India's sustainable energy future and the challenges for optimised integration of variable energy sources

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Abstract: Renewable energy penetration in India is strongly linked to growing energy consumption, energy security and access to energy. Variable energy sources, viz. solar, small hydro power and wind energy form a significant share of India's energy mix. High intermittency in these technologies can lead to system related operational issues such as varying power quality and unreliability. On the other hand, grid integration of renewable energy projects is essential for bringing about an increase in the renewable component of regional and national energy mix. This paper analyses the existing status, technical and systemic challenges in large scale integration of renewable energy sources. In order to understand the complexities therein, the experiences of renewable energy service providers were supplemented by secondary literature. This paper adopts a system-based view for analysing issues of renewable energy integration and up-scaling for India, encompassing technical, infrastructural, and user specific aspects. It stresses the specific interventions that would bolster system strength and readiness for a renewable rich India. It also highlights key challenges of power quality, constancy and grid balancing and each one's unique position in a sustainable energy future for India.

Keywords: grid integration; grid balancing; distributed energy resources; variable energy sources; sustainable energy system.

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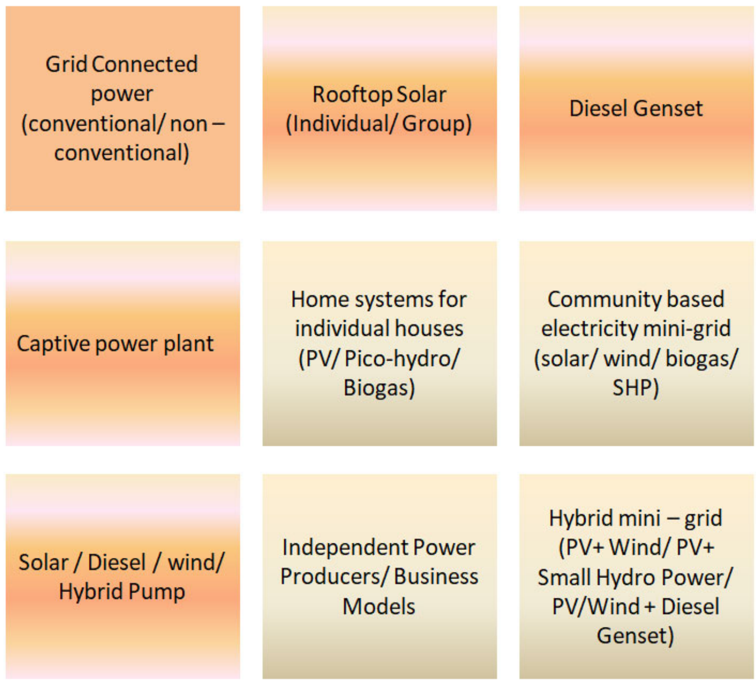
1 Introduction

There are three aspects to Sustainable Development Goal (SDG) 7: universal access to affordable, reliable and modern energy services. Together, these three define the inherent aspects for a sustainable, forward looking energy system. Additionally, another aspect that finds place in the construct of SDG 7 is improved energy efficiency. For ensuring this ideal, the SDG timeline was stated as the year 2030. How well positioned is India's current energy sector for transforming into this ideal construct by 2030? India's energy needs are growing and will soon define the energy trends for the world. With a vast population and significant ongoing shifts in the way individuals use energy in their daily lives, India's energy demands are expected to grow at an exponential rate in coming decades. It is estimated that, already the second most populous country in the world, India will further expand its population numbers to be in excess of 1.5 billion by 2035 (Komiyama, 2010). Energy use patterns are changing even faster: the nation's energy use pattern is expected to double as early as 2021–2022 (Aayog, 2015b). For instance, per capita use of energy shows a consistent increasing trend with a CAGR of 3.54% during 2011–2012 to 2016–2017 (Central Statistics Office, 2018). Currently the third largest energy consumer across the world, energy access remains a crucial area for India. Both existing trends and future projections, however, indicate that even by 2030, substantial number of households across India will be devoid of access to electricity (Bhide and Monroy, 2011; Bhattacharyya et al., 2014). Official records suggest that close to 27 million households continue to be deprived of access to electricity and 780 million people are dependent upon biomass for cooking purposes (Aayog, 2019).

