.0%		1,685	28.21

Current trajectory: Demand flexibility portfolio

Portfolio statistics

System cost (Rs/kWh)	4.5
Excess production (% of VRE)	1.7%
Emissions intensity (tonnes CO2/MWh)	0.56
Coal capacity (GW)	243
Coal capacity factor (%)	65%
Average coal loading when running (%)	86%
Demand flexibility capacity (GW)	70
Battery capacity (GW)	N/A
Pumped hydro capacity (GW)	5.8
Captive diesel generators capacity (GW)	24

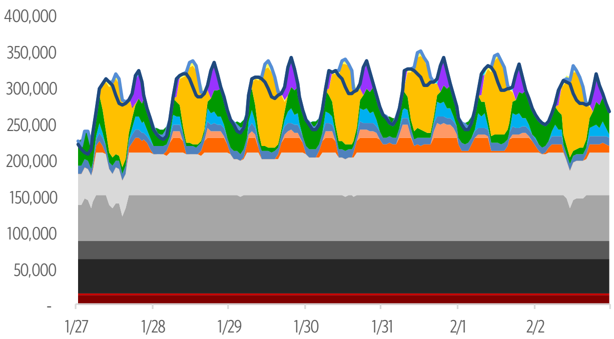
Key implementation risks

- Accessing sufficient demand side flexibility, requiring new regulatory approaches, market mechanisms and business models

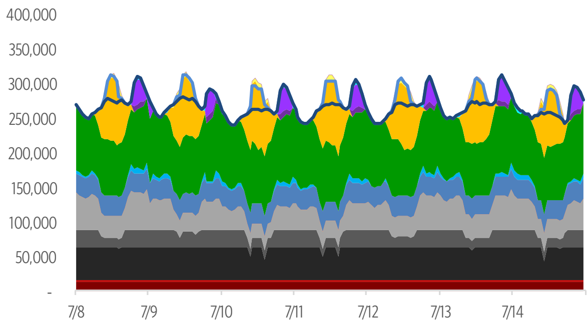
Operational challenges

- Forecasting and managing RE and demand flexibility availability
- Managing regional interchange to avoid underutilising transmission
- Seasonality of some coal and gas capacity, including extended shutdowns

Dispatch Profile - Late January



Dispatch Profile - Late July



Current trajectory: Demand flexibility portfolio (detailed data)

	Capacity (GW)	Energy Share (%)	Capacity Factor (%)	Fixed Cost (Rs/kW-yr)	Variable Cost (Rs/kWh)
Wind	123.0	16.3%	36.6%	7,000	-
Solar PV	141.0	10.8%	21.3%	4,700	-
Rooftop PV	10.0	0.7%	20.4%	7,050	-
Hydro	68.0	8.7%	35.7%	11,062	0.26
Nuclear	16.9	4.9%	80.0%	25,000	0.50
Biomass	5.0	1.2%	65.0%	14,700	7.47
Super Coal - pithead	58.3	16.7%	79.4%	10,503	1.90
Sub Coal - pithead	29.6	8.2%	77.1%	9,771	2.27
Super Coal - non-pithead	81.0	20.6%	70.5%	10,503	3.85
Sub Coal - non-pithead	74.0	11.7%	43.7%	9,771	4.66
Gas CCGT	24.9	0.9%	9.7%	9,256	5.32
Gas OCGT	-	0.0%		5,620	8.66
Diesel (grid)	0.8	0.0%	3.7%	1,685	28.21
Air conditioning	19.8	0.3%	3.7%	2,948	-
Ag pumping	37.7	-0.1%	-0.7%	3,601	-
Industry	-	0.0%		-	5.00
EV charging	12.5	-0.3%	-7.0%	1,849	-
Battery	-	0.0%		7,562	-
Pumped hydro	5.9	0.0%	-1.8%	11,062	-
Captive diesel	23.9	0.1%	1.1%	1,685	28.21

Current trajectory: Storage flexibility portfolio

Portfolio statistics

System cost (Rs/kWh)	4.6
Excess production (% of VRE)	0.5%
Emissions intensity (tonnes CO2/MWh)	0.56
Coal capacity (GW)	256
Coal capacity factor (%)	63%
Average coal loading when running (%)	89%
Demand flexibility capacity (GW)	NA
Battery capacity (GW)	60
Pumped hydro capacity (GW)	15
Captive diesel generators capacity (GW)	NA

