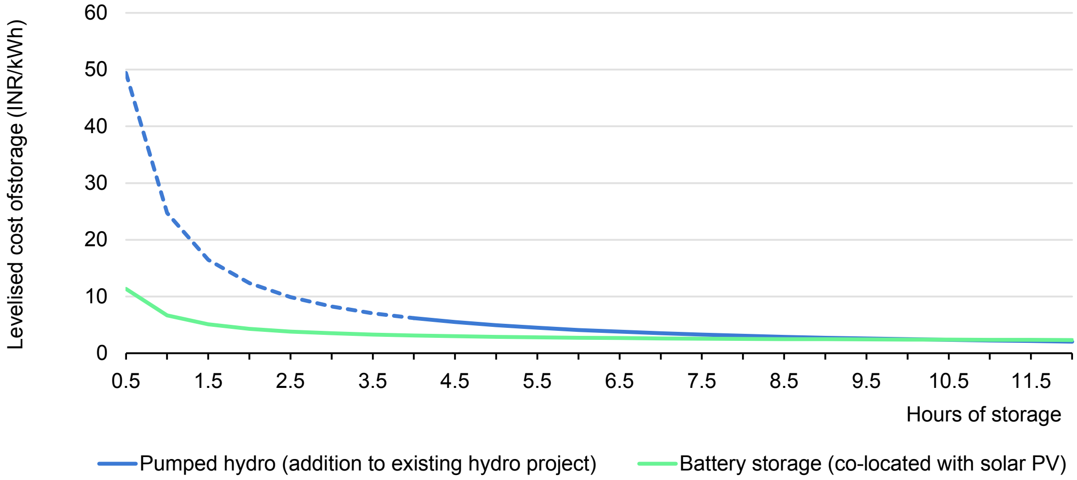
retrofit. The US Flexible Resources Initiative analysis completed by the Lawrence Berkeley National Laboratory (LBNL) shows that for up to 8 to 10 hours per day of storage, battery storage co-located with solar generation is more cost effective than pumped-storage hydro (retrofit of existing hydro plants) in Indian states. This is partly because battery systems are energy-constrained systems (increasing the energy [MWh] of a battery is more expensive than increasing its capacity [MW]), while pumped-storage hydro systems are capacity-constrained systems (increasing capacity is expensive while increasing energy [MWh] is cheap by increasing the depth of water in the dam). As such pumped-storage hydro is normally built for a storage duration of over eight hours. The LBNL analysis also showed that by 2030, four to six hours of energy storage is cost-effective for diurnal balancing. The study found that the levelised cost of electricity of solar co-located battery storage was around INR 3.5/kWh in 2025 when 30% of average daily solar PV output is stored in the battery.

Levelised cost of storage – pumped-storage hydro and battery storage, 2025



Note: Very low storage durations for pumped-storage hydropower given by the dotted line are illustrative only, as PSH projects typically offer around eight hours storage or higher.
Source: Reproduced with permission from Abhyankar, Deorah and Phadke et al, 2021 (forthcoming).

Most Indian states currently have no regulatory framework for battery storage. However, states are stepping up to fill this gap; for example the Karnataka government and regulator are currently considering the creation of a market for battery storage. Analysis by the US National Renewable Energy Laboratory (NREL) of India's policy and regulatory readiness concludes that key policy barriers include the lack of provision for storage in energy policies and masterplans, and the lack of targeted support for early storage adopters. On the regulatory side, some current regulations explicitly restrict storage from providing services or earning revenue. This presents a barrier to maximising the returns from storage investments.

The development of a regulatory and remuneration framework for energy storage (with specific details added for batteries and pumped-storage hydro) is needed to capture its full value, including avoiding inefficient thermal investments, capturing energy arbitrage opportunities from shifting energy demand within a day or week, and providing ancillary services for managing the system ramps.

The strategy of the UK regulator, the Office of Gas and Electricity Markets (Ofgem), for a modernised, smart and flexible power system now includes significant clarity, transparency and guidance for the role of storage, although storage was initially excluded from the UK government's Smart Systems and Flexibility Plan published in 2017. India, too, needs to define energy storage in a well-thought-out policy framework (for example, the Electricity Act) in order to expand deployment of storage systems in the country. Similar to the approach in the United Kingdom, the definition should acknowledge its flexible nature and applications, and its categorisation should be as either generation or transmission/distribution assets. As a result of ongoing market opportunities for batteries, the United Kingdom, with over 800 MW, is the market leader for battery storage deployment in Europe, followed by Germany with over 500 MW. Battery investors in the United Kingdom actively participate in day-ahead, intraday and imbalance markets. Additionally, they access revenues from ancillary services markets and capacity markets, and from time-of-use rates when storage is placed behind the meter. Revenue gains are also made by avoiding network charges. The conclusion and recommendation for Indian states is to start with a battery policy that can provide a long-term (over four years) revenue stream for the first battery investors and then move towards providing revenues from shorter-term services/products in the markets.

