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Flexibility requirement for large-scale renewable energy integration in Indian power system: Technology, policy and modeling options

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ABSTRACT

Reliable and stable power system operation requires flexibility, in addition to capacity adequacy. Traditional system components either have limited flexibility to suppress extensive system variation, or their role is limited due to lack of proper regulatory provisions and inefficient market design. Large-scale integration of renewable energy (RE) resources (*e.g.*, solar, wind) imposes additional variability and uncertainty to the existing system and thus enhances flexibility need. There are various solutions to the problem. Revamping system operation protocol with existing resources, retrofitting current power-generating assets, network expansion, *etc.* can provide flexible service. Investing in a new type of resources like energy storage and demand-side response (DSR) however, needs aggressive policy interventions and market mechanisms. Identifying suitable flexible resources and designing appropriate policy structures require long-term system planning. Traditional methods in this regard need to evolve to consider the operation-scale impact of large-scale RE integration at the planning stage such that long-term carbon emission reduction targets can be met. The approach towards transitioning into a flexible energy system can differ according to its present status. This paper focuses on the Indian power sector's perspective, which has ambitious RE integration goals. With a fast-evolving system configuration, flexibility related challenges are high in India due to weak infrastructure, inefficient regulatory policies, and aggregated planning methods. This article presents the current status of the Indian power system detailing existing technology types, regulatory norms, and future targets. It further details a comprehensive review of relevant technical options, market mechanisms and planning approaches for transitioning into a flexible power system for India. Comparative analysis with international experiences highlights the need for a major paradigm shift. A short-term transition towards becoming a flexible system can focus on developing adequate transmission infrastructure, exploit available pumped hydro storage potential and retrofitting existing coal-fired power plants. On longer-term, innovating market mechanisms and regulatory changes should drive investment into emerging flexible resources like DSR, storage, *etc.* Planning for this transition should be designed using improved modeling and planning approaches which should focus on the interlinking of different sector-specific models.

1. Introduction

India has expressed aggressive renewable energy (RE) expansion plans to fulfill its sustainable development targets, *i.e.*, reducing dependency on imported fuel, meeting climate change obligation, and ensure 100% access to electricity for its people. Several policy mechanisms, like state-wise Renewable Portfolio Obligation (RPO), Renewable Energy Certificates (REC), Accelerated Depreciation, and Feed in Tariff have been promulgated to promote RE generation [3–6]. In the 21st Conference of Parties (December 2015, Paris), India announced its intention to achieve 33%–35% less emission intensity per unit of GDP by 2030, compared to the 2005 level as a part of its Nationally Determined Contribution (NDC). It also includes a target to achieve 40% cumulative non-fossil-fuel based electric power generating capacity by 2030 [7]. To fulfill these targets, India has announced to increase its RE capacity to 175 GW capacity by 2022 [1] (Fig. 1). Adding on this target, recently the Indian president has asserted to increase total RE capacity beyond 175 GW to 450 GW by 2030 [8]. National Tariff

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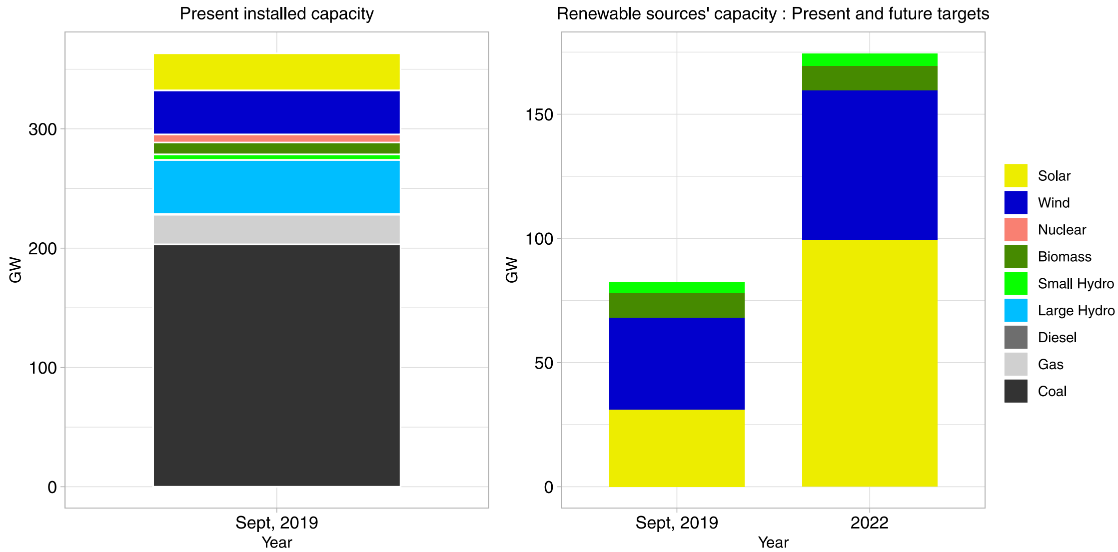


Fig. 1. Present capacity mix and future RE targets of India [1,2].

Policy 2016 has proposed to increase solar RPO target from 3% to 8% in 2022 (excluding hydropower) [9]. Thus, with various central and state initiatives, India is currently focusing strongly on renewable energy sources and steady growth is expected which can overtake the conventional generation capacity addition rate.

India's present utility-scale installed power generating capacity is around 364 GW with 63% share of fossil fuel based resources (Fig. 1). Captive power generating capacity is around 58 GW which is mostly constituted of coal-, gas-, and oil-based plants. In terms of generation, total share of fossil fuel is still around 80% with RE contributing around 9% (Fig. 2). With high RE integration targets, current generation mix will change considerably in the coming years. India's RE expansion plans are mainly constituted of solar and wind which are variable sources of electricity. Additional variability associated with these sources affects power system stability, reliability, and calls for existing system to be more flexible. Flexibility is the ability of a power system or resource(s) to respond reliably and rapidly to any changes in operating conditions at various timescales [10–13].

Flexibility of a system resource can be understood in three dimensions: range of power output (MW), speed of power output change (MW/min), and duration of providing energy (MWh). A single resource cannot always respond in these three different dimensions, and the operators need to maintain a diverse portfolio of flexible components for day-to-day balancing. Resources having wide range between maximum and minimum output can respond to a large range of variation, while others having fast response time can damp any quick imbalance within a short duration. Entities with the ability to deliver energy at longer time span can provide flexibility to address disturbances for an extended duration [11,12].

In light of increased RE penetration, ensuring system flexibility requirements in multiple time scales is critical to combat additional variability and uncertainty. Traditional power systems handle uncertainty from demand and equipment outages using operating reserve, contingency and security analysis. RE extends existing variability and uncertainty in wide spatial and temporal scale, which necessitates faster response from system resources. Though there is consensus on the importance of flexibility with respect to increased RE penetration, identification of appropriate technological options for a national energy system is still challenging. Techno-economic uncertainty of new flexible resources like storage and their higher cost *vis-a-vis* existing options (*e.g.,* gas-fired plants), and inefficient planning methods are main reason behind this.

For India, flexibility requirements are increasing with rising RE expansion targets. The objectives of this article are to identify proper technical options, policy mechanisms, and modeling approaches in the Indian context to support system flexibility. Challenges faced by other countries which have attained a high share of RE in their generation portfolio are reviewed, and comparisons have been drawn to identify strategies which could be used to mitigate the challenges in India.

The next section discusses the operation- and planning-related challenges associated with large-scale RE integration in Indian power system. Section three identifies the suitability of different flexibility options in this regard. Section four highlights the need of new and innovative policy mechanisms for flexible resources to integrate them into the existing system structure. Limitations of current planning methodologies have been outlined in Section five, along with possible improvement to identify flexible capacity. Finally, Section six summarizes the findings and draws the conclusion.

2. Challenges with large-scale variable RE integration and its implications

Large-scale integration of solar and wind energy would impact both power system operation and planning strategies (Fig. 3). For a developing country like India, both issues are equally relevant and need to be understood in totality. In this section, these issues are highlighted with emphasis on system flexibility.

2.1. Impact of large-scale RE integration on power system operation

There are three main challenges associated with solar and wind energy integration; temporal variability, output uncertainty, and location specificity [15]. Temporal variability of RE generation makes the supply uncorrelated with demand pattern, thus creating system management related challenges for operators. Uncertainty of output from RE plants creates scheduling-related challenges as RE generation forecasts deviate at real time of operation [16,17]. Finally, sudden generation inrush from RE generators at high resource potential regions creates localized grid congestion.