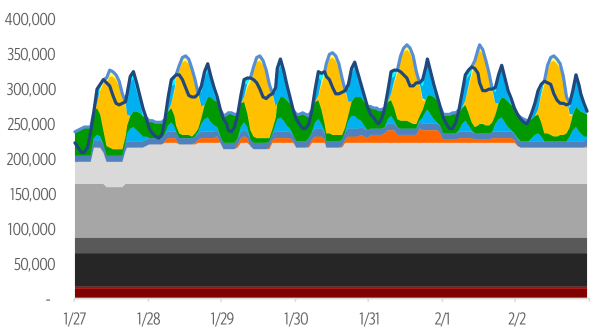
Key implementation risks

- Building battery storage supply chain to deliver 60GW of storage by 2030
- Development of 10GW additional pumped hydro by 2030

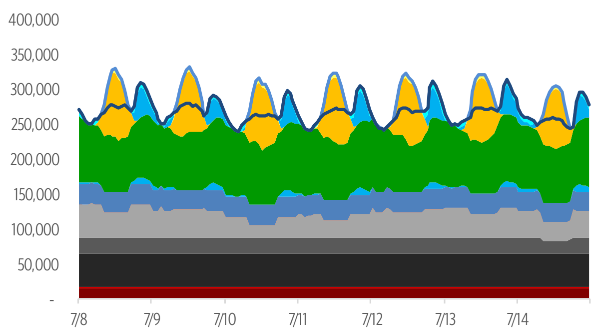
Operational challenges

- Forecasting and managing RE availability
- Optimising storage dispatch profile against multiple sources of value (customer, distribution, transmission systems)
- Managing regional interchange to avoid underutilising transmission
- Seasonality of some coal and gas capacity, including extended shutdowns

Dispatch Profile - Late January



Dispatch Profile - Late July



Current trajectory: Storage flexibility portfolio (detailed data)

	Capacity (GW)	Energy share (%)	Capacity factor (%)	Fixed cost (Rs/ kW-yr)	Variable cost (Rs/kWh)
Wind	123.0	16.3%	36.6%	7,000	-
Solar PV	141.0	10.8%	21.3%	4,700	-
Rooftop PV	10.0	0.7%	20.4%	7,050	-
Hydro	68.0	8.5%	34.8%	11,062	0.26
Nuclear	16.9	4.9%	80.0%	25,000	0.50
Biomass	5.0	1.2%	65.0%	14,700	7.47
Super coal - pithead	58.3	16.8%	79.8%	10,503	1.90
Sub coal - pithead	29.6	8.4%	79.1%	9,771	2.27
Super coal - non-pithead	94.0	23.8%	70.2%	10,503	3.85
Sub coal - non-pithead	74.0	9.3%	34.7%	9,771	4.66
Gas CCGT	24.8	0.2%	2.2%	9,256	5.32
Gas OCGT	-	0.0%		5,620	8.66
Diesel (grid)	-	0.0%		1,685	28.21
Air conditioning	-	0.0%		2,948	-
Agricultural pumping	-	0.0%		3,601	-
Industry	-	0.0%		-	5.00
EV charging	-	0.0%		1,849	-
Battery	60.0	-0.3%	-1.3%	7,562	-
Pumped hydro	15.0	-0.5%	-8.6%	11,062	-
Captive diesel	-	0.0%		1,685	28.21

Current trajectory: Balanced flexibility portfolio

Portfolio statistics

System cost (Rs/kWh)	4.6
Excess production (% of VRE)	0.3%
Emissions intensity (tonnes CO2/MWh)	0.55
Coal capacity (GW)	228
Coal capacity factor (%)	68%
Average coal loading when running (%)	94%
Demand flexibility capacity (GW)	70
Battery capacity (GW)	25
Pumped hydro capacity (GW)	10
Captive diesel generators capacity (GW)	25