System strength and inertia may need attention in some states before 2030

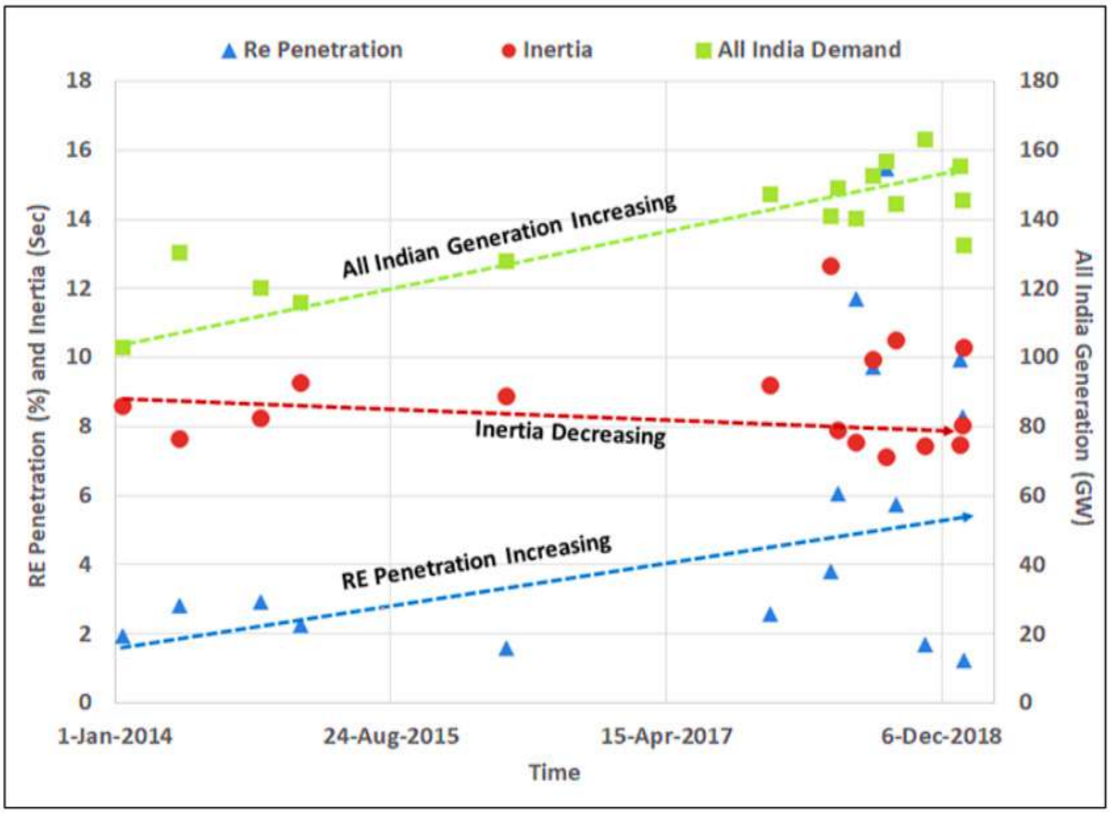
Today, the stability of large, interconnected power systems is based on the generator rotors of conventional power plants rotating together at the same frequency, set nominally at 50 Hertz in Europe as well as in most of Asia, including India, and in Africa.

These rotating machines stabilise the system by contributing to inertia and short-circuit power. This contribution is called "system strength". When the system faces a disturbance, these machines instantaneously help smooth frequency deviations by releasing some of the kinetic energy stored in the rotating mass of the rotor before slower mechanisms take over to stabilise and restore the frequency (such as the governor). In addition, they are able to generate their own voltage waveform and also synchronise independently from other electricity sources: they are naturally “grid-forming”. Rotating machines are a historical cornerstone of power system stability.

With higher shares of non-synchronous generation sources like wind and solar PV, such rotating machines would become less available. As opposed to conventional generators, wind farms and PV panels are connected to the network through power converters. Converter-based technologies do not directly contribute to system inertia, and those mostly deployed to date do not provide full system strength. Present converter technologies are also “grid-following”, as they are not able to generate their own voltage waveform and are dependent on the frequency signal given by other sources, such as conventional generation, to run properly. Future power systems will host many more converter-based connections via EV charging, grid-scale battery storage, high-voltage direct current connections and others. Low inertia or system strength is mainly a concern for the remaining synchronous generators, which become more prone to outage following system faults and contingencies.