Consequently India cannot afford to continue to rely on its constrained sources of conventional energy, i.e., coal and gas (Bhide and Monroy, 2011; Tripathi et al., 2016). The geopolitical issues related to India's continued dependence on imported sources of energy also hold significance for India's future energy scenario (Aayog, 2015a). In the span of ten years, import of coal has shown a steady increase from 49.79 MTs during 2007–2008 to 190.95 MTs during 2016–2017 while net import of crude oil grew from 121.67 MTs during 2007–2008 to 213.93 MTs during 2016–2017 (million tonnes) (Central Statistics Office, 2018). Not just access to energy, but energy security to citizens, and a shift to sustainable energy mix have also been rated as necessary parameters for India's growth as a developing nation, esp. in the forthcoming decades (Bhattacharyya, 2012). For instance, as part of its external commitment to climate change, India has committed to a target of achieving 40% non-fossil source-based installed capacity by 2022 (Aayog, 2015b, 2019)

In its attempts to provide energy access and energy security to its citizens, Government of India (GoI) has committed to a range of strategies, such as planning for both grid expansion and off-grid, or distributed energy sources (see Figure 1 for a classification of energy access strategies of GoI). This strategic mix has been esp. useful in reaching out to the most remote locations, esp. in rural areas with minimal energy consumption profiles (Bhattacharyya, 2006). With an eye on enabling universal energy access, GoI has taken up the challenge of electrification of all villages in India by 2019 through a strategy of grid extension and rural off-grid electrification (Dubash et al., 2018). There has been consistent growth in off-grid/micro-grid for renewable energy-based minimal energy access, esp. in remote and rural areas beyond access of the overarching grid system. These distributed energy sources, may, consequently be drawn from a multitude of conventional and non-conventional energy sources, or, renewable and non-renewable energy sources.

Figure 1 India's energy access strategic mix (see online version for colours)

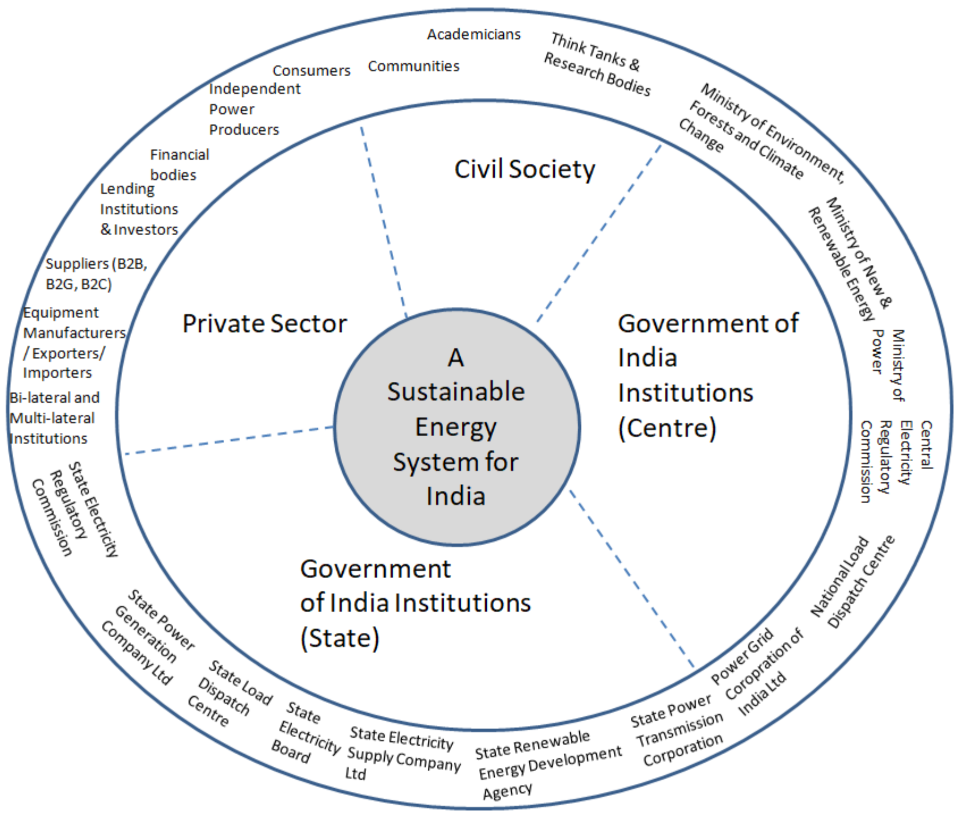


As seen from the figure, it is evident that renewable energy sources play a significant role in India's future energy scenario. It is in this context that there's a need to pursue deeper understanding of India's renewable energy sector; the sphere of interaction between grid challenges and the consequent impact on the nation's ability to make optimised use of its renewable energy potential.

1.1 India's electricity grid

There is a need for understanding the unique nuances of the Indian electricity grid system, its capability to absorb renewable energy technologies and to adapt to the special requirements associated with such technologies. Certain characteristics of the National Electricity Grid in India need to be mentioned early on. The electricity grid in India has evolved from a regional grid structure to a National Grid in recent years' (Yadav et al., 2005; Pradeep et al., 2007; Mukhopadhyay et al., 2012). The National Grid is largely public sector owned, with central and state entities making up the bulk of the power evacuation and implementation system and the role of private parties largely limited to independent generation units, or at maximum, as distribution companies (Aayog, 2015a). It was only consequent to the passage of the electricity act 2003 that a number of power system reforms and shifts were carried out, allowing the entry of GENCOs (generation companies), independent power producers (largely captive power plants for self-consumption), private distribution companies (or DISCOMs), and stand-alone systems for rural and remote areas (see Figure 2 for a classification of major stakeholders in India's Energy System) (Mukherjee et al., 2017).