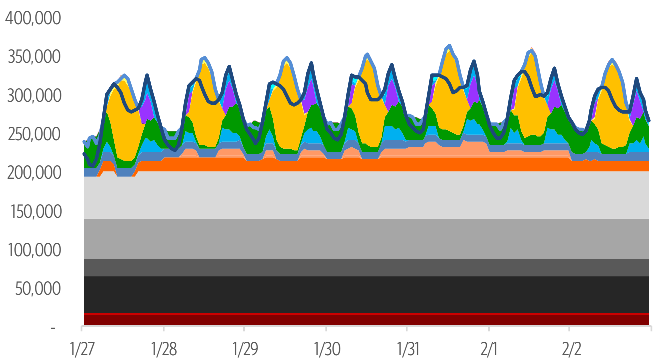
Key implementation risks

- Accessing sufficient demand side flexibility, requiring new regulatory approaches, market mechanisms and business models
- Building battery storage supply chain to deliver 25 GW of storage by 2030

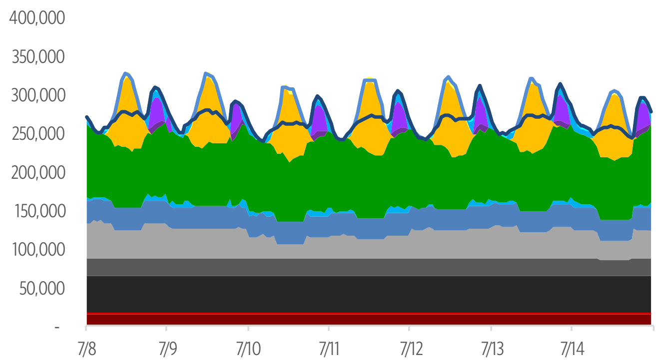
Operational challenges

- Daily ramping, part-load operation, cycling of many coal plants
- Substantial excess production
- Infrequent, seasonal use of gas
- Seasonality of coal use requiring extended shut down periods

Dispatch Profile – Late January



Dispatch Profile – Late July



Current trajectory: Balanced flexibility portfolio (detailed data)

	Capacity (GW)	Energy share (%)	Capacity factor (%)	Fixed cost (Rs/kW-yr)	Variable cost (Rs/kWh)
Wind	123.0	16.3%	36.6%	7,000	-
Solar PV	141.0	10.8%	21.3%	4,700	-
Rooftop PV	10.0	0.7%	20.4%	7,050	-
Hydro	68.0	8.7%	35.7%	11,062	0.26
Nuclear	16.9	4.9%	80.0%	25,000	0.50
Biomass	5.0	1.2%	65.0%	14,700	7.47
Super Coal - Pithead	58.3	16.8%	79.8%	10,503	1.90
Sub Coal - Pithead	29.6	8.4%	79.2%	9,771	2.27
Super Coal - Non Pithead	66.0	17.6%	73.8%	10,503	3.85
Sub Coal - Non Pithead	74.0	13.3%	49.9%	9,771	4.66
Gas CCGT	24.9	1.7%	18.6%	9,256	5.32
Gas OCGT	-	0.0%		5,620	8.66
Diesel (Grid)	0.8	0.0%	8.7%	1,685	28.21
Air Conditioning	19.8	0.3%	3.7%	2,948	-
Ag Pumping	37.7	-0.1%	-0.7%	3,601	-
Industry	-	0.0%		-	5.00
EV Charging	12.5	-0.3%	-7.0%	1,849	-
Battery	25.0	-0.1%	-1.3%	7,562	-
Pumped Hydro	10.0	-0.3%	-8.2%	11,062	-
Captive Diesel	24.7	0.2%	2.6%	1,685	28.21

High RE: Thermal flexibility portfolio

Portfolio statistics

System Cost (Rs/kWh)	5.0
Excess Production (% of VRE)	13.8%
Emissions Intensity (tonnes CO2/MWh)	0.50
Coal Capacity (GW)	292
Coal Capacity Factor (%)	48%
Average Coal Loading When Running (%)	68%
Demand Flexibility Capacity (GW)	N/A
Battery Capacity (GW)	N/A
Pumped Hydro Capacity (GW)	5.8
Captive Diesel Generators Capacity (GW)	N/A

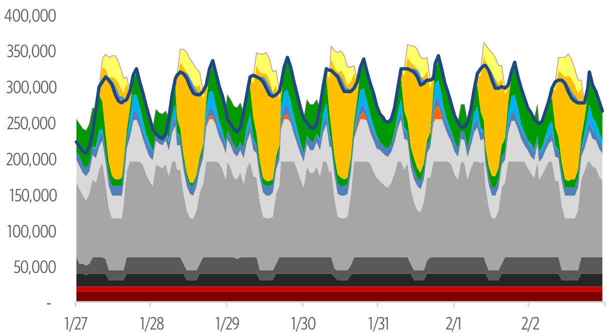
Key implementation risks

- High levels of excess energy production drive need to manage curtailment risk
- Coal fuel availability, allocation, and seasonal storage are critical to reliability
- Political / social appetite for coal-related pollution may be a challenge

