BIMSTEC ENERGY CENTRE
Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation

Renewable Energy Integration in India

Grid Operational Challenges & Solutions

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Cultural Motivation for RE integration

सूर्य आत्मा जगतस्तस्थुषश्च ॥

“The Sun is the soul of all that moves and does not move.”

वायुरेवेमाः प्राणान् धारयति ॥

“It is indeed the wind that sustains all the breaths.”

Policy Motivation for RE integration

We should not get into the mindset that RE is the intruder and conventional energy is the main player. Why not consider RE to be the main occupants of the 'house' and then work out the rest of the system around RE

- *National Institution for Transforming India (NITI Aayog)*

(India's Think Tank)

Contents

- Overview of Indian Grid
- Thrust for RE
- Operational Challenges for RE Integration
- Solutions

Indian Grid…One of World's Largest

#Map not to scale

1 National Synchronous Grid

2 Coal Generation

3
- Electricity Generation
- Electricity Consumption
- Installed Capacity
- Transmission System

4
- Wind Generation
- Solar Generation

6 Hydro Generation

9 Pumped storage capacity

**Source: IEA Key World Energy Statistics 2021 (2019 data)*

Indian Grid-Dimensions:

>484GW
Generation Capacity

>243GW
Non fossil Capacity

3.2 Million KM^2
area foot print

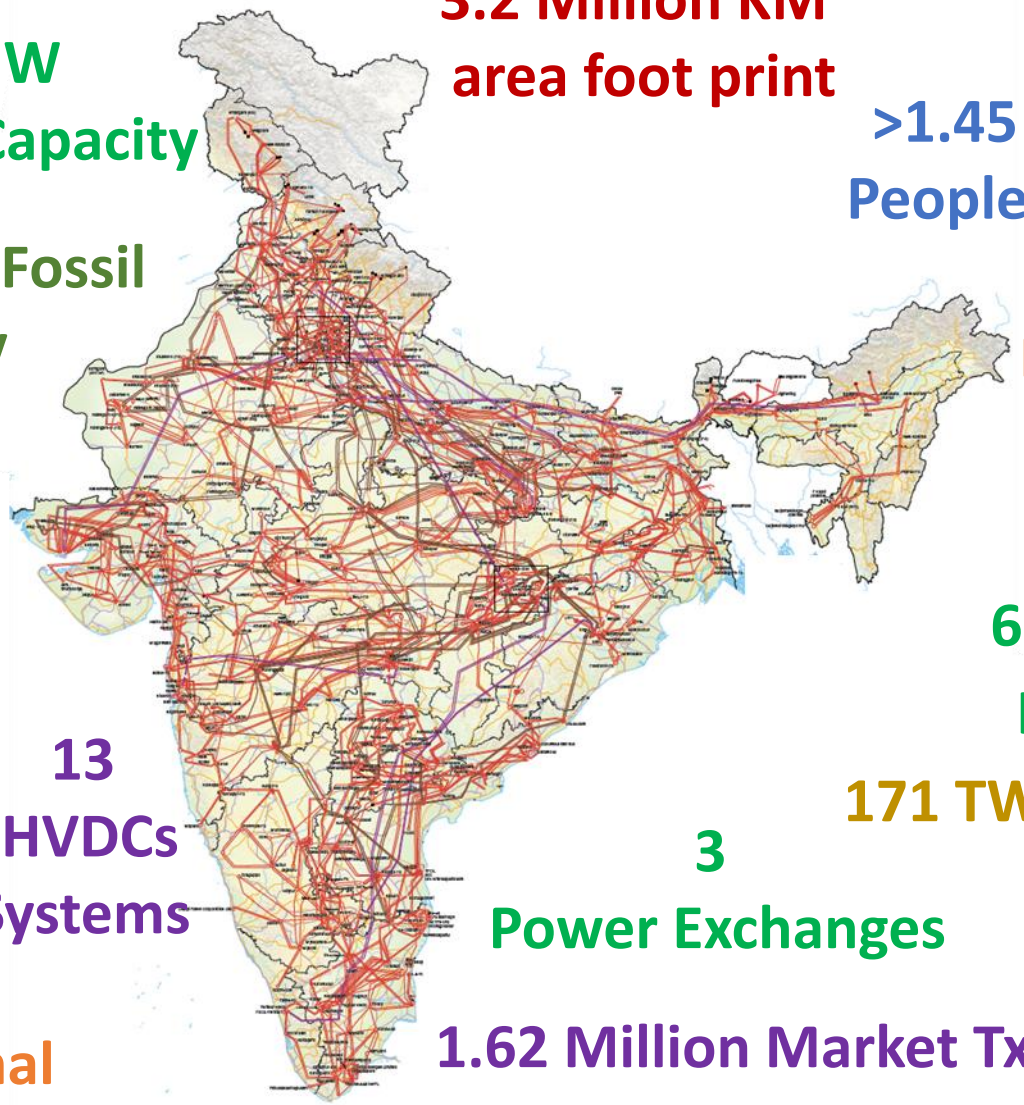
>1.45 Billion
People Served

>50% of Non-Fossil
Capacity

99.99%
Electricity Access

250GW
Peak Demand

5.46TWh
Max Daily Energy



5 Diverse Regions

6000+ Market
participants

171 TWh+ Market Trades

13
HVDCs
Systems

>4.95Lakh Ckt Kms
Of EHV Transmission
lines

3
Power Exchanges

>118GW
Inter Regional
Transmission Capacity

1.62 Million Market Txns

Source: CEA & Grid-India

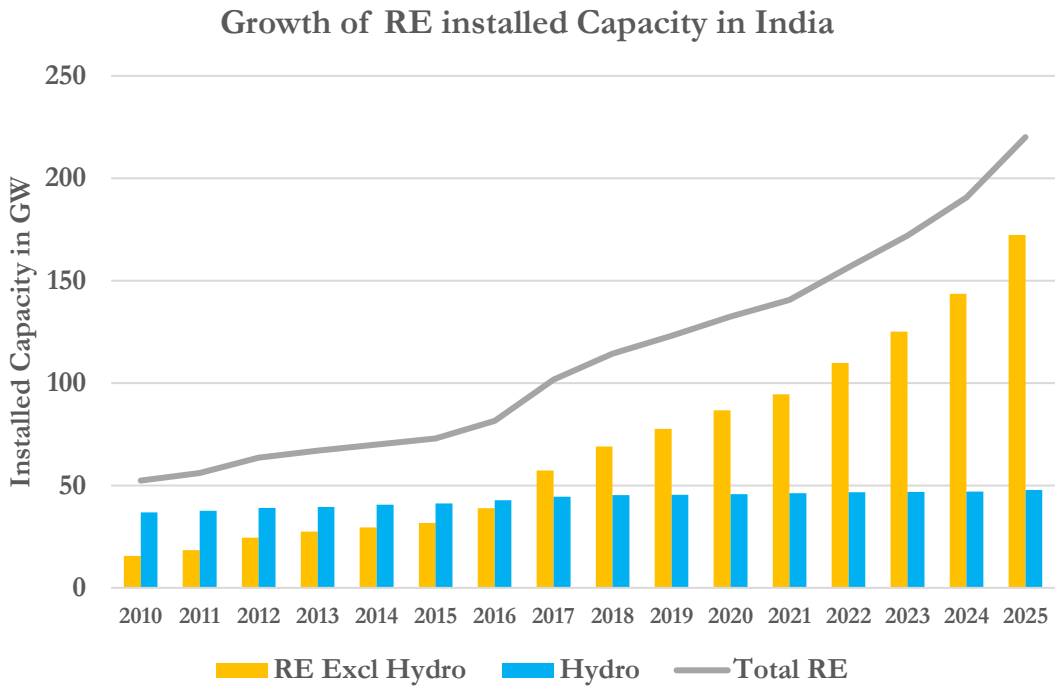
Energy Transition in India - Roadmap

Resource	June 2025 (MW)	March 2032 (MW)	% Addition
Hydro (incl. PSP)	49378	88864	80%
Small Hydro	5102	5,450	7%
Solar PV	116247	3,64,566	214%
Wind	51674	1,21,895	136%
Biomass	11594	15,500	34%
Nuclear	8780	19,680	124%
Coal + Lignite	221318	2,59,643	17%
Gas	20132	24,824	23%
Total	484818	9,00,422	86%
BESS (MW/MWh	-	47244/236220	

