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WORKSHOP REPORT, 2018

THE INDIAN POWER SECTOR

Low Carbon Transition Strategy for Renewable Energy Integration.

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FOREWORD

NITI Aayog and International Energy Agency (IEA) are working together to deliver collaborative analytical work on the Indian Power Sector, focusing on five thematic areas. These are data and statistics; energy efficiency; renewables; policy guidance and modelling; and technology development. In April, 2018, NITI Aayog and IEA with support from the Asian Development Bank (ADB) convened four regional workshops in Chennai, Pune, Delhi and Kolkata. One national level workshop was held in Delhi.

This series of workshops brought together stakeholders to discuss and analyse current trends and challenges in the electricity sector in India across regions. The workshops focused on the Power System Transformation to deliver India's ambitious 175 GW renewable energy targets. In particular the role of regional system operation, interconnection, grid/ off-grid renewables, flexible thermal power plant operation, time based flexibility solutions and storage for future electricity systems were discussed. Experts on the subject from Central/ State Governments and other stakeholders identified and highlighted issues faced by regions. They also discussed global best practices and advances related to renewable energy generation and integration.

This report reflects the outcomes of these workshops. It will hopefully set the foundation for further work on policy analysis and planning, and a possible technology roadmap for flexible thermal power generation in India.

Energy and International Co-operation Vertical of NITI Aayog led by Shri Rameshwar Prasad Gupta, Additional Secretary (Energy), has worked diligently to produce this report. I hope that policy makers and regulators in various States will take note of this report and adopt some of the key recommendations in their work.

I wish to express my sincere gratitude to all stakeholders including IEA and ADB officials for their valuable guidance and support in convening workshops and preparing the report.

(Rajiv Kumar)

Dated: 16th July 2018

स्वच्छ भारत
एक कदम स्वच्छता की ओर

अमिताभ कांत
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सत्यमेव जयते

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PREFACE

India has targeted to exploit 175 GW of renewable energy by 2002 for addressing climate concerns. Fast exploitation of renewable energy in India has brought grid stability related issues. Thus, NITI Aayog and International Energy Agency (IEA) with support from Asian Development Bank (ADB) convened 4 regional workshops in Chennai, Pune, Delhi, Kolkata and one national level workshop in Delhi in April, 2018. This series of workshops brought together stakeholders to discuss and analyse current trends and challenges in electricity sector in India with special focus on effect of renewable energy on grid in all regions of India. Technological, economic and regulatory issues related to renewable energy integration and grid stability were main focus of discussion. In particular the role of regional system operation, flexible thermal power plant operation, time based flexibility solutions and storage for future electricity systems were deliberated by technical experts from Centre/ State Governments and private sector. Stakeholders identified and highlighted local regional challenges and discussed global best practices & advances in the regional workshops.

Outcome of these workshops is this Report which would be useful for policy makers and system operators for efficient grid operation while integrating renewable energy.

Further, I would like to place on record deepest appreciation to Energy Team of NITI Aayog, Shri Surinder Singh Sur, Joint Adviser (Energy), Shri Manoj Kumar Upadhyay, Deputy Adviser, Dr. Abhinav Trivedi, Young Professional who worked relentlessly to make these workshops successful. I would also like to appreciate the efforts made by IEA team Mr Simon Müller, Head of Unit, System Integration of Renewables, Mr Alejandro Hernandez, Senior Electricity Analyst, Mr Raimund Malischek, Energy Analyst, Energy Technology Policy, Mr Michael Waldron, Energy Investment Analyst and Mr Pradeep Parera, ADB Energy Head (India) for taking up initiative and providing their leadership to make the workshops successful.

Finally, I would also like to commend the entire Energy vertical under Shri Rameshwar Prasad Gupta, Additional Secretary (Energy) who worked with passion with States and other stakeholders on the subject. I am sure that this Report would stimulate a healthy debate on some of the most important issues in the power sector.

(Amitabh Kant)
10th July, 2018

FOREWORD

International Energy Agency

In 2015 the International Energy Agency (IEA) published a special India Energy Outlook as part of our flagship World Energy Outlook. I recall telling international journalists gathered at the launch of the outlook that India was moving to the centre stage of global energy affairs. At that time, the IEA noted: "India is growing fast. Energy is central to achieving India's development ambitions, to supporting an expanding economy, to bring electricity to those who remain without it, to fuel the demand for greater mobility and to develop the infrastructure to meet the needs of what is soon to be the world's most populous country."

Fast forward to 2018 and India has made great strides in many parts of its energy transition. In April this year, India reached the impressive milestone of providing electricity to every village in the country. Progress on the deployment of LED lighting and the implementation of a comprehensive industrial energy efficiency program are grabbing attention around the world. India's targets for the deployment of solar and wind technology are some of the most ambitious, globally. And yet many challenges remain, particularly in relation to the integration of variable renewable energy and grid stability. These are challenges the IEA has been working on with a number of countries to develop best practice guides and practical advice.

The IEA and India benefit from a long, ongoing bilateral relationship built on cooperation in a broad range of areas including energy security, statistics, efficiency, market analysis, and technology. This relationship reached new heights in March 2017 when I was joined at a press conference in New Delhi by Minister Goyal and Minister Pradhan to welcome India to the IEA family as an Association country. This was followed by the development of a comprehensive bilateral work program which included a strong emphasis on power market reform, flexible power systems, and the systems integration of renewables. In this context the IEA was very pleased to partner with the NITI Aayog, with the support of the Asian Development Bank, to analyse the key power system challenges for India at a regional level. We will remain a key partner to India in its clean energy transition, providing further advice on global best practices and in the implementation of recommendations contained in this report and other collaborative projects in the future.

The participation of IEA experts in the regional workshops across India that informed this report was made possible through the IEA's Clean Energy Transitions Program. This program provides cutting-edge technical support to governments of countries whose energy policies will significantly impact the speed of the global transition toward more sustainable energy production and use, including reductions in greenhouse gas emission and local air pollution and greater access to electricity and clean cooking facilities. The Program benefits from financial contributions from Canada, Denmark, the European Commission, Germany, Sweden, Switzerland and the United Kingdom; engagement of technical experts in regional workshops in India was specifically supported by the United Kingdom's contribution to the Clean Energy Transitions Program.

Opening the doors of the IEA to the world's new major energy consumers remains one of my highest priorities. I am therefore very pleased to see the partnership between the IEA and the Indian government, industry, think tanks and academia growing so strongly. The IEA is well placed to share global best practice in addressing energy challenges for the benefit of Indian policy makers. At the same time, the solutions that India implements, as it undertakes its energy transition, will be of great interest to many around the world.

Dr. Fatih Birol
Executive Director
International Energy Agency

FOREWORD

Asian Development Bank

ADB

Asian Development Bank (ADB) is privileged to be associated with the NITI Aayog, the premier policy-making body of India, and the International Energy Agency, the global authority on energy, in deliberating how to transition India's power sector from a high level of fossil fuel dependency to one dominated by renewable energy.

ADB is fully committed to address climate change in the Asian region as it considers it a threat with the potential to reverse some of the economic and poverty alleviation achievements of developing Asian countries. ADB has pledged to increase its financing for climate change mitigation and adaptation to USD 6 billion per year, including USD 4 billion for climate change mitigation by 2020. The energy sector, especially renewable energy are expected to absorb the bulk of the funds allocated to climate change mitigation.

ADB has been a long-term development partner to India. ADB's annual lending to India exceeds USD 3 billion, and ADB has an active portfolio of ongoing loans of over USD 14 billion to India. ADB operations in India are focused on infrastructure sectors, such as promoting sustainable energy, transport linkages to promote economic development, and urban development for liveable cities. In this context, ADB has been working closely with the Indian Central Government as well as State Governments in developing integrated economic corridors with state-of-the-art infrastructure, including green and clean energy sources to provide improved connectivity between coastal economic zones and the hinterland. ADB's ongoing Energy Sector Program in India is in excess of USD 4 billion, and over USD 2.5 billion of that is allocated to improving the power transmission network at interstate as well as intrastate levels. In parallel to its investment in power transmission, ADB is directly financing renewable energy investments through financial intermediaries such as IREDA and Punjab National Bank, as well as ADB's non-sovereign operations.

ADB has been at the forefront of establishing the global climate finance architecture and has actively participated in various initiatives undertaken over the last ten years. ADB has been an accredited agency of the Green Climate Fund (GCF) and the Climate Investment Funds (CIF), and is able to mobilise concessionary financing for climate change related activities in India.

There has been a structural shift in the energy sector in most of the world's leading economies, including India, towards greener and cleaner energy solutions. Although the incremental investment in renewable energy has exceeded the investment in fossil fuel-based technologies by severalfold in recent times, the global efforts are still not adequate to limit global warming to meet the "below 2 degree scenario" that is considered a safe limit.

Hence, there is a need for a paradigm shift in how we, as development agencies, look at this problem and come up with solutions that bring both investment and knowledge solutions to address the challenge of climate change mitigation. While increased investment in clean energy sources such as renewable energy is an integral part of the solution, that alone is not sufficient. As renewable energy has different characteristics to conventional forms of energy, new electricity market structures, incentive policy frameworks and state-of-the-art smart grid technologies have to be adopted to facilitate the greater penetration of renewable energy. This requires an enabling policy framework and incentives for electricity market players, including thermal power plant operators and grid system operators, to adopt measures that will promote renewable energy integration at a greater scale.

ADB is fully committed to further collaborate with the NITI Aayog and our knowledge partners at the IEA, taking this initiative further and facilitating the formulation of policies and incentive frameworks for market players to create an enabling environment for greater integration of renewable energy in an equitable manner. There are winnings and losses when the energy sector technology paradigm is transformed, but at the same time it will create new opportunities and the possibility to create win-win solutions if not for all, at least for most of the stakeholders. We at ADB are fully committed to supporting this initiative under the guidance of the NITI Aayog and relevant Government ministries in collaboration with our international partners such as the IEA.

Kenichi Yokoyama
Country Driector
India Resident Mission
Asian Development Bank

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We would also like to convey special thanks to Shri Rameshwar Prasad Gupta, IAS, Additional Secretary (Energy), NITI Aayog for providing guidance in convening workshops. We would also like to thank energy vertical team namely Shri Surinder Singh Sur, Joint Adviser (Energy), Shri Manoj Kumar Upadhyay, Deputy Adviser (Power), Mrs. Poonam Kapur, Economic Officer (Power) and Shri Abhinav Trivedi, Young Professional for providing their enormous support for organizing the workshops & releasing the report.

GLIMPSE OF THE WORKSHOPS

SOUTHERN REGION

WESTERN REGION

NORTHERN REGION

EASTERN & NORTH EASTERN REGION

NATIONAL

The Indian Power Sector:
Low Carbon Transition Strategy for Renewable Energy Integration

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The Indian Power Sector:
Low Carbon Transition Strategy for Renewable Energy Integration

Executive summary

India's power grid is one of the world's largest synchronised networks with about 334 gigawatt (GW) of total installed capacity, of which variable renewable energy capacity comprises 63 GW (19.5 GW solar photovoltaic [PV] and 32.95 GW wind). The output of this capacity is handled by a single national grid providing flow of power from one corner of the country to another through strong inter-regional alternating current (AC) and high-voltage direct current (HVDC) links, serving one billion people and meeting a peak demand of 165 GW. The electricity grid is also one of the most rapidly growing grids globally in terms of additional line kilometres added per year.

The Government of India is promoting renewable energy sources on account of their being clean and green. At the same time, the rise of variable renewable energy (VRE) on the system can raise issues regarding renewable energy grid integration.

In the month of April 2018, the National Institution for the Transformation of India (NITI Aayog) and the International Energy Agency (IEA) with the support of the Asian Development Bank (ADB) convened four regional workshops and one national-level workshop in India. The purpose of these workshops was to bring together stakeholders to discuss and analyse trends and challenges in India's electricity sector related to achieving the country's 2022 target of achieving 175 GW of power capacity from renewable sources.

These workshops took place in Chennai (16 April), Pune (18 April) , Delhi (20 April) and Kolkata (23 April), and a national workshop in Delhi (20 April, afternoon). Each of the four regional workshops had participation of between 40 and 50 stakeholders, of whom about 10% were women.

The central element of the presentations and diversity of interesting interventions by the participants related to the various challenges that will be faced by India's power system as it moves towards the objective of integrating 160 GW of variable renewable sources.

The regional workshops had similar formats, constituting three technical sessions in addition to the introductory and concluding ones. The three sessions were "The role of flexibility in electricity distribution systems", "Flexibility in power generation and storage solutions for integration of renewable energy", and "The role of technology, policies and regulations in the low-carbon transition".

While the discussions were exhaustive, the themes that attracted detailed discussion included:

- The need for enhanced system flexibility across all areas of system operation, including planning as well as policy and market design.
- The systems and models in place for meteorological forecasting.
- Storage technologies, particularly the application of thermal storage in Indian conditions.
- Price discovery of new technologies.
- Renewable power auctions and contracting frameworks, aggressive competition and the impact on delivery of renewable energy projects.
- The role of hydropower in VRE integration.
- Financial risk management for investments and revenue sufficiency for the state distribution companies and implications of the low-carbon transition for thermal generators.

VRE generators have five technical properties that make them distinct from more traditional forms of power generation i.e. large-scale thermal power plants. First, their maximum output fluctuates according to the real-time availability of wind and sunlight. Second, these fluctuations can only be predicted fairly accurately up to a few days in advance and forecasts improve greatly if they are only for a few hours ahead. Third, they connect to the grid via power converter technology. This can be relevant in ensuring the stability of power systems, for example following the unexpected shutdown of a generator. Fourth, they are more modular and are deployed in a much more distributed fashion. Finally, unlike fossil fuels, wind and sunlight cannot be transported, and locations with the best resources are frequently at a distance from load centres.

This means that additional measures are required to ensure their cost-effective and reliable integration into the grid. A key concept in this regard is system flexibility. Power system flexibility, in its broadest sense, encompasses all the attributes of a power system that are conducive to the reliable and cost-effective management of the variability and uncertainty of supply and demand. Power system flexibility has always been important for meeting variable electricity demand and responding to the sudden losses of large generators and transmission lines. More recently, it has become increasingly relevant for the integration of VRE.