Due to policy obligation, RE generators are often operated in must-run condition. Therefore, conventional generators serve the residual or net load, which fluctuates widely due to the combined variability from RE and demand. Conventional thermal generators (*e.g.,* coal-fired plants) have several operational constraints to be maintained for stable operation. They cannot be shut down, started or frequently ramped up and down due to concerns of efficiency degradation, carbon emission increment, equipment deterioration, and lifetime reduction. They also

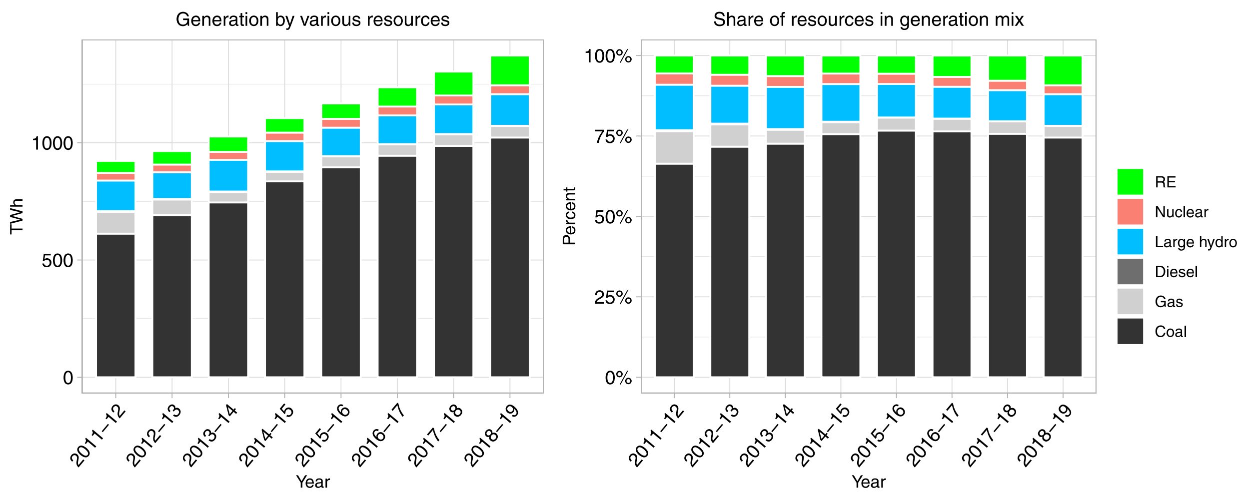


Fig. 2. India's historical generation mix [14].

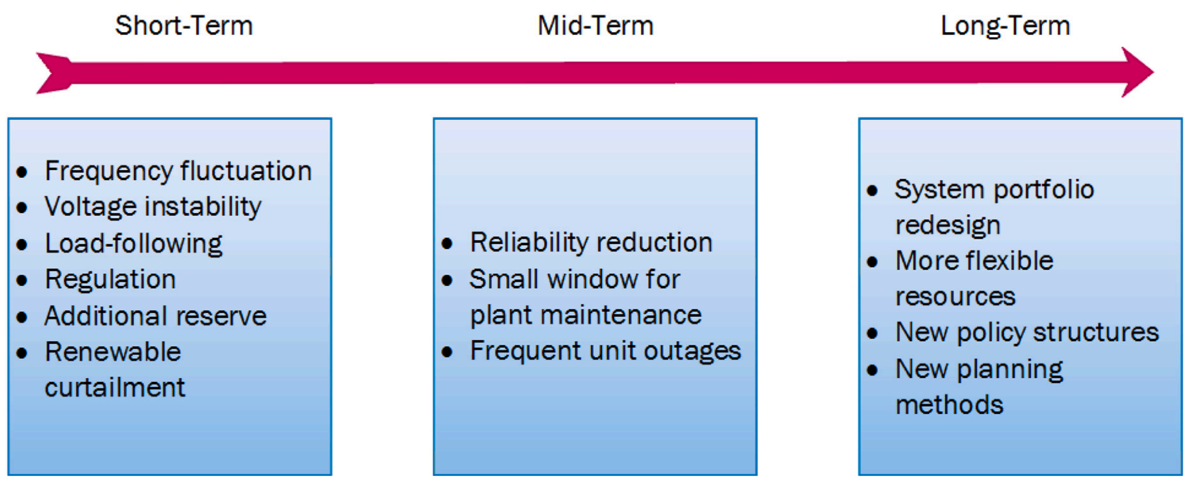


Fig. 3. Time-line of RE variability impact on power system.

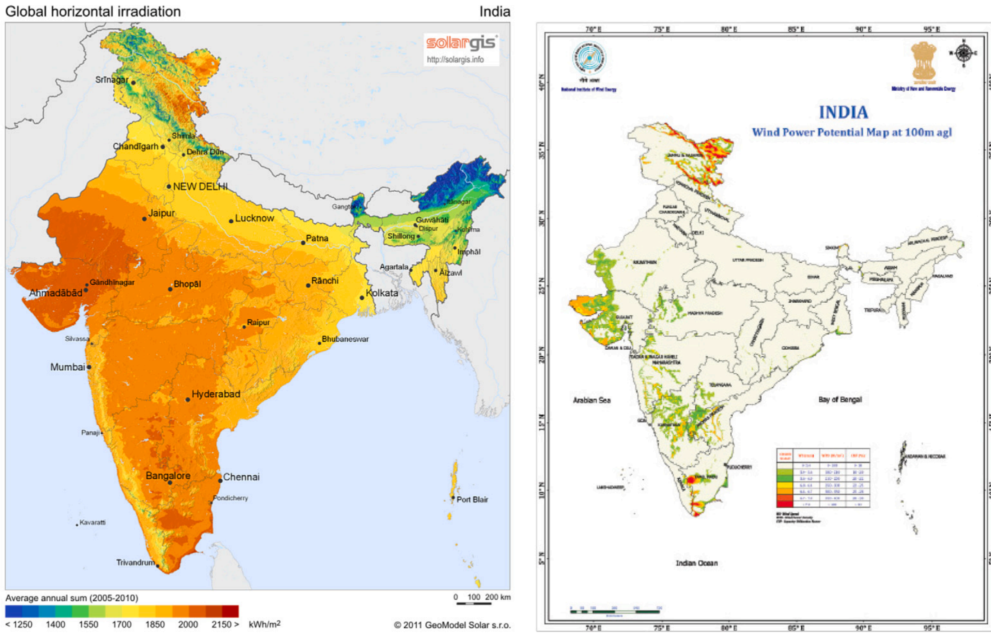
cannot accommodate excess RE generation by lowering their output beyond a certain limit. Therefore, these plants can only provide limited flexibility support for short-term RE variability. Hydropower plants with reservoir have high ramp rates and can help to mitigate system variability, but environmental and irrigation constraints often restrict their balancing capabilities. Network congestion due to insufficient capacity or security regulations also restraints excess RE power to be evacuated.

2.1.1. Renewable energy curtailment

Stable power system operation requires load and generation balance at every point of time. At times of RE over-generation, inflexibility of thermal generators and network security criteria may restrict full utilization of available RE generation [18]. This intentional reduction of generation from variable RE generators is referred to as RE curtailment, which has operational as well as economic consequences [19]. It decreases the capacity factor of RE projects, increases payback time and financing cost, and makes it challenging to meet greenhouse gas emission targets [20].

In several countries, RE curtailment has been a problem associated with large-scale RE integration. Levels of wind energy curtailment experienced in the United States differ substantially by region and utility. In Electric Reliability Council of Texas (ERCOT), 17% wind energy curtailment was observed in 2009 which reduced to 4% in 2012 and 1.6% in 2013. Transmission inadequacy, oversupply, and inefficient market design were the primary reasons in this case [21]. In California Independent System Operator (CASIO), curtailment predominantly occurs due to oversupply, generator ramping constraints, line congestion, and must-run status of hydropower plants in spring. Here, in early 2014, 19.39 GWh of wind curtailment was witnessed [20]. Bonneville Power Administration (BPA) reports around 2% wind curtailment, mainly due to shortage of reserve capacity. Wind curtailment level of 1%–4% in Midcontinent Independent System Operator (MISO) and 1%–2% in Public Service Company of Colorado are usual [21]. In China, total curtailed wind power during 2010–2013 was around 60 TWh, with some provinces having around 30% curtailment rates in 2012. This was mainly caused due to limited transmission capacity and mismatch between the generation and consumption profiles [22–25]. Curtailment rates of several European countries are low, despite having significant RE penetration levels. Strongly interconnected network and well-functioning international power market are the two primary reasons here [25].

Generation curtailment is becoming a concern in India as well with increasing solar and wind energy penetration. Countries like USA, China, and Germany with better grid management protocols and infrastructure witnessed substantial curtailment in near past, and a similar scenario is likely to be repeated here if appropriate mitigation strategies are not adopted. RE Curtailment has already been witnessed in states like Rajasthan and Tamil Nadu due to inadequate transmission capacity and unwillingness of distribution companies to buy costlier RE power. In Tamil Nadu, solar PV plants currently face curtailment up to 50%–100%, due to profile mismatch between generation and



(a) Solar Resource Potential (b) Wind Resource Potential

Fig. 4. Wind and solar resource potential of India [26,27].

demand [28]. Other states like Telangana, Karnataka, Andhra Pradesh, and Jharkhand face imminent curtailment challenges due to current PV capacity expansion plans. Though inadequate transmission capacity is often cited as the major cause for curtailment in India, other factors, such as inflexibility of coal-based thermal generators, improper operation strategies, as well as planning protocols, are increasingly becoming prominent [29].

2.2. Impact of large-scale RE integration on power system planning

Optimizing RE capacity, siting, timing, and planning progressive introduction of flexible resources over a long time frame is essential for national power system development. These tasks are usually performed as a part of long-term planning to satisfy some policy interest. The existing power system structure can handle certain quantum of variability and uncertainty from demand and unit outage using controllable reserve (*e.g.,* thermal power plants). An adjustment of the system operation protocol can only support up to a certain level of RE penetration. With large-scale introduction of generation uncertainty and variability, operational adjustment alone is not enough and significant investment planning is required.

