future of the must-run status of solar and wind must continue. Formulating practical contractual structures and policies related to compensation for curtailment will be critical.

Increasing power system flexibility enables the integration of higher shares of solar and wind generation. As a result, for a given amount of solar and wind capacity, a larger share of renewables can be utilised. This is illustrated in the two models presented in this report. Lower curtailment also brings about the benefits of reduced system operating costs and lower CO_2 emissions.

India’s clean electricity path

Historical progress towards India's ambition to integrate 450 GW of renewables by 2030

This publication provides an international framework for renewables integration in India and highlights potential power system flexibility solutions for Indian power sector stakeholders. It builds on stakeholder engagement led by the IEA and NITI Aayog since 2018, the outcomes of the past national, regional and state-level workshops and the related in-depth analysis. It highlights the findings relevant to many states and regions in India and across the globe.

The country’s power development started with small, isolated power systems. Over the years, these were interconnected to form state-wide grids. In the 1980s the government of India grouped the states into five power regions. The five regional grids today – the Northern, Western, Eastern, Southern and North-eastern – have gradually been connected to form one synchronous interconnection covering the entire country. In 2014 India’s system became the world’s largest operating synchronous grid. Since 2011 the National Green Energy Corridor programme has actively supported the buildout of transmission network infrastructure dedicated to renewables.

Integrating higher shares of VRE, such as wind and solar PV, in power systems is essential to decarbonise the power sector while continuing to meet the growing demand for energy. Thanks to sharply falling costs and supportive policies, solar and wind deployment has expanded dramatically in recent years. India is on the path towards achieving 175 GW of renewables by 2022 and has announced an ambition to reach 450 GW by 2030.

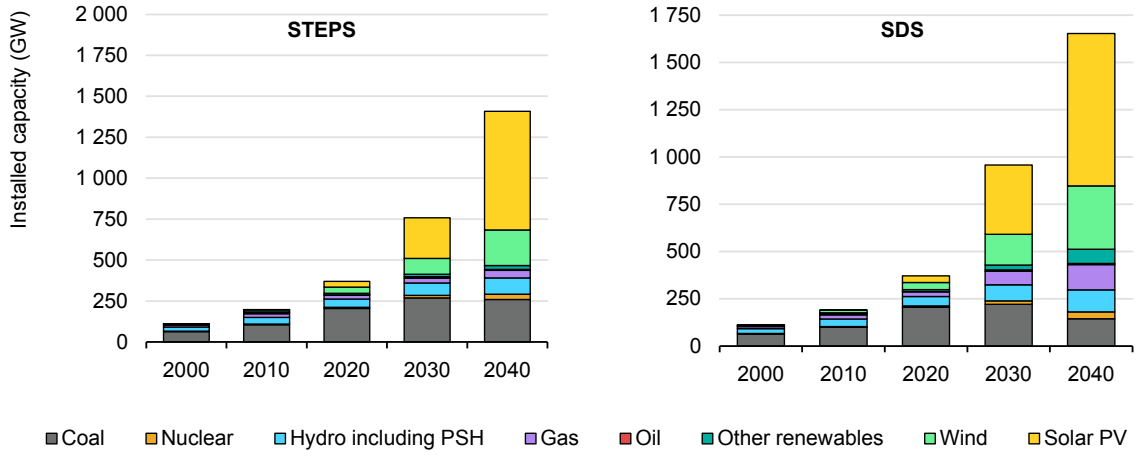
Variable renewables become dominant across all major pathways

The increase in renewable capacity will shift India’s power system from the dominance of coal to renewables. The IEA *World Energy Outlook* 2020 scenarios look at possible pathways for India to 2030 and 2040. The STEPS shows a pathway based on India’s current policies and announced policy intentions geared to meeting the country’s nationally determined contribution under the Paris Agreement. The Sustainable Development Scenario (SDS) includes additional technical potential for more sustainable development, with a lower share of coal

and higher shares of solar and wind. In the STEPS, solar and wind reach 344 GW and overtake coal capacity of 269 GW in 2030. The *WEO* shows over 620 GW of solar and 219 GW of wind capacity in the STEPS, and over 720 GW of solar and 309 GW of wind in the SDS, by 2040. In both scenarios, coal capacity increases up to 2030 and then declines. In the STEPS, coal is at 260 GW by 2040, while in the SDS it is only at 144 GW.