Figure 2 Stakeholders in the Indian energy system (see online version for colours)



This paper discusses the specific area of electricity grid management using a systems perspective wherein the two aspects of technical grid design and design of governance mechanisms are considered *in toto*.

1.2 Scope of the paper

This paper postulates that issues such as energy poverty and national energy security can be attended to a large extent through optimised and large scale integration of renewable energy supply. The renewable energy sector has considerably expanded in India in recent times. A number of policies and initiatives have had positive influence on the advancement of the sector, further buoyed by the presence of an emerging renewable energy-based private sector (Kolisetty and Jose, 2018). Yet India continues to be at a nascent stage in context of grid integration of variable energy sources. Leaving aside financial aspects, techno-managerial issues are equally crucial for large scale adoption of RET-based technologies. Issues of grid integration are also relevant for future grid extension of functional microgrid projects. Maximising the utilisation of renewable energy sources in the prevalent energy grid system is hence a key area of implementation and power sector reforms. This paper, therefore, attempts to analyse the existing technical and system challenges and current state of affairs in large scale integration of renewable energy sources. An understanding of these critical aspects is hence crucial in context of renewable energy integration and a move towards a decentralised, green and energy efficient power system.

1.3 Research methodology

This paper relies upon the existing experiences of renewable energy service providers, specifically those with experience of having implemented functional renewable energy-based grid-connected projects. Multiple sources of data include one-to-one discussion with grid officials, renewable service providers and relevant stakeholders; and data based on secondary literature, annual reports, research and other documents in public domain. Purposive sampling is used to identify service providers with adequate experience of grid integration issues.

1.4 India's renewable energy potential vs. generation scenario

The geographical position and topographical diversity of India has bestowed upon it an abundance of renewable energy sources including hydropower from its multitude of rivers, wind energy courtesy of its long coastal belts, and solar energy on account of its proximity to the equator (Nautiyal et al., 2011; Khare et al., 2013; Lolla et al., 2015; Dawn, et al., 2019). In its comprehensive roadmap for renewable energy in India, Niti Ayog stated the estimates for India's solar potential at 10,000 GW whereas similar potential for wind energy in India was estimated at above 2,000 GW (Aayog, 2015a). Of these, a major portion of India's renewable energy sources are situated in Southern region (Tamil Nadu, Karnataka, Andhra Pradesh) and Western India (Gujarat, Maharashtra, Rajasthan) with the addition of Himachal Pradesh (for hydropower). Accordingly, in 2015, GoI further upgraded its considerable renewable target to attaining 175 GW renewable energy power by 2022 (Sharma et al., 2012; Aayog, 2015b). The current plan for achieving 100 GW solar by 2022 has been sub-divided as 40 GW to be sourced via Ultra Mega Solar Parks, 40 GW via behind-the-meter rooftop solar and 20 GW through utility scale solar projects (see Table 1).

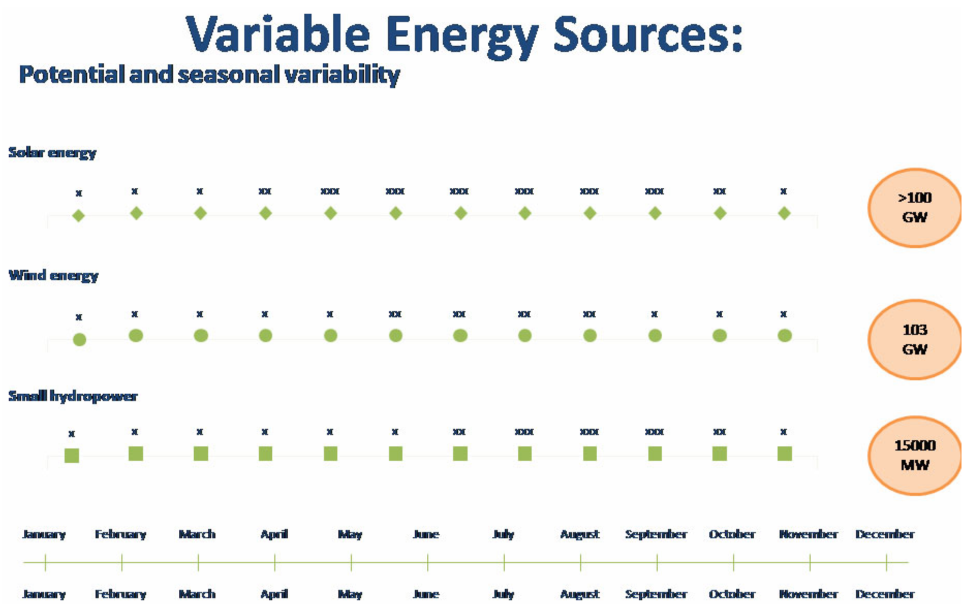
Table 1 Renewable energy potential of India

