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EEG Energy Insight

How much renewable power can India's electricity grid handle?

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Oxford Policy Management

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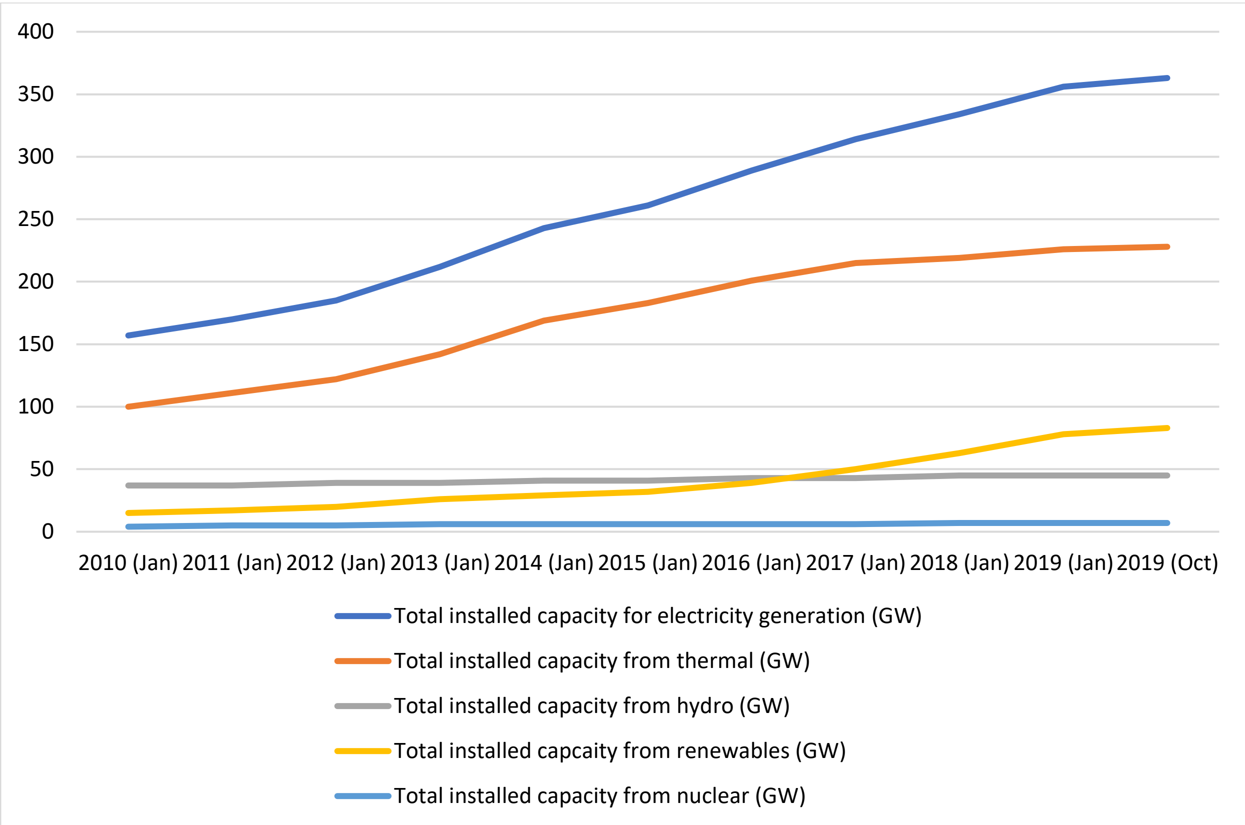
Introduction

India has achieved a rapid increase in the production of energy from renewable sources over the last decade. By October 2019, nearly 23% of installed power generation capacity came from renewable energy (83 gigawatts (GW)) (Ministry of Power (MOP), 2019). In 2019, the Government of India raised its level of ambition, from a target of 175 GW from renewables by 2022 to 450 GW. The Government is also preparing its climate change strategy for 2050, which is expected to rely heavily on renewable energy promotion.

However, the grid's ability to integrate higher rates of renewable electricity is a potential risk to India achieving its targets. A large 2017 Greening the Grid study estimated that current efforts to manage grid integration of renewables were sufficient to incorporate 100 GW of solar and 60 GW of wind (National Renewable Energy Laboratory (NREL) *et al.*, 2017). However, whether and how the grid can manage 450 GW of renewables remains largely unknown. The literature suggests that India will need a complete transformation in the policy, regulatory, and institutional structures for managing the grid to meet its ambitious new target.

Figure 1: Total installed generating capacity by source (GW)



Source: Compiled by the author from data from MOP annual reports

This paper explores grid integration of renewables in India in more detail, the solutions that have already been attempted, and what else is required. All countries are grappling with the technical, policy, and regulatory challenges of grid integration of renewable energy; India's experience to date offers useful learning for other developing countries.