The power supply transformation will significantly alter India's CO_2 emissions and climate targets. CO_2 emissions from the energy sector increased from 0.9 Gt CO_2 in 2000 to 2.5 Gt CO_2 in 2019, in line with the increase in energy demand triggered by strong population growth and industrial development. Over this time period, coal capacity expanded from 63 GW to 265 GW, but the power sector's CO_2 intensity declined by 11% to 725 g CO_2/kWh. In the STEPS, the CO_2 intensity of electricity further falls to 336 g CO_2/kWh by 2040, the level of the OECD's average intensity in 2019. The decline is much steeper in the SDS, reaching 319 g CO_2/kWh by 2030 and 59 g CO_2/kWh by 2040.

The evolution of India's electricity capacity mix in the Stated Policies Scenario and the Sustainable Development Scenario, 2000-2040



Source: IEA India Energy Outlook 2021.

There are many possible pathways for India to achieve its renewable targets, but all possible future pathways have one thing in common: high proportions of solar and wind. This in turn creates the need for greater power system flexibility.

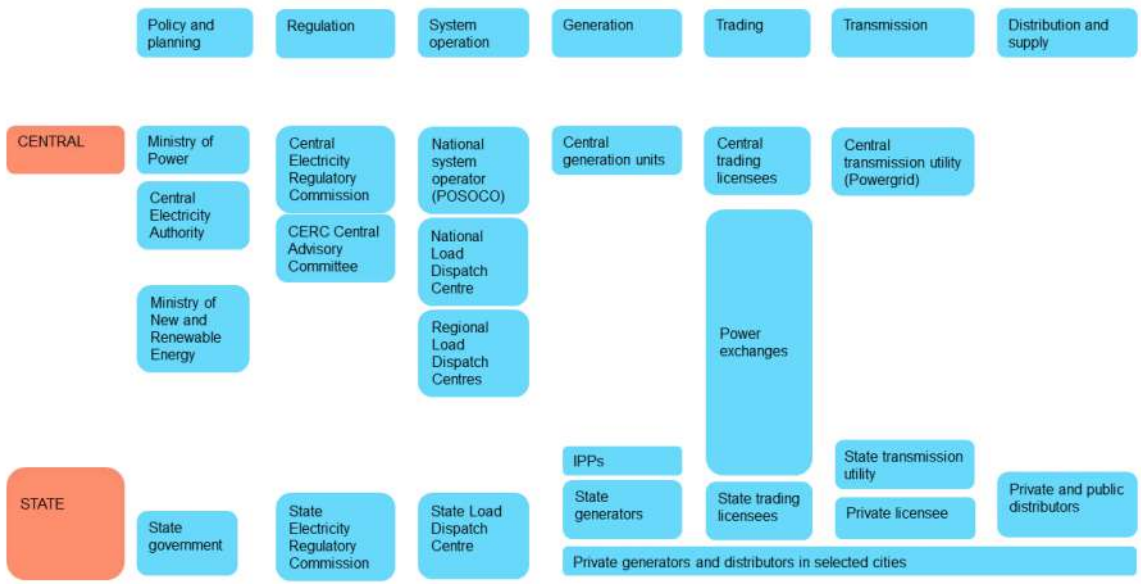
Both the STEPS and SDS significantly extend India's existing power system flexibility. Beyond grid and demand-side flexibility, the supply-side power system flexibility in the WEO scenarios is provided by a combination of batteries (increasing from minimal capacity in 2019 to 34 GW in the STEPS by 2030), hydropower plants

(increasing from 49 GW in 2019 to 76 GW in the STEPS by 2030) some of which is reservoir and pumped-storage, and natural gas (increasing from 28 GW in 2019 to 30 GW by 2030). The optimal combination of these supply-side flexibility options needs further in-depth analysis and depends on whether policy makers would like to optimise for system operating costs and end-user prices, or prefer to take into account emission impacts and other wider social and economic factors. The balance of solar and wind also has implications for power system flexibility needs, with systems relying on solar requiring storage during the day.