According to POSOCO, between 2014 and 2018 system-level inertia dropped slightly at certain moments in time, when renewables were especially high. At the national level, inertia is not expected to decline significantly by 2030 because the increase in solar and wind will also come with an increase of thermal generation (in the STEPS). However some high VRE states may already face declining localised inertia by 2030. The IEA Gujarat State Model shows significantly declining inertia in Gujarat’s contracted capacity between 2019 and 2030, in line with the increases in solar and wind, with the estimated minimum level dropping to around one-fifth of the estimate for 2019. At the same time, power system inertia at the all-India level is maintained in the STEPS due to load growth and new conventional generation entering the system alongside the growth in VRE. Further analysis will be required to estimate India’s level of inertia in the SDS, where thermal generation shows a declining trend.

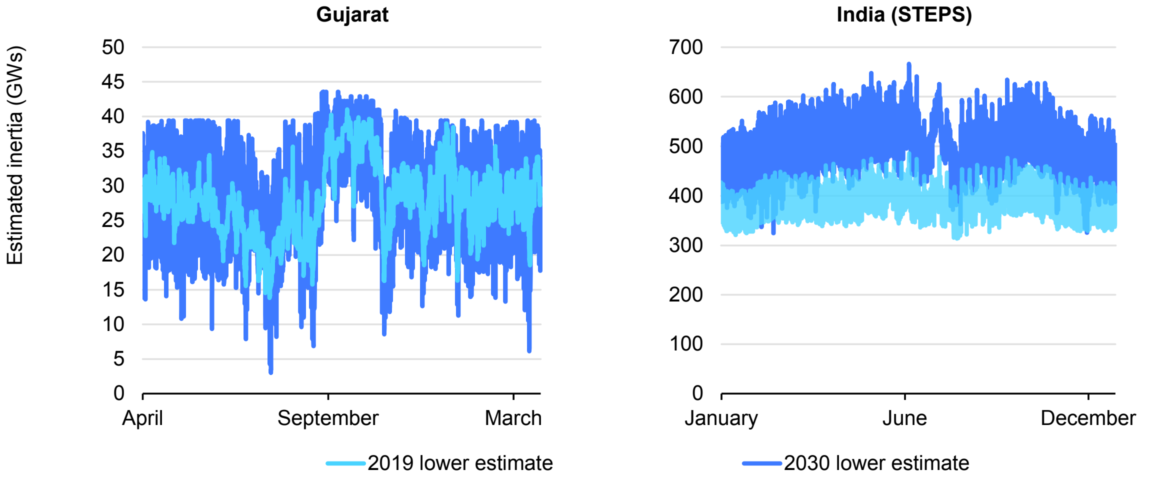
Inertia and renewables penetration in India, 2014-2018



Source: POSOCO, Western Region Load Dispatch Centre.

Since inertia is mainly relevant at the level of the entire interconnected system and relates to stability in the event of contingencies, a very large system such as India's is much less vulnerable to decreasing inertia relative to smaller power systems. Declining inertia in itself in local parts of the power system, such as in renewables-rich states, is not necessarily problematic. However, it is typically accompanied by decreasing voltage stiffness and fault current, which are local issues that need to be analysed, monitored and have interventions defined to mitigate as required. For more weakly interconnected areas, local inertia needs to be taken into account where there is a risk of islanding for that region. In addition, inertia should not be seen as a simple system-wide phenomenon. The EU-funded MIGRATE (Massive InteGRATion of power Electronic devices) project showed that a large interconnected system is made up of several centres of inertia. In the case of disturbances, the system can no longer be expected to respond as a rigid body represented by a single total inertia.

Inertia estimate for Gujarat contracted capacity (left) and all-India (right), 2019 and 2030



Sources: IEA, Gujarat State Model and India Regional Model.

Note: Inertia estimates are illustrative only, based on lower bound typical inertia constants by technology type. Grid stability studies would be required to provide a definite assessment of India's specific inertia requirements.

A recent study by the IEA and the Electricity Transmission Network of France (RTE) found that while several technical solutions exist to overcome the difficulty of inertia reduction, they are at different stages of maturity. While some are already deployed in field operations, others are at the R&D stage and will need to be tested in real-life settings before being deployed at scale.