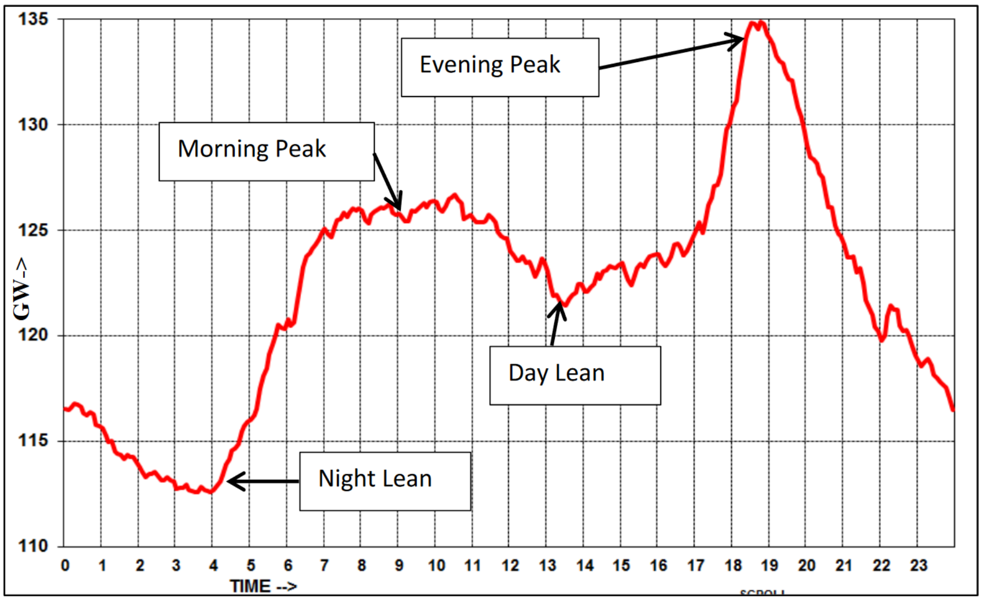
Why does renewable energy grid integration matter?

Electricity grids connect supply with demand, and system operators need to balance and manage any discrepancies between the two. Electricity generated from renewable sources makes managing grid operations more complex, difficult, and risky, as weather-dependent renewable sources, especially wind and solar, are by their nature variable and uncertain (for example, it might be windy or sunny one day, but not the next). High rates of renewable sources of electricity therefore place additional demands on the grid to ensure a constant, reliable supply.

In addition to the challenges posed by variations in the weather, there is also a mismatch between when electricity generated by renewables (particularly solar) can be supplied during the day (due to weather conditions) and when demand for electricity is at its highest.

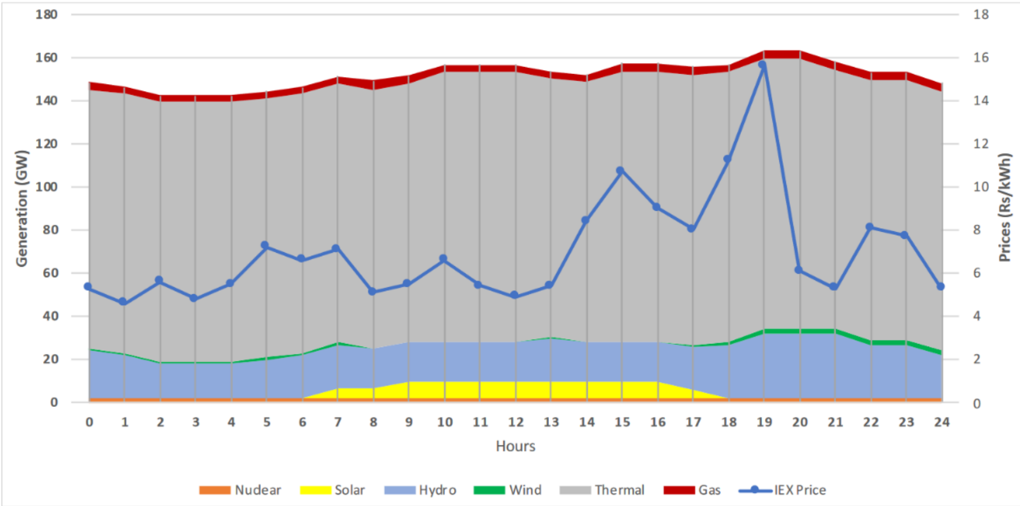
There are significant seasonal and geographical differences in the daily timing of peak supply and demand for electricity across India. Figure 2 provides a typical local curve illustrating national variation in demand for electricity during a day, and Figure 3 gives an example of a national fuel-wise generation pattern. This illustrates how peak solar power is generated at noon (while peak wind supply is more seasonable), while there is a sharp increase in demand for electricity in the evening. At this time, thermal power plants would need to increase their generation in a short timeframe to meet increased demand (and compensate for a decrease in solar power), which is difficult and costly for them (Prayas, 2016).