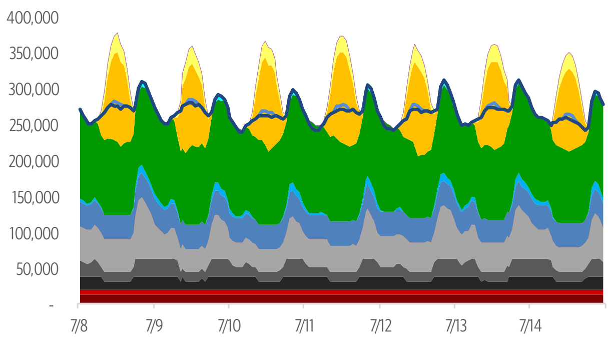
Operational challenges

- Daily ramping, part-load operation, cycling of many coal plants
- Substantial excess production
- Infrequent, seasonal use of gas
- Seasonality of coal use requiring extended shut down periods

Dispatch Profile - Late January



Dispatch Profile – Late July



High RE: Thermal flexibility portfolio (detailed data)

	Capacity (GW)	Energy Share (%)	Capacity Factor (%)	Fixed Cost (Rs/kW-yr)	Variable Cost (Rs/kWh)
Wind	160.0	21.1%	36.6%	7,000	-
Solar PV	190.0	14.6%	21.3%	4,700	-
Rooftop PV	40.0	2.9%	20.4%	7,050	-
Hydro	80.5	10.4%	35.8%	11,062	0.26
Nuclear	16.9	4.9%	80.0%	25,000	0.50
Biomass	10.4	2.4%	65.0%	14,700	7.47
Super Coal - Pithead	23.1	5.9%	70.6%	10,503	1.90
Sub Coal - Pithead	29.6	7.2%	67.1%	9,771	2.27
Super Coal - Non Pithead	165.7	32.2%	53.8%	10,503	3.85
Sub Coal - Non Pithead	74.0	4.9%	18.5%	9,771	4.66
Gas CCGT	23.1	0.0%	0.3%	9,256	5.32
Gas OCGT	-	0.0%		5,620	8.66
Diesel (Grid)	-	0.0%		1,685	28.21
Air Conditioning	-	0.0%		2,948	-
Ag Pumping	-	0.0%		3,601	-
Industry	-	0.0%		-	5.00
EV Charging	-	0.0%		1,849	-
Battery	-	0.0%		7,562	-
Pumped Hydro	5.9	0.0%	-1.4%	11,062	-
Captive Diesel	-	0.0%		1,685	28.21

High RE – Demand Flexibility Portfolio

Portfolio Statistics

System Cost (Rs/kWh)	4.6
Excess Production (% of VRE)	5.2%
Emissions Intensity (tonnes CO2/MWh)	0.45
Coal Capacity (GW)	222
Coal Capacity Factor (%)	56%
Average Coal Loading When Running (%)	80%
Demand Flexibility Capacity (GW)	70
Battery Capacity (GW)	N/A
Pumped Hydro Capacity (GW)	5.8
Captive Diesel Generators Capacity (GW)	25

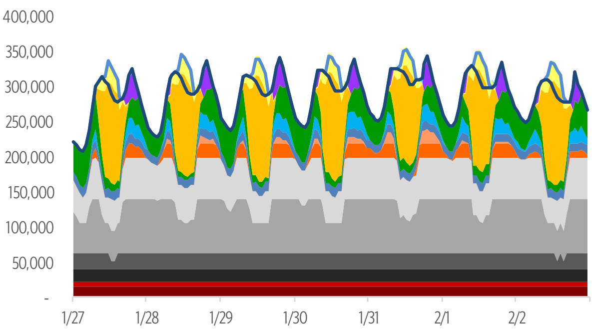
Key Implementation Risks

- Accessing sufficient demand side flexibility, requiring new regulatory approaches, market mechanisms and business models