Location specificity of RE resources is one of the major planning related challenges. Good resource sites (high solar intensity, wind power density), situated far away from load centers often create transmission related challenges. In India, geographical distribution of solar and wind resources are not uniform or spatially correlated with demand. Solar potential is high in western states while wind potential is high in western and southern coastal areas (Figs. 4a, 4b). High capacity of inter-state and inter-regional transmission is therefore needed to evacuate RE power to deficit areas. Solar and wind power plants require less installation time than network infrastructure, as securing right of way is a time-consuming process. Therefore, renewable power has to be curtailed till the transmission infrastructure is fully developed. It is also noteworthy that developing massive transmission corridor exclusively for RE is often uneconomical, as it may be underutilized due to natural variability or generation curtailment. A proper cost–benefit analysis over a long time scale is therefore needed in such cases.

Operational flexibility can be harnessed from various sources, like storage, interconnection, demand side response (DSR), and fast acting generators. Recent improvements of wind turbines with continuously flexible transmissions can also enable flexible operation [30,31]. Analysis is needed to assess the utility of these technological options under different techno-economic scenarios [32]. These resources also need innovative policy thrust to compete with existing ones. Effects of these policies, along with technology learning, cost reduction potential, market and social acceptability, *etc.* need to be understood in a long time frame for optimal portfolio planning.

RE curtailment occurs due to operational inflexibility, but it has planning related implications because development of flexible capacity such as transmission corridors, storage, *etc.* has higher lead time than renewable power plant installation. Though, curtailment is undesirable from economic point of view, it provides system flexibility when other measures are either unavailable or costly. On the other hand, allowing curtailment would lead to overbuilding of RE capacity. On national perspective, it could lead to a massive increase in effective cost of energy supply which would be detrimental to its growth prospects. Therefore, planning activities need to judge whether curtailment has long-term positive or negative effect and decide its optimum allowable level from system design perspective [33].

Planning for RE power plant siting is also important as geographical aggregation of RE generators over a large area using electricity network leads to significant statistical smoothing of fluctuations from individual generators, reducing associated integration challenges [34]. Significant planning related to siting of RE plants, erection of transmission lines, coordination between area balancing authorities are needed in this regard.

3. Flexibility options for India to support large-scale RE integration

Therefore, large-scale variable RE integration plans should be supported by suitable and adequate flexible capacity. Various flexibility options have been deployed worldwide to mitigate this variability. Similarly, for India, flexibility options for supporting RE integration are diverse. In this section, only key options for India, *e.g.,* flexible generation, energy storage, interconnection, DSR, and improvements of system operational practices are discussed.

3.1. Flexibility from supply side

3.1.1. Coal-fired plants

Coal-fired thermal generators dominate India's power generation portfolio. Though solar and wind power penetration would increase in the future, coal-based thermal power plants would continue to contribute significantly to the overall generation share. Therefore, the plants have to be more flexible, with higher ramp rates and lower minimum generation limit. Most of these plants in India were installed to ensure generation adequacy, rather than providing balancing support. Though some retrofitted and new units are suitable for faster operation, still the technical, economical, and policy-related challenges[1] restrict them to support large-scale resource variation, without compromising on their performance and lifetime. Generation from these plants can only be reduced up to 70% of rated capacity below which generally oil support is needed. Use of oil is uneconomical, which restricts further backing [35]. In India, minimum start-up time of coal-based generating units is around 15–24 h and in case of week-ends start-up it can go up to 2 days. This creates balancing challenges, leading to high operating costs and restricting generator shut down. Some large central generating stations are not used for balancing purpose (run at constant output) as the states with sharing allocation[2] avoid paying capacity charge when using less capacity [35]. Recently, the ministry of power has taken several steps for existing coal power plants' operation and future capacity expansions. Followings are some of the steps being taken by the ministry of power regarding coal-based power plants along with some recommendations.

1. The Central Electricity Regulatory Commission (CERC) has specified 55% of installed capacity as minimum load limit for central and inter-state thermal generators[3] [38].
2. All inefficient coal-based power plants older than 25 years are to be replaced by modern super-critical units. They are more flexible than traditional ones and will offer better flexibility and part-load efficiency. Centrally owned National Thermal Power Corporation is already phasing out its 11 GW capacity of old, inefficient plants within the next five years [39]. Ultra-super-critical technology based plants are also progressively introduced into the system [40].
3. Renovation and modernization of existing old thermal power stations is continuously going on through retrofitting, regular inspections, and maintenance. These initiatives could increase the efficiency, ramping and cycling ability of these plants [40,41].
4. Ideally, flexible coal-fired powered plants can have ramp rates of 4–8%/min, 2–5 h start-up times, and minimum output limits of 20%–40% of maximum rating [42]. In Denmark, coal-fired plants have ramp rates up to 3%–4% of rated output per minute, and they can cycle down to 10%–20% of maximum output. In Germany, a stable operation limit of 45%–55% is common. Same learning could be adopted in Indian case, especially for power plants located in RE rich states.
5. Coal capacity addition in the future should focus on technologies which can provide generation flexibility. Therefore, flexibility standards need to be incorporated into the supply contract as an additional criterion to develop a competitive market for flexibility.

[1] Various thermal plants in India have long-term power purchase agreement with state DISCOMs which restricts their dynamic operation (*e.g.*, frequent start-up/down or ramping).

[2] In India, power from the stations owned by the central government are allocated to the states by certain rules [36].

[3] A central or other generating station, in which two or more states have shares [37].

3.1.2. Gas-fired plants

Gas-based power plants (*e.g.* combined cycle gas turbines) have high ramp rates, lower start-up times, lower emissions, and lower generation limits. Therefore, they can be utilized to support variable RE generation as a flexible resource. Gas-based power plants are usually operated during peak times (*e.g.*, in the evening) for balancing purpose and to provide ramping support [40]. But, most of the existing gas-based plants in India are either lying idle or operating at reduced plant load factor (PLF) due to fuel shortage (Fig. 5). Plans to increase gas imports from neighboring countries are uncertain due to geopolitical reasons. Recently, some initiatives are being taken by the government regarding gas availability and enhancing capacity utilization of plants. Following is a brief summary of that, along with some recommendations.

- Considering the ability of these generators to support system variability, there is a need to allocate more gas for power generation and encourage building new gas-fired plants, especially in RE rich states [35].
- Recently, the government of India has implemented a scheme to revive and improve the capacity utilization of gas power plants.
- Supply of imported liquefied natural gas (LNG) is ensured to the stranded gas power plants as well as plants receiving domestic gas [40].
- With this initiative, India aims to increase the share of gas in overall energy consumption in next three to four years (15% from 6.5% currently), which will lead to better utilization of existing gas power plants [43].
- As this initiative is planned for short-term, sustainable long-term plans are needed to ensure future gas availability for existing as well as new capacity.

3.1.3. Hydro power plants

Hydro power plants with reservoir are suitable for supporting variations in residual demand, due to their high ramp rates and low start-up and shut-down time. Apart from RE integration, hydro generators have the ability to provide different ancillary services, such as load following, reserve, regulation, thus supporting a secure and reliable power system. But primary operational challenges with hydro plants in India are their multi-purpose use (especially for irrigation) and large seasonal water inflow variations, which cause low annual utilization. The must-run status of hydro units in the rainy season also limits their flexible dispatch and balancing ability [35]. India's hydro power potential is about 148.70 GW, of which 65% is yet to be developed (Fig. 6).

Increasing flexibility on the generation side is important for Indian power sector. Modernization of existing coal-fired power plants, full exploitation of the hydro energy potential and ensuring gas availability are the key areas in this regard. Some steps have already been taken towards coal and gas power plants' performance improvement, though environmental regulations need to be streamlined for faster clearance for hydro power expansion [44].

3.2. Energy storage

Energy storage systems have emerged as attractive flexibility options to support RE integration and energy curtailment reduction [45]. On the generation side, storage can offer different services *e.g.*, energy time shifting, capacity firming,[4] backup capacity, frequency regulation, load following, voltage support, and black start to support RE integration. On the demand side also, storage is a key technology to support DSR. Each energy storage system has unique characteristics suited to different services (Table 1). Detailed technical characteristics of various storage and their application areas are well documented [46–48].

[4] Supplying energy to provide constant power output when RE generation is below its rated power output.

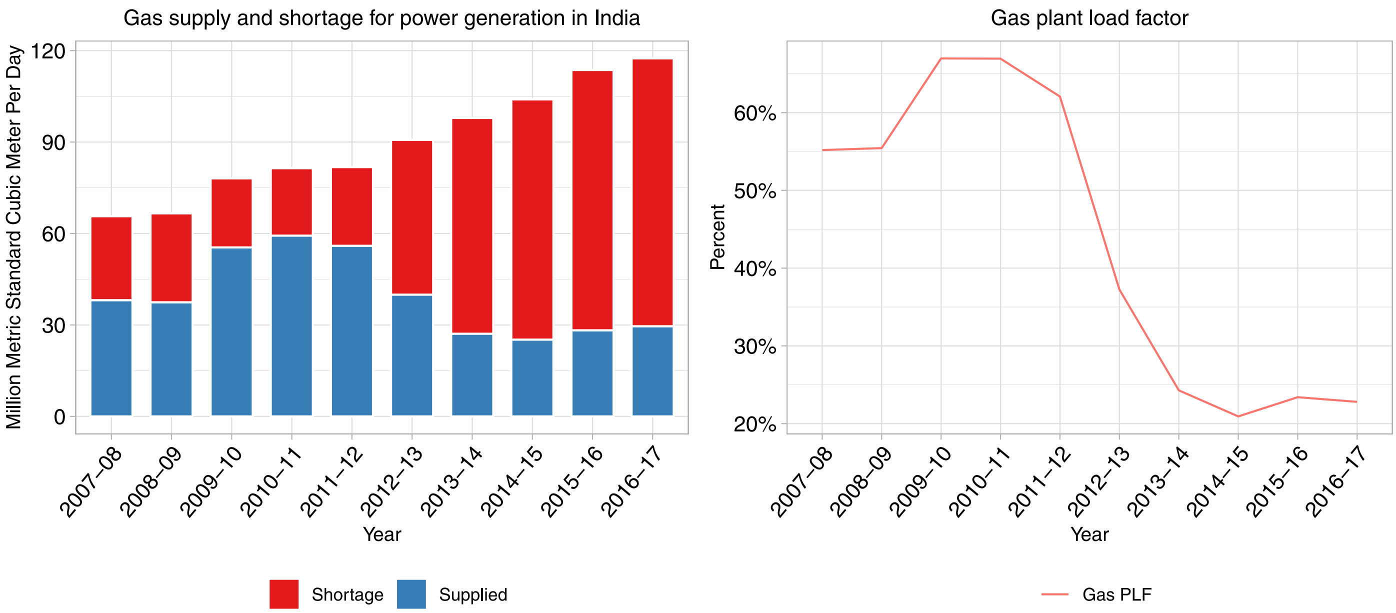


Fig. 5. Historical gas supply position and plant load factors in India [40].