Figure 2: Typical all-India load curve



Source: Power System Operation Corporation Limited (POSOCO) (2016)

Figure 3 All-India fuel-wise generation pattern and prices at IEX on 3 October 2018



Source: Buckley *et al.*, 2019

There are varied costs associated with system integration of renewables, including:

the additional investment required in transmission grids to pool variable renewable energy and demand over large areas;

the cost of balancing the grid due to uncertain forecasts and the need for more flexible operation of thermal power plants; and

the cost of grid congestion, especially compensating for curtailed output.

The challenge and cost of grid integration of renewable energy increases as the proportion of renewables within the electricity generation mix increases. There are different global estimates of the exact proportion of renewables at which costs become a potential barrier to the expansion of renewable energy. An Energy Sector Management Assistance Program (ESMAP) (2015) study states that with under 10% of renewables on the grid, the variability and uncertainty it poses is at a normal level for the grid. Beyond this, operational adjustments are required. International Renewable Energy Agency (IRENA) has estimated that a 15% capacity penetration of renewables can generally be accommodated without any significant grid modifications (IRENA, 2013). The International Energy Agency (IEA) concludes that if appropriate policy, planning, and regulatory measures are taken to address variable renewable energy (VRE) integration issues, it is possible to integrate levels of renewables even above 30% at a modest incremental cost (IEA, 2014). The Central Electricity Authority (CEA) has estimated that if India's 450 GW of renewables target is met, renewable energy will represent over half (54%) of installed capacity in 2030 (CEA, 2019). It is therefore clear that the cost of grid integration may already, and will certainly soon be, a major barrier to increasing the proportion of renewables in the electricity mix in India.

There is very little research and modelling on the exact cost of integrating variable renewables into the grid (Chaturvedi *et al.*, 2018). The CEA has produced a high-level analysis of system-level costs based on a couple of states, indicating they are about Indian rupees (INR) 1.5/kilowatt hour (kWh) today, mainly due to other generators, primarily coal, having to lower their output (CEA 2017; Tongia *et al.*, 2018). Coal-based power plants face major technical difficulties, and therefore costs, in reducing output quickly to accommodate renewables when they are available. In India, they are designed to operate at greater than 90% of their rated capacity (or plant load factor (PLF)) and below this level they operate inefficiently and their emissions of SOx and NOx increase (Mehta, 2019). Due to a huge addition in generation capacity in recent years, there is anyway currently an under-utilisation of coal-based power plants in India and the average PLF dropped to 61% during 2017/18 (CEA, 2019). This is already leading to stressed assets in the sector, and the PLF will need to drop further as the share of renewables on the grid increases. The costs of grid integration are also not evenly distributed, as the majority of renewable energy generation (especially wind) is concentrated in the south and west of India, and states in these regions are currently paying the bulk of the costs of integration (Tongia *et al.*, 2018).

One of the most visible costs associated with grid integration of renewables currently receiving attention in India is the cost of curtailment. There is some dispute about the extent to which power grid operators are issuing instructions to limit the power output of renewable energy generators. In India, renewable energy has a 'must run status', meaning curtailment is only allowed if grid security or the safety of personnel and equipment is at risk. There are no official data on the extent and reasons for curtailment, although a recent order by the electricity regulator of Tamil Nadu against curtailment gives some ideas. The data from 10 plants included in the regulator's order show that during the first half of 2017, plants faced up to 100% of generation curtailment on several days in a given month. The data suggest that these curtailments were not due to technical reasons (grid frequency crossed the limit by only 1% during the period) but perhaps due to commercial interests and overriding of the 'must run status' of renewables. For example, solar plants with fixed higher tariffs were curtailed more than newer plants with fixed lower tariffs (Singh, 2019).

The challenge of grid integration of renewables in India

The size, scale, and governance structure of India's electricity grid makes it particularly costly to integrate renewable sources, and difficult to implement the typical policy, regulatory, and technical solutions used to reduce these costs. See Box 1 for details on the specifics of India's grid. Other countries have successfully integrated higher rates of renewables than India: for example, Denmark has accommodated a particularly high (42%) share of renewables and Ireland has 23%, using a range of different measures (REN21, 2016). However, it is difficult to directly apply these lessons in India given the very different contexts, and as such India is having to develop, pilot, and implement home-grown solutions.