Renewable energy source	*Potential (MW)*
Solar energy potential	20–30 MW/sq km or >100 GW
Wind potential (@80 m hub height	103 GW
Biomass/bagasse power	17,000 MW and 5,000 MW
Micro/mini/small hydropower	15,000 MW

Source: PGCIL (2012)

India's renewable energy ecosystem has advanced tremendously in recent years. Lowering costs of photovoltaic panels, shifts in competitive bidding mechanisms, and an inconsistent policy atmosphere have been responsible for the push and pull taking place within the system. Yet, current scenario also illustrates the slow uptake of decentralised energy models such as rooftop grid connected solar systems across states. In addition, the quantum of energy generated from renewable energy sources such as solar and wind energy show considerable variation including over immediate, short term and medium timeframe due to factors such as inclement weather, seasonal variations, wind flow variability and cloud cover. While wind and solar show intra-day and seasonal variability (wind is predominant during the monsoon season, or in June to July in Southern India, and solar radiation decreases progressively during winter season), hydropower is largely available during the monsoon months, with flowing water availability in rivers decreasing thereafter) (see Figure 3) (PGCIL, 2012; Chattopadhyay, 2014).

Figure 3 An illustration of the potential scope and seasonal shifts of variable energy sources in India (see online version for colours)



Currently in India, approximately 56% of electricity generation takes place through operation of conventional coal-based thermal plants. Further, the electricity grid largely operates devoid of substantial ancillary services (or storage mechanisms), hence, generation and transmission have to be adeptly balanced (Ministry of Power, 2016). This scenario, coupled with the emerging increase in proportion of renewable energy mix through wind and solar power (Khare et al., 2013) leads to rising variability and systemic challenges as detailed further.

In addition to resource availability, a number of technical and systemic barriers continue to persist that prevent the uptake and optimum utilisation of renewable, esp. variable energy sources in India. There are also specific barriers linked with deployment of renewable energy technologies (see Ellabban et al., 2014) (see Table 2). These technical and infrastructure barriers reflect the state of readiness of the power system and its capacity to adapt to the specific requirements of renewable energy sources (Painuly 2001, see also Ravindranath and Balachandra, 2009; Luthra et al., 2015). While a lot of focus has been on the technological models, policies and state incentives, the capacity of the system to accept and integrate these newer, decentralised and flexible generation technologies also needs equal focus.

Table 2 Barriers to renewable energy technology deployment

Regulatory and administrative barriers					
Technical barriers	*Infrastructure barriers*	*Public acceptance and environmental barriers*	*Market barriers*	*Financial barriers*	*Economic barriers*
Grid integration	Grid integration	External benefits and costs	External benefits and costs		External benefits and costs
Noise, visual etc		Noise, visual etc	Up-front costs	Up-front costs	Up-front costs
Policy		Policy			Policy
		Site choice			Site choice
Capital demand and operation costs					Capital demand and operation costs

Source: Adapted from Ellabban (2014)

Table 3 Installed capacity of renewable energy sources (in MW)

Programme/scheme wise physical progress cumulative up to March, 2019	*Cumulative achievements (as on 31.03.2019)*	*Potential (Central Statistics Office, 2018)*
1 Grid-interactive power (capacities in MWp)		
Sector		
Wind power	35,625.97	3,02,251 MW
Solar power-ground mounted	26,384.30	6,49,342 MW
Solar power-roof top	1,796.36	
Small hydro power	4,593.15	21,134 MW
Biomass (bagasse) cogeneration)	9,103.50	7,260 MW (sugar mills)
Biomass (non-bagasse) cogeneration)/captive power	674.81	18,601 MW
Waste to power	138.30	2,554 MW (including off-grid below)
Total	78,316.39	
2 Off-grid/captive power (capacities in $Mw_{eq)}$		
Waste to energy	178.73	
Biomass gasifiers	163.37	
SPV systems	915.61	
Total	1,257.71	

Note: Status as of 31/03/2019

Source: MNRE (2019)

For instance, in a number of states, Aayog stakeholder discussions established that state owned discoms were more attuned to seeking curtailment from renewable energy suppliers rather than asking conventional plants to step down, leading to operational and financial issues for renewable energy project managers. On the other hand, states that are deficient in renewable energy have not attempted to maximise renewable energy sources even to the extent possible as per the existing resource availability (Aayog, 2015a). All of the above significantly impacts the current low utilisation of renewable energy sources vis-á-vis the overarching renewable energy potential of the nation (see Table 3).