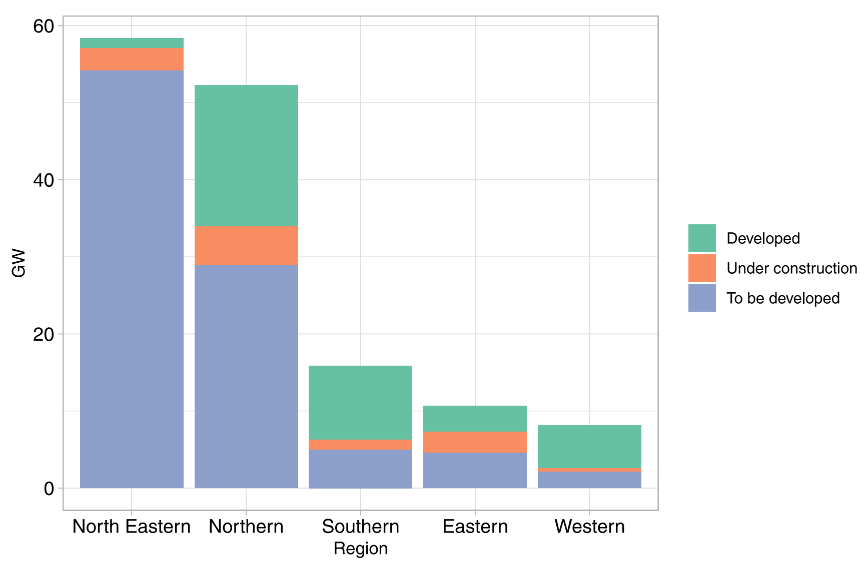


Fig. 6. Region-wise hydro potential and development status in India (GW) [40].

Table 1
Energy storage application areas [46,49].

Category	Services	Discharge time	Storage technologies
Power quality	System stability, transition stability, frequency regulation	Seconds to minutes	Flywheels, super capacitors, lithium-ion, lead-acid
Bridging power	Contingency reserve, ramping	Minutes to one hour	Lead acid, nickel–metal hydride, nickel–cadmium, sodium sulfur, and flow batteries
Energy management	Energy arbitrage, load leveling, transmission and distribution capacity deferral, *etc.*	Hours to days	Pumped hydro, compressed air and battery storage technologies like sodium sulfur, vanadium redox, and zinc bromide

3.2.1. *Pumped hydro energy storage system*

In India, pumped hydro storage (PHS) constitutes the major portion (95%) of current grid connected storage capacity (Fig. 7). Due to its ability to provide peak power, balancing service, and RE integration support, development of pumped storage plants is becoming relevant. A decline of suitable sites for developing conventional hydro power stations, a decrease in the water volume in rivers due to enhanced upstream consumption are crucial motivations for PHS development.

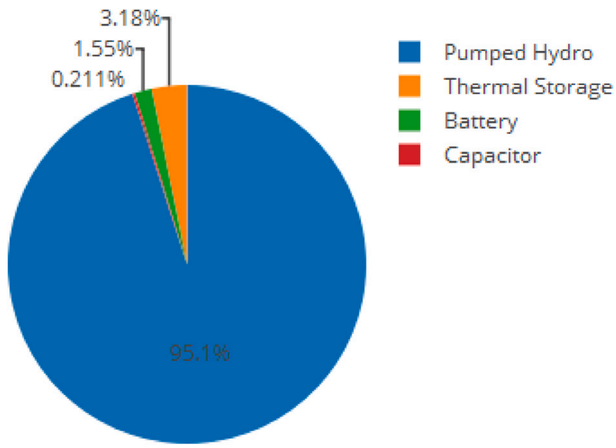


Fig. 7. Current storage capacity distribution in India [50].

Out of 96,524 MW of PHS potential identified in India by the Central Electricity Authority (CEA) at 63 sites, only nine schemes with aggregate capacity of 4786 MW are currently in operation [42].

PHS plants in India are primarily used for energy arbitrage, *i.e.,* utilizing cheap electricity during off-peak periods, to be used during peak load to increase power plant utilization, thus improving the economy of system operation. But due to growing demand, sufficient surplus energy is unavailable, causing existing PHS plants to operate at reduced capacity (50–60)% [51]. Also, several PHS schemes in India face water scarcity due to irrigation demand [52]. Out of currently running 9 PHS plants, only 5 with total capacity of 2600 MW are being operated in pumping mode and the remaining 4 with a total capacity of about 2200 MW are being operated as conventional hydro plants [42].

With increasing penetration of large-scale RE, the importance of PHS is continuously increasing. CEA plans to expand the PHS capacity by additional 10 GW within the next 5–6 years [53]. Future PHS capacity expansion planning needs an understanding of following challenges:

1. Lack of surplus energy is primarily responsible for the slow growth of PHS in India. This could be mitigated by coupling PHS plants with large-scale RE farms. PHS units could store surplus RE generation during off-peak periods and thus reduce energy curtailment. Availability of pumping power at off-peak will ensure better utilization and improve operating efficiency of PHS [54]. So, PHS capacity expansion needs to be linked with RE integration plans, and their co-development, especially in RE rich states needs to be focused.
2. Reassessment of PHS capacity potential (the latest assessment was done almost three decades ago) is needed in light of technological improvements (mines as reservoirs [55], sea water PHS [56] *etc.*), changes in environmental regulations, *etc*. Some identified PHS sites may have to be scrapped and new sites could be found [57].
3. Present market structures and the regulatory framework do not support adequate investment into PHS capacity. There is a need to develop new market mechanism and tariff structures to incentivize PHS capacity expansion.
4. Detailed system planning studies using improved tools are required to optimize PHS capacity expansion plans, which is yet to be performed for India. The storage capacity calculated earlier by some studies in this regard is not optimal as elaborated in Section 5.

3.2.2. Other energy storage systems

The share of storage technologies other than pumped hydro is still small in utility scale, with some installation of electro-chemical and thermal storage systems [50]. There is a large market of battery-based storage in India's residential and commercial sector for power backup. The Indian Energy Storage Alliance (IESA) has estimated over 70 GW of energy storage (all type) opportunity in India by 2022, which is one of the largest in the world. Out of 70 GW, over 35 GW is expected to be deployed for new applications like RE integration, frequency regulation, peak management, Transmission and distribution (T&D) capacity deferral, diesel usage reduction, and electric vehicles [58]. There is an increased interest in deploying electric vehicles (EV) with battery storage in India. The National Electric Mobility Mission targets yearly sales of 6–7 million hybrid and electric vehicles, and a cumulative sales of 15–16 million of EV by 2020 [59]. Energy storage technologies such as battery also has opportunities in RE integrated rural micro-grids.

Mainstreaming of storage technologies, such as flywheels or batteries at utility scale needs suitable economic signals for their services. The development of innovative market mechanisms is crucial in this regard so that they capture storage benefits at single and multiple timescales. Section 4 further discusses these issues. Other options like hydrogen storage are still in the research and development stage. Significant technological innovation, commercialization, and infrastructural investment will be required to integrate them at the system level.

3.3. Network interconnection

As discussed in Section 2, a robust and adequate electricity network is the backbone of successful RE integration. System operational flexibility can be imported or exported fast upon requirement via transmission lines [60]. Thus, a strongly interconnected system reduces the negative impacts of RE variability and thereby lowers the RE curtailment rate [61]. India has five interconnected regional grids which form one national synchronous network with 418,710 CKM (circuit kilometers) of transmission lines (220 kV and above) and 927,783 MVA of transformation capacity [62]. Development of India's transmission capacity is outlined in Fig. 8.

Issues like low voltage, frequency fluctuation, load shedding, high distribution losses, *etc.* prevail in different parts of the country. Despite having surplus in several areas, power transfer to deficit areas is severely restricted due to network congestion, which is a critical issue for system operation in India. Congestion has a significant impact on system reliability, security and power dispatch. Indian Energy Exchange has reported a loss of 5.3 and 3.1 billion units (kWh) of electricity in 2013–14 and 2014–15, respectively due to grid congestion [63]. From an economic point of view, it is desirable that transmission lines should not be under-utilized, while from the operational point of view, they should not be congested to prevent load shedding or generation curtailment events. Congestion cannot be eliminated practically, but it can be mitigated to an extent by enhancing network capacity, using distributed generation and reducing peak demand. With higher penetration of RE in some states in India, congestion is likely to increase, especially in the local grids to which they will be connected. Ensuring sufficient inter and intra-regional transmission capacity is, therefore, critical in those networks. Recent long-term transmission expansion planning studies have put additional interest on developing new transmission corridors for RE capacity expansion [64–66]. Prospective inter-regional transmission corridor capacity up to 2034 is outlined in Fig. 9.