India has one of the world's largest synchronised networks, with over 350 GW of installed capacity, and 1 billion users. The grid is expanding rapidly to meet growing demand for electricity. The transmission network capacity had an average compound growth rate of 12% between 2013/14 and 2017/18 in terms of megavolt ampere and 7% in terms of circuit kilometres (Buckley and Shah, 2019b). In 2019, India claimed success in achieving 100% electrification of all villages and households, and with this an increase in demand for electricity. There are different estimates of how demand will increase in the future (e.g. CEA, 2016; Chaturvedi *et al.*, 2018), reflecting different estimates of GDP growth rates, penetration of electric vehicles, adoption of efficiency measures, and other variables. One study estimates that generation capacity could grow from 261 GW in 2015 to between 655 GW and 1,271 GW by 2030 (Chaturvedi *et al.*, 2018). India's current grid infrastructure is struggling to manage the increasing rates of supply and demand, outside of the challenge of integrating renewables. The relatively weak infrastructure is characterised by high line losses, load shedding, low voltage at the distribution tail end, high variation in frequency, lack of adequate reserves, and additional issues (Prayas, 2016).

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Box 1: About India's electricity sector

Generation, transmission, and distribution

Since the early 1990s, generation of power has been open for private sector competition and there are separate generators, transmission companies, and distribution companies. Generation is still dominated by central and state-owned generation companies, with a relatively small proportion of private players. The Power Grid Corporation of India (PGCIL) is the Central Transmission Utility that owns, operates, and maintains the inter-regional and inter-state transmission networks, whereas the intra-state transmission networks are operated by the State Transmission Utilities. The transmission network is divided into five geographical regions. Distribution is mostly Government-owned, with a small number of private distribution companies supplying electricity to end consumers through the intra-state network. The distribution business is based on a cross-subsidy model, with industrial, commercial, and large domestic consumers typically being charged more to subsidise agricultural and small consumers.

Management of the grid

State planning agencies are responsible for ensuring sufficient supply of power to meet consumer demand – either through state-owned generation, bilateral contracts with independent power producers, and/or allocations from central generators. Independent state Load Dispatch Centres (LDCs) choose which supplier to use to meet demand at any time. When necessary, state LDCs and regional LDCs coordinate inter-state flows of power. State LDCs are responsible not just for technical issues related to balancing the grid, but also for running the system at the lowest cost. India relies on day-ahead scheduling for operating the grid, coordinated by state and regional LDCs and based on forecasts of demand from distribution companies and others, and generation from generation companies. The Power System Operation Corporation Limited (POSOCO) has overall responsibility for managing the grid and operates the national and regional LDCs.

Regulation and oversight

The CEA defines standards and safety procedures for the operation of the grid and power plants, and plans for the nationwide development of the electricity system. The Central Electricity Regulatory Commission (CERC) frames operational and commercial rules and regulations at the central level, while the State Electricity Regulatory Commissions formulates the operational rules for the grid in the state based on CERC norms. The most important regulations are the Indian Electricity Grid Code and Deviation Settlement Mechanism. The regulatory norm is that the electricity tariff is set to recover all 'prudent' costs incurred by companies, rather than being a performance-based norm.

(Sources: Prayas, 2016; Tongia *et al.*, 2018; Palchak *et al.*, 2017)

India's approach to grid integration of renewables

The Government of India has recognised that grid integration is a critical issue as regards realising its ambitions for higher shares of renewables in the electricity mix. In the 2018 National Electricity Plan, a whole suite of operational, policy, and regulatory changes are proposed, and there is a relatively advanced policy-level discussion on how to increase flexibility into the system (IEA, NITI Aayog, Asian Development Bank (ADB), 2018).

This section reviews some of the most important potential strategies for grid integration of renewables in India, including those currently being considered and implemented by the Government of India, and also considers what more is required. It is not a comprehensive listing, but highlights some of those strategies from India's experience that might be of interest to other countries.

Diversifying the location of renewable generation

There is an urgent need to upgrade India's transmission and distribution infrastructure given the increased demand for electricity and the increasing share of renewable energy. The evacuation infrastructure available for renewable energy projects is one of the biggest constraints. The Government is trying to address this with a massive investment of nearly US$ 6 billion for a dedicated transmission network for renewable energy, called the Green Energy Corridor project. Following a tariff-based competitive bidding process, the construction of the corridor is underway, focusing on connecting renewable energy-rich states and solar parks. However, the project has faced serious delays, which has meant that completed solar projects have been unable to connect to the grid for a significant period of time (Indian Renewable Energy Federation, 2018).

There is also increasing interest in bilateral cross-border electricity trade between India and Bhutan, Bangladesh, and Nepal. India has been importing hydro-electricity from Bhutan for decades, and both Nepal and Bangladesh have increased their imports of electricity from India in recent years. Currently, only around 3,000 MW of electricity is being traded bilaterally between these countries; however, this is expected to increase rapidly in the coming decades, including an estimated annual 43% increase of imports of hydro-electricity from Nepal until 2045 (Integrated Research and Action for Development (IRADe), 2018). One of the major benefits of this cross-border trade is being able to balance the intermittency of solar and wind with imports of hydro-electricity.