A general consensus was reached on the need for more "flexible" systems. Regarding hardware and infrastructure, flexible power plants and grid infrastructure (both transmission and distribution) were highlighted as near-term priorities. In the longer term, demand-shaping technologies (including thermal energy storage-enabled demand response and electric vehicles as smart loads) and electricity storage (both batteries and pumped storage hydro) were highlighted. Moreover, forward-looking technical connection standards (grid codes) were seen as critical to ensuring VRE can contribute to its own integration.

Unlocking this flexibility hardware in practice calls for upgraded operating procedures and market rules. This includes stringent load, hydro and VRE forecasting, as well as innovations in market design (more frequent market operation, rewarding ancillary services, being open to new technologies, efficient scheduling and dispatch). From an institutional perspective, improved coordination between regions and states was highlighted as critical to ensure efficient short-term trade of electricity across the entire country in order to maximise benefits to all stakeholders. Last but not least, improving investment conditions for VRE and flexibility options via measures to address financial risks, especially for state distribution companies were seen as crucial.

Based on the results of these workshops, a set of actionable next steps is proposed. As detailed in Chapter 6, this includes actions to upgrade grid technology, upgrade operational protocols, improve market design and renewable energy procurement, expand balancing areas, support flexible demand and balancing resources, improve evacuation of renewable energy and share international best practices.

The NITI Aayog, IEA and ADB are committed to strengthen their collaboration in the following areas:

- Jointly organise and implement regional/state-level power system transformation training weeks, with three different topical strands: i) enhanced system operation, power plant flexibility and grid codes, ii) power market design, renewable energy procurement mechanisms and attracting investment and iii) integrated power system planning, advanced flexibility strategies and distributed energy resources.

- Jointly establish a discussion platform to convene state, regional and national workshops/conferences focusing on strategies for a low-carbon transition.
- Establish bespoke technical assistance capabilities hosted by the IEA, providing an interface where analytical requests can be submitted and a first answer provided within a few weeks, while conducting deeper analysis on selected topics.

Across all the three areas above, the IEA will carry out this work in close collaboration with partner organisations in India and technical assistance programmes that are conducting related work.

The Indian Power Sector:

Low Carbon Transition Strategy for Renewable Energy Integration

1. Introduction

India is the third largest energy consumer in the world, but per-capita electricity consumption is around a third of the world average. Moreover, Indian electricity demand is expected to continue to expand as a result of economic and population growth, along with increased urbanisation and industrialisation. India is therefore faced with a triumvirate of challenges: how to i) expand energy access, ii) meet growing electricity demand and iii) integrate renewable energy, all while transitioning to a low-carbon electricity system in order to achieve ambitious economic, social and climate objectives.

The NITI Aayog has been actively taking up new initiatives to achieve co operative federalism by facilitating the working together of the Union and the states as equals, while also sensitising the states and to build strong states that will come together to build a strong India. Prior to these workshops, in November 2013, the NITI Aayog (then the Planning Commission of India) undertook a stakeholder-driven study, entitled India's Renewable Electricity Roadmap 2030, to analyse the opportunities and barriers to rapid deployment of renewable power in India. The report was released at RE-Invest 2015 and proposed strategic interventions to accelerate India's renewables program. To translate the roadmap into state-level implementation, the NITI Aayog embarked on the second phase of the project which involved working with the state governments to facilitate the process of generating and integrating renewables into their energy mixes.

India and the IEA share a long, ongoing bilateral relationship built on cooperation in a broad range of areas, including energy security, statistics, efficiency, market analysis, implementation agreements and technology. India has been the focus of many recent IEA analyses and reports. High-level policy dialogue has been further intensified over the last few years, as demonstrated by the signing of a recent Statement of Intent on data and research cooperation by the IEA Executive Director and the Vice-Chairman of the NITI Aayog.

Under this statement, the NITI Aayog in collaboration with the IEA organised a one-day workshop focusing on best practices adopted worldwide for flexible generation and storage solutions for renewables integration on 9 March 2017 in New Delhi. During this workshop the IEA proposed four or five regional workshops in India with a focus on flexible generation and storage solutions for integrating renewables. Separately, ADB approached the NITI Aayog with a view to funding energy-related (flexible generation and storage solutions, carbon capture and storage, waste to energy, electric vehicles etc.) joint study projects, workshops and conferences as part of its corporate social responsibility activities. Furthermore, after discussion, ADB showed interest in funding the four or five regional workshops in India as proposed by, and in collaboration with, the IEA.

The NITI Aayog and IEA are working together to deliver collaborative analytical work, technical cooperation, training and capacity building, and strategic dialogue with a focus on five thematic areas, covering: data and statistics; energy efficiency; renewables, including system integration; policy guidance and modelling; and technology development and innovation. Consequently, the NITI Aayog and IEA, with support from ADB, convened four regional workshops and one national-level workshop during April 2018. Southern, Western, Northern and Eastern/North Eastern workshops were held on 16, 18, 20 and 23 April 2018 in Chennai, Pune, Delhi, Kolkata, respectively. A national-level workshop was held on 20 April 2018 in New Delhi.

This series of workshops brought together stakeholders to discuss and analyse current trends and challenges in the electricity sector covering all regions of India. The workshops focused on the steps required to achieve successful power system transformation to deliver India's ambitious 175 GW renewable energy targets, looking at technological, economic and regulatory challenges and ways to overcome these. Specific topics that were addressed included coordination of regional system operations, the role of regional transmission/interconnection, flexible thermal power plant operation, time-based flexibility solutions such as demand response and storage, and grid-connected and off-grid renewables, as well as issues related to distribution and the financial viability of the sector. A range of stakeholders, including experts and state representatives, identified and highlighted regional challenges and discussed global best practices and advances during the regional workshops. Challenges faced by states and other stakeholders in respect of renewable energy generation and its integration were also discussed.

A few of the key institutions that had representation in these workshops included the Power System Operation Corporation (POSOCO), National Smart Grid Mission, Indian Renewable Energy Development Agency, National Institute of Solar Energy, Indian Institute of Technology (IIT) at Madras and Mumbai, Indian Space Research Organisation (ISRO), National Institute of Wind Energy (NIWE), GIZ India, Adani Power, Uttar Pradesh Power Corporation Limited (UPPCL), Malaviya Solar Energy Consultancy, Ankur Scientific Energy Technologies, Jadavpur University, Neotia University, GRIDCO, Asian Development Bank and PwC.

In addition to these, officials from the state governments of Tamil Nadu, Andhra Pradesh and Kerala (in the Southern region workshop in Chennai); Maharashtra and Gujarat (in the Western region workshop in Pune); Uttar Pradesh, Haryana and Punjab (in the Northern region workshop in Delhi); and West Bengal, Jharkhand and Assam (in the Eastern and North Eastern regions workshop), were also participants.

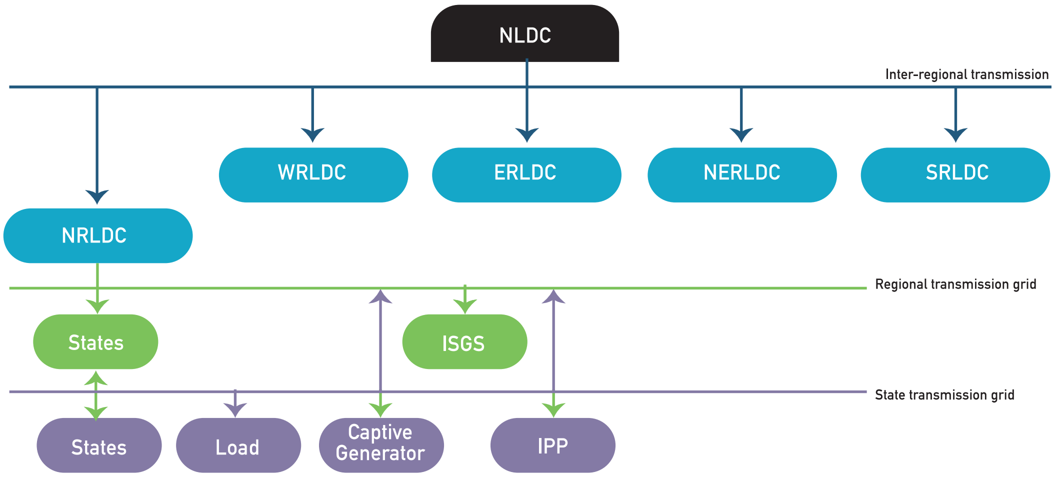
2. Background on regional context for renewable energy integration and priority action areas

India is a country with a large geographical span and an equally complex power network. Today's power sector is a result of years of generation and transmission planning, as well as distribution system development and deployment. A large number of government bodies is associated with the Indian power sector. Furthermore, operational responsibilities are entrusted to system operators at various levels. All these entities taken together form a very large and complex framework for the power sector.

The country's power development started with small isolated power systems. In the following decades, these small power systems were interconnected to form state-wide grids. In the seventies, the inter-connection of state grids with each other began in order to allow the exchange of surplus power, which was available occasionally. In the eighties, the Government of India stepped into power development on a regional basis by dividing the country into five regions. This division is still present in the five regional grids today: the Northern regional grid, the Western regional grid, the Eastern regional grid, the Southern regional grid, and the North Eastern regional grid. The regional grids are in turn co ordinated at the national level.

This structure is reflected in the operation of the system (Figure 1). Country-wide coordination and system operation is ensured via the National Load Dispatch Centre (NLDC). Each region has a Regional Load Dispatch Centre (RLDC), which operates the regional transmission grid and schedules the Inter-State Generating Stations (ISGS) of that region. A regional grid comprises a number of states. For example, the Western regional grid has seven constituent states: Gujarat, Madhya Pradesh, Chhattisgarh, Maharashtra, Goa, Dadra-Nagar-Haveli and Daman-Diu. Each state then has its own State Load Dispatch Centre (SLDC). This structure implies that system operation is influenced by decisions at state, regional and national levels. Hence, to achieve a flexible system there needs to be close collaboration between the different levels, while fully accommodating the specific requirements of each region and state.

Figure 1 • Structure of system operation in India



Notes: NLDC = National Load Dispatch Centre; NRLDC = Northern Region Load Dispatch Centre; WRLDC = Western Region Load Dispatch Centre; ERLDC = Eastern Region Load Dispatch Centre; NERLDC = Northern Eastern Region Load Dispatch Centre; SRLDC = Southern Region Load Dispatch Centre; ISGS = Inter-State Generating Station; GENCO = generating company; IPP = independent power producer.

Source: Ministry of Power.

2.1 Status of the power sector in the regions

2.1.1 Northern region

The Northern region of India comprises the states of Rajasthan, Haryana, Punjab, Himachal Pradesh, Uttarakhand, Uttar Pradesh, Jammu and Kashmir, and Delhi. The region covers around 30% of the geographical area and 28% of the population of India. The renewable share of installed capacity in this region is 13% (11.5 GW), which is expected to increase to 34% (45.5 GW) by 2022 (Table 1). Meanwhile, the renewable share of generation in the region is 6% (18 billion kilowatt hours [kWh]) which is expected to increase to 17% (78.8 billion kWh) by 2022.

Table 1 • Status of renewable energy in the Northern region

	2017	2022*
Total installed capacity (GW)	89.5	134.3
Renewable installed capacity (GW)	11.5	45.5
Total generation (billion kWh)	290.6	468.1
Renewable generation (billion kWh)	18.0	78.8

Note: * Forecast.
Source: Central Electricity Authority.

The Northern region is coal power dominated (out of a total installed capacity of 92.77 GW in the northern region, 52.84 GW is coal-based capacity) with the largest capacity located in Uttar Pradesh (17.97 GW) and Rajasthan (10.93 GW). However, solar is expected to be the next-highest installed capacity in the region by 2022. Due to the region's low growth in demand for electricity and aggressive thermal capacity addition, thermal power plants in the region are being operated at a plant load factor (PLF) of just 58%, which is the lowest among all the regions in India.

2.1.2 Eastern and North Eastern regions

The Eastern region comprises of states of West Bengal, Odisha, Bihar and Jharkhand, while the states of Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura represent the North Eastern region. These two regions of the country have a total installed generation capacity of 34.4 GW and 3.9 GW, respectively. Fossil fuel capacity – gas, coal and diesel – combined contribute approximately 82% and 58% of the installed capacity of the Eastern and North Eastern regions, respectively.

According to the CEA, there is currently a gap of 3.3% between the requirement for and availability of electricity in the North Eastern region, which is the highest in India. Tables 2 and 3 below show the status of renewable energy in the Eastern and North Eastern regions.

Table 2 • Status of renewable energy in the Eastern region

	2017	2022*
Total installed capacity (GW)	34.4	75.1
Renewable installed capacity (GW)	1.0	13.0
Total generation (billion kWh)	185.3	171.2
Renewable generation (billion kWh)	2.5	45.2

Note: * Forecast.
Source: CEA.

Table 3 • Status of renewable energy in the North Eastern region

	2017	2022*
Total installed capacity (GW)	3.91	11.00
Renewable installed capacity (GW)	0.28	1.56
Total generation (billion kWh)	15.02	23.80
Renewable generation (billion kWh)	0.30	5.42

Note: * Forecast.
Source: CEA.

As evident from Tables 2 and 3 above, presently the renewable shares of installed capacity in the Eastern and North Eastern regions are 3% and 7%, respectively, which are expected to become 17% and 14% in 2022, respectively. In the North Eastern region small hydro power (SHP) is the most exploited renewable source of electricity.

As confirmed by a representative from the Meghalaya State Renewable Energy Department, solar and wind power are the most underutilised sources of renewable energy in these regions; in particular the regions have huge potential for solar power. Hydro development in the region could provide a good complement to the wide deployment of variable renewables. However, advanced forecasting and scheduling needs to be done for adequate balancing, as these are intermittent and variable sources of energy.

2.1.3 Western region

The Western region comprises the states of Maharashtra, Gujarat, Goa, Madhya Pradesh, Chhattisgarh and union territory of Daman and Diu. As per the CEA (Table 4), the total installed capacity of power plants in the region is 107.0 GW, with a renewable share of 17% (18.3 GW). The region's renewable capacity is expected to rise to 54.3 GW by the year 2022. Annual electricity generation in the region is around 422 billion kWh, which increases to 481.5 billion units, including renewable generation of 96.2 billion kWh (20%), by the year 2022.