	Mar 2032
Maximum Demand Met (GW)	366
Total Generation Installed Capacity (GW)	900
Non-fossil Fuel Based Generation Installed Capacity (GW)	600
Wind & Solar Installed Capacity (GW)	486

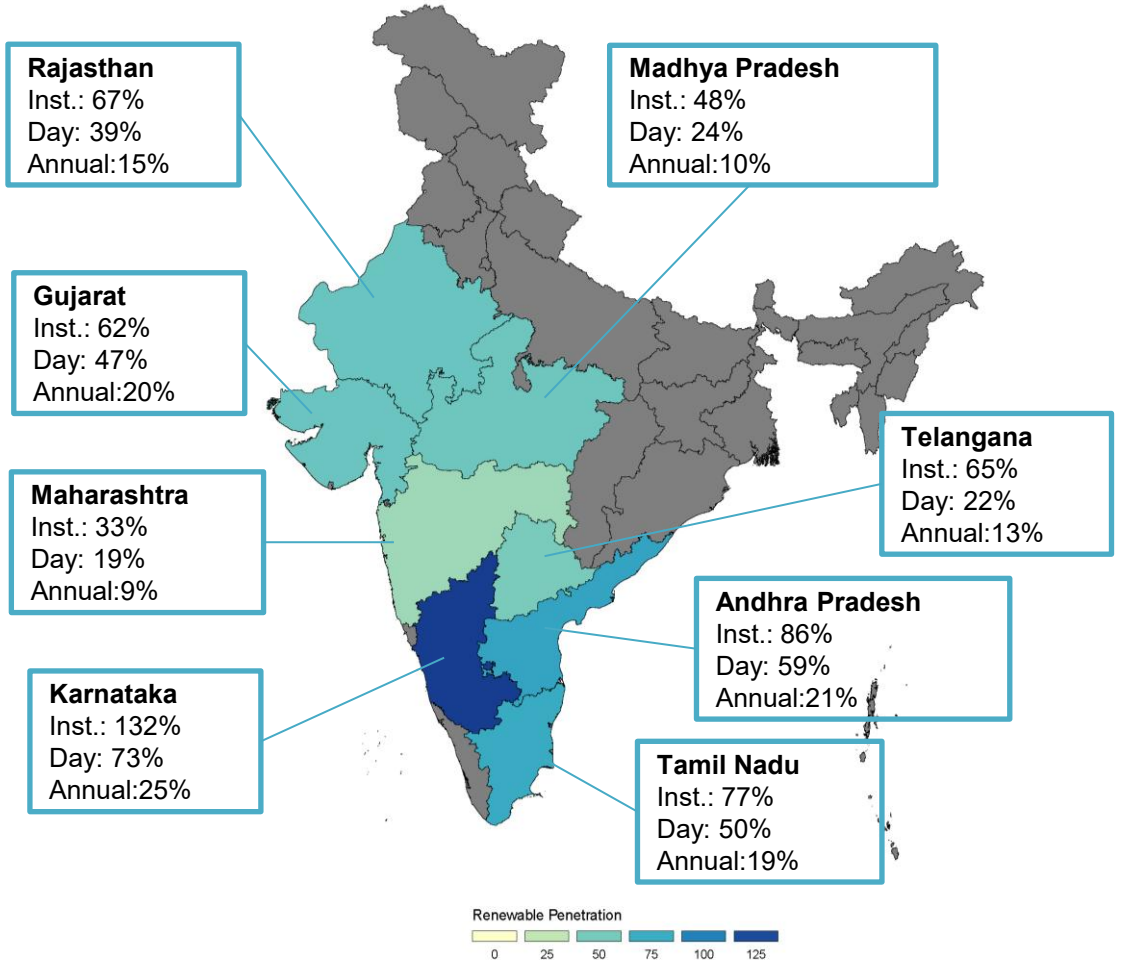
Source: CEA National Electricity Plan 2022-32

