### Technical flexibility resources for different timescales

| Flexibility timescale / Flexibility resource | Ultra-short term (sub-seconds to seconds) | Very short term (seconds to minutes) | Short term (minutes to hours) | Medium term (hours to days) | Long term (days to months) | Very long term (months to years) |
|---|---|---|---|---|---|---|
| **State-of-the-art VRE** | Controller to enable synthetic inertia; very fast frequency response | Synthetic inertial response; AGC | Downward/ upward reserves; AGC; ED of plants including VRE | ED tools; UC tools; VRE forecasting systems | UC tools; VRE forecasting systems | VRE forecasting systems; power system planning tools |
| **Demand-side resources** | Power electronics to enable demand response | Demand-side options including electric water heaters, EV chargers, large water pumps and electric heaters; variable-speed electric loads | Air conditioners with cold storage and heat pumps; most equipment listed under very-short-term flexibility | Smart meters for time-dependent retail pricing | Demand forecasting equipment | Demand forecasting equipment; power-to-gas |
| **Storage** | Supercapacitor; flywheels; battery storage; PSH modern variable speed units | Battery storage | Battery storage; CAES; PSH | PSH | PSH | PSH; hydrogen production; ammonia or other power-to-gas/liquid |
| **Conventional plants** | Mechanical inertia; generation shedding schemes | Speed droop control; AGC | Cycling; ramping; AGC | Cycling; quick-start; medium-start | Changes in power plant operation criteria | Retrofit plants; flexible power plants; keeping existing generators as reserve |
| **Grid infrastructure** | Synchronous condensers and other FACTS devices | SPS; network protection relays | Interaregional power transfers; cross-border transmission lines | Internodal power transfers; cross-border transmission lines | Control and communication systems to enable dynamic transmission line ratings; WAM; HV components such as SVC | Transmission lines or transmission reinforcement |

Notes: AGC = automatic generation control; CAES = compressed air energy storage; ED = economic dispatch; FACTS = flexible alternative current transmission system; HV = high voltage; PSH = pumped storage hydro; SPS = special protection schemes; speed droop control = the sensitivity of governor response to frequency changes; SVC = static VAR compensator; UC = unit commitment; WAM = wide area monitoring system.

Source: IEA, Status of Power System Transformation 2018.

# Power sector modelling provides system-specific insights

To evaluate the impact of increasing renewables and the role of flexibility solutions in India, the IEA has developed two new detailed power system models for this report. The first model, the India Regional Power System Model (hereafter, **India Regional Model**), is an update of the IEA five-region national model of India for the STEPS in 2030, building on past IEA hourly modelling of India. The second model, the Gujarat State Power System Model (hereafter, **Gujarat State Model**), is a DISCOM-level model of Gujarat State, developed by the IEA in collaboration

with CER, IIT Kanpur to evaluate the impact of diverse flexibility options on the Gujarat power system. It is described in more detail in the Gujarat Power System Transformation Workshop Report. The Gujarat State Model is the first state-level hourly model undertaken by the IEA, recognising the need for subnational modelling to capture the highly state-specific power system context in India.

Each model includes a number of scenarios to illustrate the impact of different flexibility options, as well as a downside case where additional flexibility does not materialise, to provide a reference point. The two models and the full set of scenarios analysed are described in more detail in the annex. This report provides results from both models to illustrate the renewables integration challenges and solutions at both the national and state levels.

# Renewables integration challenges

## India's states face many local renewables integration challenges

The IEA and NITI Aayog have collaborated with a wide range of state-level stakeholders, in particular in Maharashtra, Gujarat and Karnataka, to identify, collate and prioritise the following list of renewables integration challenges that affect Indian states. The stakeholders agreed that the states face significant challenges in reaching the country's national 2030 renewables targets. While some of these challenges are already the daily reality for certain states, other states expect to face them according to their level of VRE penetration.