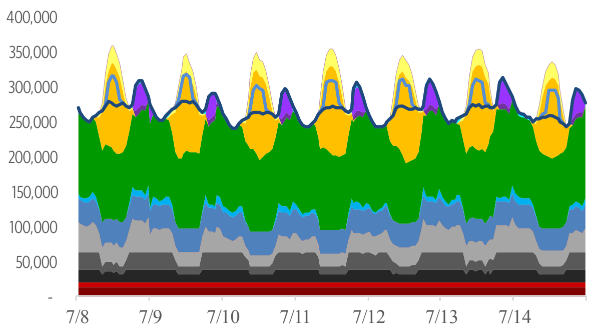
Operational Challenges

- Forecasting and managing RE and demand flexibility availability
- Managing regional interchange to avoid underutilizing transmission
- Seasonality of some coal and gas capacity, including extended shutdowns

Dispatch Profile – Late January



Dispatch Profile – Late July



High RE – Demand Flexibility Portfolio (Detailed Data)

	Capacity (GW)	Energy Share (%)	Capacity Factor (%)	Fixed Cost (Rs/ kW-yr)	Variable Cost (Rs/kWh)
Wind	160.0	21.1%	36.6%	7,000	-
Solar PV	190.0	14.6%	21.3%	4,700	-
Rooftop PV	40.0	2.9%	20.4%	7,050	-
Hydro	80.5	10.7%	37.0%	11,062	0.26
Nuclear	16.9	4.9%	80.0%	25,000	0.50
Biomass	10.4	2.4%	65.0%	14,700	7.47
Super Coal - Pithead	23.1	6.3%	75.5%	10,503	1.90
Sub Coal - Pithead	29.6	7.7%	71.9%	9,771	2.27
Super Coal - Non Pithead	95.7	21.4%	61.9%	10,503	3.85
Sub Coal - Non Pithead	74.0	9.8%	36.8%	9,771	4.66
Gas CCGT	24.9	0.6%	6.7%	9,256	5.32
Gas OCGT	-	0.0%		5,620	8.66
Diesel (Grid)	0.8	0.0%	2.5%	1,685	28.21
Air Conditioning	19.8	0.3%	3.7%	2,948	-
Ag Pumping	37.7	-0.1%	-0.7%	3,601	-
Industry	-	0.0%		-	5.00
EV Charging	12.5	-0.3%	-6.1%	1,849	-
Battery	-	0.0%		7,562	-
Pumped Hydro	5.9	-0.1%	-2.7%	11,062	-
Captive Diesel	24.9	0.1%	0.8%	1,685	28.21

High RE – Storage Flexibility Portfolio

Portfolio Statistics

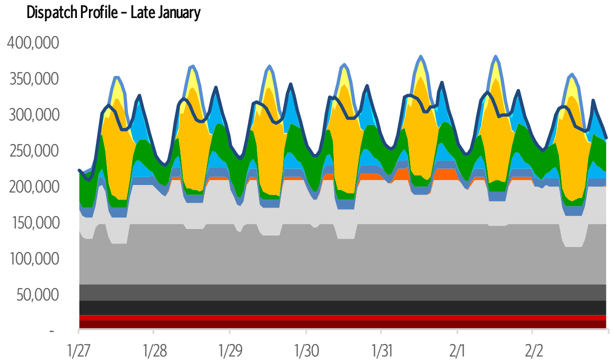
System Cost (Rs/kWh)	4.7
Excess Production (% of VRE)	2.8%
Emissions Intensity (tonnes CO2/MWh)	0.45
Coal Capacity (GW)	232
Coal Capacity Factor (%)	54%
Average Coal Loading When Running (%)	80%
Demand Flexibility Capacity (GW)	N/A
Battery Capacity (GW)	60
Pumped Hydro Capacity (GW)	15
Captive Diesel Generators Capacity (GW)	N/A

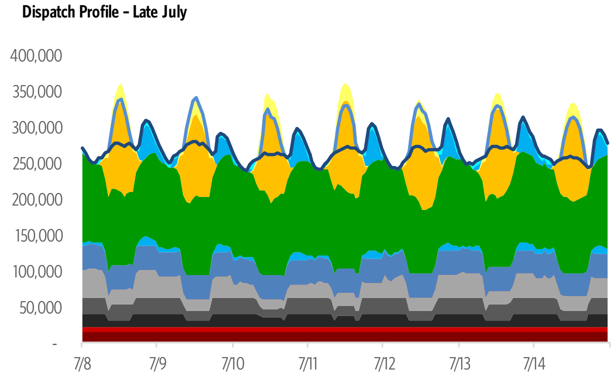
Key Implementation Risks

- Scaling battery supply chain in India
- Overcoming barriers to pumped hydro development

