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Executive summary

India's demand for energy is growing rapidly

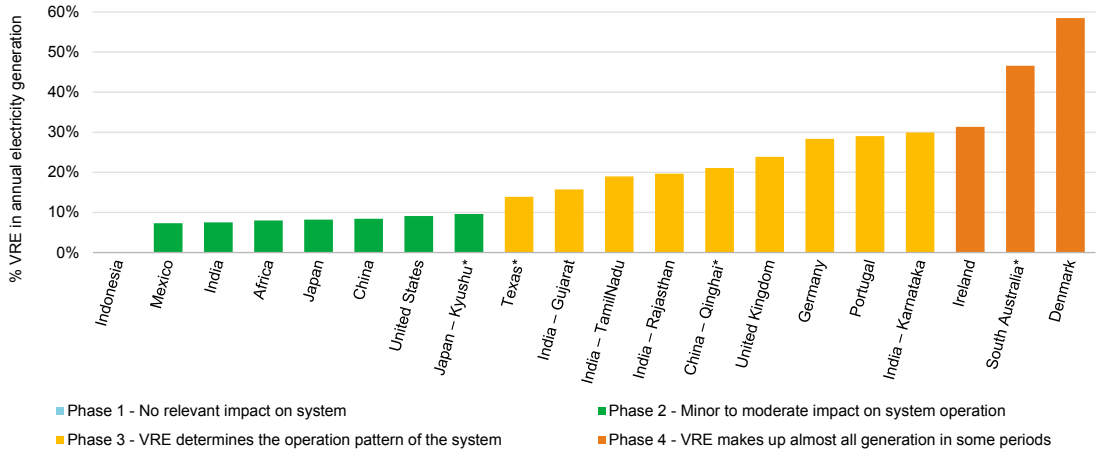
India is the third largest energy-consuming country in the world. It has become one of the largest sources of energy demand growth globally and has made significant progress towards its universal electrification target for residential users, with 100 million people gaining access in 2018 alone. Per capita electricity consumption across the 28 Indian states and eight union territories is still around a third of the world average, and is expected to continue increasing despite the government's intention to pursue strong energy efficiency standards, including LED lighting, efficient cooling and building standards. Total Indian electricity demand has begun to expand again following a significant decline in 2020 due to Covid-19. The pandemic has affected the financial viability of the electricity distribution companies (DISCOMs), which were already struggling with mounting debts and a liquidity crunch.

India faces three principal challenges: (1) how to expand reliable energy access and use while maintaining affordability for consumers and financial stability for the DISCOMs; (2) how, at the same time, to integrate increasing shares of renewable energy in a secure and reliable manner; and (3) how to reduce emissions to achieve ambitious social and climate objectives while meeting economic goals.

Growing renewables increasingly challenge the power system

Renewable energy penetration is highly variable by state in India. The share of solar and wind in India's ten renewables-rich states (Tamil Nadu, Karnataka, Gujarat, Rajasthan, Andhra Pradesh, Maharashtra, Madhya Pradesh, Telangana, Punjab and Kerala) is significantly higher than the national average of 8.2%. Solar and wind account for around 29% of annual electricity generation in Karnataka, 20% in Rajasthan, 18% in Tamil Nadu and 14% in Gujarat (financial year [FY] 2020/21). India's renewables-rich states already have a higher share of variable renewable energy (VRE) than most countries internationally. As a result, many states are already facing system integration challenges.

Countries and regions in phases of renewables integration, 2019



* 2018 values.

Sources: IEA, Renewables 2020; IITK Energy Analytics Lab.

Furthermore, in the coming decade the Indian power system is due to undergo an even more profound transformation. The government plans to increase renewable generating capacity from 175 GW in 2022 to 450 GW in 2030. Some state leaders have expressed concern that they will face excess VRE generation and the need to: (1) export significantly more power to other states; (2) allow renewables to displace some coal power plants locally; or (3) curtail more solar and wind to ensure system security. Recent trends underlying the main renewables integration challenges include the increasing variability of hourly demand, increasing ramping requirements due to the impact of solar on net demand, short-term frequency variations and local voltage issues.