3.3.1. International power exchange and trading

Apart from intra-region transmission capacity development, international power trading utilizing demand pattern differences with neighboring countries could act as a source of flexibility. A prominent example in this regard is the European international energy market. At present, India trades electricity with Bangladesh, Bhutan, and Nepal

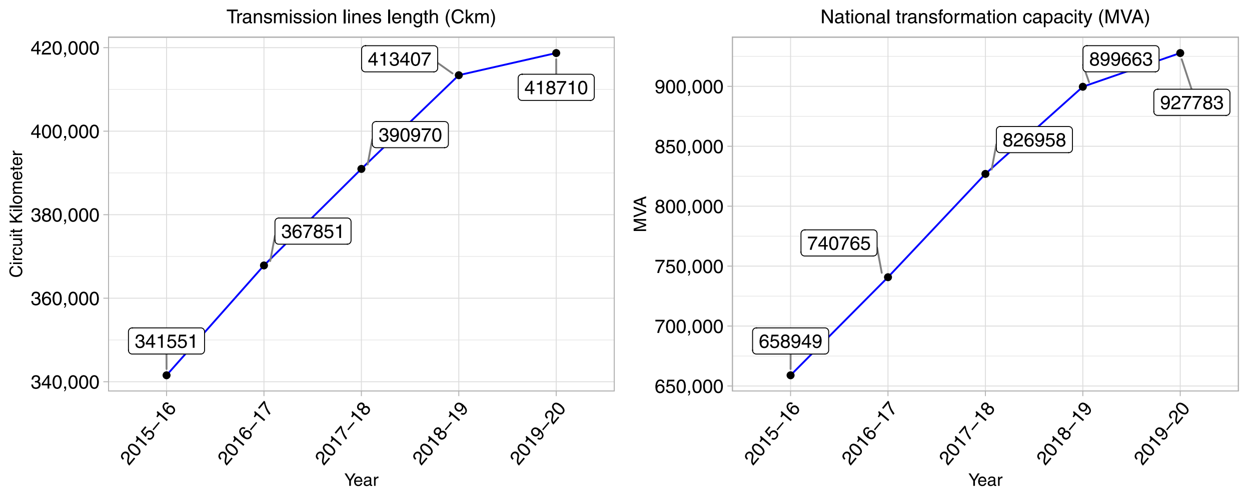


Fig. 8. India's transmission line length and power transformation capacity.

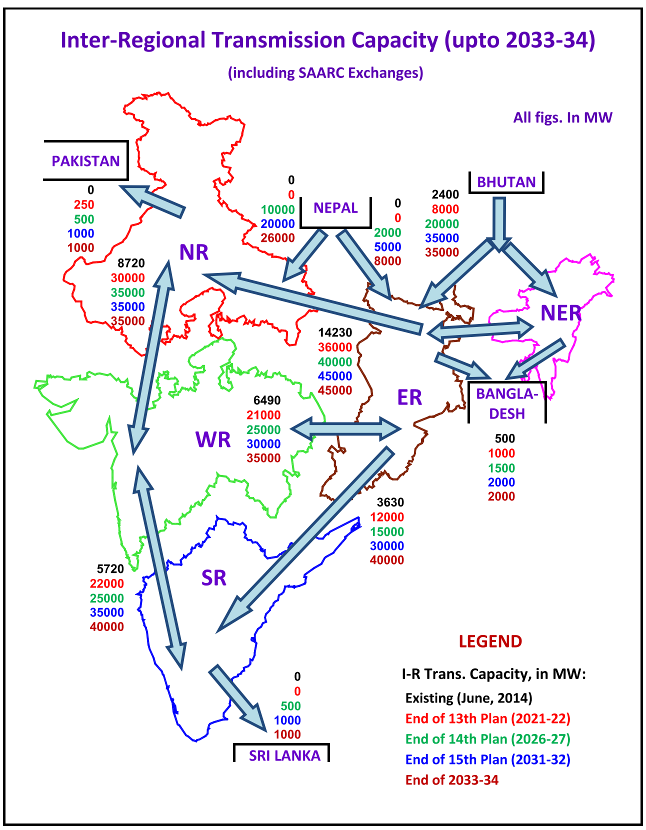


Fig. 9. Prospective inter-regional transmission corridor capacity [66].

Fig. 10. South Asia region [67].

under bilateral Memorandum of Understanding/Power Trade Agreements (Table 2). International cooperation in the field of electricity has positive consequences for South Asian countries (Fig. 10), as follows,

- Better utilization of the region's existing hydro resources, *e.g.*, in Nepal and Bhutan, which in turn will decrease electricity supply cost [68,69].
- Increased system reliability and flexibility from diversified cross-country generation options, and reserve sharing via an interconnected network [70].
- Reduced challenges of system balancing associated with variable RE (wind, solar) [70,71].
- Carbon emission reduction by utilizing clean generating options (hydro, solar, wind, natural gas).

Noting these benefits, the 'SAARC Framework Agreement for Energy Cooperation (Electricity)' was signed in the 18th SAARC (South Asian Association for Regional Cooperation) Summit. This comprises the joint development of infrastructures and operating protocols (scheduling, dispatch, energy accounting, and settlement) for secure and reliable cross-border trade.

Cross border transmission capacity need can be high to change generation portfolio and emission intensity of participating countries [70]. Geopolitical issues and differences in regulatory and operational protocols are major bottlenecks to develop a functional South Asian power grid. Formation of nodal authority to resolve power trading and disputes, coordinated planning and operation, and open access of power transfer are the key areas that need attention [72,73].

Table 2
Cross border power trading: Current and future plans [65].

Countries	Current connections	Under construction	Future connections
India–Bhutan	1500 MW power from Bhutan to India from hydro projects	Power evacuation facilities for hydro projects (2940 MW)	Project-wise transmission system for ten hydro projects (11 GW) is being taken up progressively
India–Bangladesh	500 MW power from India to Bangladesh	Strengthening of existing connection to by additional 500 MW by 2017	Phase I: New connection for transmitting 500 MW power to Bangladesh. Phase II: Increase capacity to 1000 MW
India–Nepal	320 MW power from India to Nepal	Additional power of about 100 MW from India to Nepal	Eleven connectors for power transfer from Nepal to India depending on hydro project development (17.5 GW) and surplus power availability
India–Myanmar	2–3 MW power India to Myanmar.	–	–

3.4. Demand side response and smart grid

Demand side response (DSR) is an effective mechanism to mitigate challenges associated with variable RE sources by joint participation of customer and utility. It is the intentional change in electric usage by end-use customers from their normal consumption pattern (timing, level of instantaneous demand or total power consumption) in response to the changes in the electricity price or other incentives provided by utility. Maintaining system reliability is the major objective of DSR [74]. Incentive-based DSR programs include direct load control, load curtailment, and demand side bidding, while price-based mechanisms include time of use tariff, critical peak pricing, and real-time pricing [75,76].

DSR improves the management of renewable generation fluctuations. It reduces system operating cost and facilitates higher RE penetration than conventional generators. It can improve reliability by providing flexible services such as ramping and reduce instances of operating conventional generators at part loads. As DSR helps to mitigate RE fluctuations locally, it reduces the dependency on importing or exporting power to/from another region via transmission lines, which may be costly [77]. Another advantage of DSR is energy time shifting, which allows demand increase during periods of excessive RE generation, thereby reducing curtailment [78].

There is enormous potential of DSR in India, which could be effectively utilized to enhance RE integration. Only small initiatives have been taken in this regard till date. DSR is practiced only for large industrial and commercial consumers in the form of time-of-day tariff, and incentives based on power and load factors. Other sectors like commercial, domestic, railways, agriculture, and small-scale industries are outside the domain of DSR. The focus of DSR in India is peak load reduction rather than balancing. Main constraints to non-implementation of system wide DSR in India are a lack of proper metering infrastructure, awareness, existence of regulated environment, priority of generation adequacy over quality, political and social obligations, and the poor financial status of state owned distribution companies [79,80]. Some private utilities (Tata Power Company Distribution in Delhi and Mumbai) have implemented DSR programs for commercial and industrial consumers [81].

Effective communication between the power utility and consumer is crucial for DSR implementation. Advance monitoring and communication equipment are critical to this. Smart grids can intelligently integrate the behavior and actions of generators as well as customers [82,83]. Apart from that, it can also utilize the flexibility of demand-side storage, such as electric vehicles (EV), to ensure efficient, sustainable, economic, and secure electricity supply [84]. Smart grid development in India is taking shape through various government initiatives. The Ministry of Power took early steps in 2010 by constituting the India Smart Grid Task Force and the India Smart Grid Forum. Development of advanced metering infrastructure, data management, application of GIS (Geographical Information System), enterprise asset management, distribution automation, and customer relationship management are some focus areas in this regard [85]. Several smart grid projects have been set up around the country.

3.5. Improvement in system operation protocol

In the Indian power system, there is ample scope to improve flexibility by just adopting better operational practices or codes. A substantial gain in the ability to handle system's variability can be achieved by better RE and demand forecasting techniques, smaller balancing intervals, and wider balancing areas. These institutional changes can be the least cost flexibility options, as compared to other resources.