Table 4 • Status of renewable energy in the Western region

	2017	2022*
Total installed capacity (GW)	107.0	182
Renewable installed capacity (GW)	18.3	54.3
Total generation (billion kWh)	422.1	481.5
Renewable generation (billion kWh)	27.6	96.2

Note: * Forecast.
Source: CEA.

As evident from Table 4 above, the current shares of installed renewable capacity in the region is 17% which is expected to become 30% by 2022. The region's renewable generation share is 6.5% which becomes 20% by 2022. The region has an increasingly high penetration of wind and solar energy, which require advanced forecasting and scheduling to deal with the variable nature of renewable energy.

The large central government targets for net-metered solar rooftop projects and solar PV for agriculture under the Kisan Urja Suraksha evam Utthaan Mahaabhiyan (KUSUM) scheme are expected to further increase the penetration of renewable energy in the grid, and the grid operators will require innovative tools and skill sets to manage the integration of VRE.

2.1.4 Southern region

The Southern region comprises the states of Tamil Nadu, Karnataka, Telangana, Andhra Pradesh, Kerala and union territories of Puducherry, Andaman and Nicobar Islands, and Lakshadweep Islands. The state of Karnataka in the region is setting up the Pavagada Solar Park, which will become the world's largest when it attains its full potential of 2000 MW. As per the CEA, renewable energy in the Southern region contributes 28% of the region's total installed capacity. Table 5 below showcases the status of renewable energy in the Southern region.

Table 5 • Status of renewable energy in the Southern region

	2017	2022*
Total installed capacity (GW)	91.8	144.9
Renewable installed capacity (GW)	26.1	59.7
Total generation (billion kWh)	241.3	420.7
Renewable generation (billion kWh)	33.1	101.2

Source: CEA.

As evident from Table 5 above, at present the share of renewable installed capacity in the region is 28%, which is due to reach 41% in 2022. The renewable share of total generation in the region is currently 12%, which reaches 24% in 2022 according to the CEA. The region has a very high penetration of wind and solar energy, which requires advanced forecasting and scheduling to deal with the variable nature of VRE.

During the peak generation period of renewables in the Southern region, the overloading of transmission lines causes tripping and curtailment of VRE on the grid, as evacuation of VRE happens through transmission lines which do not meet the N-1 criterion; augmentation of the intrastate grid evacuation system is therefore required. Also, old renewable generating plants are not compliant with LVRT (low voltage right through), thus causing the tripping of renewable resources in the region from the grid during voltage dips. Power from old renewable plants that have signed a high-tariff power purchase agreement (PPA) is not demanded by distribution companies (DISCOMs) during their peak generation period due to availability of cheaper power in the market. As the Southern region has a very high penetration of wind and solar generation, accurate forecasting and scheduling by the hour are required. Presently, state- and regional-level forecasting of wind is conducted for day-ahead scheduling.

2.2 Action to be taken by the Centre and States for renewables integration and grid stability

Issues related to the integration of 175 GW of renewables by 2021-22 and grid stability were brought out in the National Electricity Plan, drafted by the CEA and prepared under the aegis of the Ministry of Power and in consultation with POSOCO, state governments, the Central Electricity Regulatory Commission (CERC), the NITI Aayog and various other stakeholders. The following are the principal challenges related to renewable energy integration and grid stability nationwide as reported by the CEA:

- Improve coordination of scheduling and dispatch with neighbouring states for better access to least-cost generation.
- Adopt state-of-the-art automated load and renewable energy forecasting systems.
- Upgrade scheduling and dispatch to 5 minutes from current 15-minute basis.
- Introduce CERC guidelines for coal flexibility, reducing minimum operating levels for coal plants.
- Develop new tariff structure that specifies performance criterion (ramping), and that addresses the value of coal as PLFs decline.
- Create model PPAs for renewable energy that move away from must-run status and employ alternative approaches to limit financial risks.
- Address integration issues on the distribution grid, including rooftop PV and utility-scale wind and solar that are connected to low-voltage lines.
- Require renewables generators to provide grid services such as automatic generation control (AGC) and operational data.
- Create policy and regulatory incentives to access the full capabilities of existing coal, gas turbine, hydro and pumped storage generation.
- CERC/State Electricity Regulatory Commissions (SERCs) to issue regulations to enable policy-related interventions.
- Central Transmission Utility (CTU)/State

Transmission Utilities (STUs) to upgrade the technologies and make necessary investments to handle intermittency through appropriate technical interventions.

- Improve availability of substantial flexible generation that can ramp up very quickly.
- Increase availability of storage devices as reserve.
- Develop a procurement mechanism for flexible generation to assure grid stability.
- Establish rapid trading of power at a power exchange to manage variable generation.
- Facilitate fair price discovery and compensation of flexible resource providers.
- Expand balancing areas to reduce variability by offering more balancing resources/demand.
- Enable evacuation of power through Green Energy Corridors from the regions with a high concentration of renewable energy sources.
- Upgrade grid operational protocols to ensure that renewable energy does not affect the grid.

3. Views of stakeholders on renewable energy integration

This chapter summarises selected findings from the different workshops. Several key themes emerged during the workshop discussions and the content is structured accordingly:

- technical flexibility enhancement
- power plant flexibility
- innovative balancing technologies (smart grids, storage and demand response)
- technical connection standards (grid codes).
- operational aspects
- load and VRE forecasting, scheduling and imbalance handling
- renewable energy management centres
- market design and investment framework
- wholesale power market design and interstate trade
- investment conditions for VRE generation and flexibility options
- measures addressing the financial risks of state distribution companies.

From an international perspective, the workshops demonstrated that the overall discussion on transformation of the power system, especially integration of renewable energy, is already quite advanced in India. There is a clear political will to achieve the 175 GW target, and consensus exists among stakeholders over the operational priorities and risks facing the investment needed to reach this objective. An overarching view expressed by all stakeholders in the workshop was the need to enhance the flexibility of the power system.

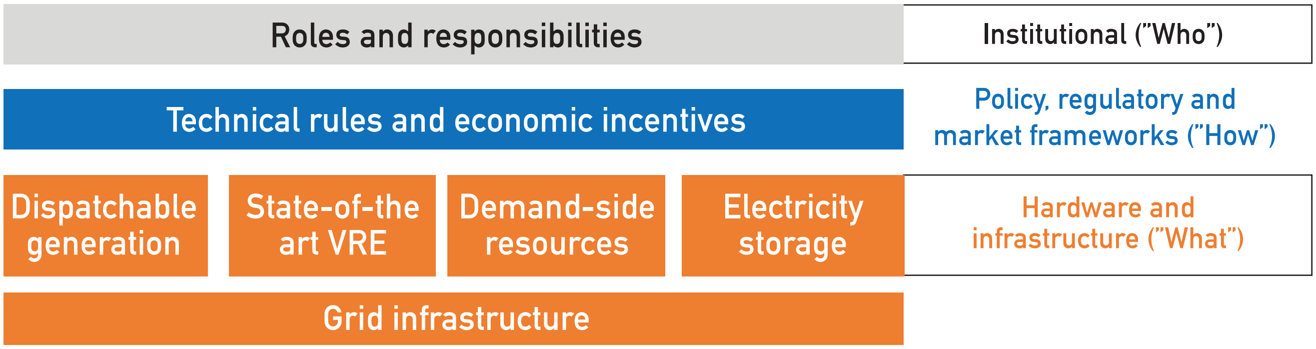
3.1 Concept and relevance of power system flexibility

Stakeholders who participated in these workshops reached the conclusion that power systems need to be more flexible and designed to accommodate not only variable and uncertain load, but also to cope with increasing supply-side variability and uncertainty due to rising levels of VRE. Power system flexibility, in its broadest sense, encompasses all the attributes of a power system that are conducive to the reliable and cost-effective management of the variability and uncertainty of supply and demand. Power system flexibility has always been important for meeting variable electricity demand and responding to the sudden loss of large generators and transmission lines. More recently, it has become increasingly relevant for the integration of VRE (IEA, 2018a).

All power systems have an inherent level of flexibility. Flexible power systems decrease the risk of curtailment and negative pricing, and increase confidence in revenue streams. Flexibility can also reduce overall system costs and consumer prices, via more efficient power system operation. Flexibility can also improve the environmental impacts of power system operations via increased optimisation of demand response, more efficient use of transmission and reduced renewable curtailment.

Unlocking flexibility requires actions across different "layers" of the power system (Figure 2). First, appropriate hardware and infrastructure need to be in place. These include sufficiently flexible dispatchable power plants (this may call for retrofits to existing assets, see below), state-of-the-art VRE plants that can provide ancillary services, sensors and controls to enable demand-side response, electricity storage and, most importantly, a strong and smart grid. These need to be combined with appropriate policy, market and regulatory frameworks that allow agents in the system to use the hardware in practice. Finally, the institutional setup needs to ensure that there are no conflicts of interest that may stand in the way of operating the system more flexibly.

Figure 2 • Different layers of power system flexibility



Source: IEA (2018a), Status of Power System Transformation 2018: Advanced Power Plant Flexibility.

Flexibility is required from both a geographic and temporal perspective. For example, one region may be experiencing abundant VRE generation while a neighbouring region is undergoing a period of low wind and solar availability. This requires a sufficiently strong and dynamically operated grid to balance supply and demand at least cost. From a temporal perspective, flexibility requirements can be differentiated according to different operational timescales, with different technology options available to provide each type of flexibility (Tables 6 and 7).

Table 6 • Different timescales of power system flexibility

Flexibility type	Ultra-short-term flexibility/ stability	Very short-term flexibility	Short-term flexibility	Medium-term flexibility	Long-term flexibility	Very long-term flexibility
Timescale	Subseconds to seconds	Seconds to minutes	Minutes to hours	Hours to days	Days to months	Months to years
Issue	Ensuring system stability (voltage, and frequency stability) at high shares of non-synchronous generation	Ensuring short-term frequency control at high shares of variable generation	Meeting more frequent, rapid and less predictable changes in the supply/ demand balance, system regulation	Determining operation schedule of the available generation resources to meet system conditions in hour- and day-ahead time frame	Addressing longer periods of surplus or deficit of variable generation, mainly driven by presence of a specific weather system	Balancing seasonal and inter-annual availability of variable generation with power demand
Has relevance for following areas of system operation and planning	Dynamic stability (inertia response, grid strength)	Primary and secondary frequency response, which include AGC	AGC, ED, balancing real time market, regulation	ED for hour- ahead, UC for day-ahead time frame	UC, scheduling, adequacy	Hydro-thermal co ordination, adequacy, power system planning

Notes: ED = economic dispatch; UC = unit commitment.
Source: IEA (2018a), Status of Power System Transformation 2018: Advanced Power Plant Flexibility.

Table 7 • Specific hardware and infrastructure options (equipment and services) organised into technical flexibility resource categories for different timescales of system flexibility

Flexibility timescale Flexibility resource	Ultra-short term (subseconds 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 governor 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 load shedding	Demand-side options including electric water heaters, electric vehicle 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	Supercapacitors; flywheels; battery storage; PSH ternary 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	Governor droop; 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	Internodal 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: CAES = compressed air energy storage; FACTS = flexible alternative current transmission system; SPS = special protection schemes; SVC = static var compensator; WAM = wide area monitoring system.

Source: IEA (2018a), Status of Power System Transformation 2018: Advanced Power Plant Flexibility.

From a market design perspective, three broad areas are relevant to establishing a flexible wholesale power market:

- FASTER: Liquid trading close to real time reduces the impact of forecast errors and allows better management of variability.
- BIGGER: Larger market areas help smooth variability and increase the pool of flexible resources.
- BROADER: Remunerating all relevant system services ensures assets have an incentive to provide all relevant services to the power system.

During the workshops, participants presented and discussed specific solutions that are best adapted to the specific regional contexts in India, in addition to addressing national priorities for enhancing system flexibility.

3.2 Technical flexibility enhancements

3.2.1 Power plant flexibility

For enhanced flexibility of thermal power plants, the IEA has recently concluded a comprehensive analysis of the available technical options and policy priorities (IEA, 2018a), which was presented at the workshop.

Historically, baseload, intermediate and peaking plants helped meet specific segments of electricity demand at least cost by providing the appropriate mixture of energy and capacity. These plants were designed, from a technical standpoint, with these specific operating conditions in mind. From an economic standpoint, the plants were financed under the expectation of a certain number of operating hours. Today, as a new generation of technologies with distinct cost structures and technical characteristics enters power markets at scale, many existing power plants are being asked to operate with greater flexibility, and in some cases for a reduced number of operating hours. Flexible power plant operation can take many forms, from rapidly changing plant output, to starting and stopping more quickly, to turning plant output down to lower levels without triggering a shutdown (IEA, 2018a).

A variety of strategies is available to make power generation more flexible. This includes (IEA, 2018a):

- **Changes to operational practices for existing plants.** Significant new capital investment is not necessarily required to operate power plants more flexibly. Changes to certain plant operational practices – often enabled by improved data collection and real-time monitoring – can be used to unlock latent flexibility at existing plants. For example, better monitoring and control equipment can allow plants to start more quickly and ramp up output more dynamically without compromising reliability.
- **Flexibility retrofit investments for existing plants.** Depending on the plant technology, a range of retrofit options may be available to improve various flexibility parameters of power plants (e.g. ramp rates, start-up times, minimum economic or technical generation levels). This report details specific retrofit opportunities across various power generation technologies, including coal, Combined Cycle Gas Turbine (CCGT), co-generation, Carbon Capture and Storage (CCS), nuclear, bioenergy and hydropower.
- **New flexible generation opportunities.** Many state-of-the-art flexible power plant technologies can be deployed in power systems;

several of these technologies are described in this report. Good long-term planning practices can ensure new flexible power plant investments are risk-hardened against a range of uncertain futures.

In the context of India, retrofits to existing plants appear timely, especially in the Southern and Western regions where VRE increases are expected to happen most rapidly and there is a sizeable amount of recent generation capacity. While the technical details of such interventions will differ according to plant-specific factors, a number of general best practice rules can be identified (Box 1).