While the Power System Operation Corporation (POSOCO), a wholly owned public sector undertaking under the Ministry of Power, highlighted that national-level inertia has declined slightly from the 2014 level at certain times, India does not yet face system inertia challenges. However, with future increases in solar and wind power, the renewables-rich states will experience periods when wind and solar make up the majority of generation, and it will then become imperative to monitor local system strength and inertia requirements. The report covers important international experience in managing systems with declining inertia levels.

Indian states should leverage all potential sources of power system flexibility to maximise the value of solar and wind

This report highlights potential sources of power system flexibility in renewables-rich Indian states, including demand-side flexibility, power plant flexibility, storage (pumped-storage hydro and batteries) and grid flexibility, as well as policy, market and regulatory solutions that can be implemented in the short to medium term until 2030. The optimal mix of flexibility resources needs to be determined for each state, taking into account the regional and national context. For example, there are trade-offs between investing in batteries, pumped-storage hydro, demand response and coal power plants that depend upon the existing generation and demand profiles of each system. This report fills a gap in the international literature by focusing on renewables integration in individual states, rather than at the national level in India. It builds on the ongoing power sector stakeholder engagement that the IEA and NITI Aayog have been leading since 2018, including the outcomes of a series of workshops in recent years – one national, four regional and three state level – and the related in-depth analysis. The report also draws on two detailed production cost models developed by the IEA to illustrate flexibility challenges and solutions: a five-region India Regional Power System Model and a Gujarat State Power System Model. Power system flexibility challenges, solutions and priorities are very different in each state. This report highlights the findings applicable to multiple states in India, and potentially across the globe.

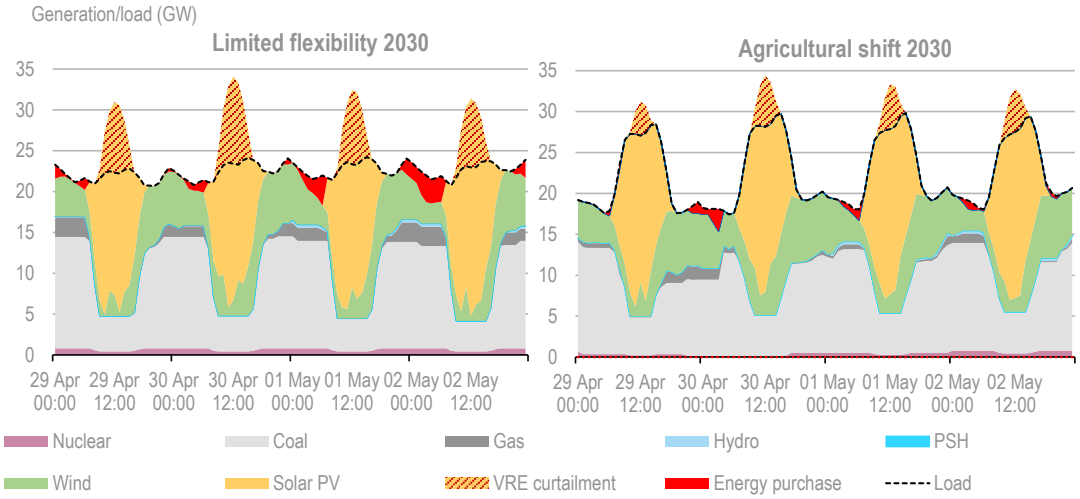
Policy and tariff reforms can tap into demand response potential

Power system transformation in India will be supported by the transformation of electricity demand from passive consumption to more proactive participation by demand sectors. Agricultural users already play an important role in balancing power supply and demand through involuntary irrigation load shifting, and the IEA analysis foresees more active participation from the agricultural sector, buildings (including cooling) and industry by 2030.

The existing agricultural demand shift from high to low demand hours already provides a significant source of low-cost power system flexibility in India, and has assisted some states in reaching high levels of solar and wind penetration without major system events. This shift has been largely enabled by the availability and use of existing distribution networks dedicated to agricultural users in certain states, which allow the system operator to control irrigation loads without impacting other grid users. Looking ahead, transitioning from involuntary

agricultural demand shift to proactive agricultural demand response (e.g. active response to a price signal) can be one of the most cost-effective solutions to improve power system flexibility, although its use must be balanced against the potential impact on the water stress of each region.