The most important technical challenges relevant to many Indian states in the short to medium term are the following:

- Transmission challenges include new bottlenecks inside states and limited capacity available across states (interstate transmission lines) as solar and wind sites tend to be concentrated in certain regions within states and also in certain states within India.
- Many states lack real-time solar and wind generation data, and the accuracy of solar and wind forecasts must improve. Regulations often allow for forecast errors of +-15%, which for Karnataka may lead to more than 1 000 MW renewable generation deviation at certain times. To address these issues, India has 11 Renewable Energy Management Centres (co-located with load dispatch centres) managing a cumulative solar and wind power capacity of 60 GW+ and sharing data among state, regional and national grid operation centres. There is a lack of reliable long-term demand projections and forecasts at the state level.
- Increasing peak demand is being driven by new demand sources such as air conditioners and EVs.
- Ramping requirements are increasing, and for existing coal generation plants at the state level there is a lack of flexibility and standard operating procedures.
- The current and future curtailment of solar and wind is both a challenge and a solution for managing the system in emergency situations. While solar and wind have must-run status in most states, this can be secondary to the priority given to hydropower or coal generators in some states at certain times.
- Concerns regarding distributed energy resources, such as rooftop solar and EVs, include local voltage issues, reverse flows, lack of visibility of existing and new installations, and challenges with forecasting.

- Other technical challenges include declining system strength, increasing fluctuations in frequency and voltage levels in certain regions, and the slight decline of inertia in India in recent years at certain times (illustrated by POSOCO in the dedicated section).
- There is a lack of co-ordination among state-level transmission planners and central planning agencies such as the Power Grid Corporation of India. A unified planning model across the country is also absent. As a step towards addressing this, as part of the 19th Electricity Power Survey of India mid-term review report, the Central Electricity Authority (CEA) adopted an econometric forecasting model for the first time to project long-term electricity demand scenarios from 2018 to 2036. The model accounts for economic, demographic and weather variables, and enables better informed decisions in relation to new investments.

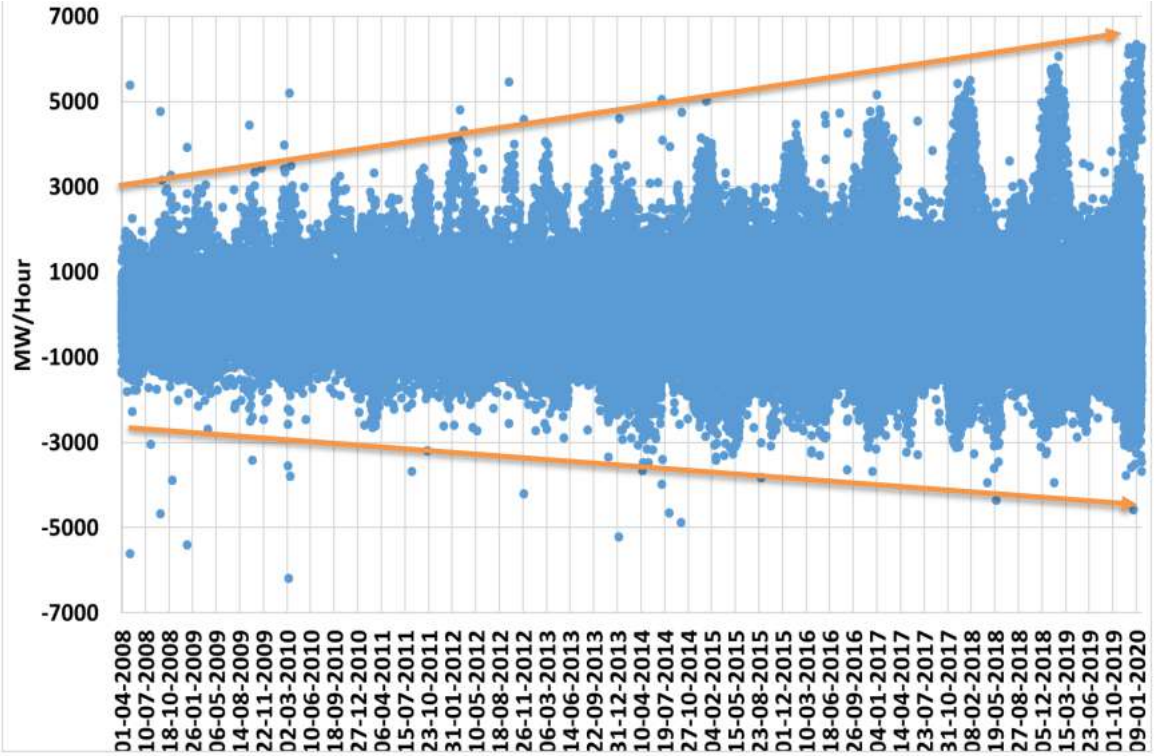
In most cases, these technical challenges have numerous policy, market and regulatory implications as well. Emerging policy, market and regulatory challenges and implications include the following:

- There is an absence of market signals for power system flexibility, and a lack of ancillary services regulations, products and markets in states. National-level ancillary services regulations – that India's Central Electricity Regulatory Commission introduced in 2016 in the form of automatic generation control pilots – are not applicable within the states. The current national regulatory framework for ancillary services is primarily targeted at enhancing the reserve margin, while the framework currently excludes the role of fast response technologies.
- There is a lack of remuneration for solar and wind curtailment, which can affect investor confidence.
- There is a lack of grid codes to ensure VRE plants support system security, e.g. frequency support.
- There is no remuneration for coal power plants in the event that investment in increased flexibility is required by the state.
- The priority given to coal power plants (at technical minimums) reduces the system operators' ability to balance the system with lower-carbon sources in some states at certain times.
- There is a lack of regulatory frameworks to allow adequate remuneration of demand response and storage technologies such as batteries.
- The long-term contracts for conventional power plants create a long-term economic burden and other challenges due to their requirement for capacity payments (referred to as a fixed cost in Indian tariff determination) alongside the energy payments (referred to as variable costs).
- There is low liquidity in the short-term wholesale markets.
- The increasing transmission system investments translate into increasing transmission charges, but are only partially compensated by lower generation costs due to the aforementioned constraints on coal plants.

- Renewables integration affects the financial stability (costs and revenue streams) of the DISCOMs, which need to pay the fixed charges of coal plants bound by long-term PPAs even when using solar and wind, while also being bound by national renewable purchase obligations.
- There is increasing pressure on end-user electricity tariffs from the abovementioned increase in transmission charges, level of DISCOM risk, long-term PPAs and market inefficiencies.

Recent trends behind the main renewables integration challenges today include the increasing variability of hourly demand, which for the whole of India increased from ±8 GW in 2008 to +14 GW and -10 GW in 2018. In 2020 the increasing variability of hourly demand in the Western Region, which includes several renewables-rich states, increased from ±3 GW in 2008 to +6 GW and -4 GW by 2020.