Box 1 • Ten steps for power plant flexibility

- Raise the awareness of flexibility. Provide background information about the need for flexibility, explain its necessity for and impact on the operation and management (O&M) of the plant, and initiate training programmes.
- Check the status of the plant and identify bottlenecks and limitations with respect to flexible operation. Consult with original equipment manufacturers to assess the influences of low load operation and temperature and pressure gradients on main components and equipment. Ensure smooth operation of all control loops.
- Plan and execute test runs to evaluate the plant's flexibility potential. Create transparency about the plant's performance with respect to minimal load, start-up and cycling behaviour in the current setup. Identify constraints and process limitations, as well as improvement potential.
- Optimise the information and communication system. This is the most cost-effective way to enhance the flexibility of the plant. A certain level of automation is a prerequisite for tapping this potential.
- Implement mitigation measures to manage the consequences of flexible/cycling operation. This includes a reassessment of all O&M procedures. The use of appropriate condition monitoring systems is essential.
- Optimise combustion. Stable combustion is the key aspect of ensuring minimum load operation.
- Optimise start-up procedures. Check start-up related temperature measurements and consider replacement; automate start-up procedures.
- Improve the plant efficiency at part load and the dynamic behaviour of the plant. Use the potential of the water-steam cycle and enhance the performance of important equipment and components, e.g. fans or feed water pumps.
- Improve the fuel quality. The better the fuel quality, the better the combustion process.
- Consider storage options to enhance the overall flexibility performance of the plant. This refers to battery or thermal storage systems.

Source: VGB as presented in IEA (2018a), Status of Power System Transformation 2018: Advanced Power Plant Flexibility.

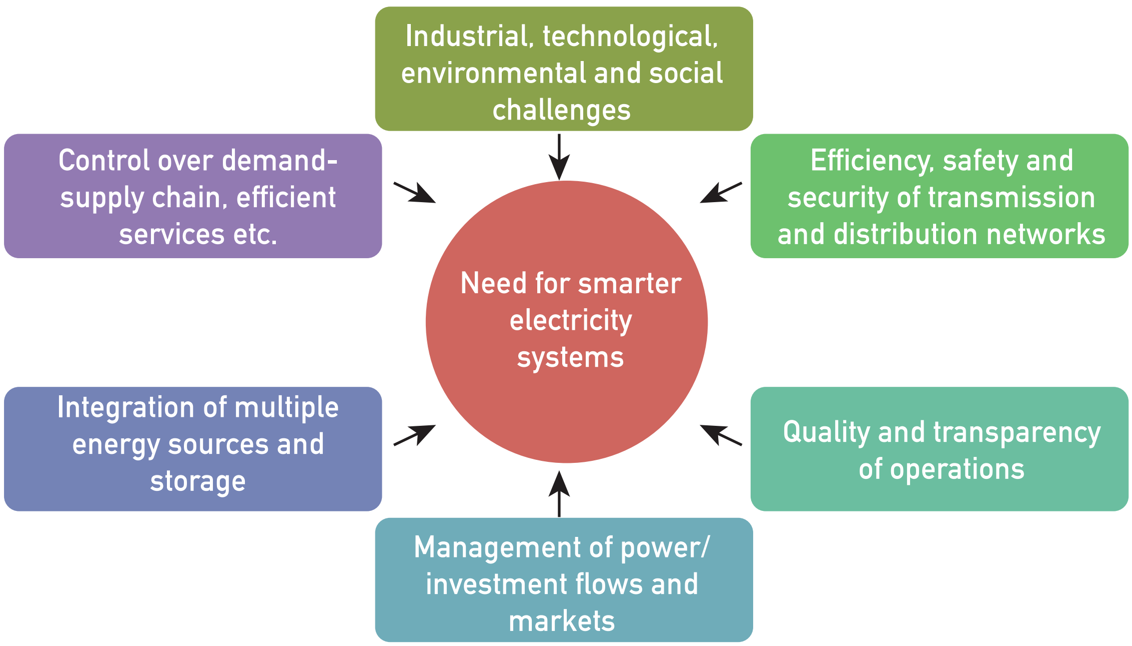
While there was consensus on the general potential and importance of more flexible operation, questions remained as to the exact economic impact of more flexible operation of plants in India and to what extent current compensation levels are appropriate to stimulate needed investment.

3.2.2 Innovative balancing technologies (smart grids, storage and demand response)

As per the National Smart Grid Mission, enhanced grid interconnections and related information and communication technology support will facilitate the integration of electricity supply and demand and increase power system flexibility. At present, a comprehensive EHVAC (extra-high voltage alternating current) and HVDC system for flexible operation and grid stability is being installed as a part of hybrid network development (Extra High Voltage and High Voltage), alongside digitalization of substations, to improve reliability, reduce O&M costs and facilitate rapid power restoration.

A number of drivers – in addition to flexibility enhancement – underpin the development of smart grids (Figure 3).

Figure 3 • Drivers of smart grid adoption



Source: National Smart Grid Mission, presentation at Northern region workshop.

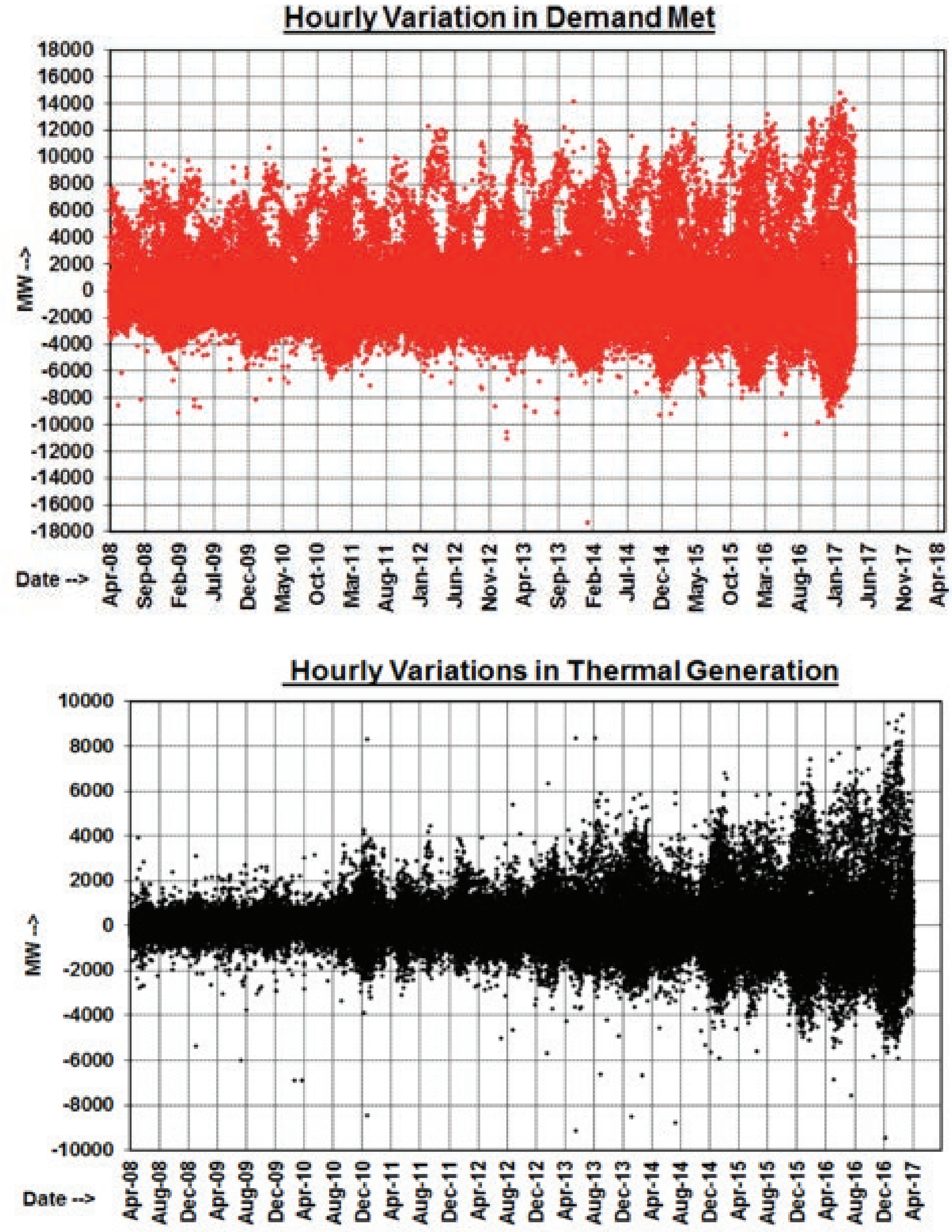
Energy storage systems (ESS) are an important option for increasing flexibility in the Indian power system. ESS can facilitate the storing or releasing of energy immediately in response to system needs. The Government of India is working on a National Storage Mission with the aim of firming renewable energy capacity, removing transmission congestion and curtailment of wind and solar generation, and facilitating energy shifting, and to increase power quality, reliability and resilience. Internationally several energy storage systems are being utilised, such as pumped storage, CAES, flywheels, batteries and power to gas. As the Western region demonstrates as one of the regions with the highest potential for renewable energy expansion, ESS can support system integration for energy producers and grid operators in that region by providing benefits and helping to address issues, as follows:

- Provide fast response system services for voltage and frequency control.
- Provide firm capacity to meet peak demand needs in the context of shifting renewables output.
- Limit ramp rates of VRE generators, if co-located en masse, especially in large solar parks.
- Minimise deviation from scheduled dispatch or drawl.
- Help avoid or defer grid upgrades, including for the integration of distributed energy resources, such as rooftop PV or electric vehicles.

Load shaping and demand response are other potentially important sources of flexibility in the context of India. Load shaping is a broad concept that encompasses all measures that facilitate an improved match between VRE availability and electricity demand. A number of ongoing trends in India are already contributing to an improved match between solar PV and load, notably the installation of more efficient lighting. Lighting that is more efficient translates into less electricity consumption during times of solar PV unavailability, improving the structural match between supply and demand.

Targeting the demand side to become a source of flexibility is particularly timely in India, because demand has been becoming increasingly variable in recent years, driven by increased uptake of air conditioners (Figure 4).

Figure 4 • Increasing load variability in India and power plant ramping requirements



Source: POSOCO, presentation at Western region workshop.

If left unchecked, electricity demand from cooling could substantially surpasses peak electricity demand and exacerbates integration issues due to high cooling loads after sundown. The IEA has recently conducted a study on the global implications of the future of cooling, with specific emphasis on India (IEA, 2018b). The study found that in addition to minimum energy performance standards and improved building envelopes, thermal energy storage can unlock demand-side flexibility (Box 2).

Box 2 • Systems integration of renewables and thermal storage on peak cooling in India

In long-term IEA scenarios, the deployment of solar PV in India grows strongly, with up to 1100 GW of installed capacity by 2050. This means there will more often be times when more power is being generated than is required, leading to curtailment of excess PV generation during the sunniest times of the day. At the same time, cooling demand is expected to grow substantially, typically peaking in the early evening around 7pm, which is later than the peak in electricity supply by solar PV.

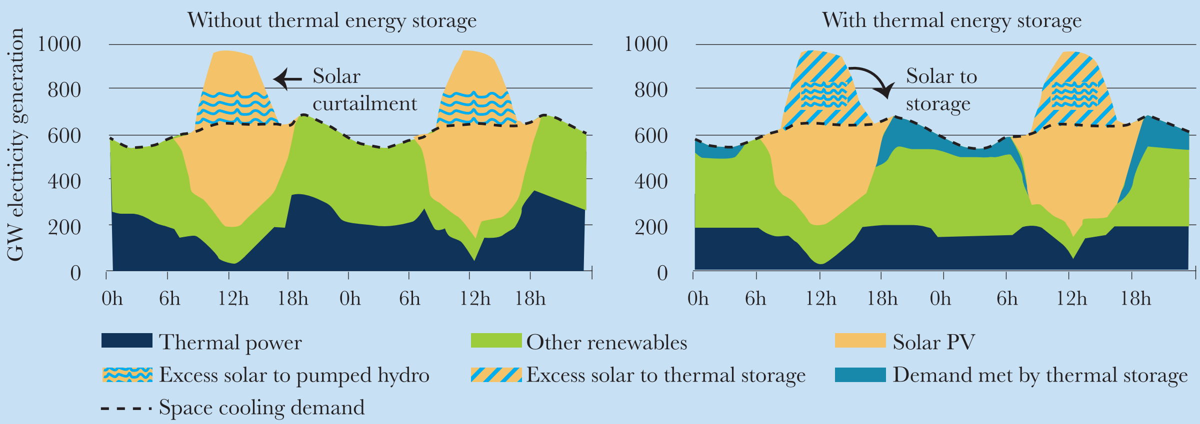
One potential way to address this mismatch is through thermal storage and integrated district cooling networks. For instance, heat pumps could produce chilled water or ice when the solar electricity is available, and then use that storage (e.g. by melting the ice) to meet cooling loads later in the evening.

To demonstrate the potential benefits of using thermal storage with solar PV and integrated district cooling, the IEA modelled the operation of the Indian power system during a peak cooling week in 2050. This simulation contains a scenario in which India's cities – where the expected growth of cooling demand will be concentrated – would use district cooling networks with thermal storage to partially meet cooling loads from cold generation produced using daytime solar PV. The scenario does not suggest that district cooling would be practical or economically viable in all Indian cities; rather, it provides a sense of the potential and magnitude of the thermal storage needs to meet rapidly growing peak cooling demand in India through the country's large solar generation potential (Figure 5).

The model system assumes a total thermal storage of 2400 GWh thermal, corresponding to an equivalent of about 600 GWh of electrical storage. The IEA estimates that roughly one-fifth of the total solar PV output could be stored during the day as chilled water or ice (represented by the orange and blue striped area in Figure 5), which otherwise could be curtailed. That cold storage could then be discharged later in the evening through district cooling networks, meeting around 15% of total space cooling demand after the sun goes down. To give a sense of the magnitude of such a system, the required volume would be comparable to around 20000 Olympic sized swimming pools (if the thermal storage medium were ice).

Discharge from such a system could meet peak cooling demand between 5pm and 7pm, while equally reducing the need for conventional peak generation capacity (e.g. using coal- or gas-fired thermal power generation, shown in dark blue). The model results show a reduction in peak residual demand of 11%, or 80 GW (Table 8). In addition, the thermal storage adds system flexibility through balancing of supply and demand, which allows the provision of electricity from cheaper generation sources during additional periods of the year not shown in Figure 5.