The Government of India is in the process of putting the necessary policy and regulatory framework in place, and making investment in physical infrastructure, to facilitate this trade. For example, in 2019 the Government issued regulations for cross-border trade of electricity and a designated authority will be established for planning the transmission infrastructure and coordinating with the neighbouring authority. The regulations state that the tariff for the import or export of electricity across the border will be determined through competitive bidding or through mutual agreements signed between the parties under the overall framework of agreements signed between India and the neighbouring countries.

Flexibility in generation

One of the most obvious ways to manage increased shares of variable renewables is through greater flexibility in the generation of other sources of electricity. However, there are limits and costs associated with the ability of these sources to change output in response to renewable power.

Regarding coal-based power plants, there is a debate in India about the extent to which they can and should be able to flex their output, particularly downwards when the supply of renewables is available (Tongia *et al.*, 2018). A 2016 amendment to the Electricity Grid Code requires all plants to have a technical minimum operating capacity of 55% and provides for compensation to plants for lowering their outputs. However, for older plants it is estimated that retrofitting to reduce the technical minimum by 10% would cost INR 1–2 lakh/MW (Ministry of New and Renewable Energy, 2015), while Tongia *et al.* (2018) suggest that for older plants, the costs appear to exceed the compensation provided. Gas- and hydro-powered plants are more easily able to ramp generation up and down; however, in India their potential is seen as limited. Due to a lack of domestic gas and the high cost of the imported fuel, generation of gas-based power has slowed down and 15 GW of gas plants have been stranded and another 25 GW operate at less than one-fifth of their capacity (Mehta, 2019). The

Government of India is heavily promoting dammed hydro energy, partly due to plants' ability to start and close quickly and to meet peak load on the grid. The generation pattern of dammed hydro energy also matches the load curve of the grid (high production during summer/monsoon season, when demand from the agriculture sector is also high). India has exploited only an estimated 26% of its hydropower potential (Mukuteswara, 2015) and as such in 2019 the Government introduced a suite of measures to promote it, including reclassifying it as a renewable source of energy. However, traditionally, the growth of hydropower has been severely constrained by land and social and environmental challenges, and competing demands for water, which has made banks wary of lending to hydropower projects. One study of seven large hydropower plants in India showed they suffered a decline in streamflow and hydropower production due to climate variability between 1951 to 2007, although there may be benefits from climate change for other plants in the future. In general, however, the effect of climate change on hydropower remains unexplored (Ali *et al.*, 2018). For these reasons it is unclear whether the Government's current push on hydro will be sufficient to build investor confidence.

Energy storage

The Government of India is also putting a lot of emphasis on promoting energy storage, due to the variety of benefits it can provide in regard to managing India's electricity grid and the transition to electric mobility. It has estimated that by 2022 the total requirements for energy storage for grid support to meet 175 GW of renewables on the grid is 17 gigawatt hours (GwH). In addition, the Government's current massive push towards electric mobility will require an estimated 40 GwH of energy storage. The cumulative demand for energy storage by 2032 is estimated to be in excess of 2,700 GwH (India Smart Grid Forum), 2019). The deployment of energy storage technologies, such as batteries and pumped hydro storage (PHS) plants, which can absorb excess power and release it when needed, are still limited and expensive. India has significant potential for PHS, which works by storing energy in water in a reservoir and releasing it into a turbine when there is demand for energy. 2.6 GW of PHS are already operational, with another 3.1 GW under development, although PHS faces many of the same constraints as hydro-electric power plants (Buckley and Shah, 2019a). The cost of advanced grid-level storage technologies like electric batteries has come down significantly in the last few years (Prayas, 2016), although India currently relies on imports of lithium-ion batteries from China. A major thrust of the 2019 National Mission on Transformative Mobility and Battery Storage is to create an enabling environment for domestic manufacturing. The Solar Energy Corporation of India is also now issuing tenders for 'round the clock' provision of renewable energy, with solar, wind, or hybrid installations to be augmented with energy storage technologies of any type.

Smart grid technologies

There is a range of 'smart' digital technologies and related equipment (meters, transformers etc) that can be integrated into the grid to control the performance of the system in real time, assess changes in production from renewables or consumption, and automatically adjust the load dispatch in seconds (Gogoi *et al.*, 2016). In 2015, the Government launched the National Smart Grids Mission to support the adoption and scaling up of smart grid technologies and standards by utilities, through pilots and enabling business models (MOP, 2018). The Mission is expected to act as a knowledge hub, and supports pilot projects, although these have faced challenges in respect of both procurement and delivery (Koshy, 2019).

Advanced metering infrastructure – a network of smart meters with a two-way communication ability – is the most widely talked about aspect of the smart grid concept in India, although it remains complex and expensive to implement. Smart meters are already required for those consuming more than 500 Kwh per month and the roll-out is soon expected to be expanded significantly (Singh and Upadhyay, 2019). The Smart Meter National Programme includes a 'build-own-operate-transfer' model, under which the public Energy Efficiency Services Limited (EESL) undertakes all the capital and operational expenditure, with zero upfront investment from states and utilities, and EESL receive an internal rate of return. Using this model, EESL has already installed over 625,000 smart meters and has plans to scale this up to 250 million in the next few years (EESL / National Investment and Infrastructure Fund (NIIF), 2019).