3.5.1. Modifying system scheduling and balancing protocol

In real time, power system operators regularly check for system balance and security. They assign re-dispatch needed in the already scheduled generators or bring on-line fast reserves to avoid any system imbalance, which may lead to instability and system failure. The system's balancing interval depends on the quality of available resource, uncertainty level, manpower, and infrastructures. Making scheduling and dispatch decisions closer to real time (shorter time duration) significantly reduces uncertainty as it allows the grid to respond rapidly to changes in supply from variable renewables. It also helps to clearly identify the system's flexibility requirement at different points in time, which leads to lower operation cost. A faster scheduling and balancing protocol provides a better alignment of the system operation with the timescale of RE resources variability, thus enabling better utilization of generation forecasts and reducing RE curtailment. In India, day-ahead scheduling and intra-day dispatch of generators occurs at fifteen minutes intervals. Improvements in this case needs to be judged in view of feasibility of infrastructural and regulatory changes.

Similar to the faster balancing protocol, larger control areas or better co-ordination between multiple balancing authorities reduces operational uncertainty. Normally, the controlling authority of a balancing area maintains the supply and demand balance within its own geographic boundary, with limited imports and exports. A single wider balancing area can better address geographical diversity of the system resources having RE generators. Coordination between multiple areas offers the opportunity to share reserves, which allows operating less reserve capacity and lowering costs. Apart from sharing reserves in real time, joint unit scheduling, dispatch and balancing operations are possible through better coordination. This lowers other ancillary service requirement, reduces RE curtailment and overall cost [86]. In India, scheduling and balancing operations are often done independently. For example, an SLDC (state load dispatch center) which is responsible to schedule its own system assets, does not have the authority over the grid or resources of neighboring states. Thus, it often schedules higher reserve capacity, which may be procured from neighboring states at lower cost. RLDCs (regional load dispatch centers) and the NLDC (National Load Dispatch Center) further check the SLDC schedules and commit centrally owned generators. But, they do not improve the SLDC schedules in view of area coordination. Therefore, there is a need for either a single national-level balancing authority to manage entire grid or increase autonomy of SLDCs so that they can coordinate with each other for economic system operation.

3.5.2. Accurate weather forecasting

Due to variability of RE generation and demand, system operators rely on their forecasted values to schedule conventional generating assets. While day-ahead forecasts are used for unit commitment, short-term forecasts are used for schedule correction and calling other mitigating options like demand response or storage. Accurate forecasting can reduce the negative effects of RE variability and uncertainty on system operation. Due to low forecast errors, dispatch of non-RE generators need not deviate drastically from their schedules. This could effectively increase system flexibility, reliability, and significantly reduce RE curtailment either due to limited availability of ramping resource or network congestion [87]. Accurate information could be provided to RE generators in day ahead operation through improved forecasting, thus enhancing their economic returns from electricity market [21].

Countries like the USA, Germany, and Denmark use highly accurate wind or solar generation prediction techniques. In India, forecast errors in the range of 20%–30% of rated output is observed [35]. CERC mandates all wind generators having an installed capacity of over 10 MW and connected at the transmission level of 33 kV and above to forecast their generation with at least 70% accuracy. For actual generation beyond +/−30% of the scheduled value, the concerned generator has to bear penalty [88]. This 30% error band needs to be lowered further to minimize variability from renewable generation. It is also vital that accurate forecasting be incentivized appropriately. In the USA, electricity market operators are working with National Center for Atmospheric Research to improve their forecasting. In India, State and Regional load dispatch centers can collaborate with the Indian Meteorological Department, and Indian Space Research Organization to improve solar and wind forecasting.

4. Policy and regulatory support required for flexible resources in India

RE integrating technologies providing faster flexibility response, such as rapid generation, flexible demand, storage, and interconnections, involve high operational and investment costs. Due to costly economic attributes of these technologies, it would be difficult for them to compete with conventional options to provide such support. Separate regulatory provisions are required for appropriate economic incentives to service providers offering flexibility. Considering the increasing valuation of system flexibility in recent years, policy makers need to focus on the development of corresponding regulations and policy frameworks in this nascent segment [89]. Operational flexibility requirements in shorter time frames could be met reliably with the support of long-term advance planning of their procurement to ensure adequate availability of flexible resources. Countries world-wide are in the process of adopting various regulations to ensure fulfillment of flexibility requirement over the short term by its procurement over a longer term.

4.1. Short-term operational flexibility regulations

Short-term operational flexibility requires that supply and demand fluctuations should be met on a daily, hourly, sub-hourly, or real time basis. Such flexibility could be obtained through ancillary services, which help to enhance operation reliability and grid stability. Procurement of ancillary services, like operational reserves, voltage and frequency regulation, reactive power requirements, and black start capability, could be done through specifically designed market mechanisms. Such mechanisms are presently operational in several power markets, including PJM (Pennsylvania New Jersey Maryland Interconnection), NYISO (New York Independent System Operator), ERCOT, UK, CAISO, Nordpool, and India [90,91]. System operators procure various forms of ancillary services to maintain grid balance. These could be obtained from both the demand and supply sides, through auction based Ancillary Services Market (ASM) or by direct mandate. Examples of ASM include CAISO, AEMO (Australian Energy Market Operator), NYISO, UK, and Nordic markets.

In India, a multilateral coordinated scheduling framework is adopted over long to short term, to meet real-time energy requirements as outlined in Fig. 11. As per Electricity Act 2003, Regional and State Load Dispatch Centers (RLDCs/SLDCs) are responsible for optimum scheduling and dispatch of electricity from state and inter-state generating stations (ISGS) considering forecasted demand of their regions. Depending upon its requirement, each SLDC carries out a local cost optimization from the entitled generating stations based on merit order dispatch. Apart from power transactions through long-term Power Purchase Agreements (PPA), states fulfill their electricity demand in short term through sub-yearly contracts. This is done via bilateral transactions through Inter-State trading licensees, Power Exchanges, and Deviation Settlement Mechanism (DSM) [92].

Given the coordinated multilateral scheduling model in India, there is a need for thin layer of optimization at the inter-state level duly factoring technical constraints for residual balancing of demand for real power with supply in real time. This residual balancing, after energy markets are closed (gate closure), is managed by the system operators through ancillary service markets to maintain grid frequency at its nominal value, without compromising grid stability [93].

Increasing shares of variable renewable energy in the Indian power system have led to the initiation of ancillary services market since 2015 [91,94]. Based on collective load forecasts for the next day, the system operator procures ancillary services to support tertiary frequency control (few minutes) in terms of the Reserve Regulation Ancillary Services (RRAS) [94]. RRAS utilizes un-requisitioned[5] generation surplus based on merit order stack of variable cost of all RRAS providers. Individual up and down regulation requirements are assessed based on consistent grid frequency conditions over 5 min, where only generators can participate [91].

Under tertiary frequency control, the real-time flexibility requirement for imbalance settlement in the Indian grid is regulated under the Availability Based Tariff (ABT) mechanism [95]. This mechanism includes frequency linked incentives/penalties for beneficiaries/suppliers committing an Unscheduled Interchange (UI) of power [94]. UI gets reflected as a charge on supply and consumption differing from the defined schedule, and depends on temporal grid frequency conditions. This embeds the compensation for frequency control, with ex-ante pricing structures. Since 2014, this is called the Deviation Settlement Mechanism (DSM). This is an evolving regulation with the frequency band narrowing down to 49.7–50.05 Hz, and stronger restrictions on defaulting entities [96]. Secondary control, *i.e.* Automatic Generation Control (AGC), is absent by design in the Indian grid. Primary frequency control (in 2–5 s time frame) is achieved by regulatory mandates on all generating units above 200 MWs, to operate on restricted governor mode as per IEGC-2010 [94].

To help the stakeholders manage their energy portfolio closer to real time, discussion papers have been floated on ‘Real Time Energy Market’ and ‘Re-designing Ancillary Services Mechanism in India’, by CERC. The proposed co-optimization framework of energy and ancillary services is intended to optimally utilize least-cost generation resources.

5 Un-requisitioned surplus (URS) is energy surplus available to some ISGS if the total requisition from generators is lower than the total entitlement.

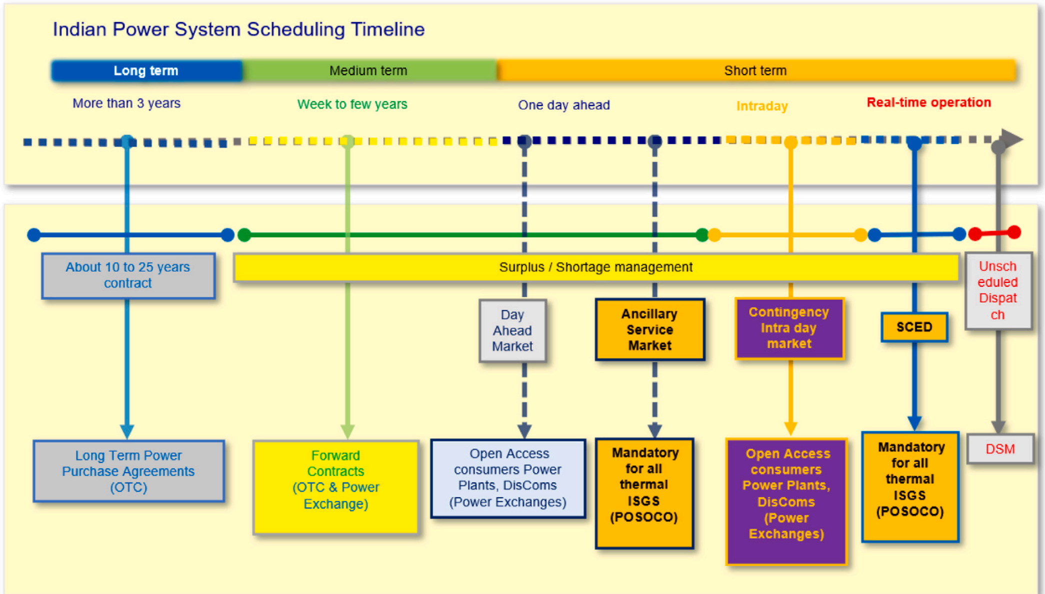


Fig. 11. Indian power system scheduling timeline.