Figure 5 • Illustrative analysis of the potential role of thermal storage using solar PV power for district cooling over two days in April, 2050 during the peak cooling period in India



Notes: Thermal power includes coal and gas fired power generation as well as nuclear electricity generation; other renewables include wind, concentrated solar power and hydro power, which includes pumped hydro produced using excess solar generation.

Key message • Thermal storage could take advantage of surplus solar output to alleviate the strain of peak cooling demand on the electricity system in the evenings.

Estimates of total system costs reveal a net saving from the deployment of energy storage capacity to meet space cooling loads through excess PV generation, as compared to a scenario without storage, which effectively requires more conventional peak power generation. The annual system savings estimated in this assessment are higher for thermal storage (USD 9.7 billion) than using battery storage (USD 7.5 billion). This is the result of lower costs for thermal storage capacity at around 10 USD per kWh thermal compared to targets of around USD 300 per kWh electric for battery storage in 2050. Those annual savings would likely outweigh additional costs for the district cooling system (e.g. network pipes and substations), given the long life of typical district energy networks and their investments that can be amortised over time.

While this analysis does not provide a detailed assessment of the specific local conditions or system dynamics that would be required for sound energy system planning and investments, it does suggest that system-wide thinking, combining different supply and demand side elements, could offer great potential for cheaper, cleaner and more flexible solutions to meet space cooling demand in India. These types of integrated solutions, allowing for greater use of renewable energy sources, could also compliment broader economic and social policy objectives – for instance, cutting local air pollution from electricity generation from conventional peak power generation during peak cooling demand hours .

Table 8 • Key power system parameters for a scenario without and with thermal storage

	No storage	Thermal storage
Peak residual demand (GW)	713	633
Curtailment (TWh)	50	0.5
Total system cost saving (USD billion per year)	-	9.7 (7.5 with battery storage)

Note: TWh = terawatt hour.
Source: IEA (2018b), The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning.

Many innovative demand and storage options are small-scale technologies. The development of these options depend on communication and control infrastructure, which can incur a greater cost. Thus, deciding on the appropriate scale of options (distributed/centralised) requires a case-by-case cost-benefit assessment in order to understand the cost and system value of each option.

3.2.3 Technical connection standards

In general, grid codes provide the rules for power system operation and planning, ensuring operational stability, security of supply and proper co ordination of all relevant components. With an increasing share of VRE, grid codes are becoming increasingly essential due to the unique characteristics of VRE and the way they are connected to the grid (via power electronics) compared to conventional generators. The behaviour of VRE sources is not only dictated by their design, but also by the way they are programmed to operate. The function of a grid connection code covering VRE is to provide technical requirements for wind and PV plants when connecting to a country's electricity grid (IRENA, 2016). Stakeholders expressed that with the growing importance of VRE on the system, a forward-looking, enforceable and nationally consistent grid connection standard for VRE is indispensable. Additional impetus to achieve this in a timely manner may be needed.

3.3 Operational aspects

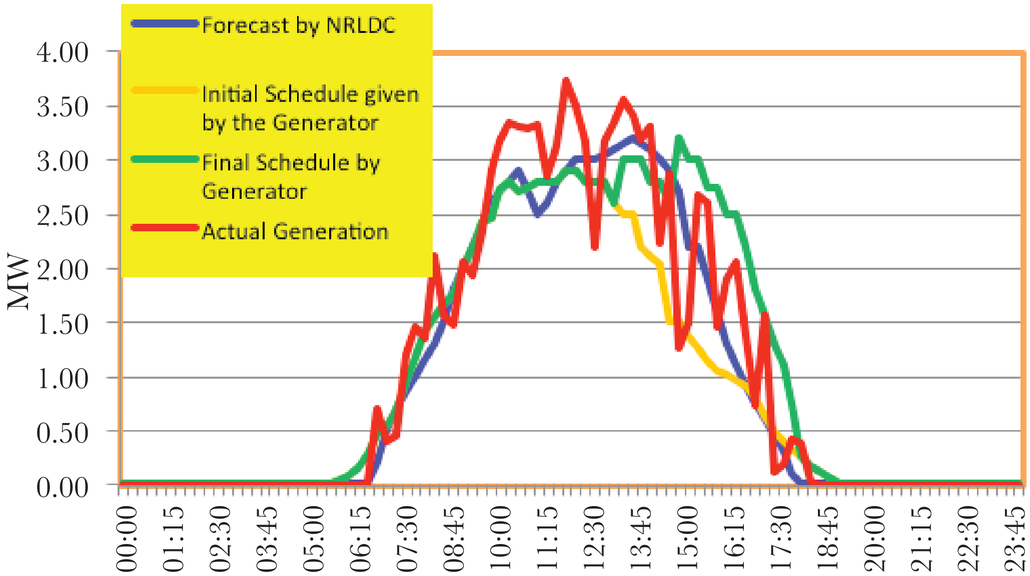
3.3.1 Load and VRE forecasting, scheduling, reserves and imbalance handling

A critical step in power system transformation is minimising the amount of flexibility that is required and maximising the pool of resources that can provide flexibility. In this regard, day-ahead and intraday forecasts and schedules play a critical role. Accurate forecasts for both load and VRE generation will minimise unexpected deviations during operations, effectively reducing the amount of flexibility that is required. Accurate scheduling of power plants (variable and dispatchable) ensures that sufficient flexibility is available on the system, and regular updates of schedules close to real time make sure that the latest forecast information is reflected in schedules.

Holding an appropriate amount of different reserves during operations helps to cater for unexpected events that were not forecast correctly, while maintaining reliability. Finally, settling deviations from schedules and imbalances between schedules and actual operation is critical to provide an economic incentive to report accurate schedules and to remunerate reserve providers.

The Northern Region Load Dispatch Centre (NRLDC) cited major challenges in forecasting variables such as irradiance, cloud cover and fog, and other environmental conditions like fly ash, coal dust, etc. NRLDC emphasised that uninterrupted availability of generation and SCADA (Supervisory Control and Data Acquisition) data in real time should be possible for better scheduling and forecasting. They also emphasised the challenge of output ramp forecasting during cloudy and foggy days. Figure 6 depicts the actual generation and forecast for Dadri solar plant for 3 August, 2016. The figure clearly depicts the difference between actual generation and the schedule provided by the generator. The difference in the forecasts by the two institutions is clearly visible, as the forecast by NRLDC has a root-mean-square (RMS) error of 9.9% and the forecast by the generator has an RMS error of 12.2%. This figure also conveys the benefit of having a central or regional agency for forecasting, as it is easier for them to forecast, their having access to different and state-of-the-art forecasting methods.

Figure 6 • Actual generation and forecast for Dadri solar plant



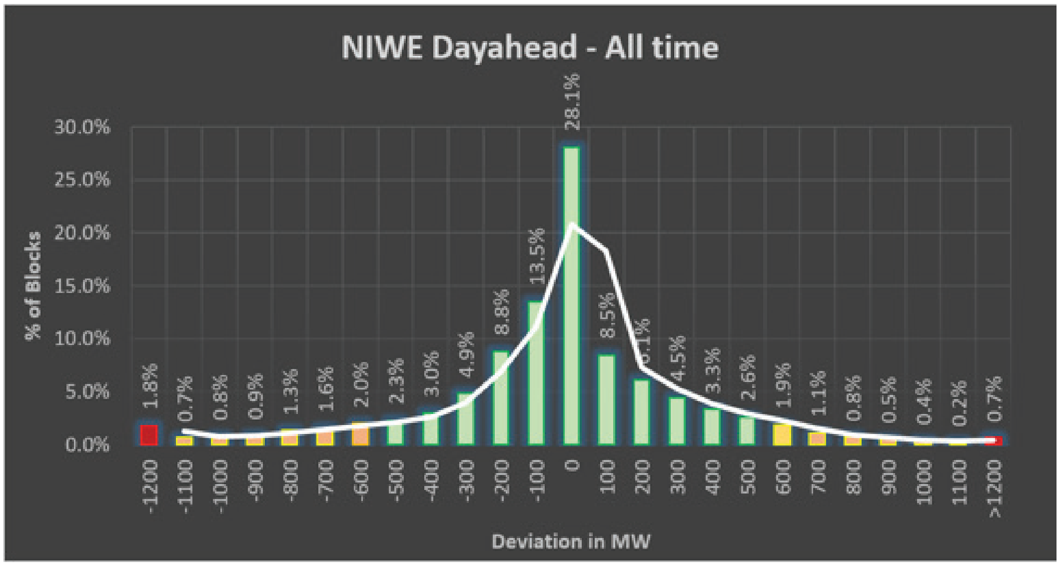
Source: NRLDC, presentation at Northern region workshop.

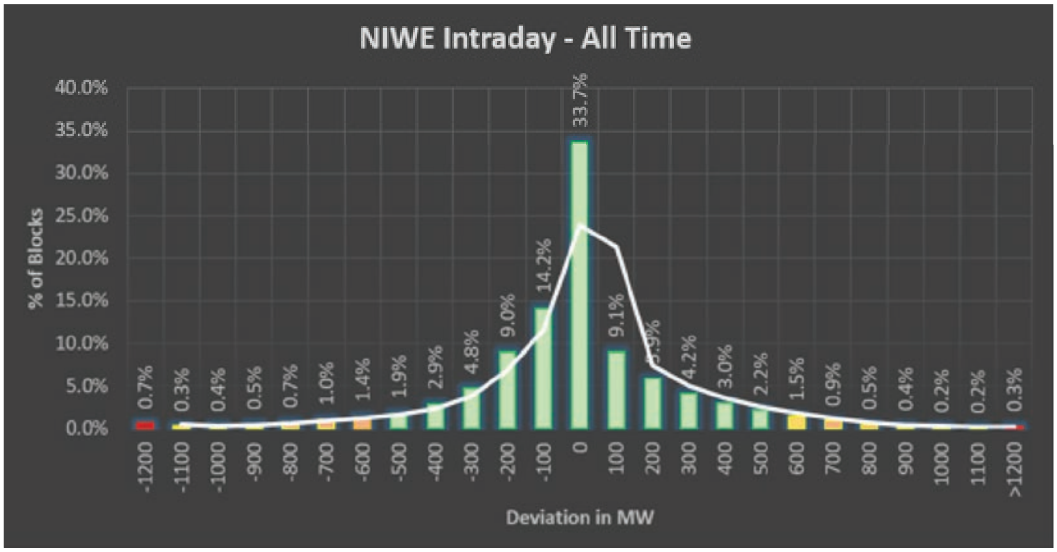
The Eastern Region Load Dispatch Centre (ERLDC) stated that the general scheduling of renewable energy is being done on the basis of historical generation data, which often leads to errors.

The National Institute of Wind Energy (NIWE), an autonomous institution supported by the Ministry of New and Renewable Energy, has presented an indigenous forecast model, which has been used for forecasting in the state of Tamil Nadu since 2015. It has also been implemented in the state of Gujarat since April 2018. The indigenous model version 1.0 was developed and validated in all seven of the renewable energy rich states. Furthermore, NIWE is actively carrying out various steps to develop competence in advanced statistical and dynamic downscaling techniques. A method for assessing the wake effect/distribution of wind turbines needs to be incorporated into the current forecast system and is under development by NIWE. Forecasting will be an additional source of information for utilities and the Renewable Energy Management Centre (REMC, see next section), over and above the Power Grid Corporation India, Limited (PGCIL) architecture.

The Indian Space Research Organisation (ISRO) has presented a facility for weather forecasting for solar and wind energy. They capture images every 15 minutes and can provide a forecast 72 hours in advance with 3-hour intervals for solar installations. ISRO also provides a two-day-ahead prediction at 15-minute intervals for all wind energy installations across India. Many techniques are available with ISRO to solve issues such as errors in the initial conditions, errors in the model (systematic/random) and intrinsic predictability limitation.

Figure 7 • NIWE forecast error analysis





Source: NIWE, presentation at Southern region workshop.

Current forecast error distributions (Figure 7) emphasise the need for research and development in the field of forecasting. Weather Research and Forecasting (WRF) model version 3.9, a numerical weather prediction system, is being developed by ISRO so that Indian satellite data can be used for forecasting in India. Using local topographical facts, systematic errors in simulation results can be corrected using ground observations.

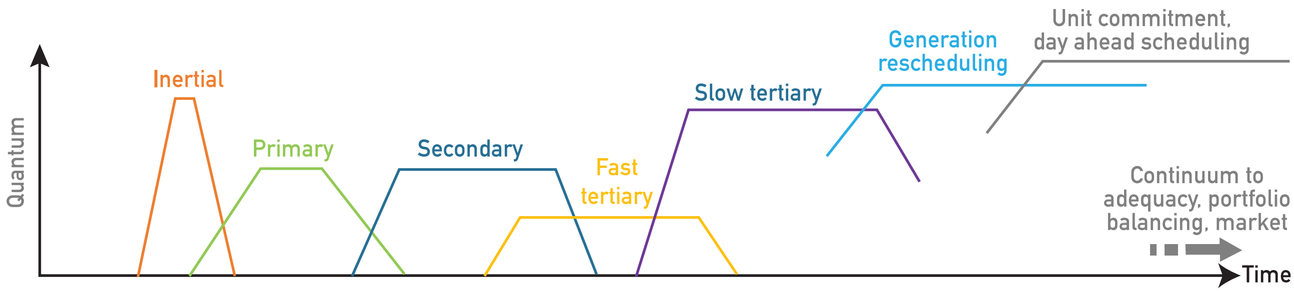
These observations highlight the pressing need to improve renewable energy forecasting.

Similarly, techniques for forecasting electricity demand may also provide room for improvement.

Turning to scheduling practices, stakeholders agreed that protocols need to be updated to enable 5-minute scheduling from the present 15-minute scheduling. This would reduce the requirement for ancillary services and lower the cost of power to the consumer. However, stakeholders also emphasised the need to enforce scheduling for all types of generation at the intrastate level in order to match the achievements that have been made on scheduling at the interstate level.

A similar disparity between the interstate and intrastate level can be observed regarding reserves and ancillary services. For example, while a number of different frequency control services exist in India, participation in these services varies between state and central plants (Figure 8).