India's Journey with Renewables



Source: CEA Installed Capacity Report (data as on April 2025)
https://cea.nic.in/installed-capacity-report/?lang=en

Maximum Wind + Solar penetration in instantaneous MW and energy (day/year) terms till FY 2024-25



Highest Instantaneous RE penetration of ~47% recorded - 13th Sep 2024 (Wind + Solar +Hydro)*

Thrust for RE integration

India's commitment at COP26 at Paris

- ✓ Net Zero by 2070.
- ✓ 50% of Non-fossil Installed Capacity by 2030. Achieved in June 2025 itself
- ✓ 45% Reduction in Emissions Intensity from 2005 levels

प्रवर्ततां प्रकृति हिताय पार्थिवः
The ruler should behave in the interest of Nature – Kalidas (One of the greatest Indian poets)

- ✓ Integration of such massive amounts of RE which are intermittent and distributed in the power system pose serious challenges to grid operations.
- ✓ Flexible energy resources are needed for managing the RE efficiently.
- ✓ Energy Storage is going to play critical role in grid integration and management of RE as the share of RE in the grid increases.
- ✓ Integration of flexible energy resources such as Energy Storage System, PSP with the existing and upcoming VRE resources is one of the most viable solutions

National Electricity Plan (NEP) of India for the period of 2022-32

Projected All India peak electricity demand and energy requirement

- ✓277.2 GW and 1907.8 BU for the year 2026-27
- ✓366.4 GW and 2473.8 BU for the year 2031-32

Increase in Non-fossil fuel based generation capacity

- ✓57.4% of Total Gen Capacity by the end of 2026-27
- ✓68.4% of Total Gen Capacity the end of 2031-32

Average emission factor reduce to :

- ✓0.548 kg CO_2/kWh_{net} by 2026-27
- ✓0.430 kg CO_2/kWh_{net} by 2031-32.

Energy storage requirement (2026-27)		
16.13 GW/ 82.37 GWh	BESS	8.68GW/ 34.72 GWh
	PSP	7.45GW/ 47.65 GWh

Energy storage requirement (2031-32)		
73.93 GW/ 411.4 GWh	BESS	47.24GW/ 236.22 GWh
	PSP	26.69GW/ 175.18 GWh