Development of fully operational frameworks would take time. As of now, system cost optimization is obtained through regional operational coordination by Security Constrained Economic Dispatch (SCED) as a mandatory procedure for ISGS on pan-India basis [97].

Traditionally, procurement of ancillary services ensures sufficient online generation to meet forecasted demand under merit order-based market clearing. This does not explicitly value short-term operational flexibility, which is helpful for dynamic matching of demand and supply [98]. Contemporary grid flexibility requirements could only be met by deployment of fast response resources, such as energy storage and flexible consumption. Separate regulatory provisions or market products are required to incentivize and encourage participation of these costly technologies.

Developed markets elsewhere are introducing commercial products explicitly designed to bring in rapid flexibility services in the grid. These commercial products include Flexible Ramping Product (CAISO), Short-Term Operating Reserves (UK), Fast Frequency regulation Markets (PJM, UK, NYISO), Fast Reserves (UK, NYISO), and Energy Imbalance Markets (ERCOT) [99–102]. These market products offer payments for flexible resources for their ability to provide controlled rapid variations. This encourages faster resource services to survive in the market, as compared to slower ones.

In addition, markets with shorter trading intervals are emerging to reduce imbalance quantity. The trading interval of CAISO's Energy Imbalance Market (EIM) was reduced to five minutes, while the trading interval in India has evolved from 1 h to 15-min time blocks [102,103].

Regulatory provisions also need to focus on area balancing for trading residual power between connected areas to enhance grid reliability and improve system flexibility. This helps to enlarge the system resource portfolio in an economical way [104]. CAISO's EIM permits participating area balancing authorities to trade residual power among existing balancing areas to satisfy demand of each area [102]. Wider network interconnections are evolving to connect several countries, *e.g.*, Synchronous Grid of Continental Europe, Central American Interconnection System (SIEPAC) and Association of Southeast Asian Nations (ASEAN) [105]. Technical and legal arrangements for such flexibility enhancing interconnection are still evolving.

Flexible resources, such as storage and demand response (DR), have significant implementation costs due tothe requirements for smart control and management and advanced infrastructure. Therefore, appropriate economic signals, policies, and regulations are required to develop such smart infrastructure. Further, retail market designs are evolving to increase participation from large as well as small consumers to encourage demand side energy management. Aggregation can also offer an opportunity to exploit the flexibility potential of smaller consumers.

4.2. Long-term flexibility planning regulations

Capacity assurance from flexible resources is essential to avoid failures from demand and supply imbalance at real time. An optimal planning for such capacity can restrict low reliability and high cost events occurring due to last minute resource procurement. A capacity procurement mechanism should be designed to provide a certain stream of revenue to attract capacity providers capable of supplying appropriate services to fulfill grid requirements. System operators need to maintain additional capacity in standby mode to balance the grid for safe operation and for rapid system adjustment/rescheduling. Hence, offering payments for capacity, in addition to energy payments would incentivize their providers to stay in business. Capacity assurance is incentivized across the globe through various models based on obligations, mandates or auction based markets.

In the Indian power sector, capacity payments are reflective of fixed cost components in long-term Power Purchase Agreements (PPA) for electricity providers or generators. Capacity payments have been inherited as one of the components of the two-part tariff structure under ABT as 'Capacity Charge'. These charges are recovered annually based on a target availability of the plant, *i.e.*, 100% capacity charges can be recovered for plant availability up to 85% . However, to encourage generators to maximize their energy sale, an incentive is offered based on the actual achievement of generation based upon PLF above the target availability [106]. But, there is no provision for capacity payments for generators trading in power exchanges.

Existing capacity payment models focus on ensuring sufficient online capacity, which may lack flexibility to handle short-term imbalances. Flexibility is an emerging need of the future grid dominated by variable renewable energy (VRE) generation. Merely keeping online capacity, without considering capability of dynamically matching demand with supply will no longer serve actual system requirements [107]. Flexible capacity (storage, demand response, *etc.*) is costlier and cannot compete with conventional capacities when markets are dispatched based on the merit order. Instead, procurement of capable resources necessitates a proper market design. This would help to ensure that resources are remunerated based on their capabilities to provide the necessary flexibility range based on actual grid requirements [108]. Hence, different kind of capacity payments or market designs are required, which may reflect the need for specific flexible capabilities on a long-term investment time scale.

Learning from the presently emerging practices being adopted world-wide, India requires a policy environment to enable a wider variety of tools. This would help to attain grid flexibility through regulatory mechanisms, policy directions, economic signals, and market design to meet large renewable targets. Presently, India is emerging from a centrally regulated structure, where 93% of power transactions are performed through long-term power purchase agreements and only 7% power is traded competitively through exchanges. Therefore, a blanket adoption of mechanisms of developed markets may not work well for India. The current regulatory framework for ancillary services in India provides RRAS, which primarily targets to enhance the reserve margin. The framework currently ignores the role of fast response technologies, especially those which can be supported by capacitors, flywheels, battery storage systems, *etc*. Also, current capacity procurement mechanisms adopted in India are not capable to support flexible system development, and they should recognize the quality of technologies that enhance system flexibility.

5. Revision of modeling practices needed in India for flexible system planning

In light of additional dynamics and variability from RE, system resource capacity simultaneously needs to be adequate and flexible to manage supply and demand variability (discussed in Section 2). It requires modifying system planning practices currently in India. In this section, first, an outline of various types of energy and power system planning activities is presented, followed by their limitations. Some plausible approaches to improve the present paradigm are then proposed.

5.1. Current system planning practices in India

In India, power system planning approaches related to renewable energy integration are diverse. A wide range of models/tools are being used by utilities and national-scale planners to handle various challenges. Power utilities typically use integrated resource optimization models for network as well as generation expansion planning. These models aim to identify least-cost reliable capacity expansion options, their location, required investment, associated emission as well as retirement schedule of existing assets. In India, CEA is responsible for overall power sector planning activities. In their planning activities they utilize commercial modeling tools like EGEAS for planning power system expansions [40]. On the other hand, various energy system planning authorities in the government (*e.g.*, NITI Ayog, Ministry of Environment, Forest and Climate Change), academia and research institutions use integrated assessment models or econometric models to design pathway(s) for meeting certain policy goal(s). Some of the widely used modeling framework used by these authorities are MARKAL, TIMES, MESSAGE, LEAP, GCAM, *etc.* Outputs of energy system models are similar to integrated resource optimization models, but their reach extends beyond the power sector only, *i.e.* they can interact with other non-electricity sectors while designing a future portfolio. The power sector is represented within these models endogenously and is affected by the dynamics of other energy sectors.

Apart from capacity expansion models, several short-term models such as production cost, network reliability, optimal power flow, *etc.* are used for planning purposes by utilities and research institutions. Production cost modeling tools allow a detailed representation of system operational constraints and can optimize day-to-day generator scheduling and dispatch. These kinds of models are primarily used by research organizations. Detailed simulations of the transmission network, including contingency events, are performed by power flow and network security models. They are widely used by regional load dispatch centers, state/regional and national power transmission utilities. Though these models do not quantify future capacity, they give an indication of system performance. Planning using these models involves analyzing multiple portfolio scenarios by drawing capacity and techno-economic assumptions, either from separate expansion planning model or by forecasting, and choosing the best based on expert knowledge [109] (Figs. 12, 13).

5.2. Limitations and challenges in current modeling approaches in India

Consideration of system dynamics in a detailed temporal and spatial resolution framework is crucial to reflect the RE variability impact in planning studies [110,111]. The modeling frameworks used in India have certain limitations in this regard.

The core focus of energy system models is not to optimize generator scheduling or dispatch; rather their strength lies in chronological investment planning over a long-term horizon. These models focus on resource adequacy, ignoring operational details associated with power plants or transmission units. They do not usually track the effect of spatial or temporal variation of RE resource on power flow and network congestion [10,112,113]. Operational constraints on generators, transmission line, *etc.*, are often ignored, or their representation becomes unrealistic due to limited temporal and spatial resolution in these models. Modeling in absence of operational constraints in low temporal and spatial resolution can lead to overestimation of system capability to assimilate RE, underestimation of operational costs and flexibility requirement [114–118].

Power sector operational models have limited applicability for long-term optimization due to computational complexity. In general, power sector specific planning models can analyze the operational aspect and RE resource variability with higher resolution, as compared to energy system models. But they have limited planning horizon and do not consider interactions with other energy sectors (non-electricity). Thus, these models are not very useful for national level energy policy analysis (*e.g.*, national carbon emission reduction targets) [119].