Very high shares of renewables mean that converter-based generation starts to dominate the system and then takes a significant role in operations. New services are needed to cope with the reduction in inertia. These services, known as fast frequency response or synthetic/virtual inertia, can be provided by specific converters that allow renewable generation to adjust very rapidly to a deviation in the frequency signal, e.g. by temporarily increasing power output, thereby helping to re-establish system frequency. Such services have already been implemented in Ireland and Quebec. These solutions are also being investigated in Australia and are being studied at the R&D project level in India. However, these solutions do not have the same effect as the inertia of rotating machines and cannot guarantee secure operation of the system if the instantaneous shares of PV and wind become very high, for example above 60-80%, in the synchronous area. It is therefore necessary to go beyond such solutions in systems based on wind and solar PV and significantly revamp the way the power system is operated.

To go further, one solution would be to deploy synchronous condensers. They operate similarly to synchronous generators: their motors provide inertia and short-circuit power and, therefore, system strength, but they rotate freely, without producing electrical power. Synchronous condensers are a well-known and proven technology, historically used to maintain voltage in specific areas. They have been used in France, and more recently, also in Denmark and South Australia and have proven effective at ensuring system stability. While this solution has been proven in specific situations, a generalised rollout in the context of large-scale system strength has yet to be evaluated. The associated costs of deployment are low on an individual basis, but they must be taken into account with other system costs in a thorough economic evaluation of scenarios with high shares of renewable production. Some types of hydropower generators are also able to operate in synchronous condenser mode.

Another possibility would be to develop grid-forming controls for converters that give wind and solar power plants the ability to generate their own voltage wave. This solution has been successfully tested in the laboratory (for example, in MIGRATE) and on microgrids, but not yet at the scale of larger power systems, where other complications could arise. Full-scale experiments are planned in Europe in the coming years to validate this concept.

Interstate trading still faces technical and economic barriers

India has made significant progress over the past decade in wholesale power market design. From a market design perspective, three broad areas are relevant to establishing a robust wholesale power market:

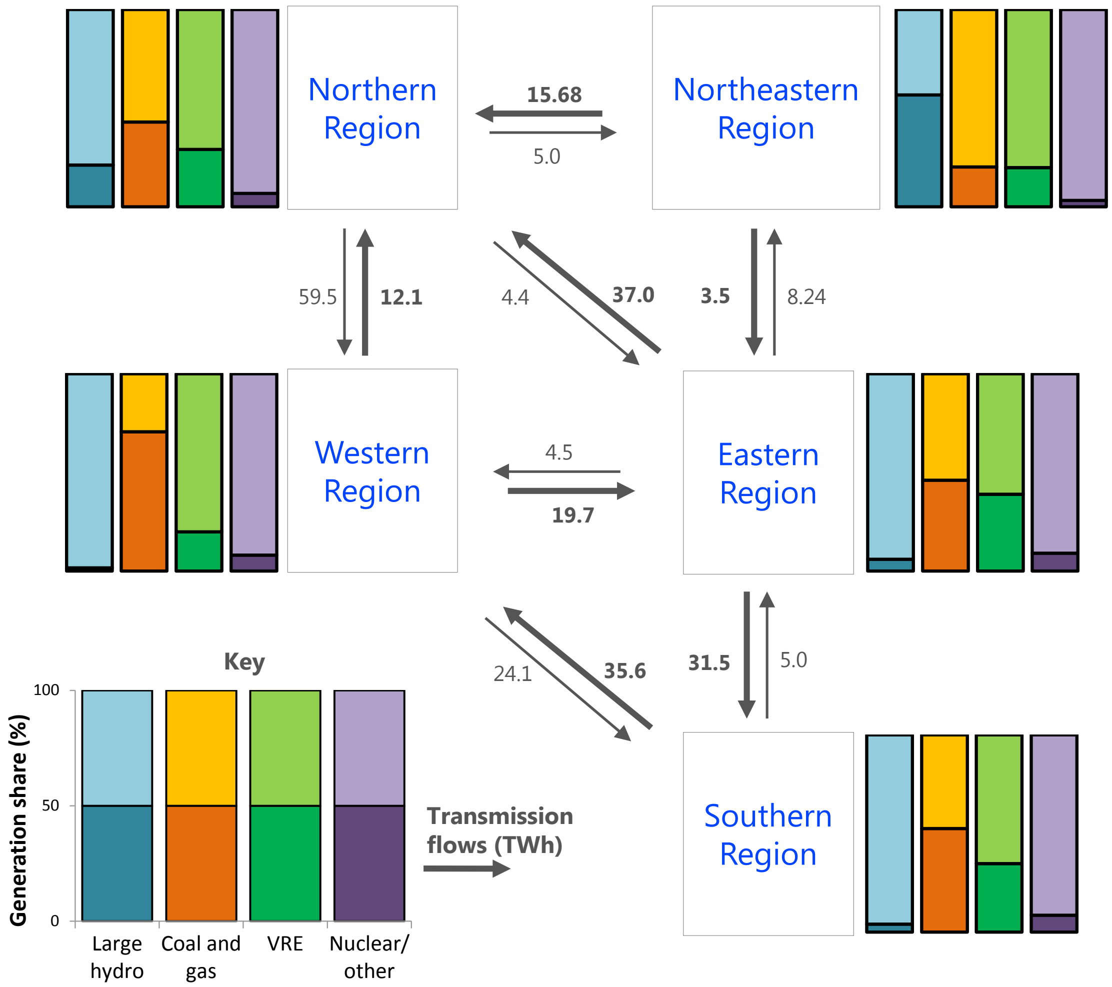
- **Faster**: Liquid trading close to real time reduces the impact of forecast errors and allows better management of variability. Addressing this point, India introduced real-time power trade in 2020.
- **Broader**: Remunerating all relevant system services ensures that assets have an incentive to provide these services to the power system. Addressing this point, India introduced national-level ancillary services regulations in 2016, while state-level regulations are yet to be designed and implemented. The introduction of green markets in 2020 is another example.
- **Bigger**: Larger market areas help smooth variability and increase the pool of flexibility resources.