Operational Challenges

- Managing and optimizing storage across multiple sources of value
- Managing regional interchange to avoid underutilizing transmission
- Seasonality of some coal and gas capacity, including extended shutdowns





High RE – Storage Flexibility Portfolio (Detailed Data)

	Capacity (GW)	Energy Share (%)	Capacity Factor (%)	Fixed Cost (Rs/ kW-yr)	Variable Cost (Rs/kWh)
Wind	160.0	21.1%	36.6%	7,000	-
Solar PV	190.0	14.6%	21.3%	4,700	-
Rooftop PV	40.0	2.9%	20.4%	7,050	-
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Gas OCGT	-	0.0%		5,620	8.66
Diesel (Grid)	0.8	0.0%	0.0%	1,685	28.21
Air Conditioning	-	0.0%		2,948	-
Ag Pumping	-	0.0%		3,601	-
Industry	-	0.0%		-	5.00
EV Charging	-	0.0%		1,849	-
Battery	60.0	-0.3%	-1.3%	7,562	-
Pumped Hydro	15.0	-0.4%	-7.1%	11,062	-
Captive Diesel	-	0.0%		1,685	28.21

High RE - Balanced Flexibility Portfolio

Portfolio Statistics

System Cost (Rs/kWh)	4.6
Excess Production (% of VRE)	2.5%
Emissions Intensity (tonnes CO2/MWh)	0.44
Coal Capacity (GW)	207
Coal Capacity Factor (%)	59%
Average Coal Loading When Running (%)	86%
Demand Flexibility Capacity (GW)	70
Battery Capacity (GW)	25
Pumped Hydro Capacity (GW)	10
Captive Diesel Generators Capacity (GW)	22

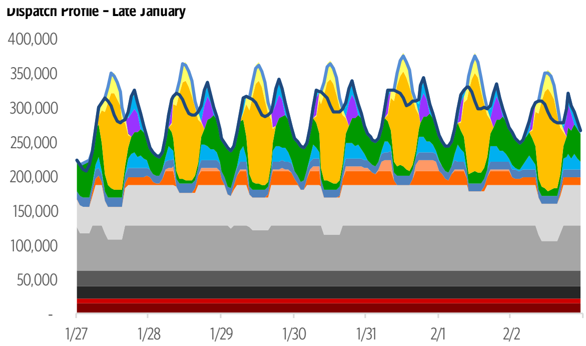
Key Implementation Risks

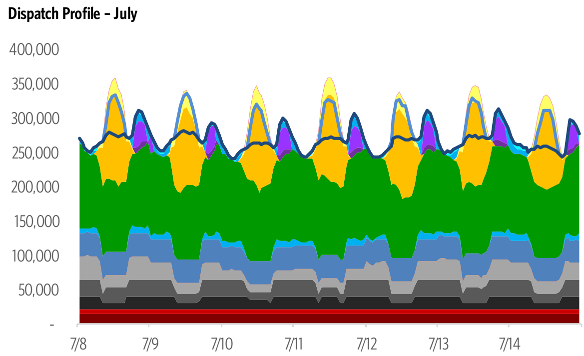
regulatory approaches, market mechanisms and business models

- Building battery storage supply chain to deliver 25 GW of storage by 2030

Operational Challenges

- Forecasting and managing RE and demand flexibility availability
- Optimizing storage dispatch profile against multiple sources of value (customer, distribution, transmission systems)
- Managing regional interchange to avoid underutilizing transmission
- Seasonality of some coal and gas capacity, including extended shutdowns
- Ensuring availability of gas, demand-side diesel when called upon





High RE – Balanced Flexibility Portfolio (Detailed Data)

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Gas OCGT	-	0.0%		5,620	8.66
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Air Conditioning	19.8	0.3%	3.7%	2,948	-
Ag Pumping	37.7	-0.1%	-0.7%	3,601	-
Industry	-	0.0%		-	5.00
EV Charging	12.5	-0.3%	-6.1%	1,849	-
Battery	25.0	-0.1%	-1.3%	7,562	-
Pumped Hydro	10.0	-0.3%	-7.3%	11,062	-
Captive Diesel	22.4	0.1%	1.0%	1,685	28.21

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