**Increasing demand variation in the Western Region, 2008-2020**

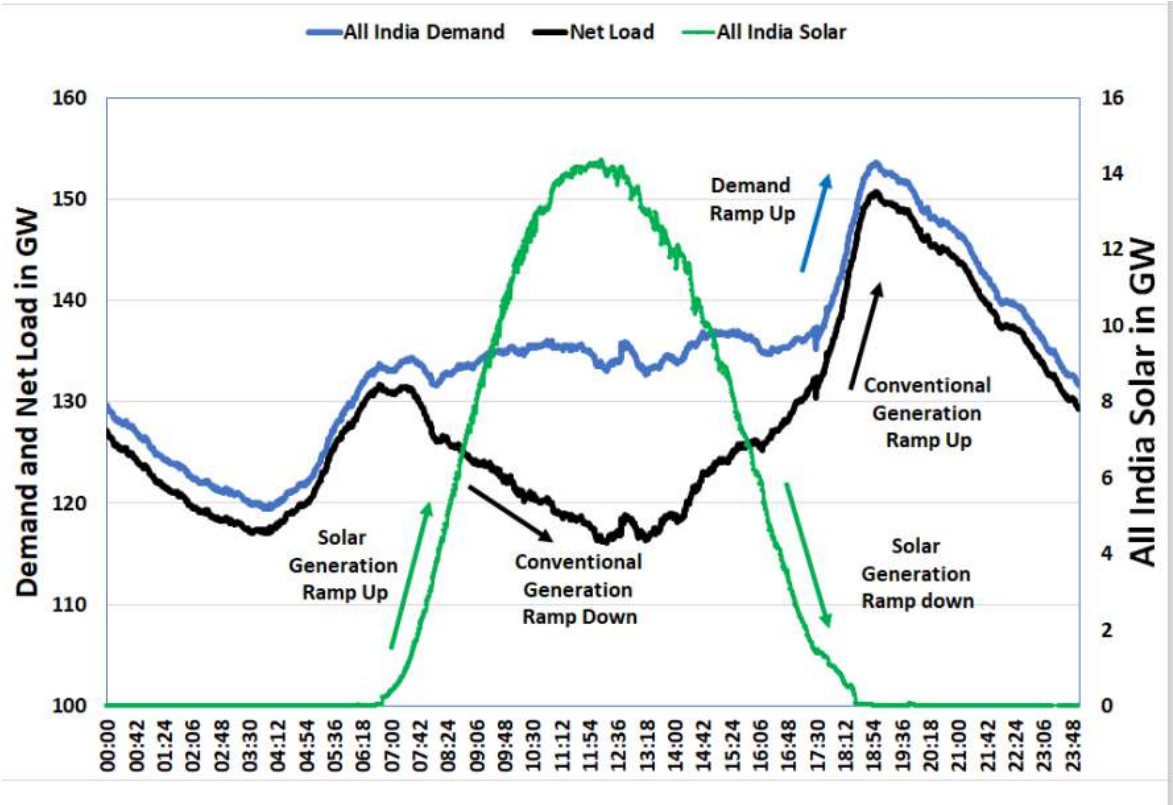





Source: POSOCO, Western Load Dispatch Centre.

Ramping needs have increased significantly with the addition of substantial solar capacity in recent years. On a typical day in India conventional generation needs to back down in the morning between 8:00 and 12:00, followed by an increasingly steep ramp-up between 14:00 and 19:00.

**Increasing ramping needs driven by the impact of solar power on net demand**





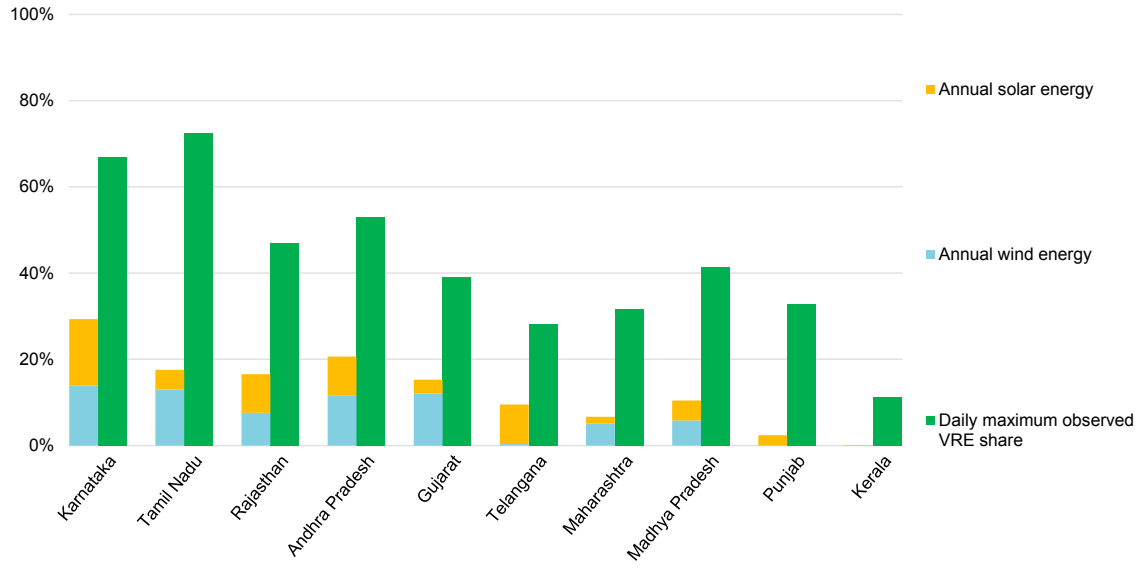

Source: POSOCO, Western Load Dispatch Centre.