Due to these factors, traditional long-term planning approaches employed in India fail to consider short-term RE variability and uncertainty. Analysis of flexibility options to integrate renewable energy in future scenarios were out of the scope of earlier studies [120–124]. Therefore, the system portfolio reported by these exercises corresponding to future large scale RE expansion plans is often unrealistic. It is not guaranteed that the system's resources planned by these models could be operated in a flexible and reliable manner in real time. As the variable renewable sources would play a major role in future generation portfolio, a major revision of the current planning methodologies is required.

5.3. Modeling modification required

An improvement of traditional planning approaches can be achieved in various ways, like direct inclusion of operational constraints, adopting higher temporal and spatial resolution in planning models and linking planning and operational models [125,126]. Recently, several attempts have been made to utilize bi-directional hybrid modeling frameworks for long-term RE integration planning [127–130]. In the Indian context, there are various possibilities of modeling related enhancements. Some recent studies in India have started to look into these avenues such as using high resolution production cost models, representing some operational aspects in planning models *etc.* [131–134]. Following is a brief outline of some hybrid modeling approaches which future studies in India may consider for long-term power sector planning to ensure system flexibility.

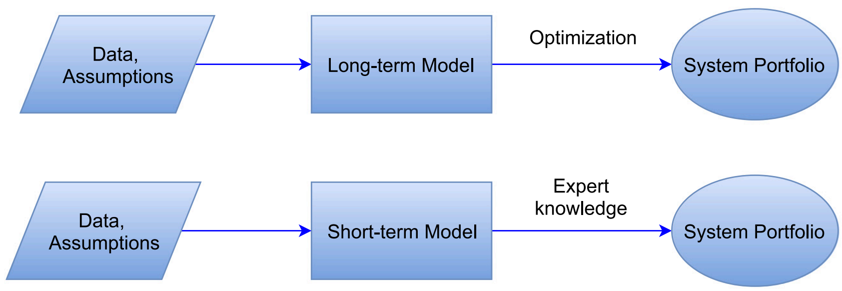


Fig. 12. Traditional planning approaches.

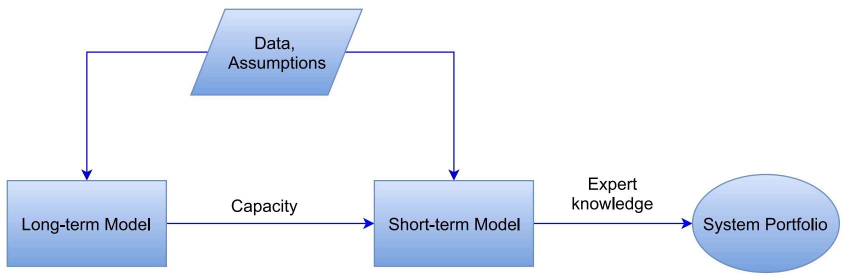


Fig. 13. Unidirectional model linking approach.

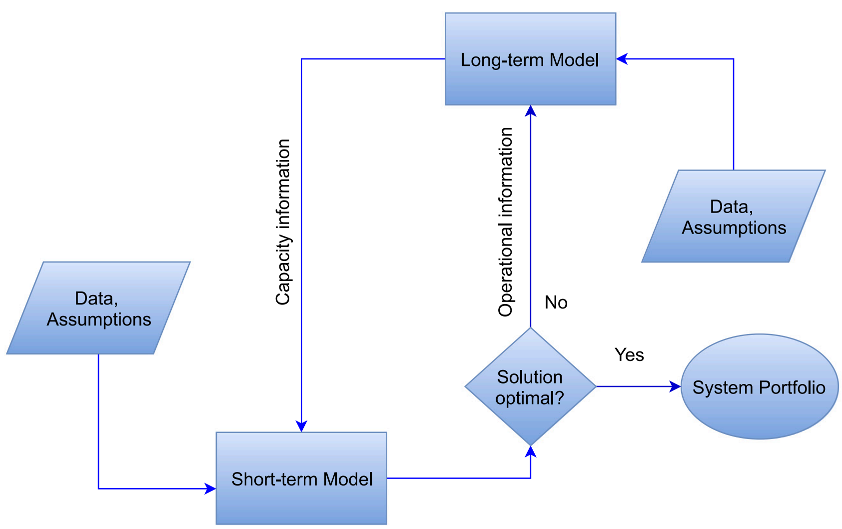


Fig. 14. Bi-directional model linking approach.

5.3.1. Hybrid modeling approaches

- Hybrid approaches, involving power sector operational and energy system models in an iterative framework via bi-directional data exchange, can be a major improvement in long-term planning paradigm in the Indian context. In this method, an operational-scale model checks the suitability of a system portfolio designed by the long-term model, by simulating unit commitment and dispatch. Then, it returns operational-scale information (*e.g.*, RE curtailment factor, role of storage) back to a system model, which then reruns the optimization and attempts new solutions (Fig. 14).
- Operational models can be further used in connection with geospatial tools to develop realistic supply curves of RE sources, considering grid integration cost. The integration cost includes grid infrastructure related cost (new transmission network), profile cost (due to reduced full load operating hours of the thermal generator, additional ramping requirement, and curtailment), and balancing cost (additional cycling of conventional generators) [15,135]. The supply curve reflecting integration cost can be utilized by long-term models to consider the impact of RE resource variability in system planning [136].

6. Discussions and conclusions

Large-scale grid integration plans of solar and wind energy are changing the paradigm of traditional operation and planning of the Indian power system. The negative impacts are being witnessed in the form of operational complexities and generation curtailment in several states across India. With high penetration target already set, these problems will enhance in the future. Thus, it is becoming necessary to bring additional flexibility into the system portfolio to maintain reliability, stability and security. This paper tries to identify suitable technological options from where flexibility can be procured. Alongside, it also recognizes different policy and regulatory mechanisms to encourage flexible capacity development as well as system operation.

Finally, it points out newer planning and modeling approaches to optimize long-term system portfolio focusing on flexibility need.

For increasing flexibility in the Indian power system, areas that require immediate attention include rapid exploitation of hydro and pumped hydro storage potential, retrofitting existing coal-fired power plants, and developing adequate transmission infrastructure. An improved system operation protocol, such as better area coordination, and accurate RE generation forecasting should also be the interest areas which can significantly enhance flexibility within minimum time and cost. Fresh additions of firm capacity (*e.g.*, coal-based plants) need to have higher part-load efficiency, ramp rates, and lower start-up time. With adequate regulatory support in place, DSR and energy storage system both on the supply and demand sides (*e.g.*, MW scale battery, and EV) can turn out to be attractive flexibility options in the long term to mitigate large scale RE fluctuations. Recent initiatives to revive the stranded gas power plants will help to cater some part of the flexibility need. Though gas availability is uncertain in the long term, continuation of adequate gas supply to the plants especially in RE rich states will be key to handle grid-balancing related issues.

Despite a consensus on additional system flexibility needs for increasing RE penetration, issues of countries like India are unique. Aiming for a highly flexible system involves high infrastructure investment, which can significantly increase power supply cost. This may, in turn, hinder achieving sustainable development related goals. Assessment of incremental cost for transitioning into a flexible system scenario needs to be undertaken thoroughly. The role of suitable policy and market mechanisms are critical in this regard to balance the aims of social welfare maximization and new RE investment encouragement. In India, regulatory provisions need to be developed to enable existing resources for flexible operation and promote new flexible resources such as storage to become mainstream. For that, newer policies should value system resource for their service quality in addition to their capacity. Further, power system deregulation, political consensus and infrastructural adequacy can open opportunities to adopt a robust market structure to attract investment for flexible capacity.

Short-term operational flexibility regulations should acquire ancillary services through market mechanisms on the demand and supply sides. New robust market products should be designed to bring rapid flexibility for system operation. This may include new mechanisms for trading residual power between multiple grids over a market platform. Energy storage and geographical aggregation of small balancing areas are the essential ingredients of any future operational planning. In the longer term, generation capacity including storage procured by different mechanisms should provide flexibility through obligations, mandates or auction-based markets. For that, capacity market designs need to be modeled according to country's specific needs. Overall, a broader policy environment is required to maintain grid flexibility through regulation, policy directions, and market types such that emerging flexible resources like DSR, storage, *etc.*, get proper economic signals for investment.

Apart from infrastructure and policy related bottlenecks associated with flexible system development, methodological challenges also need equal attention. Designing a long-term flexible system portfolio requires operational-scale information to be considered in planning models. Earlier national-level studies in India are weak in this regard. Improved modeling and planning approaches are therefore necessary to design new energy policies and identify an optimal flexible system portfolio. Traditional approaches/models used earlier for this purpose need to consider the importance of different sector specific models and their interlinking.

Thus, the development of a flexible system in India needs to consider several factors. System flexibility, which is available in the current power system portfolio but under-utilized, should be harnessed properly. Flexibility needs will vary from state to state according to existing infrastructure, future economic development plans, availability of energy resources, and RE capacity development. Therefore, national-scale planning studies using granular models having state-level details are necessary to optimize future system design. National level planners, power system operators, regulatory authority, and academics should coordinate more to develop efficient tools and algorithms, advanced data maintenance, and management practices in this regard.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Partha Das: Conceptualization, Writing - original draft, Visualization, Methodology, Investigation, Writing - review & editing. **Parul Mathuria:** Writing - original draft, Visualization. **Rohit Bhakar:** Writing - review & editing, Supervision. **Jyotirmay Mathur:** Writing - review & editing. **Amit Kanudia:** Writing - review & editing. **Anoop Singh:** Writing - review & editing.

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