Figure 8 • Frequency control continuum in India

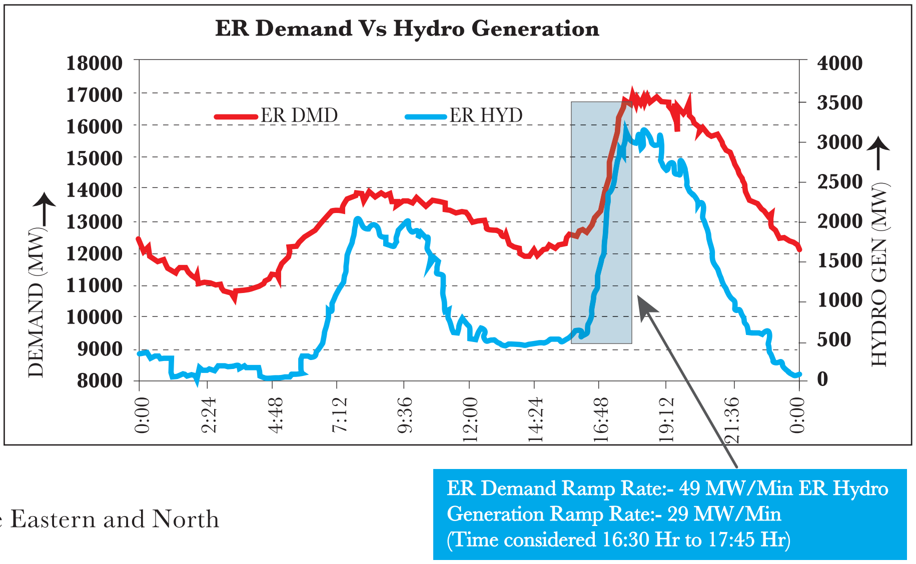


Attribute	Inertial	Primary	Secondary	Fast Tertiary	Slow Tertiary	Generation Rescheduling /Market	Unit Commitment
Time	First few secs	Few secs to 5 min	30 secs to 15 min	5 to 30 min	> 15 to 60 min	60 min	Hours / day ahead
Quantum	~10 000 MW/Hz	~ 4 000	~ 4 000 MW	~ 1 000 MW	~ 8 000 to 9 000MW	Load Generation Balance	Load Generation Balance
Local / LDC	Local	Local	NLDC / RLDC	NLDC	NLDC / SLDC	RLDC / SLDC	RLDC / SLDC
Manual/Automatic	Automatic	Automatic	Automatic	Manual	Manual	Manual	Manual
Centralised / Decentralised	Decentralised	Decentralised	Centralised	Centralised	Centralised / Decentralised	Decentralised	Decentralised
Code / Order	EGC / CEA Standard	IEGC / CEA Standard	Roadmap on Reserves	Ancillary Regulations	Ancillary Regulations	IEGC	IEGC
Paid / Mandated	Mandated	Mandated	Paid	Paid	Paid	Paid	Paid
Regulated / Market	Regulated	Regulated	Regulated	Regulated	Regulated/ Market	Regulated/ Market	Regulated/ Market
Implementation	Existing	Partly existing	Pilot	Yet to start	Existing	Existing	Existing

Source: POSOCO, presentation at Southern region workshop.

Enhanced ancillary service markets, combined with improved spot markets (see below), are critical to remunerating flexible plant operation. For example, in the Eastern region hydropower plants predominantly meet the peak demand load. Figure 9 shows the demand ramp rate of the Eastern region, along with ramp rate available at hydro plants. It is clear from the figure that the demand ramp rate is met by the hydro plants.

Figure 9 • Eastern region demand vs hydropower generation



Source: ERLDC, presentation at the Eastern and North Eastern regions workshop.

Turning to the last component, the deviation settlement mechanism (DSM), the same pattern can be observed. There is an effective mechanism in place between states via the DSM, while a similarly comprehensive and effective mechanism is not present at the intrastate level.

3.3.2 Renewable energy management centres

GIZ elaborated that under the Indo-German Energy Programme – Green Energy Corridors (IGEN-GEC), Renewable Energy Management Centres (REMCs) have been conceived, identifying their functional mandate and infrastructural requirements. These REMCs will have their own dedicated SCADA procedures, and an external forecasting module. Hence, forecasting by REMCs will be an auto-adaptive way of forecasting for a particular location without human intervention. This data will be independent of weather forecast data, for which there will therefore be no need. The REMCs will receive schedules from individual generators (renewable energy, solar and wind), which will be passed to main generators (conventional generators, thermal and hydro). So far seven REMCs in renewable energy-rich states, three regional REMCs and one REMC at the national level have been conceptualised as nodal institutions for addressing operational issues on the grid integration of renewables, and will be operational in 2019.

3.4. Market design and investment framework

3.4.1 Wholesale power market design and interstate trade

The Indian power sector has a strength in the existence of a power market that began operations in 2003, 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.

The largest share of energy trade takes place through long-term and medium-term contracts, although spot market transactions on a day-ahead basis have been increasing. However, India currently faces a challenge in achieving least-cost dispatch of the system via existing commercial arrangements. A principal issue behind this is the physical delivery requirement in legacy contracts. Moving forward, a decoupling of long-term contracts and physical delivery obligations – including for existing plants – could be conducive to reducing operational costs. Such a step would require careful consideration of how additional flexibility could be mobilised while honouring existing contractual obligations.

Another issue discussed by stakeholders was the exchange of electricity over a wider geographic footprint. Further strengthening the role of spot markets (day-ahead and intraday) could help to allow states to exchange electricity more dynamically, increasing the overall efficiency of system operation. The further strengthening of transmission infrastructure is also needed to enhance trade between states; the Green Energy Corridor programme will be instrumental in this regard.

An enhanced spot market could also provide signals for the more flexible operation of existing thermal generation, the retirement of old inefficient plants, and investment in new flexible resources such as hydropower and storage.

3.4.2 Investment conditions for VRE generation and flexibility options, reducing financial risk

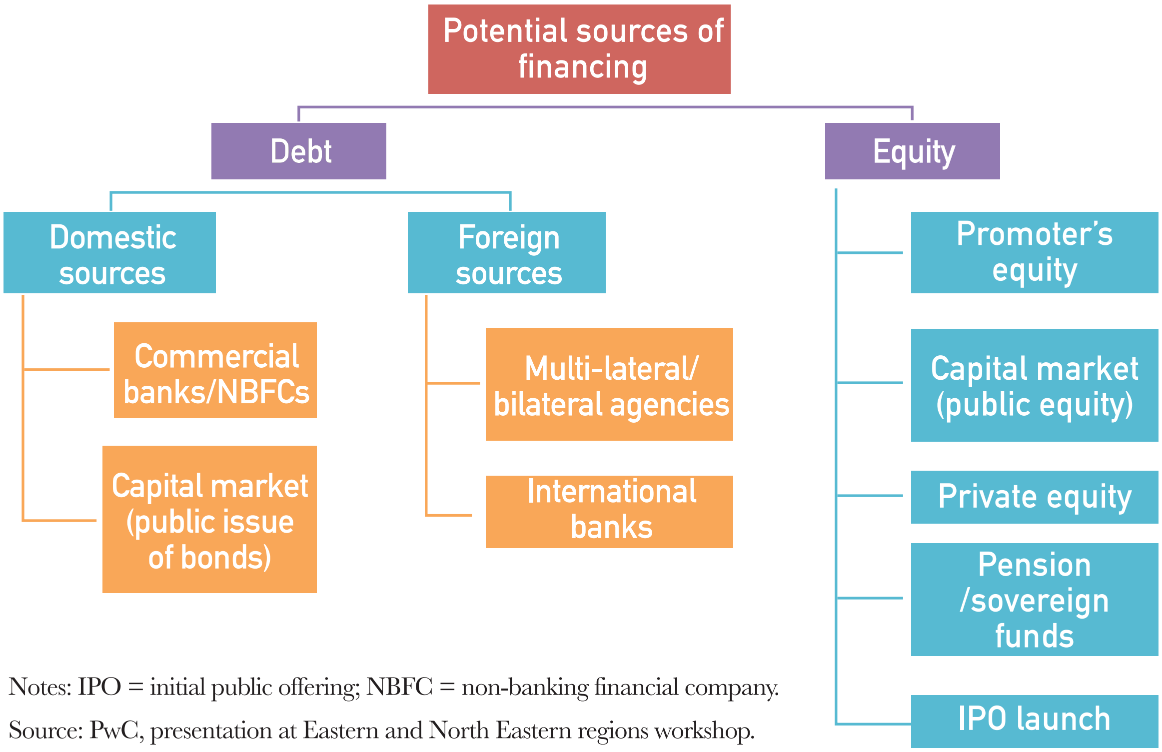
Reducing project risk and improving access to low-cost debt financing will be important in spurring private investment in power generation and flexible assets. Policy and financial approaches need to address both the risk and the value of investments. India's transition to a low carbon electricity system requires increased investment in all forms of flexibility.

Addressing the frameworks and mechanisms for power purchase is another key factor for financing the transition. This may include creation of model power purchase contracts with standardised commercial clauses that simultaneously facilitate long-term debt finance and provide generators with exposure to short-term market signals. Managing investment and financing risks may also benefit from explori new models for public-private partnership and third-party involvement in power purchase and distribution.

Recent work by the Council on Energy, Environment and Water (CEEW) and IEA suggests that investment is also a function of the evolution of the industry landscape for renewable development and the enabling environment for projects (Chawla et al., 2018). Their project-level analysis reveals four key trends. First, there is evidence of greater market concentration among renewable developers, which is facilitating financing, but there may also be limits to higher levels of industry consolidation. Second, solar parks, which aggregate land and infrastructure, are making India's renewable development more accessible to investors around the world. However, stakeholders face persistent challenges in scaling up this unique model. Third, ambitious targets and supportive policies have enabled bigger project sizes, allowing renewables to benefit from economies of scale. Finally, the creditworthiness of offtakers, which affects the timeliness and reliability of payments for power purchase, is having a strong impact on renewable investment decisions. Future work under their collaboration will seek to analyse the sources of finance in more depth.

Ultimately, enhancing the availability of a diversity of lower-cost funding sources will be critical to financing the low-carbon transition. PwC has also worked on potential sources of funding, as presented below in Figure 10. As regarding the domestic sector debt financing, green energy funding commitments were given by the nationalised banks at the RE-Invest 2015 event. Some of the leading banks are committing support to renewables include the State Bank of India, IREDA, ICICI Bank, L&T finance, PTC India, Yes Bank, and IIFC. A total of INR 121 crore was committed by 29 domestic banks to promote renewable energy deployment in the country. Various international lines of credit (totalling USD 4.5 billion) are also supporting Indian solar deployment. Agencies such as the World Bank, JICA, KfW, ADB, AfD, EIB and GEF are supporting very large investment by offering funds available at concessionary lending rates, which are blended with those provided by commercial finance sources. One example is KfW which is investing in and funding the Green Energy Corridor initiative to support interstate/intrastate transmission of renewables in India.

Figure 10 • Potential sources of funding of renewables in India



Notes: IPO = initial public offering; NBFC = non-banking financial company.

Source: PwC, presentation at Eastern and North Eastern regions workshop.

There has been a recent shift from the traditional model of investors providing their own equity toward IPOs, private equity investments and pension funds as routes to generating finance through equity. This, in turn, reflects a huge interest in the Indian power market due to the regulatory framework, with the push towards renewables, technology upgrading and improved returns. The high level of interest from pension funds and private equity firms has seen names such as Abu Dhabi Investment Authority, the Canadian Pension Fund, the Singapore Sovereign Fund, Goldman Sachs, GIC, I Square and Morgan Stanley investing in solar and wind companies in the Indian renewables sector.

3.4.3 Measures to address financial risk of state distribution companies

IEA representatives made presentations on the relevance of cost recovery to the financial health of utilities in order for them to undertake fixed investments in the grid, connect and improve the quality of service for consumers and reduce the risks of generation investments related to the purchase of power. Many of the comments of the participants on this subject were related to the poor financial health of the state distribution companies in India.

There were two schools of thought related to the financial viability of the state distribution companies. Some stakeholders believed that overarching efforts, such as the ongoing Ujwal Discom Assurance Yojana (UDAY) reforms to tackle financial restructuring, reductions in losses and tariff adjustments, would improve the situation, although it was acknowledged that most gains to date by UDAY have come about from financing improvements (lower interest costs) rather than from operational gains or electricity pricing reforms. Other stakeholders believed that financial guarantees or the provision of short-term liquidity would better address the risks related to the state distribution companies, acknowledging the difficulty in executing fundamental reforms in a timely manner. Approaches to financial viability may need to encompass all these aspects, including tapping into international best practice for incentive-based regulation.

4. Preparation by ministries/agencies of the Government of India

4.1 NITI Aayog

In November 2013, the NITI Aayog (erstwhile Planning Commission) initiated a stakeholder-driven analysis of the opportunities and barriers to rapid deployment of renewable energy electricity. Entitled "A Report on India's Renewable Electricity Roadmap 2030", the process was facilitated by the NITI Aayog in conjunction with its role of co-leading the 21st Century Power Partnership (21CPP), a multilateral effort of the Clean Energy Ministerial (CEM) that serves as a platform to advance the large-scale deployment of renewable energy. A steering committee for the exercise was created, led by the then-Member (Energy – Planning Commission of India) and composed of Secretaries of the Ministry of Power, Ministry of New and Renewable Energy (MNRE), Ministry of Finance, Ministry of Environment and Forests, Central Electricity Authority (CEA), Power Grid Corporation of India, Ltd. (PGCIL), and the Energy Secretaries of Tamil Nadu and Rajasthan.

Both the purpose and the challenge of this roadmap exercise has been to assist policy makers and stakeholders to grasp what is at stake, and what they would need to do in order to make a choice in favour of renewables, at scale, successful. The analysis and practical "next-step" policy recommendations that follow are based, in large part, on the broad and robust open-ended conversations conducted under the "Chatham House Rule" with over 250 power sector stakeholders from 13 states. The stakeholders included the steering committee members, chairpersons/members and senior staff of central and state electricity regulatory commissions, energy secretaries of states, managing directors of generation, transmission and distribution companies, grid operators, power sector planning agencies, grid managers, civil society, industry and finance, developers, and bilateral and multilateral institutions.