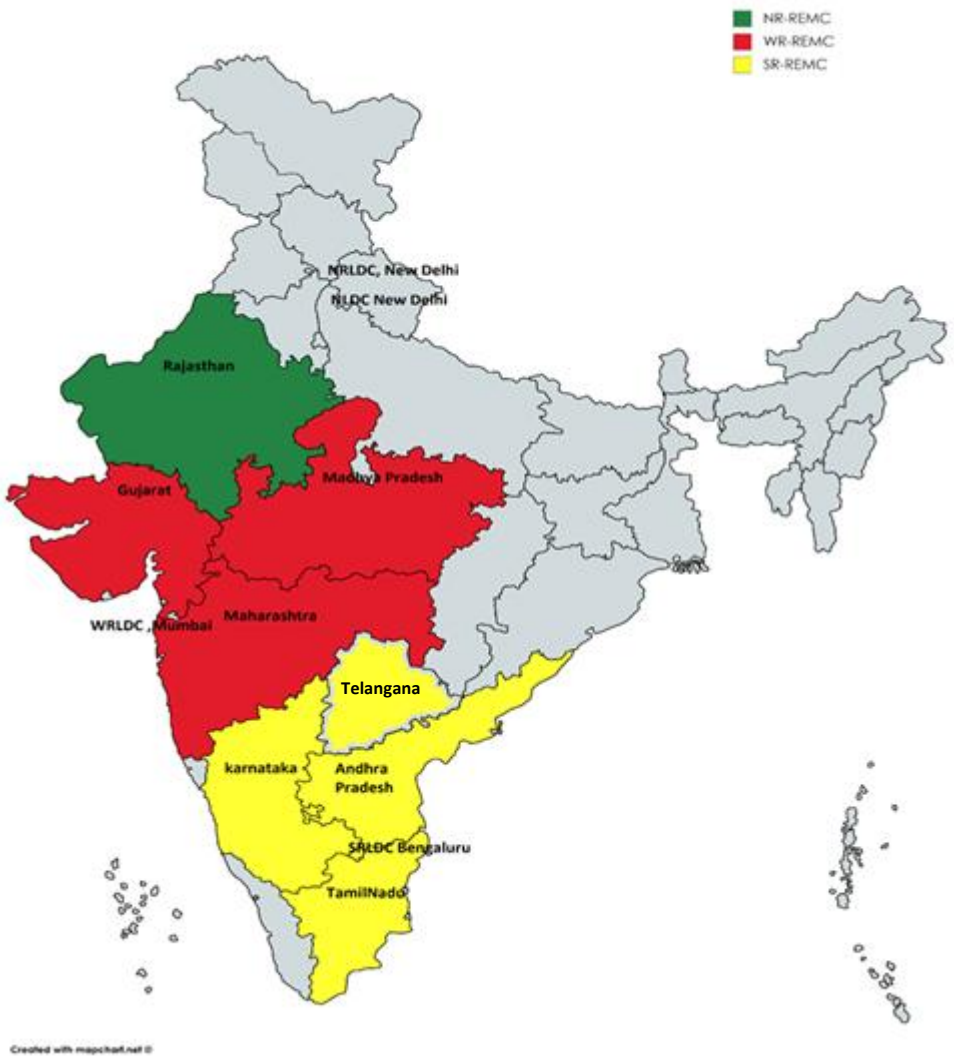
Financial Year (FY): 1st April to 31st March

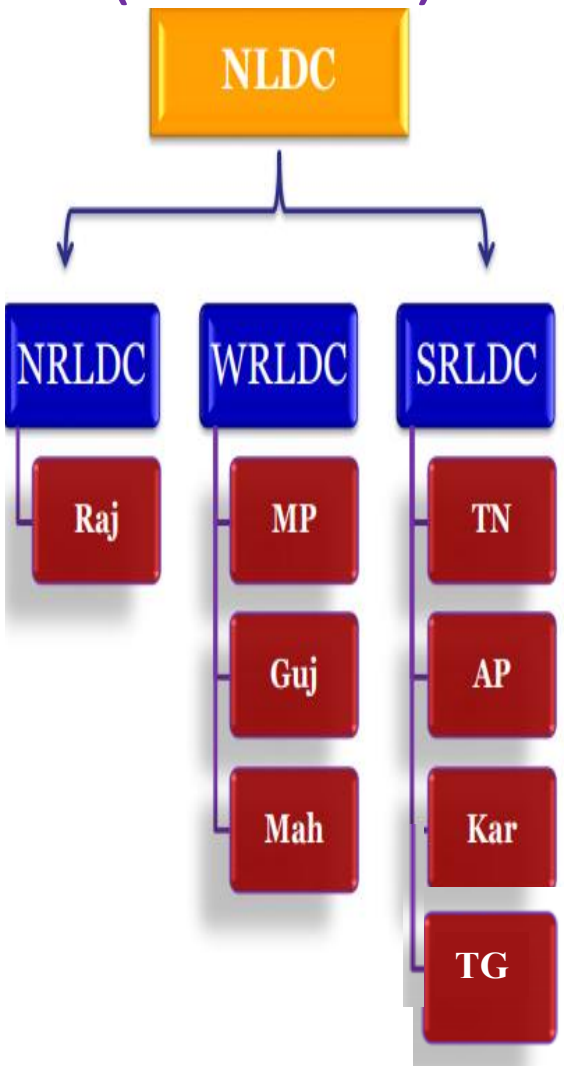
Source : National Electricity Plan (NEP) (Vol-I Generation) for the period of 2022-32.