Operational strategies

The accurate forecasting of renewable energy is extremely difficult, but is also essential. In India, day-ahead scheduling is based on data provided by generators estimating demand and generation using a combination of weather forecasts, modelling, historical data, and machine learning. Various regulatory initiatives have attempted to improve the operation of the grid. For example, under the Deviation Settlement Mechanism (DSM), renewable energy generators are expected to accurately predict the exact generation of power in a 5x5 km area in 15-minute time blocks, and if they deviate by more than 15% from this forecast they are liable to pay a fee. Due to these and other measures, the operating frequency band has improved from roughly 48.75 Hz to 50.5 Hz in 2004 to an operating frequency band of 49.7 Hz to 50.3 Hz in 2015 (MOP, 2016). However, by 2018, only a few of the renewable-rich states in India had adopted the necessary regulations to implement the DSM, and there were inconsistencies in the rules across states, and uncertainty in the charges (Council On Energy, Environment and Water (CEEW), 2018; Parikh, 2019).

Policy and market reform

A whole suite of additional policy, regulation, and market reform measures have been proposed by various experts as being helpful to the integration of renewables into the grid. This includes the functioning of the 'open access' market, which allows large consumers to buy power from suppliers directly, rather than through the local electricity distribution company. This facilitates the purchase and transmission of electricity from renewable-rich states to others, and makes it easier for commercial and industrial users to purchase renewable energy. Currently, the open access market suffers from restrictions being imposed by states, high and volatile changes, and frequent switching between the open access market and distribution companies, which is affecting the financial health of overall sector (Singh, 2017).

Electricity tariff reform is also an imperative for strengthening the electricity sector for a variety of reasons, including for the integration of renewables. For example, with the existing tariff structure it is not lucrative for power developers or investors to set up fast ramping capacity to meet peak demand. The existing structure is largely a flat tariff, providing little incentive for network or consumer efficiency through load smoothing. Only a few states have peak prices that better reflect the cost of peaking power (Buckley *et al.*, 2019). In addition, through regulatory or contractual measures, renewable energy generators need to be compensated in the event of curtailment to the extent that generated power is not being utilised due to the incapacity of the grid to take on renewable power that has already been contracted (CEEW, 2018).

Conclusion – is India on track?

The Government of India and other stakeholders are taking a whole of range of measures to make the grid strong and flexible enough to incorporate higher shares of renewables. There is limited research on whether this will be sufficient to meet the 175 GW target for 2022 and the commitment to increase the target to 450 GW. In one of the few major studies on the subject, the United States Agency for International Development-funded Greening the Grid study (NREL *et al.*, 2017) concluded that assuming the fulfilment of current efforts to provide better access to the physical flexibility of the power system, power system balancing with 100 GW of solar and 60 GW of wind is achievable at 15-minute operational timescales with minimal renewable energy curtailment. Additional changes, such as lowering minimum operating levels of coal plants and coordinating scheduling and dispatch over a broader area, will further reduce renewable energy curtailment. Although this study has been labelled as a best-case scenario by others (for example, Tongia *et al.*, 2018), it suggests that things are at least moving in the right direction.

The Government of India has demonstrated that it recognises the scale of the challenge. The country needs to completely overhaul the policies, regulations, and market mechanisms for managing the grid, which were all originally designed for conventional power generation. This process has started, with the Government of India in the last few years introducing a range of policy and regulatory reform measures, and making massive investment in grid infrastructure. With its federal structure, the central government relies on states to align their own regulations and guidelines to those of the centre. So far, only a few renewable-rich states have been proactive in doing this: for example, adopting changes to the Grid Code, the DSM, ancillary services operation etc. The challenge will be in implementation, and whether the Government can plan and coordinate the many different actors and interests.

References

Ali, S. (2018) 'The future of Indian electricity demand: How much, by whom, and under what conditions. Brookings India', Brookings, New Delhi, available at www.brookings.edu/wp-content/uploads/2018/10/The-future-of-Indian-electricity-demand.pdf

Ali, S.A., Aadhar, S., Shah, H. L. and Mishra, V. (2018) 'Projected Increase in Hydropower Production in India under Climate Change', *Scientific Reports* 8, p. 12450.