Initial interviews and small group conversations were conducted throughout the country during December 2013 through March 2014. Preliminary findings were presented to the steering committee in April 2014, then circulated and commented upon by close to 100 stakeholders and domestic and international experts. The draft policy recommendations drawn from the roadmap exercise process went through an iterative process from August through October, 2014 as the roadmap team solicited feedback from diverse stakeholders and domestic and international experts, both through correspondence and in person.

The "Report on India's Renewable Electricity Roadmap, 2030" summarises both the processes and the result of the stakeholder exercise. It presents the opportunities for and barriers to renewable energy as reflected by stakeholder input and provides a summary of the rationale for, as well as benefits and cost of, renewables within the context of the Indian power system. Drawn from the stakeholder input and international experience, the report suggests a framework of integrated policy strategy for rapid renewable energy implementation that complements both the existing and planned conventional power plants. The framework includes:

- A new comprehensive national renewable energy law and/or policy and its components.
- Support mechanisms to ensure timely implementation.
- Grid reforms to ensure smooth integration of renewables.

The policy framework outlined above would facilitate that rethinking, was based on extensive inputs from stakeholders and international experience, and was specifically designed to overcome the barriers to success and to meet the renewables challenge.

4.2 Ministry of Power

The Ministry of Power constituted a Technical Committee for "Large-Scale Integration of Renewable Energy, Need for Balancing, Deviation Settlement Mechanism (DSM) and associated issues". Subsequently, the Hon'ble Minister of State (IC) for Power, Coal and New and Renewable Energy took a meeting on 19th June, 2015 regarding "Large-Scale Integration of Renewable Energy, Need for Balancing, Deviation Settlement Mechanism (DSM) particularly with reference to 150 MW limits, Regional Grids and associated issues". At the meeting, there was convergence, as deliberated by the Technical Committee, that the large-scale integration of renewables requires, amongst other things, forecasting, flexible power systems, markets, spinning reserves, frequency control and an imbalance handling mechanism. Also, at the state level there is a need to forecast load and generation, balance the portfolio, maintain generation reserves and put in place an intrastate imbalance handling mechanism. The following technical requirements are important at all levels for integrating large quantities of renewable generation in the Indian grid:

- Robust transmission services to ensure that renewable generation curtailment is minimal.
- Adherence to grid standards and regulations by renewable generators.
- Load forecasting at DISCOM, SLDC, RLDC and NLDC levels.
- Renewable generation forecasting at pooling station, groups of pooling stations, SLDCs, RLDCs and NLDC levels.
- Establishment of REMCs at SLDC, RLDC and NLDC levels with full real-time data availability from renewable sources, including forecast data.
- Need for primary, secondary and tertiary generation reserves
- An ancillary services framework at interstate and intrastate level to operationalise reserves.
- Primary, secondary and tertiary frequency control
- Automatic generation control (AGC) to implement secondary control on a regional basis.
- More flexibility from the conventional generation fleet, comprising coal, gas and hydro.
- More flexible resources, such as pumped storage hydro resources, in the country.

4.3 Ministry of New and Renewable Energy

The Ministry of New and Renewable Energy and GIZ, under the IGEN-GEC, launched a summary report on "Market design for renewable energy grid integration in India". The report suggested that the mitigation of renewable energy variability and intermittency can be achieved through forecasting, balancing and ancillary services. While renewable generation forecasting is rapidly evolving, there is no methodology for estimating renewable generation with 100% accuracy. The following are the barriers to the large-scale integration of renewables into the Indian grid:

- Renewable power (solar and wind) is non-dispatchable, which means the plants can generate power only when solar and wind resources are available. Therefore, the power system requires dispatchable plants during the period when renewable generation is not available.

- Grid support services are required to manage the grid integration of renewables. There is a need for flexible generation and load which can respond rapidly and maintain a balance between generation (renewable and conventional) and load.
- Presently, flexible frequency bands and deviation settlement mechanisms, alongside a few storage reserves, are playing a crucial role in balancing minute-to-minute variation in load and supply. These mechanisms also take care of unscheduled generator outages. The adequacy of this mechanism is challenged with the increasing integration of renewable energy and an increasing variability in net load (load minus renewable generation).
- Offtake of renewable power is still a challenge due to its price competitiveness with conventional sources of power. Renewable Purchase Obligations (RPOs), feed-in tariffs, competitive bidding, tax policy and many other policy, fiscal and regulatory interventions are providing impetus to facilitate the offtake of renewables. However, the question arises whether in future such interventions will continue to facilitate the offtake of additional large shares of renewable generation, such as solar and wind, into the grid. Hence, it is imperative to develop a market-driven mechanism in addition to regulatory interventions in order to foster higher shares of renewables on the grid.
- Sufficient low-cost financing mechanisms and adequate financial instruments are needed to foster an increased share of renewables on the grid.

To enable the large-scale integration of renewables onto the grid, the evolution of regulations, policy and market mechanisms will be required. In India, these are currently designed for a predominantly conventional generation power system. A future roadmap is needed which will chalk out the changes in regulatory, policy, institutional, capacity-building and market measures required to support the power system achieve the following:

- Must-run status for renewable power is honoured via market mechanisms.
- 100% offtake of renewable power.
- 100% power to be traded on the power exchanges in the long term.
- Ancillary and balancing reserve products to be traded on the power exchanges.
- Introduction of reserve products derived from flexible loads.
- Incentivising of grid discipline by introduction of generator and/or consumer balancing groups.
- Incentivising flexible generation and load.
- Capacity building of central as well as state agencies

In order to accomplish the above, the current power system operations and market operations should go through a phased transformation without subjecting the system to any sudden changes in regulations, policy or market mechanisms. This report describes the measures required over a 15 year period for such a transition. This timeline is only representative and may be modified as seen appropriate at the time of implementation. The transition is proposed in three major phases as below:

- Phase 1: Initiation of transition: The most crucial phase is to initiate transformation in the system and prepare for large-scale renewables capacity addition and grid integration. This phase will witness many policy, regulatory, capacity-building and new market/financial instruments that will ensure the capacity addition. The introduction of new grid support services and products through market mechanisms would ensure grid stability and renewables offtake. It can be expected that the volume of power transactions through power exchanges will gradually increase in this phase.

- Phase 2: Mid-transition measures: This phase will witness the gradual maturity of critical actions undertaken in Phase 1 and also enable the tremendous addition of renewables capacity. This phase of the market transition will feature two major milestones: the involvement of consumers in supporting grid stability and the trade of more than 50% of power on the power exchanges post completion of Phase 2. This phase will enable the introduction of demand-side management and incentivise consumers to forecast loads and also provide demand response products.
- Phase 3: Completion of transition: This is the final phase of the transformation. This phase would not involve extensive regulatory measures. On completion of Phase 3 all power would trade via the power exchanges, and all reserve products and ancillary services would also be provisioned via the power exchanges.

4.4 Central Electricity Authority

The CEA is a statutory body under the Ministry of Power. In its Draft National Electricity Plan (Volume 1), the CEA projected renewable energy generation in India. This was based on the projection of renewable capacity addition targets by the year 2021-22, as furnished by MNRE, and considering a renewables capacity addition of 100 000 MW during the period 2022-27. The expected electricity generation from various renewable energy sources has been estimated and is given in Table 9. It can be seen that contribution of renewables is forecast to be around 20% of the total energy requirement of the country in the year 2021-22 and 24% by 2026-27.

Table 9 • Estimated electricity generation from renewables in years 2021-22 and 2026-27

Year	Installed capacity of renewables	Expected generation (billion kWh)					Total energy requirement (billion kWh)	Contribution of renewables to total energy demand %
		Solar	Wind	Biomass	SHP	Total		
2021-22	175 GW	162	112	38	15	327	1611	20.3
2026-27	275 GW	243	188	64	21	516	2132	24.2

4.5 Power System Operation Corporation

Power System Operation Corporation (POSOCO), alongside the National Renewable Energy Laboratory (NREL) and Lawrence Berkeley National Laboratory, prepared a report entitled "Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. I – National Study" (USAID and Ministry of Power, 2017). The study was funded by the US Agency for International Development (USAID) as a part of its Greening the Grid program with other sponsors including the US Departments of Energy and State, and the World Bank (Energy Sector Management Assistance Program).

The use of renewable energy sources, primarily wind and solar generation, is poised to grow significantly within the Indian power system. The Government of India has established a target of 175 GW of installed renewables capacity by 2022, including 60 GW of wind and 100 GW of solar, up from 29 GW of wind and 9 GW of solar at the beginning of 2017. Using advanced weather and power system modelling made for this project, the study team explored operational impacts of meeting India's renewables targets and identified actions that may be favourable for integration.

Their primary tool was a detailed production cost model, which simulates optimal scheduling and dispatch of available generation in a future year (2022) by minimising total production costs subject to physical, operational and market constraints. The model includes high-resolution wind and solar data (forecasts and actuals), unique properties for each generator, the CEA/CTU's anticipated build-out of the power system, and enforced state-to-state transmission flows. Assuming the fulfilment of current efforts to provide better access to the physical flexibility of the power system, the report suggests that 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. This renewables capacity meets 22% of total projected 2022 electricity consumption in India with annual renewable energy curtailment of 1.4%, in line with experiences in other countries with significant renewable energy penetrations. Changes to operational practice can further reduce the cost of operating the power system and reduce renewable energy curtailment. Coordinating scheduling and dispatch over a broader area is the largest driver to reducing costs, saving INR 6 300 crore (USD 980 million) annually when optimised regionally. Lowering minimum operating levels of coal plants (from 70% to 40%) is the biggest driver to reducing renewables curtailment – from 3.5% down to 0.76%. In fact, this operating property is more influential than faster thermal generation ramp rates in lowering the projected levels of curtailment.

While this study does not answer every question relevant to planning for India's 2022 renewables targets, it is an important step toward analysing operational challenges and cost-saving opportunities using state-of-the-art power system planning tools. Further analysis can build upon this basis to explore optimal renewable resource and intrastate transmission siting, system stability during contingencies, and the influence of total power system investment costs on customer tariffs.

5. Outcome of the workshops

The NITI Aayog-IEA-ADB regional workshops brought together stakeholders to discuss and analyse regional issues of renewable energy integration and challenges in the electricity sector in India. These workshops focused on the power system transformation necessary to deliver India's ambitious 175 GW renewable energy targets. Experts identified and highlighted regional challenges and discussed global best practices.

A general consensus was reached on the need for more "flexible" systems. Regarding hardware and infrastructure, flexible power plants and grid infrastructure (both transmission and distribution) were highlighted as near-term priorities. In the longer term, demand-shaping technologies (including thermal energy storage-enabled demand response and electric vehicles as smart loads) as well as electricity storage (both batteries and pumped storage hydro) were highlighted. Moreover, forward-looking technical connection standards (grid codes) were seen as critical to ensuring VRE can contribute to its own integration.

Unlocking this flexibility hardware in practice calls for upgraded operating procedures and market rules. This includes stringent load, hydropower and VRE forecasting, as well as innovations in market design (more frequent market operation, ancillary services, open for new technologies, efficient scheduling and dispatch). From an institutional perspective, improved co ordination between regions and states was highlighted as critical to ensuring efficient short-term trade of electricity across the entire country in order to maximise benefits to all stakeholders. Last but not the least, improving investment conditions for VRE and flexibility options via measures to address financial risk, especially for state distribution companies, were seen as crucial.

Expert groups strongly recommended that all non-financial support options should be made available to renewables, such as support with initial project development. The ecosystems should also ensure that all direct and indirect incentives should be reflected in the tariff of renewables at the procurement end. Options that do not require any project-specific government approvals, such as accelerated depreciation, should be made available in any case, with appropriate changes so that operational performance is assured. Lenders (banks and financial institutions) should be made aware of the specific requirements and characteristics of renewable energy projects so that they can take informed decisions, resulting in reduced risk perceptions, and hence better terms of finance. Sector-specific financing mechanisms (low-cost money-based refinancing, interest subvention etc.) need to be structured, avoiding the possibilities of market distortion. Generation-based incentives should be used as a bridge tool. Being a tail-end incentive, they can be designed to be very effective in encouraging DISCOMs to buy renewable energy and bring down their cost of renewable energy procurement.

Another way forward would be to create and widen the scope of applicability of an ancillary services market. The following could be a roadmap for CERC to incentivise reserve generation in India:

- Primary response through governor operation, available instantaneously, to offset the impact of major tripping or sudden loss of generation.
- Secondary response through AGC to offset the impact of short duration marginal load-

generation imbalance, available after the observation of a few minutes as per set logic.

- Tertiary response through manual control to offset the impact of sustained load generation imbalance, available after assessment by the operator

In addition, specific outcomes of the discussions during the workshop, alongside recommendations, can be found in Table 10.