Integrating renewables in India will require action at both the central and state level

A large number of government bodies are associated with the Indian power sector, with operational responsibilities entrusted to system operators at various levels. Together, these entities form a very large and complex framework for the power sector. To date, most of the focus in the international literature and IEA analysis has been on renewables integration challenges at the national level. However, the states face several specific challenges. Around 30% of power generation is owned by state governments and 25% by the central government. The remaining 45% is privately owned and delivers electricity to state or privately owned DISCOMs. State institutions, such as state regulators, have complete control over the regulation of state transmission, distribution and retail, as well as electricity tariff setting.

National and state-level players in the Indian electricity sector

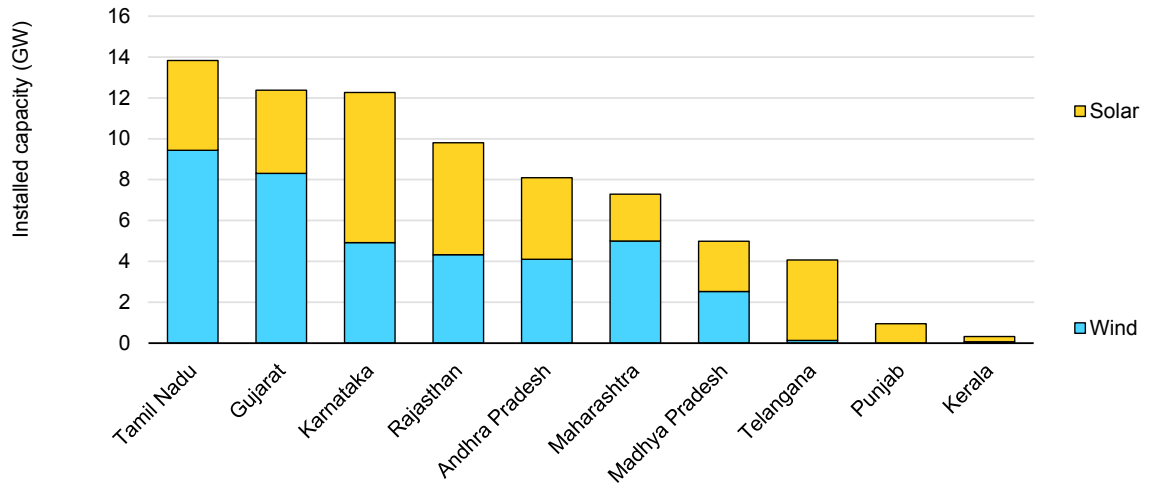


Note: IPP = independent power producer.
Source: IEA, India 2020 Energy Policy Review.

India’s states are at the forefront of renewables integration globally

The renewables integration challenges, solutions and priorities vary greatly among India's 28 states and eight union territories. The majority of India’s renewable capacity additions take the form of solar and wind, and they will continue to be largely concentrated in the country’s ten most renewables-rich states: Tamil Nadu, Gujarat, Karnataka, Rajasthan, Andhra Pradesh, Maharashtra, Madhya Pradesh, Telangana, Punjab and Kerala. Historically, capacity additions have been dominated by wind, but projects in the pipeline include more solar than wind.