It is a strength of the Indian power sector that the power market has been established since 2003, when it began operations based on physical energy transactions. The technical integration of the whole country into a single synchronous system in 2014 opened new opportunities for more efficient operation of the system across a wider geographic area, which is conducive to the cost-effective integration of low-carbon sources.

Further improvement in interstate trading is a cost-effective solution for the integration of higher shares of solar and wind for each Indian state because it helps smooth variability across larger areas and provides access to low-cost generation in other states. In the IEA five-region India Regional Model, flows between regions increase more than 40% by 2030 in the STEPS from 2019 levels (allowing for similar limitations on transfer capability to those seen today). 2030 sees increasing flows from the Eastern Region towards the Northern and Southern Regions. Trade between states is also expected to increase significantly. Transmission transfer capability limitations also become a driver of renewables curtailment by 2030, resulting in around 3% curtailment in contrast to less than 0.5% if the infrastructure is able to be fully utilised.

There are still significant barriers hindering a large increase in interstate trade. 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 PPAs between the DISCOMs and generators (which contribute to low liquidity).

Total annual transmission flows between regions in the STEPS, and generation share by region, 2030



Source: Analysis based on IEA, India Regional Model

Interstate transmission is an enabler of more power trade and thus power system flexibility

The country as a whole and the states already have significant transmission reinforcement plans to support the integration of renewables and benefit from balancing solar and wind over a larger geographical area. The main concern of electricity stakeholders is that delivery of transmission infrastructure takes longer than the delivery of solar and wind projects. There is therefore a risk of structural delay in harnessing new transmission infrastructure.

Additionally, the low availability of transmission infrastructure crossing state boundaries is also of concern. States would also benefit from improving the co-ordination of scheduling and dispatch with neighbouring states for better access to least-cost generation.

CSTEP's Southern Region transmission study highlights the need for additional transmission infrastructure to be made available for interstate trade, which would help accommodate regional renewables by 2030 (with the assumption of no additional power system flexibility improvements, beyond transmission).

CSTEP conducted a transmission planning study to understand the impact of renewables addition to the Southern Region grid in 2022 and 2030. To meet 2030 demand without additional thermal capacity (beyond existing plans), 34 GW of solar and 18 GW of wind were added to the electrical model of the Southern Region, bringing their total capacity to 60 GW and 48 GW, respectively. The study found that the power generated at critical instants in 2030 could be well in excess of regional demand, making it necessary to upgrade interregional transmission corridors to handle the export of power up to 50 GW. It also found a significant need for intraregional transmission upgrades, primarily at 220 kV renewables injection points and transmission lines, beyond existing upgrade plans.

The results of this type of transmission study should be assessed together with studies that assess alternative power system flexibility resources, such as demand-side response, storage, and power plant flexibility.

Additionally, synchronous connections with Bangladesh and Nepal, in addition to those that already exist with Bhutan, would enlarge the geographical footprint for balancing.

Wholesale power market reforms enable greater system flexibility

Wholesale power markets provide power system flexibility by enabling the balancing of supply and demand through economic dispatch. The newly established green markets in India also provide a trading platform for clean electricity, and newly established real-time markets provide an opportunity to trade solar and wind to compensate for their variability close to real time – one hour ahead – thus enabling participants to manage variability.

The international experience highlighted in this section shows that specific market and regulatory innovations are required to access the flexibility from many new and innovative power sector assets and solutions, such as solar, wind, demand-side response, storage and batteries.