Batra, P. (2017) 'Grid Integration of RE – challenges, roadmap and way forward', available at: http://integrationworkshops.org/2019/wp-content/uploads/sites/14/2017/09/1_2_GIZ17_xxx_presentation_Pankaj_Batra.pdf

Buckley, T. and Shah, K. (2019a) 'Pumped Hydro Storage in India', IIEFA, New Delhi, available at: http://ieefa.org/wp-content/uploads/2019/03/IEEFA-India_Pumped-Hydro-Storage_Mar-2019.pdf

Buckley, T. and Shah, K. (2019b) 'India's Grid Transmission Infrastructure Needs Further Modernisation, Urgently', IIEFA, New Delhi, available at http://ieefa.org/wp-content/uploads/2019/01/IEEFA-India_Grid-investment_January-2019.pdf

Buckley, T., Gupta, A., Garg, V., and Shah, K. (2019) 'Flexing India's Energy System: Making the Case for the Right Price Signals through Time-Of-Day Pricing', IIEFA, New Delhi, available at http://ieefa.org/wp-content/uploads/2019/01/India_Time-of-Day-Pricing_January-2019.pdf

CEA (2016) *Draft National Electricity Plan, Volume 1, Generation*, CEA, New Delhi, available at www.cea.nic.in/reports/committee/nep/nep_dec.pdf

CEA (2017) 'Report of the Technical Committee on Study of Optimal Location of Various Types of Balancing Energy Sources/Energy Storage Devices to Facilitate Grid Integration of Renewable Energy Sources and Associated Issues', CEA, New Delhi, available at www.cea.nic.in/reports/others/planning/resd/resd_comm_reports/report.p

CEA (2019) 'Draft Report on Optimal Generation Capacity Mix for 2029–30', CEA, New Delhi, available at http://cea.nic.in/reports/others/planning/irp/Optimal_generation_mix_report.pdf

Chaturvedi, V., Koti, P. N. and Chordia, A. R. (2018) '*Sustainable Development, Uncertainties, and India's Climate Policy: Pathways towards Nationally Determined Contribution and Mid-Century Strategy',* CEEW, New Delhi, available at www.ceew.in/publications/sustainable-development-uncertainties-and-india%E2%80%99s-climate-policy

EESL/NIIF (2019) 'NIIF and EESL Partner for Smart Meters deployment across India', online, available at https://eeslindia.org/content/dam/doitassets/eesl/pdf/pressrelease/2019/NIIF_and_EESL_Partner_for_Smart_Meters_deployment_across_India.pdf [Accessed: 11 December 2019]

ESMAP (2015) 'Bringing Variable Renewable Energy Up To Scale: Options for Grid Integration Using Natural Gas and Energy Storage', Technical Report 006/15, World Bank, Washington DC, available at: https://openknowledge.worldbank.org/bitstream/handle/10986/21629/ESMAP_Bringing%20Variable%20Renewable%20Energy%20Up%20to%20Scale_VRE_TR006-15.pdf?sequence=4

GIZ (2015) 'Indo-German Energy Programme Green Energy Corridors : Summary Report, Market Design for Renewable Energy Grid Integration in India', GIZ, New Delhi, available at https://mnre.gov.in/file-manager/UserFiles/Summary-Report.pdf

Gogoi, E., Sindou, E., and Botidzirai, B. (2016) *Power Sector Topic Guide*, EPS Peaks, London, available at www.gov.uk/dfid-research-outputs/power-sector-topic-guide

Gopalakrishnan, M. (2015) 'Hydro Energy Sector in India: The Past, Present and Future Challenges', in: Proceedings of the Indian National Science Academy, available at 81.10.16943/ptinsa/2015/v81i4/48305.

IEA (2014) 'The Power of Transformation: Wind, Sun and the Economics of Flexible Systems', IEA, Paris, available at https://doi.org/10.1787/9789264208032-en.

IEA, NITI Aayog, ADB (2018) 'Indian Power Sector', in *2018 Workshop: Low Carbon Transition Strategy for Renewable Energy Integration*, online, IEA, NITI, ADB, New Delhi, available at https://niti.gov.in/writereaddata/files/document_publication/Workshop-Report-2018-The-Indian-Power-Sector-Low-Carbon-Strategy-for-Renewable-Energy-Integration.pdf

Indian Renewable Energy Federation (2018) 'Addressing Barriers to Scaling-up Renewable Energy through Industry Involvement', Indian Renewable Energy Federation, New Delhi, available at https://shaktifoundation.in/report/addressing-barriers-to-scaling-up-renewable-energy-through-industry-involvement/

India Smart Grid Forum Energy Storage System: Roadmap for India: 2019–2032, India Smart Grid Forum, New Delhi, available at https://niti.gov.in/node/905

IRADe, (2018) 'Gains from Multilateral Electricity Trade among BBIN Countries', IRADe, New Delhi, available at https://sari-energy.org/wp-content/uploads/2018/09/Gains-from-Multilateral-Electricity-Trade-among-BBIN-Country.pdf

Joos, M. and Staffell, I. (2018) 'Short term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany', *Renewable and Sustainable Energy Reviews* 86, pp. 45–65.