Impact of agricultural demand shift on total demand and solar generation absorption



Notes: PSH = pumped-storage hydro; PV = photovoltaic.
Sources: IEA, Gujarat State Power System Model and analysis based on Khanna (2021).

Time-of-day (or time-of-use) tariffs for industry are offered in most states as the basis of the existing industrial demand response incentive. In the medium to longer term, a shift towards time-of-use tariffs as the default option is recommended, following the rollout of advanced metering infrastructure, for the activation of demand response potential from buildings and transport (such as cooling and electric vehicle [EV] smart charging). On the residential side, shifting towards advanced digital metering, automation and smart home appliances is a prerequisite, whilst ensuring cybersecurity and avoiding proprietary standards that could limit interoperability and consumer choice.

Rooftop solar systems need to be monitored and managed

State system operators and DISCOMs are concerned about the rise of rooftop solar systems, due to their impact on DISCOM financial stability (from revenue loss), distribution system issues (from reactive power, voltage impacts and reverse power flows) and demand forecast uncertainty. This report highlights international experiences, illustrating how these can become system-friendly

assets and support the low-voltage network with voltage stability and reactive power. To improve the visibility of rooftop solar assets in India, connection codes need to stipulate the registration of individual systems, with state- and national-level registers of these assets. The rooftop solar database should first be built in states. Later, a national-level standardised interface and data model can bring more efficiency and transparency. Requiring all rooftop solar customers to be on time-of-use tariffs can help mitigate the revenue loss suffered by DISCOMs while also balancing the shift in costs between consumers with rooftop solar and consumers without it. Regularly revisiting time-of-use timeslots will be required as rooftop solar additions and demand response reshape the state demand curves.

New regulatory and policy frameworks can activate more flexibility from storage and power plants

Most states are concerned about the future role of existing coal-fired power plants. Coal plants are expected to operate less as renewable technologies supply more generation, which leads to reduced revenues. At the same time, to operate flexibly and meet stricter emissions standards, some coal plants may also require further investment. Such investment needs to be weighed against investment in flexibility sources in other parts of the system (storage, demand and grids) and emission reduction targets. Government officials are also concerned that historical dependence on long-term power procurement contracts as the tool for ensuring capacity adequacy creates an economic burden by locking in long-term fixed capacity payments to coal power plants.

In the Stated Policies Scenario (STEPS) of the IEA *World Energy Outlook* (WEO), coal capacity in the Indian power system will increase to 269 GW by 2030 compared to 235 GW in 2019. The analytical results of the IEA India Regional Power System Model show that the use of coal power plants in India will change dramatically by 2030. Use will shift from typically steady baseload operation to frequent operation near minimum and maximum output levels. Coal plants in some states have the potential to better support the integration of high shares of VRE with increased flexibility, such as faster ramp rates, lower technical minimum levels and shorter start-up times. Additional flexibility, however, requires new investment and new compensation designs for these power plants. In contrast to the current tariff structures focused on capacity and energy payments, emphasis should be placed on tariff and market-based compensation for flexibility.

Retrofitting hydropower plants to allow operation in pumped-storage mode seems to be the preferred storage solution in many states in India. However, batteries are also likely to play an important role in India. Analysis by the Lawrence Berkeley National Laboratory suggests that battery storage coupled with solar farms can be a more cost-effective solution than pumped-storage hydro retrofits for morning peaks or evening ramps requiring a storage duration of less than six hours. The optimal sizing and location of battery storage will differ by region and requires detailed studies in each state.

Changes to wholesale markets and power purchase agreements can remove barriers to interstate trade

The current regulatory and market frameworks present significant gaps and barriers for power system flexibility resources, including demand response, batteries, pumped-storage hydro and power plant flexibility. Comprehensively reviewing and removing the wholesale and retail market barriers to new technologies and creating an equal playing field for all resources is an important ongoing task not only in India, but worldwide.