Solar and wind capacity in India's renewables-rich states, February 2021

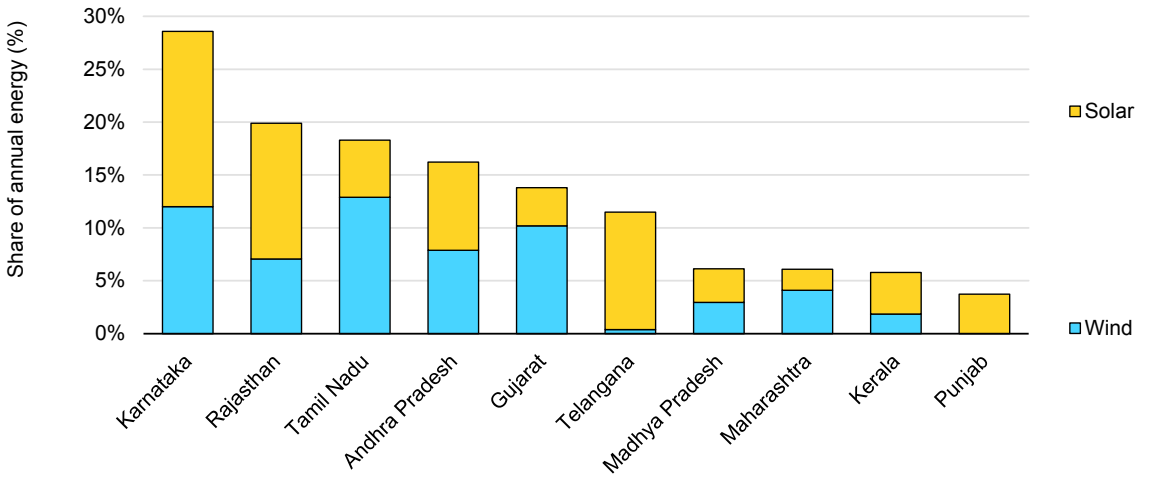


Source: MNRE renewables data.

By the end of February 2021 Tamil Nadu had the highest level of solar and wind capacity (13.8 GW), followed by Gujarat (12.4 GW), Karnataka (12.3 GW), and Rajasthan (9.8 GW).

A good indicator of the degree of challenge in each state is the share of solar and wind in total power generation. In 2021 the ten renewables-rich states represented almost 97% of India's power generation from solar and wind. The annual energy share of solar and wind in these states was significantly higher than the national average of 8.2%. In 2020-21 it was highest in Karnataka (29%), followed by Rajasthan (20%), Tamil Nadu (18%), Andhra Pradesh (16%), and Gujarat (14%). These states already have higher shares of VRE than most countries internationally, and are already facing system integration challenges. With ambitious renewables expansion targets, they will expect to face further challenges in the future.

Solar and wind as a share of total annual generation in India's renewables-rich states, FY 2020/21



Note: FY = fiscal year

Source: Based on CEA renewables data.

This report's state-level analysis draws on examples from the three states of Maharashtra, Gujarat and Karnataka, because they have large renewable capacity and are among the most advanced in their power sector development. They have significant renewables potential, robust deployment targets and financially stable DISCOMs with Grade A financial credit ratings.

These three states also play an important role in India's economy. Maharashtra has the highest GDP, contributing over 13% of India's total GDP, while Karnataka accounts for 8% and Gujarat for 8%. Maharashtra has the second highest population in India with over 120 million residents, after Uttar Pradesh with over 199 million. The three states of Maharashtra, Gujarat and Karnataka together represent 18% of India's population.

Maharashtra faces one of the steepest renewables deployment curves in all of India. It has the sixth largest solar and wind capacity installed in the country (over 7 GW) and the most ambitious rooftop solar target, nearly 5 GW by 2022.

Gujarat and Karnataka are facing renewables integration challenges sooner than many other states. Gujarat has the third largest solar and wind capacity (over 12 GW) across the country, and its 2030 targets include over 44 GW of solar and wind capacity to satisfy the state's power requirements, along with an additional 20 GW to be constructed in the state and contracted to other states. Gujarat also has a state-wide commitment to stop the commissioning of new coal-fired projects

from 2022. These ambitions would increase its annual share of the country's total solar and wind generation to almost 40% by 2030, from around 15% today.