## How high shares of solar and wind challenge the status quo

What does the inherent variability of wind and solar PV power generation mean in practice and how will this change from today to 2030? A very high share of solar and wind at any point in time (within a day, an hour or minute) can pose system integration challenges. The variability of solar and wind generation tends to be higher at finer time resolutions and when concentrated geographically. For example, the variability in daily output of solar generation is much less than the hour-to-hour variability, and the aggregated solar and wind generation for the whole of India is more consistent than the output of a single plant, a tendency referred to as geographic smoothing. While the annual share of solar and wind energy for the whole of India was only 8.2% in 2021, the local solar and wind energy contribution in renewables-rich states was much higher than this both annually and at certain points in time. This is a result of both diversity in the generation mix between the states and the averaging effects across time and geography.

While annual solar and wind shares in the renewables rich states are currently still at or below 30%, when we examine them with more granularity on a daily basis, the highest daily share of solar and wind in FY 2019/20 was already close to 70% in both Tamil Nadu (73%) and Karnataka (69%). The daily maximum solar and wind share also masks higher hourly solar and wind generation peaks. Hourly solar and wind generation data is not currently available for most Indian states. It would be a valuable addition to existing national-level data sources in the future.

**Daily maximum annual solar and annual wind generation in Indian states, FY 2019/20**






Note: FY = fiscal year

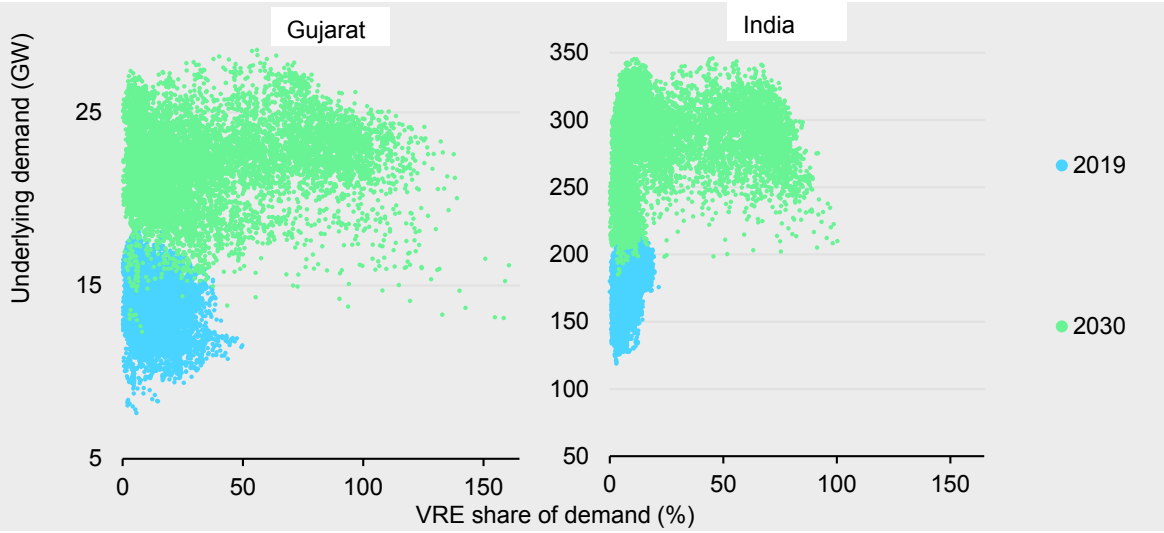
Sources: Based on data from CEA and IITK's Energy Analytics Lab.

Looking ahead, the share of solar and wind power in India as a whole on an annual basis is projected to reach 24% by 2030 in the STEPS and 39% in the SDS. Based on current Gujarat government targets, the annual share of solar and wind would reach around 37% in the state by 2030.