The next section is a comprehensive literature review on issues related to grid readiness and flexibility (including emerging opportunities such as demand side management) and the scope for large scale renewable energy integration for India.

2 Literature review

2.1 Policy initiatives for up-scaling renewable energy

A number of policy initiatives have taken place in the sphere of ensuring energy access to all, including the Electricity Act, 2003, the National Electricity Policy 2005, and National Rural Electrification Policies (NREP), 2006. In 2008, India launched the National Action Plan for Climate Change (NAPCC) with eight missions designed to mitigate climate change impact. The National Solar Mission was one of these, with the objective of installing 20 GW solar power capacities by 2022 (now advanced to 100 GW). Advances in the Indian renewable energy sector have been guided by national and state policies of incentives, subsidies, preferential tariffs exemptions and large scale investments by the state or private producers (Kolisetty and Jose, 2018; Tarai and Kale, 2018).

Table 4 Standards, regulations and policies on Indian power system and grid integration of renewable energy sources

Standard/regulation/policy	*Year of passage*
Indian Electricity Grid Code (IEGC): setting up of the National and Regional Load Despatch Centres (NLDCs, and five SLDCs)	2010
Power System Operation Corporation (POSOCO) (overseeing NLDCs and SLDCs) – independent govt. company in 2017	2010
National Mission for Enhanced Energy Efficiency (NMEEE)	2010
Technical Standards for Connectivity to the Grid	2013
Technical Standards for Connectivity of Distributed Generation Resources	2013
National Electric Mobility Mission Plan (NEMMP) 2020	2013
National Smart Grid Mission (NSGM)	2015
Central Electricity Regulatory Commission (deviation settlement mechanism and related matters) (third amendment) Regulations	2016
Draft National Policy on RE-based Mini/Micro Grids	2016
Setting up of the Renewable Energy Management Centres (REMCs)	2016–2017
Procedure on Forecasting, Scheduling and Imbalance Handling for Variable Renewable Energy Sources (Wind and Solar) at Inter-state level	2017
Framework on Forecasting, Scheduling and Imbalance Handling for Variable Renewable Energy Sources (Wind & Solar) at Inter-state level	2017

Policy initiatives have included renewable purchase obligation (RPO), renewable energy certificate (REC), clean development mechanism (CDM), along with now discontinued generation-based incentives for wind sector (Kar and Gopakumar, 2015). Tariff setting has also moved from fixed to competitive bidding in both solar and wind industries. Research around renewable energy technologies have focused on the policy and regulatory frameworks (Schmid, 2012; Sargsyan et al., 2011), optimal sizing and technology selection, and implementation of community energy projects (Nouni et al., 2008; Hiremath et al., 2009; Kaundinya et al., 2009; Kumar et al., 2009; Kanase-Patil et al., 2011; Pandey, 2012). Khana and Barroso (2014) studied India's experience with auctions of solar energy products under the National Solar Mission and the linkage with regulatory stability. Khare et al. (2013) focused on supportive policy instruments as well as regulatory, institutional, financial and technological barriers related to RET in India. Table 4 lists recent changes in technical regulations and standards that have and will considerably impact the renewable energy sector's implementation trajectory (PGCIL, 2012; CERC, 2017).

2.2 Grid modernisation, balancing and integration of renewable energy

In recent years, power generation, transmission and distribution architecture has been modified from a one-way, centralised process located around large scale energy generation plants with requirement of high voltage transmission infrastructure to low voltage, decentralised generation and local distribution, with Smart Grid architecture, real-time customer engagement and participation, and mutual benefits to utilities and customers (Alvial-Palavicino et al., 2011; Pargal and Banerjee, 2014; IEA-ETSAP and IRENA, 2015). Further, new age grid design aims to be more flexible, smart, and functional in real time. It also includes multiple components with the potential to enhance integration of renewable energy sources while ensuring power quality, constancy and balance.

IRENA differentiates between dispatchable and non-dispatchable renewable energy sources wherein the latter are subject to intermittency and sudden spikes and drops; hence these are also called as variable energy sources. This implies that intermittent resources such as wind and solar may at best be forecasted with a certain level of uncertainty (Madrigal and Porter, 2013). This variation can lead to issues of power quality; reliability and failure in grid connected RET projects (IEA-ETSAP and IRENA, 2015).

The two most prominent challenges to large scale integration of renewable sources of energy, esp. variable energy sources (i.e., wind, solar, including concentrated solar power, and wave and tidal power) are

a the inability of the conventional electric grid to adapt to intermittent generation nature, as also the sudden spikes or drops on account of renewable energy sources

b the remote location centred nature of renewable energy, placing stress on weak transmission networks with consequent faults and high energy losses (Mukhopadhyay et al., 2013; Pargal and Banerjee, 2014, IEA-ETSAP and IRENA, 2015).