India's wholesale power trade achieved important milestones in 2020, with improved trading across Indian states and the introduction of real-time markets and green markets. Since 2020 the real-time market has filled an important gap by providing corrections on an hour ahead timeframe for variable and uncertain generation such as solar and wind. The newly established green market enables clients such as the DISCOMs to fulfil the states' renewable purchase obligations through market purchases.

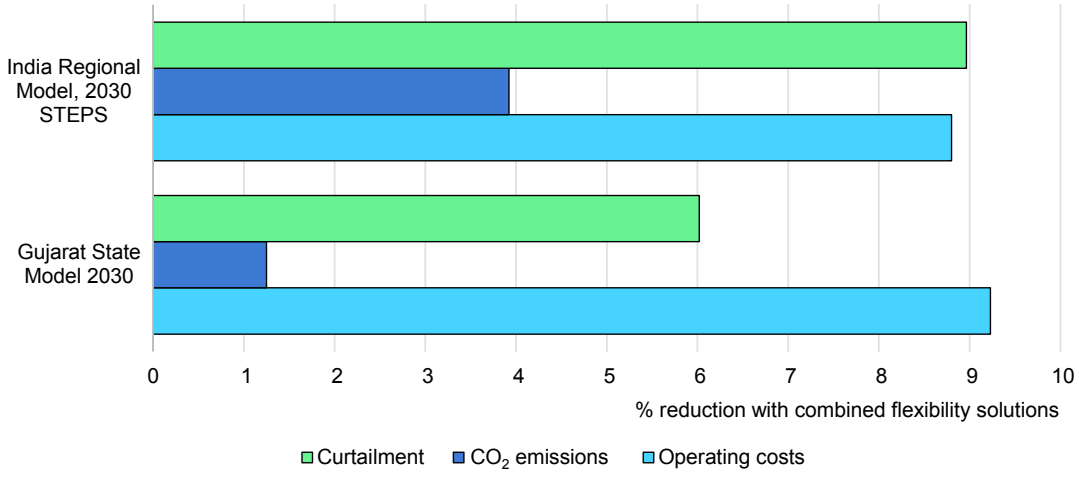
Analysis based on the IEA India Regional Power System Model suggests that additional power trading across states is an effective renewables integration solution that could reduce curtailment by around 2.5% in the STEPS in 2030. However, significant barriers remain to reach this potential. These include: (1) the lack of transmission capacity available for interstate trade; (2) the low level of liquidity in wholesale markets; and (3) the inflexible existing contractual structures, namely long-term physical purchase power agreements (PPAs) between the DISCOMs and generators (also contributing to the low liquidity).

States will need to weigh the costs and benefits of potential new transmission investment against the costs and benefits of other flexibility options. In India existing long-term physical PPAs represent about 90-95% of total generation. The current practice of using these PPAs to meet resource adequacy requirements may not be the most cost-effective tool for achieving resource adequacy. Existing

PPAs also pose a barrier to improved power system flexibility from both interstate trade and power plant flexibility. Thus, states could consider creating alternative resource adequacy mechanisms and using financial PPAs. In the longer term, a sophisticated financial market for power sector products could be introduced in India.

Flexibility reduces curtailment, and lower curtailment means reduced system operating costs and lower CO_2 emissions

Reduction in curtailment, CO_2 emissions and operating costs due to combined flexibility options in India and Gujarat



Note: Percentage savings show the impact of increased flexibility from power plants, demand response, energy storage and transmission in the IEA India Regional Power System Model and Gujarat State Power System Model.

Some level of curtailment is present in most systems with high solar and wind penetration – typically up to 3% of annual solar and wind output.

While renewables have must-run status in India, renewable generators can be curtailed due to system security considerations. For example, states such as Tamil Nadu and Karnataka have seen solar and wind curtailment in recent years.

Increasing solar and wind generation curtailment and lack of related mitigation policies are a major concern, particularly for investors. Power sector investment in India fell by USD 10 billion to USD 39 billion in 2020, including a decline in solar and wind investment, mainly due to the impacts of Covid-19. Improving investor confidence will be important in the coming years as India aspires to attract greater power system investment. To better address curtailment risk, discussions on the