Koshy, S. M. (2019) 'National Smart Grid Mission is stumbling only a few paces from the starting line', blog, DownToEarth, available at www.downtoearth.org.in/blog/energy/national-smart-grid-mission-is-stumbling-only-a-few-paces-from-the-starting-line-63370 [Accessed 11 December 2019]

Mehta, N. (2019) 'Energy Storage is Crucial to India's Clean Energy Goals', blog, SterlitePower, available at www.sterlitepower.com/blog/energy-storage-crucial-india%E2%80%99s-clean-energy-goals [Accessed 11 December 2019]

Ministry of New and Renewable Energy (2015) 'GEN-GEC Report on Forecasting, Concept of Renewable Energy Management Centres and Grid Balancing', Ministry of New and Renewable Energy, New Delhi, available at http://mnre.gov.in/file-manager/UserFiles/draft-report-fscb-remcs.pdf

MOP (2016) 'Report of the Technical Committee On Large Scale Integration of Renewable Energy: Need for Balancing, Deviation Settlement Mechanism and Associated Issues', available at http://powermin.nic.in/sites/default/files/uploads/Final_Consolidated_Report_RE_ Technical_Committee.pdf

MOP (2018) *National Smart Grid Mission Implementation Framework*, MOP, New Delhi, available at www.nsgm.gov.in/sites/default/files/NSGM-Framework-Final.pdf

MOP (2019) 'All India Installed Capacity (In MW) of Power Stations (As of 31.10.2019)', online, available at www.cea.nic.in/reports/monthly/installedcapacity/2019/installed_capacity-10.pdf [Accessed 11 Dec. 2019]

NREL, POSOCO, and Lawrence Berkeley National Laboratory (2017) 'Greening the Grid: Pathways to integrate 175 GW of Renewable Energy into India's Electric Grid, Vol 1 – National Study', USAID, New Delhi, MoP, Government of India, available at: https://www.nrel.gov/analysis/india-renewable-integration-study.html

Parikh, A. (2019) 'Accurate Forecasts of Renewable Energy Generation a Tough Task for Solar and Wind Developers', blog, Mercom, available at https://mercomindia.com/accurate-forecasting-renewable-generation/ [Accessed 11 December 2019]

POSOCO (2016) *Electricity Demand Pattern Analysis, Vol 1*, POSOCO, New Delhi, available at https://posoco.in/download/all-india/?wpdmdl=8873

Prayas (Energy Group) (2016) 'Grid Integration of Renewables in India: An Analysis of Forecasting, Scheduling and Deviation Settlement Regulations for Renewables', Prayas, Pune.

Singh, D. (2017) 'Newer challen*ges for Open Access in Electricity: New for Refinements in the Regulations*', Brookings, New Delhi, available at www.brookings.edu/wp-content/uploads/2017/04/open-access_ds_042017.pdf

Singh, M. (2019) 'Tamil Nadu power regulator orders against solar output cut', blog, DownToEarth, available at www.downtoearth.org.in/news/energy/tamil-nadu-power-regulator-orders-against-solar-output-cut-63957 [Accessed 11 December 2019]

Singh, R. and Upadhyay, A. (2019) 'India considers mass rollout of smart meters to revive utilities', *The Economic Time*s, online, available at https://economictimes.indiatimes.com/industry/energy/power/india-considers-mass-rollout-of-smart-meters-to-revive-utilities/articleshow/69985130.cms?from=mdr [Accessed 11 December 2019]

Tongia, R. (2015) 'The Indian power grid: if renewables are the answer, what was the question?' Brookings, New Delhi, available at www.brookings.edu/wp-content/uploads/2015/01/renewable-energy_ch3.pdf

Tongia, R., Santosh, H., and Walawalkar, R. (2018) 'Integrating Renewable Energy Into India's Grid–Harder Than It Looks', Brookings India, New Delhi, IMPACT Series No. 112018-01, available at www.brookings.edu/wp-content/uploads/2018/11/Complexities-of-Integrating-RE-into-Indias-grid.pdf

Viswamohanan, A. and Aggarwal, M. (2018) 'Rethinking Renewable Energy Power Purchase Agreements: Curtailing Renewable Energy Curtailment', CEEW, New Delhi, available at https://shaktifoundation.in/wp-content/uploads/2018/07/PPA-Curtailment.pdf

About the author

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Elizabeth has prior experience as the India and Nepal manager for the Climate Development Knowledge Network (CDKN) and at the Overseas Development Institute (ODI). She has also worked on EU and US climate legislation, including as a researcher for a senior Member of the European Parliament (MEP) working on the revision of the EU Emissions Trading System (ETS) and EU renewable energy policy. She has lived and worked for NGOs in India, Pakistan and Tanzania. Elizabeth has a MSc in International Political Economy and Graduate Diplomat in Economics from London School of Economics (LSE).

Front cover image: Workers at a 1 MW solar power station Delhi, India