Researchers have focused on technical challenges (esp. stability) arising from integration of large scale PV (see Shah et al., 2015; Adefarati and Bansal 2016). Manditereza and Bansal (2016) discuss the different short-circuit characteristics of various types of distributed generation resources and their overall impact on system stability and protection. Hare at al. (2016) review various failure modes that may occur in micro-grid components (inclusive of conventional and renewable technologies).

Challenges arising from high integration of distributed energy resources, predominantly PV systems assigned to low voltage grid system (closer to user end) include sudden rise in voltage, reversal of power flow with consequential issues of protection, higher losses, and transformer, cabling related issues (Passey et al., 2011). The traditional distribution networks are designed to flow from medium to low voltage networks. Integration of high numbers of PV systems may lead to unbalancing of this directional flow, resulting in reverse power flow, and high active and reactive power losses, impact transformer loading (rated power) and conductor ratings (Kenneth and Folly, 2014). Reactive power losses form a significant proportion of losses under wind power generation, considering that restarting of wind turbine takes up substantial amount of generated power, further weakening the already stressed power system. This showcases the need for advanced protection systems at both customer (load conditioning) and utility end (line conditioning systems) to ensure newer standards of power quality for intermittent generation systems (see Khadem et al., 2010).

Integration may also take into account the flexibilities generated through a mix of renewable energy technologies, with complementary generation timings and patterns, as also regional diversities. Thus, in India, a Southern Grid positive in peak wind generation may be able to supply available power to other grids, both as a means of handling power deficit and for fulfilling renewable power obligations (RPOs) of other states. George and Banerjee (2009) attempted to use an approach based on annual load duration curve calculations for the state of Tamil Nadu as a means to illustrate the potential for integrating wind power in generation expansion planning for the state. Mukhopadhyay et al. (2013) envisioned the high potential of wind and solar capacity addition in southern and western regions of India and stressed on the need for strengthening extra high voltage (EHV) transmission system at 220 kV, and 400 kV levels or laying down of specific corridors for transferring additional renewable energy to other states. This has been the basis for GoI's initiative of green corridors and establishment of Renewable Energy Management Centres with advanced forecasting abilities in renewable energy rich states (PGCIL, 2012; Ministry of Power, 2016).

Large scale integration of variable, distributed, or renewable energy sources requires nuanced response from the grid for acceptance of technological constraints, assimilation of resource availability patterns and location specific requirements, appropriate power evacuation, priority despatch, and considerations linked with the scale of resource. For instance, the complexities arising in a large metro city feeder with high adoption of rooftop solar and bidirectional metering will be at variance with those of a utility scale solar plant and say, a small scale wind-solar hybrid system. Probably the easiest integration would be in case of an ultra mega solar park, connected directly to state or central transmission utility. This is because of the higher levels of generation predictability i.e., a typical daily generation curve largely impacted only by seasonal insolation pattern, cloud cover, and occasional faulty panel or balance of system connections. In contrast, with mini or micro grids linking large number of lower capacity generation devices, there may be higher variation on account of user behaviours such as household load pattern, changes in load curve during weekends, festivals or other special occasions. Here, then, the role of demand management and smart metering gains prominence.

2.3 Smart grids and demand side management

Allowing a smart grid to function has a number of advantages, both for the utilities and the customer. The smart grid, at its core, is a two way communication mechanism under which data can percolate from the generation end to the user end and vice versa. This data exchange allows for real-time information on generation availability, outage event or scenario and other power availability aspects from isolated/distributed generation units to the regional or national load despatch centres. At the customer end, data is available about load profile, metering data, energy storage capacity, and data from 'smart' appliances, electric vehicles etc. (Sood et al., 2009; Balijepalli et al., 2010; Sinha et al., 2011a; for a review on smart grid distribution, please see Cardenas et al., 2014). There, however, are a number of prerequisites essential to functioning of a Smart Grid, including secure platforms for data exchange and communication, data management protocols, and a resource intensive yet efficient architecture. Benefits of a smart grid include real-time information sharing, active power curtailment or balancing, graded load shedding, and flexible system management. Smart grid is also a necessity for exploring applicability of emerging initiatives around efficient use of vehicle to grid mechanism for load balancing and improving system reliability (see also Thakur and Chakraborty, 2015).

Demand side management may be considered as the application of smart grid architecture for balancing loads through engagement with the user. While generation capacities (both conventional and renewable) may be limited in nature, it is possible to bring about a change in customer end usage patterns towards energy efficient appliances, off-peak utilisation through dynamic pricing, and incentivising generation (such as behind-the meter options including rooftop solar, electric vehicles connected to grid during non-use and non-charge periods) (Palensky and Dietrich, 2011; Sinha et al., 2011b; Thakur and Chakraborty, 2015).