Karnataka currently has the highest annual share of solar and wind generation in India and the third highest solar and wind capacity (12.3 GW). It is a good example of a state that has benefited from agricultural demand response while facing emergency curtailment of its must-run solar and wind resources since 2019.

The IEA has a global framework for understanding renewables integration challenges

This report highlights insights for India reflecting international experiences of integrating high shares of VRE, particularly from Ireland, the United Kingdom, Germany, the United States, California and Australia. These insights could be considered in and adapted to the Indian context, help some states leapfrog common integration challenges, and assist the system transformation process in other Indian states and the country as a whole.

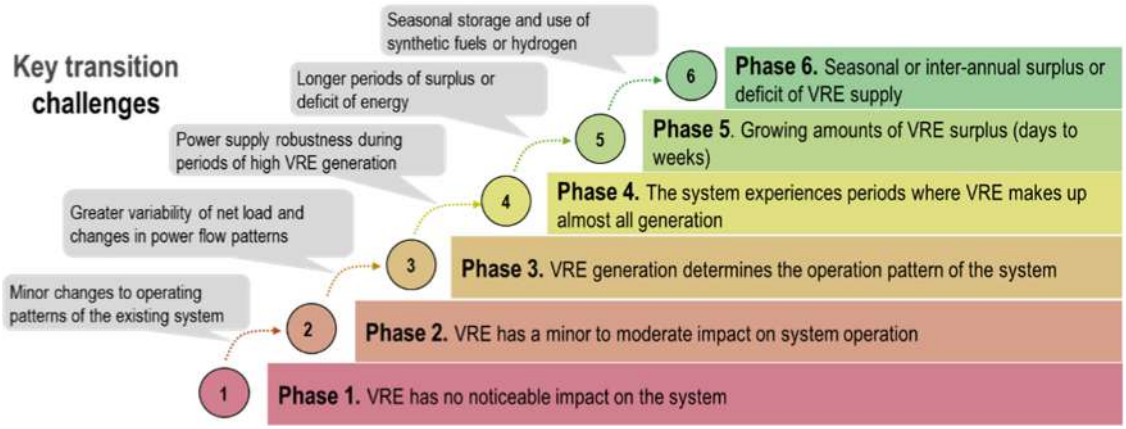
While the focus of this report is on wind and solar generation technologies, it also takes into account the impact of other renewables, namely hydro and bioenergy, noting that these normally assist the system integration of renewables, as they are often dispatchable forms of power generation.

The IEA system integration of renewables framework has six phases, with suggestions on how integration can be successfully managed in each phase. Various phase-specific challenges can be identified in the deployment of VRE, and decision makers can use this framework to prioritise different measures to support the flexibility of their system. The IEA has previously described these phases in detail, and also provided recent examples and insights.

Most countries, globally, are in Phases 1 and 2 of system integration of renewables, and as such experience minor system integration challenges. India as a whole and Maharashtra are in Phase 2 alongside the United States, China and Mexico. Portugal, Germany, Spain, the United Kingdom, Italy and the Indian states of Karnataka, Rajasthan, Tamil Nadu, Gujarat and Telangana are in Phase 3, and are already facing challenges related to integrating high shares of VRE. In Phase 3, VRE determines the operating pattern of the power system. Karnataka, Tamil Nadu and Rajasthan are fast approaching Phase 4. Very few countries and regions globally have entered Phase 4; they include Denmark, Ireland and South Australia. These countries/regions and the Indian states of Karnataka and Tamil