Operational Challenges for Integration

- Variability
- Balancing Reserves
- System Inertia
- Voltage Ride through
- Predictability
- Net Load Ramp
- Reactive power management
- Observability

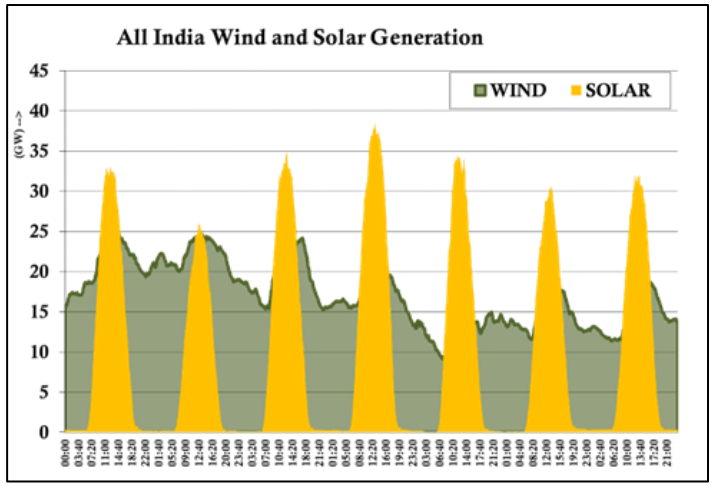
Renewable Energy Management Centre (REMC)



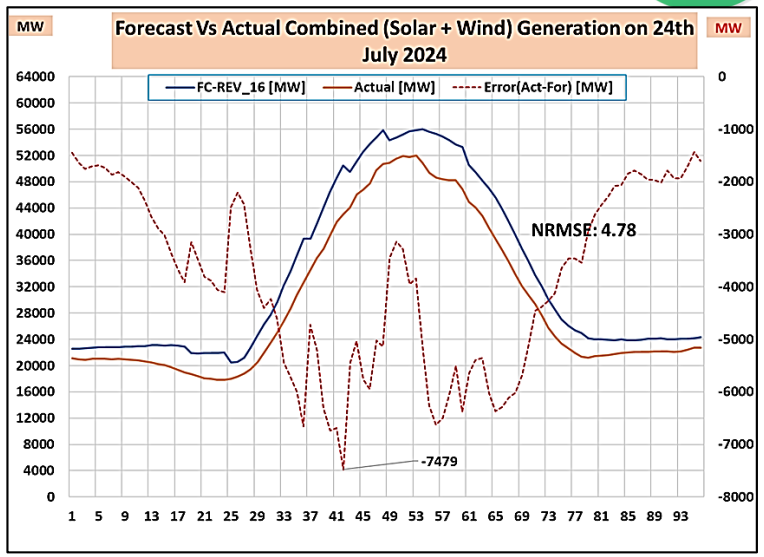


- Dedicated control centers for managing renewables
- Co-located with LDCs at 12 locations
- Intra day, day-ahead and week ahead basis forecasting
- Dedicated scheduling platform for RE generation for day ahead and intra day scheduling.
- RE Schedule Integration with existing scheduling tool
- Real time tracking of generation from RE sources
- SCADA data integration with state & National REMC and respective LDC

Key Challenges to Expanding Renewables



Approx. 12000 MW reduction in Solar Generation in 2.5 hours due to Large Cloud Cover