3 Results

One of the prominent challenges before both generators and grid operators has been the intermittent nature of renewable energy. Operators have incorporated the use of customised software and forecasting models for selecting the right mix of renewable energy generation (as per location). For instance, this includes complementarities of wind and solar energy generation scenario in specific areas (e.g., the states of Rajasthan). Since solar energy is more available during the day and wind availability is more prominent during morning and evening (for Karnataka, for instance; again, in Rajasthan, wind curves are generally higher during evening/night), forecasting scenarios and designing systems with the right mix of the two renewable technologies has the potential towards improving integration and variability issues.

Grid operators underlined the present system as being satisfactorily under control specifying that only once higher renewable penetration is attained would they switch to strategies such as active power curtailment, reactive power control, and/or demand management. Given the power deficient status of specific states, the emphasis continues to be on provisioning of constant power with minimal outages and load curtailment. This scenario however differs across states given the higher renewable energy mix in some states. The scenario of Tamil Nadu, with higher RE curtailment levels illustrate the need for further reflection (Singhla and Chugh, 2017).

At the same time, operators also indicated awareness of the management towards introducing pilot smart grid experiments for demand side management. Finally, recent initiatives by the NLDC have included operationalisation of weather portal systems for national and regional load despatch centres. As per an agreement between the Indian Meteorological Department and POSOCO, power system operators would be able to gain access to real-time weather information (currently 30 min satellite image availability) for better load management and smoother interconnections. A number of these shifts are very recent and are therefore, in the transition phase.

Discussions with grid operators also suggested that the current scenario of slow uptake of grid connected rooftop solar mechanism may be on multiple accounts including need for administrative approvals such as clear land title, statement of no objection from all involved parties, non-conducive design of existing roof structures (for example reduced available space due to placement of water storage tanks), annual clearance mechanism followed by grid utilities (calculation of generation vs. consumed units done annually at one go) resulting in perceived ambiguity on savings vs. cost incurred, caps on generation as per net metering policy, and lack of technical awareness of users. Consequently, rather than domestic, it is the institutional customers who have been at the forefront of rooftop solar projects. However, operators also felt that across states, net metering policies have slowly become more nuanced. Delhi's net metering policy, for instance, allows for innovative models such as group apartments making collective use of solar power, though it is too early to showcase implementation examples. A number of other innovative models such as cloud-based monitoring systems for remote nanogrid systems and formation of solar cooperatives using solar irrigation pumps and selling remaining power generated to local DISCOM are at the forefront of newer user-based models (see Karnataka's Surya Raitha policy; Shah et al., 2016).

Energy storage is an under-utilised area in the current push for renewable energy. Even in rooftop solar, grid-tie inverter design is mandated to switch off at the time of power shortage leading to non-usage of generation capacity and added customer inconvenience. Current system design even at utility scale do not incorporate energy storage services for price management. In recent years, prices of batteries have also dropped significantly, and the potential for grid balancing through ancillary services including storage technologies is now evident. India Energy Storage Alliance (IESA) is advocating strongly with GoI and power producers for incorporation of energy storage technologies. Under GoI's timeline, 2018–2019 shall be the period for demonstration projects on energy storage technologies, under which PGCIL has already launched a demonstration project in Puducherry focusing on advanced batteries for the purpose of grid frequency management and control. Puducherry also happens to be the site for India's first smart grid pilot project with plans to install 87,000 smart meters covering the entire city (Thakur and Chakraborty, 2015).

3.1 Recommended strategies

The paper underscores a number of strategies for successful integration of renewable energy sources (see Table 5 for consolidated listing), involving a number of shifts in the business-as-usual scenario, including:

a Upgrading and extension of transmission capacities is more time consuming with longer gestation periods in comparison to timelines for setting up of variable energy projects (provided land availability concerns are met). Hence, proactive transmission upgradation in renewable rich states and geographical sectors needs to be taken up on a large scale in order to prevent power evacuation and capacity utilisation issues.

b Setting up command and control centres in renewable rich states and at regional and national level (REMCs) with advanced software, real-time weather scenario availability, and suitable personnel for advance (day ahead) and nowcasting (5–15 minute interval as per standards) is most essential for smooth integration of renewable energy sources.

c Ensuring communication mechanisms across regional and national grid infrastructure and better interconnectivity of regional load despatch centres for improving grid balancing capabilities, reliability and stability is essential for a shift towards a more sustainable energy system for India.

d Incentivising individuals, institutions, communities and private sector developers to generate captive and generational power in places of significant distributed generation source availability is not enough. The power ecosystem has to put into place additional support mechanisms, esp. smart grid and demand-based management such as bi-directional energy flow mechanisms that additionally improve overall stability of the grid.