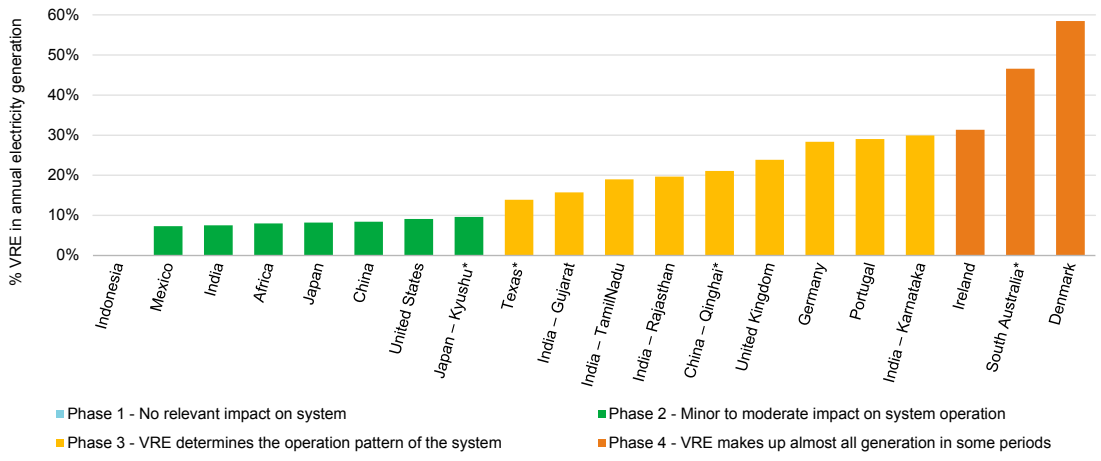
Nadu are at the forefront of global integration experiences and already see periods (minutes, hours or days) when solar and wind constitute almost all of the power generation.

Phases of system integration of renewables



Source: IEA, Status of Power System Transformation 2019.

Countries and regions in phases of renewables integration, 2019



* 2018 values.

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

The flexibility of a power system refers to the extent to which the system can modify electricity production or consumption in response to variability, expected or unforeseen, while ensuring system security. Flexibility can therefore refer to the capability to change power supply or demand in the system as a whole or in a particular unit. Flexibility can be provided at different timescales, from

sub-seconds to months and years. According to the IEA phase assessment framework, different flexibility resource types acting at different timescales will be more pronounced during specific phases of integration.

Flexibility at different timescales and phases

Flexibility type	Ultrashort-term flexibility	Very short-term flexibility	Short-term flexibility	Medium-term flexibility	Long-term flexibility
Timescale	Sub-seconds to seconds	Seconds to minutes	Minutes to days	Days to weeks	Months to years
Issue	Ensure system stability (voltage, transient and frequency stability) at high shares of non-synchronous generation	Short-term frequency control at high shares of variable generation	Meeting more frequent, rapid and less predictable changes in the supply/demand balance	Addressing longer periods of surplus or deficit of variable generation	Balancing seasonal and inter-annual availability of variable generation
Most relevant integration phase and example regions	Phase 4 Several VRE-rich states by 2025	Phase 3 Gujarat, Karnataka, Tamil Nadu in 2021	Phase 2 India as a whole, Maharasthra in 2021	Phase 4	Phase 5 Phase 6

Source: IEA, Maharashtra Power System Transformation Workshop Report.

For example, in Karnataka and Gujarat, currently in Phase 3, the greatest system flexibility need is for resources that provide flexibility within seconds to minutes to hours, thus helping to overcome very short-term variability in solar and wind output. Higher penetration of solar energy will place greater demands on flexibility resources with an even faster response time. In Phase 4, more focus on ultrashort-term flexibility capabilities will be required so as to provide flexibility within seconds, with additional focus on flexibility on a timescale from days to weeks. Then in Phases 5 and 6, the focus on flexibility shifts to months and years, often referred to as seasonal flexibility, due to the structural imbalances of solar and wind generation over the seasons.

Different resources can provide flexibility in specific timeframes. These power system flexibility enablers include generation, grids, storage assets, demand-side management and sector coupling.