Table 10 • Main workshop findings and related recommendations

	Issues	Recommendations
Balancing reserve	Availability of balancing reserves	Participation from more players (state and other types including renewables, load, storage) would add to effectiveness of mechanism
		Regulation regarding 5-minute scheduling replacing 15-minutes scheduling needs to be implemented early for better load management
	Absence of regional or national balancing markets	Regional/national balancing market mechanism is required
		Ramping up or down, minimum turn-down and hot start-up are major concern for power generation companies; best practices in the world can be adopted for development of flexibility of thermal power plants and compliance to be assured
	Slow development of REMCs in states	Development of REMCs in states needs to be expedited, which is under advanced stages of implementation
		REMCs to have visibility on real-time renewables generation equipped with state-of-the-art visualisation and situational awareness tools
	SLDCs have limited visibility on real-time renewables generation	For dynamic scheduling, close to real-time data is required along with an accounting and settlement mechanism; there is a need for SAMAST implementation at intrastate level
	Accurate forecasting by renewable energy generator is not available	Need of additional flexibility through better demand forecasting to minimise the requirement of reserves
	Slow pace of development of intrastate transmission infrastructure	Intrastate transmission infrastructure and Green Corridor needs to be developed at faster pace; optimised use of capacity in short term would also be beneficial

Table 10 • Main workshop findings and related recommendations

	Issues	Recommendations
Regulatory issues	Low demand in the RECs	Cost recovery is a key point for integration of renewable energy; policy and financial approaches need to address both risk and value of investment
	Delay in implementation of model regulations	Currently, grid codes are not forward looking for future role of renewables; prioritise development of grid code in low-carbon scenario
	Lack of long-term regulations to support renewables	Deployment of renewables should minimise overall system costs, not only LCOE
	Lack of a regulatory framework and financial mechanisms to support and incentivise DISCOMs to prioritise uptake of renewables	Detailed modelling studies are required for estimating system integration cost; there is a need for developing a mid-term flexibility strategy/flexibility mission for least-cost renewables
		Reduction in carbon footprint due to renewables penetration on a large scale should translate into monetary benefits to DISCOMs; this would offset the cost component by way of grid management required to integrate renewables within the system

Table 10 • Main workshop findings and related recommendations

	Issues	Recommendations
Economic issues	Decline in growth rate of power consumption	Policies and financial measures should address the entire value chain for investment; link measures to enhance investment framework with making the system more flexible
	Incremental growth in both conventional and renewable capacities	Intermittency is not only in renewables generation, but also in demand; incentivise flexibility for generators as well as distribution system; systematically develop demand-side response/load shaping to make load part of the solution
	DISCOMs' needs to run down cheaper conventional sources of power, adding to their losses	Large-scale consumers are setting up their own captive solar plants for RPO compliance; this is an issue for DISCOMs as they lose high-end consumers
	Longstanding PPAs with conventional power developers	
Effectiveness of market	Lack of a vibrant and effective renewables market	There is a need to create a market for renewables by implementing the following: Frequent clearing of dues Developing new renewables aggregators Supporting fast ancillary services Process automation for better control
	No pricing framework to trade surplus renewable power	
	Drastic fall in prices for both solar and non-solar certificates	
	Some renewable sources are not receiving impetus	Renewable energy sources that are not variable (hydro, biomass) are not receiving impetus due to lack of true value being ascribed to them; as cost of generation is high, these sources are not growing

Note: LCOE = levelised cost of electricity; SAMAST = scheduling, metering, accounting and settlement of transactions in electricity.

6. Actionable agenda and way forward

In order to facilitate the integration of 175 GW of renewable power within the synchronised Indian grid by 2022, the following issues must be addressed:

- Upgrade grid technology
  - Ensure visibility and controllability of all large-scale renewable energy systems by SLDCs and RLDCs in their respective areas, with clear responsibilities on operational control. Ensure sufficient visibility and controllability of small-scale VRE assets.
  - Ensure effective scheduling and dispatch at the state level in all states and enhance power exchanges with neighbouring states for better access of least-cost generation.
  - Deploy sensors for real-time data on grid conditions coupled with sophisticated analytical tools to provide necessary information for grid operations.
  - Renewable generators to provide grid services such as AGC and operational data.
  - Adopt state-of-the-art automated load and satellite-based renewables forecasting mechanism integrated with system operation.
  - CTU/STUs should upgrade technologies and make necessary investments to handle the variability through appropriate technical interventions.
  - Adopt advanced decision-making and control systems to enable system operators to respond significantly faster under changed grid conditions.
- Upgrade grid operational protocols
  - Upgrade scheduling and dispatch to 5 minutes from current 15 minute basis. System operations technologies and protocols should be updated to enable 5 minute scheduling and despatch of all resources connected to the grid.
  - State regulators should upgrade their grid code to ensure renewable energy addition does not affect the grid and acknowledge attributes unique to renewable energy generators.
- Improved market design and renewable energy procurement
  - Create model PPAs for renewables that move away from must-run status and employ alternative approaches to limit financial risks.
  - Allow buying/selling of power at rapid speed at power exchanges to manage sudden ramping up and down.
  - Enable fair price discovery and compensation of flexible resource providers.
  - Adopt merit order dispatch based on system wide production costs; supplementary software may be required.
- Expand balancing areas
  - Larger balancing areas can help reduce variability by offering more balancing resources/demand, making it easier to manage. However, due to jurisdictional issues, regulation and management is being done at state level.
  - A single national-level load despatch centre that is non-profit, independent and regulated by CERC could be empowered to manage the entire national grid as one, with appropriate markets and regulatory frameworks in place.

- Promote flexible demand and balancing resources Systems with a high share of renewables require access to sufficient flexible resource.
  - Create policy and regulatory incentives to access the full capabilities of existing coal, gas turbine, hydro and pumped storage generators.
  - Improve availability of substantial balancing, peaking, ramping and flexible resources that can adjust output very quickly, such as flexible conventional sources of energy (gas turbines, flexible thermal generation, hydropower) as well as advanced options such as storage devices and advanced demand-side response enabled by smart grid technologies. Introduce a procurement mechanism to assure grid stability and market participation of all options.
  - Improve the flexibility associated with conventional generating units to accommodate the variability and uncertainty of generation from renewables.
  - Introduce CERC guidelines for coal flexibility, reducing minimum operating levels for coal plants, and a new tariff structure that specifies performance criterion (ramping) and that addresses the value of coal as PLFs decline.
  - Address integration issues on the distribution grid, including rooftop PV and utility-scale wind and solar that are connected to low-voltage lines.
  - CERC/SERC to issue regulations to enable policy-related interventions.
- Promote evacuation of renewable power

Evacuation of power through Green Energy Corridors from the regions with high concentrations of renewable power sources is crucial.

Future collaboration and sharing of international best practices

In order to facilitate with the adoption of the above steps and make enhanced progress on power system transformation, a number of steps regarding future collaboration and sharing of international best practices

First, the IEA and ADB may provide a year-long capacity-building programme under ADB's Regional Technical Assistance programme for selected participants from DISCOMs, REMCs, POSOCO, RLDs, CEA, state renewable energy agencies, the NITI Aayog, and technical staff for the renewable energy expansion programme on issues related to its integration onto the grid. More specifically, Regional/State-level Power System Transformation training weeks are proposed (Box 3).

Box 3 • Regional/State-level Power System Transformation training weeks

In consultation with the NITI Aayog and other relevant stakeholders, the IEA will design Power System Transformation Training weeks.

The weeks consist of a training course of three full-days, focusing on specific topical issues:

- Enhanced system operation (scheduling, forecasting, variable renewable visibility and control, reserve requirements, regional co ordination), power plant flexibility (retrofit possibilities, low-cost strategies for enhancing flexibility) and grid codes.
- Power market design (wholesale spot market design, ancillary services markets, design of

long-term contracts that support efficient system operation), renewable energy procurement mechanisms (auction design, system-friendly deployment) and attracting investment (how to create investment-grade policy and market frameworks, attracting low-cost financing).

- Integrated power system planning (long-term planning tools, production cost modelling, grid planning, reserve requirements), advanced flexibility strategies (electricity storage, electric vehicles, demand-side response) and distributed energy resources.

Two days of the week are dedicated to events for participants from all three strands. The first day is held as a high-level forum that brings together more senior representatives and provides a platform for discussion of the main challenges and possible solutions on the second day. The last day brings together participants to work across work streams on specific issues that emerged from the first day of the training week.

The NITI Aayog-IEA-ADB will jointly decide if such training courses are best conducted for specific states or regions. It is suggested that in any case training courses are allocated to both advanced states/regions with a more urgent need to enhance system integration as well as regions/states where the longer-term impact would be greatest. The total number of training courses should be 4 over the period of 18 months. ADB would support the training courses financially (venue, participant travel as appropriate, funding of external speakers), the IEA would cover staff time to design and implement the training courses, and the NITI Aayog would provide support for the organisation of the events.

Second, ADB's Regional Technical Assistance programme shall support the IEA and NITI Aayog in organising state, regional and national workshops/conferences on a strategy for the low-carbon transition, with a focus on regulatory frameworks that accelerate the uptake of economic and environmentally sound low-carbon energy technologies and system integration strategies (Box 4).

Box 4 • Indian Power System Transformation discussion platform

Jointly, the NITI Aayog and the IEA are in a very good position to design and convene state, regional and national workshops/conferences focusing on strategies for a low-carbon transition. Such events can bring together all relevant domestic organisations in India working on power system transformation and representatives from bilateral technical assistance programmes, as well as international experts. This will ensure that results from different work streams are shared in a timely and comprehensive manner, avoiding duplication and maximising impact. Through its international network, the IEA can ensure that recent, relevant international developments are fed into the discussion process in India rapidly and that innovative solutions developed in India can be shared more widely.

ADB would support the events financially (venue, participant travel as appropriate, funding of external speakers), the IEA would cover staff time to design and implement the events, and the NITI Aayog would provide support for the organisation of the events.

Third, ADB's Regional Technical Assistance programme shall support the IEA and NITI Aayog in establishing bespoke technical assistance capabilities that are tailored to the needs to states in India and leverage and co ordinate ongoing technical assistance efforts (Box 5).

Box 5 • Bespoke technical assistance capabilities hosted by IEA

There will be certain concrete implementation issues that will arise in various states on power system transformation that are of general relevance to India and the IEA "family". The IEA could establish an interface to which analytical requests related to such issues could be addressed and initial answers provided within a few weeks. This could be implemented

jointly via the expert networks that the IEA has, including other governments, industry, technology collaboration programmes and contacts with think tanks and technical assistance bodies active in India. This platform could be accessed via the NITI Aayog and by states directly, with a number of criteria specifying which issues might be taken up. Where there is a need, more detailed and in-depth analysis with a longer time horizon could be conducted.

In a first phase, the IEA would work with representatives from the national and state level, as well as with other relevant institutions (development organisations, think tanks) to scope out the subject areas on which the platform would have the strongest capabilities. At this point, issues that may fall into this category appear to be:

- Market design reforms to enable merit-order dispatch, trade across states and regions, including the benefit of making fuel procurement and PPAs more flexible.
- Benchmarking the flexibility of the existing system and flexibility options.
- Strategies to unlock flexibility from thermal power plants.
- Procurement mechanisms for system-friendly renewables deployment.
- Reforms and instruments to enhance revenue sufficiency of the overall sector.
- Opportunities for load shaping: demand response and smart cooling.
- Integrated power system and energy planning.

Across all three of the above areas, the IEA will carry out this work in close collaboration with partner organisations in India as well as technical assistance programmes that are doing related work. Specific emphasis will be given to countries that are supporting the Clean Energy Transitions Programme of the IEA.

ADB's Regional Technical Assistance programme shall support the NITI Aayog in preparing a state energy roadmap, regional energy roadmap and national energy roadmap for increasing per-capita electricity consumption in the country and promoting clean energy through a low-carbon transition in the energy mix of the country (biomass, waste-to-energy, in addition to solar and wind) and preparing a requirement of second-generation fuels and alternative energy sources for electric vehicles.

References

CEA (Central Electricity Authority) (2018), National Electricity Plan Vol. 1, Generation, Ministry of Power, New Delhi, www.cea.nic.in/reports/committee/nep/nep_jan_2018.pdf.

Chawla, K. et al. (2018), Clean Energy Investment Trends: Evolving Landscape for Grid-Connected Renewable Energy Projects in India, Council on Energy, Environment and Water (CEEW) and OECD/IEA, New Delhi, http://ceew.in/publications/clean-energy-investment-trends (accessed June 2018).IEA (2018a), Status of Power System Transformation 2018: Advanced Power Plant Flexibility, OECD/IEA, Paris.

IEA (2018b), The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning, OECD/IEA, Paris.

IRENA (2016), Scaling up Variable Renewable Power: The Role of Grid Codes, International Renewable Energy Agency, Abu Dhabi.

USAID (US Agency for International Development) and Ministry of Power (2017), Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. I – National Study, www.nrel.gov/docs/fy17osti/68530.pdf.

Abbreviations, acronyms and units of measure

AC	Alternating current
ADB	Asian Development Bank
AGC	Automatic generation control
CAES	Compressed air energy storage
CCGT	Combined-cycle gas turbine
CCS	Carbon capture and storage
CEA	Central Electricity Authority
CEM	Clean Energy Ministerial
CERC	Central Electricity Regulatory Commission
CIF	Climate Investment Funds
CSE	Centre for Science and Environment
CTU	Central Transmission Utility
DISCOM	Distribution company (in India)
DSM	Deviation settlement mechanism
ED	Economic dispatch
EHVAC	Extra high voltage alternating current
ERLDC	Eastern Region Load Dispatch Centre
ESS	Energy storage systems
FACTS	Flexible alternating current transmission system
GCF	Green Climate Fund
GENCO	Generating company
HVDC	High-voltage direct current
IGEN-GEC	Indo-German Energy Programme – Green Energy Corridors
IEA	International Energy Agency
IIT	Indian Institute of Technology
INR	Indian rupee
IPO	Initial public offering
IPP	Independent power producer
ISGS	Inter-State Generating Station
ISRO	Indian Space Research Organisation
IREDA	Indian Renewable Energy Development Agency, Ltd.
KUSUM	Kisan Urja Suraksha evam Utthaan Mahaabhiyan
LCOE	Levelised cost of electricity
LED	Light emitting diode
LVRT	Low voltage right through
MNRE	Ministry of New and Renewable Energy
NBFC	Non-banking financial company
NITI Aayog	National Institution for the Transformation of India
NIWE	National Institute of Wind Energy
NLDC	National Load Dispatch Centre
NRLDC	Northern Region Load Dispatch Centre
O&M	Operation and management
OECD	Organisation for Economic Cooperation and Development
PGCIL	Power Grid Corporation India, Ltd.
PLF	Plant load factor

POSOCO	Power System Operation Corporation, Ltd.
PPA	Power purchase agreement
PSH	Pumped-storage hydroelectricity
PV	Photovoltaic
REC	Regional electricity company
REMC	Renewable Energy Management Centre
RLDC	Regional Load Dispatch Centre
RPO	Renewable purchase obligation
RMS	Root-mean-square
SAMAST	Scheduling, metering, accounting and settlement of transactions in electricity
SCADA	Supervisory control and data acquisition
SERC	State Electricity Regulatory Commission
SHP	Small hydro power
SLDC	State Load Dispatch Centre
SPS	Special protection schemes
STU	State Transmission Utility
SVC	Static var compensator
UC	Unit commitment
UDAY	Ujwal Discom Assurance Yojana
UPPCL	Uttar Pradesh Power Corporation Limited
USAID	US Agency for International Development
USD	United States dollar
VRE	Variable renewable energy
WAM	Wide area monitoring system
WRF	Weather research and forecasting
21CPP	21st Century Power Partnership
GW	Gigawatt
kWh	Kilowatt hour
MW	Megawatt
TWh	Terawatt hour

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