d Incorporating smart grid architecture and demand side management for reducing peak loads, enhancing system protection and security, and ensuring flexible grid management requires a shift in not just the design of the grid system. At a more human level, there is a need to manage perceptions of involved entities and building in-depth coordination across multiple states.

e A neglected area of attention is the need for upgrading existing and functional variable energy resources such as already operational wind farms, solar systems that were set up prior to the newly introduced power quality standards. The inefficiencies inherent in their design (for e.g., low turbine heights and blade span) have played a role in building negative perception of renewable energy sources and prevented them from reaching the ideal status of grid parity.

f Ensuring and periodically assessing implementation of national grid codes, standards for renewable energy integration (for operational stability and fault reduction (e.g., frequency, voltage, power balance) needs a more nuanced power governance mechanism, the basics of which continue to be a work in progress.

g Strengthening system specific energy storage capacity and ancillary services for optimised usage of generation capacities of variable renewable sources esp. at peak generation timings can play a substantial role towards improved system flexibility and security of supply, as well as ultimately, in scaling up renewable energy integration.

h India needs much more financial investment, not just in enhancing its renewable energy capacity and share in energy mix, but also in system strengthening and grid infrastructure so that the capacities generated can be incorporated much more effectively in its diverse, yet dynamic energy system.

Table 5 Challenges and potential solutions towards large scale renewable energy integration in India

Identified challenges to large scale integration of renewable energy sources	*Possible solutions to the challenges in large scale RE integration*
Inability of RE rich and deficit states for maximum assimilation of RE resources in grid	Technical and institutional capacity building of state DISCOMs and generators for optimal generation dispatch, prevention of active curtailing of RE resources, managing load-generation balance
Power quality issues as a consequence of large scale low voltage PV systems as RE penetration increases	Implementation of automatic generation control (AGC); smart grid and technology upgradation; learning from high RE integration systems across the world; strategies for power system balancing (Joshi et al., 2017; Mehta et al., 2017)
Remote location of RE resources (weak transmission network and energy losses)	Preparation of resource corridors and transmission systems, remote monitoring, introduction of SCADA, energy Panchayats and village committees (last mile governance mechanisms)
Inclement weather, seasonal, daily and real-time variations in RE generation, issues of uncertainty and intermittency	Data analytics and specialised software for scientific weather prediction, monitoring and forecasting made available at all levels and scales (individual users, village communities, private/institutional generators, state and regional monitoring centres)
Grid devoid of substantial ancillary services esp. storage mechanisms for load balancing	Small scale to large scale storage system design at the centre of R&D push; stress on rejuvenation of non-operational pumped hydro stations; piloting designs for intelligent grid, dynamic pricing, dump loss prevention strategies
Inadequate grid infrastructure and older regulations and standards resulting in barriers for RE integration	Prioritisation of setting up of HVDCs and green corridors for power evacuation; scientific and research community needs to create robust, implementable standards for modern energy and distribution system; tweaking of technical regulations and standards to adapt to gradual increase in RE energy mix
Slow uptake of decentralised energy models such as rooftop grid connected solar	Consumer information programme with technical capacity building of users, RWAs, electricity department officials; single window permissions for simplifying subsidy applications; enabling framework, use of influencers to improve implementation at different scales (institutional, individual, group or community projects)
Poor availability of data and technical analysis for RE integration across states and regions	Collation of evidence/state level studies on load generation, RE resource availability and generation patterns (short and long term), RE curtailing patterns
Variability due to changing energy mix	Detailed load, generation forecasting and dispatch planning, evaluating possibility of increasing flexibility of coal power plants and optimising with other available balancing methods (pumped hydro storage/gas/battery/demand management)
Biases and perceptions among stakeholders within the grid system and electricity market	Training and sensitisation of all line and allied officials, capacity building of SNAs, DISCOMs, IPPs, user committees, community bodies etc.

4 Conclusions

The Indian power sector is currently a work in progress with newer developments and institutional mechanisms currently being established with context to renewable energy integration and management. Stakeholders within the grid system have taken a number of regulatory, systemic and technical measures to facilitate large scale integration of renewable energy resources in India. Recent initiatives have additionally focused on smart grid, automation, and decentralised generation of electricity as the way forward in building of a sustainable energy system for India. Yet, these measures are still a long way from assuming reality in the day-to-day business of the Indian electricity grid system. Discussion and research in this area would be helpful for policy makers, utilities and energy service providers in charting the way forward for putting into place an equitable, sustainable and highly efficient grid network with a focus on optimum integration of renewable energy sources.

5 Limitations and future research possibilities

The scale of this study is unable to do justice to the myriad number of perspectives that can be brought out via a detailed system-based endeavour. The current paper may at best be seen as a snapshot of the existing electricity grid scenario and the potential for integration of renewable energy generation capacities in India. It is therefore prudent to update the status of existing mechanisms, and their actual implementation scenario on a periodical basis.

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