This transformation is even more pronounced when looking at the hourly maximum solar and wind generation before accounting for curtailment. While the highest contribution of solar and wind to meeting hourly demand in Gujarat in 2019 was 39% (at 13:00 on 14 July), this is expected to rise to as high as 80% in 2022, and according to the IEA Gujarat State Model it could reach up to 160% of demand during some hours by 2030. On a national level in the IEA India Regional Model, the country could see available generation from solar and wind reaching more than 90% of underlying demand during numerous hours a year in 2030. Solar and

wind generation levels beyond 100% of demand can be curtailed or achieved through strong interstate interconnections.

**Hourly share of uncurtailed solar and wind generation as a percentage of demand in Gujarat versus India in the Stated Policies Scenario**






Source: IEA, India Energy Outlook 2021.

Renewables-rich states such as Gujarat are already coping with higher hourly shares than the rest of India, and are now facing integration challenges that will emerge more widely in the future.

## Flexibility lowers curtailment, and lower curtailment comes with reduced system operating costs and lower $CO_2$ emissions

In most countries with a high proportion of solar and wind generation, some level of curtailment is present. China sustained high levels of dispatched-down VRE from 2011 to 2017 (7-20%), reaching an absolute historical high of almost 50 TWh in 2016. By 2019 the share of solar and wind curtailment had dropped to less than 4%, mainly due to new interprovincial transmission capacity, changes to dispatch rules and improved market operations. Even though dispatched-down VRE electricity overall increased in absolute terms in the United States, Germany and Italy between 2017 and 2020, the share of wind and solar PV curtailment remained stable at 1-3%, which means that most systems have been able to evolve to accommodate increasing VRE generation as capacity expanded. In contrast, record curtailment levels were reached in California in 2020, with the system operator (CAISO) curtailing over 318 GWh in April (7% of VRE output). This was 67% more than in 2019 and was a result of falling demand for electricity (an 8% decline) caused by Covid-19 and newly added solar and wind capacity.

Curtailment started to become a major challenge in a few Indian states between 2013 and 2019, and there is increasing concern among policy makers and investors about the increasing trend for curtailment of solar and wind towards 2030. At the same time, transparent data on the amount of curtailment (e.g. the percentage of annual generation) and reasons for it are not publicly available. The IEA India Regional Model indicates that flexibility options become critical for minimising curtailment by 2030. In the limited flexibility case we see 9% of VRE generation curtailed at the national level, in contrast to only 0.4% curtailment in the flexible case.

The state of Karnataka has been facing increasing solar and wind curtailment since 2019. Renewable generation enjoys must-run status in India as defined in the Indian Electricity Grid Codes and under various state codes, where its curtailment is allowed only for grid security and not for commercial reasons. In 2019 and 2020 there were days when the state load dispatch centre (SLDC) in Karnataka announced the need to curtail between 10% and 25% of both wind and solar generation in the interests of grid security during the middle of the day in the months of June, July, August and September. Analysis by the Center for Study of Science, Technology and Policy (CSTEP) indicates that VRE curtailment could increase further by 2030.

The IEA Gujarat State Model shows that states with less solar and wind can face similar challenges in the medium term, to 2030. For example, the model found that the Gujarat system had zero curtailment of VRE generation in 2020, and curtailment is expected to remain negligible in 2022. However, by 2030, in a case with no increase in flexibility, curtailment would increase to around 7% of annual solar and wind generation. This indicates the need for greater power system flexibility where the renewables share increases, to ensure cost-effective use of VRE.

IEA analysis of the impact of power system flexibility solutions on Gujarat's curtailment levels by 2030 shows that the most effective flexibility solutions for the state are agricultural demand response (resulting in a low annual curtailment of just over 2%) and battery storage (with the lowest 2% annual curtailment with a 4 GW battery). Power plant flexibility (with over 6% annual curtailment in 2030) and the planned pumped-storage hydro (also with over 6% annual curtailment) have much lower impacts on curtailment, reducing it by less than 1% compared to the limited flexibility scenario. At the same time, all of these flexibility options result in operating cost savings, compared to the limited flexibility scenario. For example, in the 4 GW battery scenario, variable operating costs including the cost of market purchase are around 7% lower than in the inflexible case.