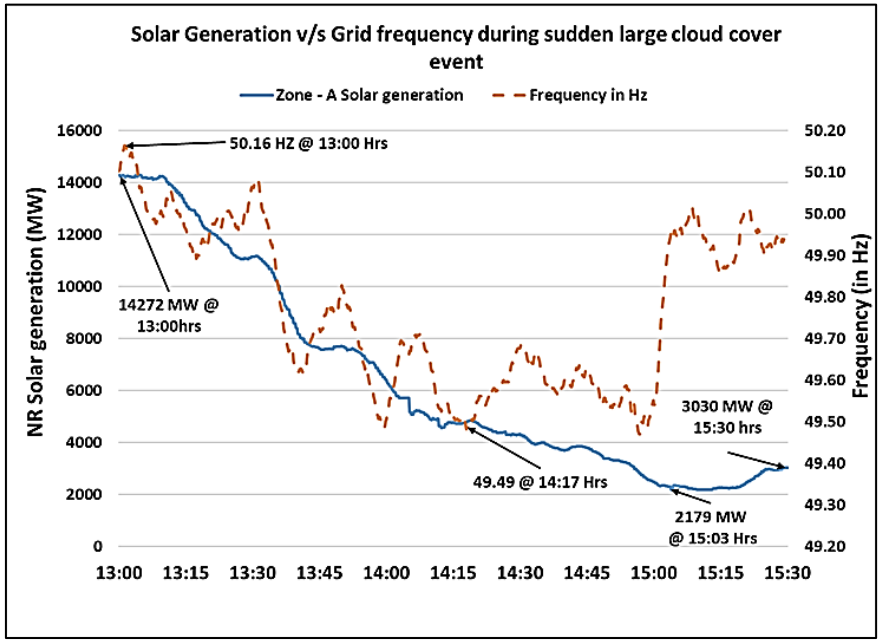
Intermittency

Variability

Reduction in available reserves

- **Morning peak**
- **Evening peak**

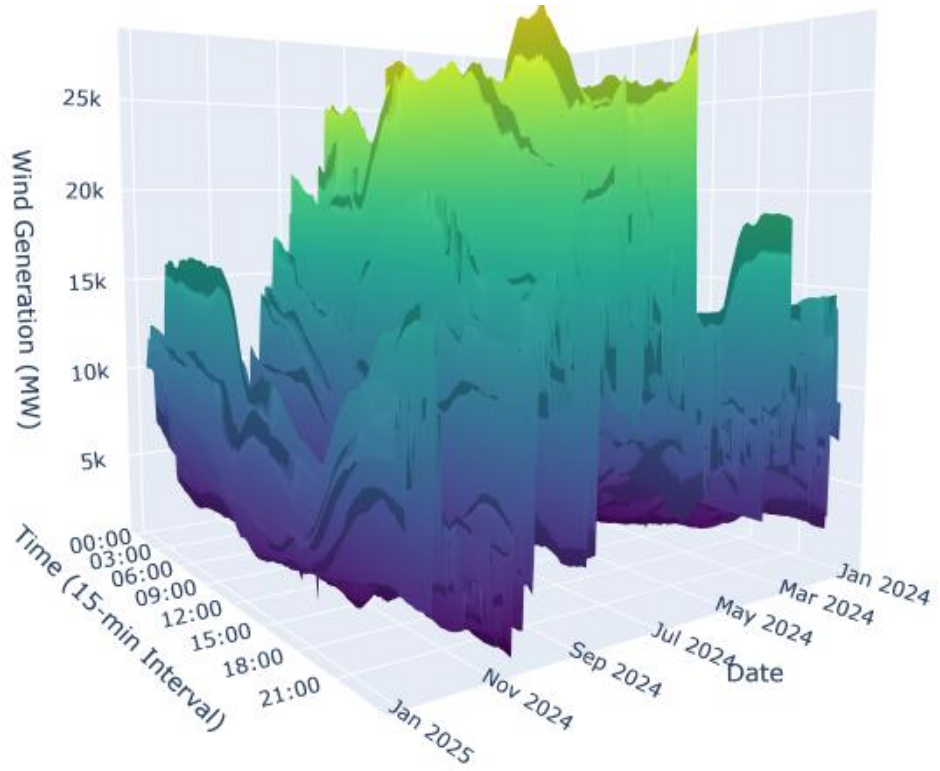
Need for fast acting reserves



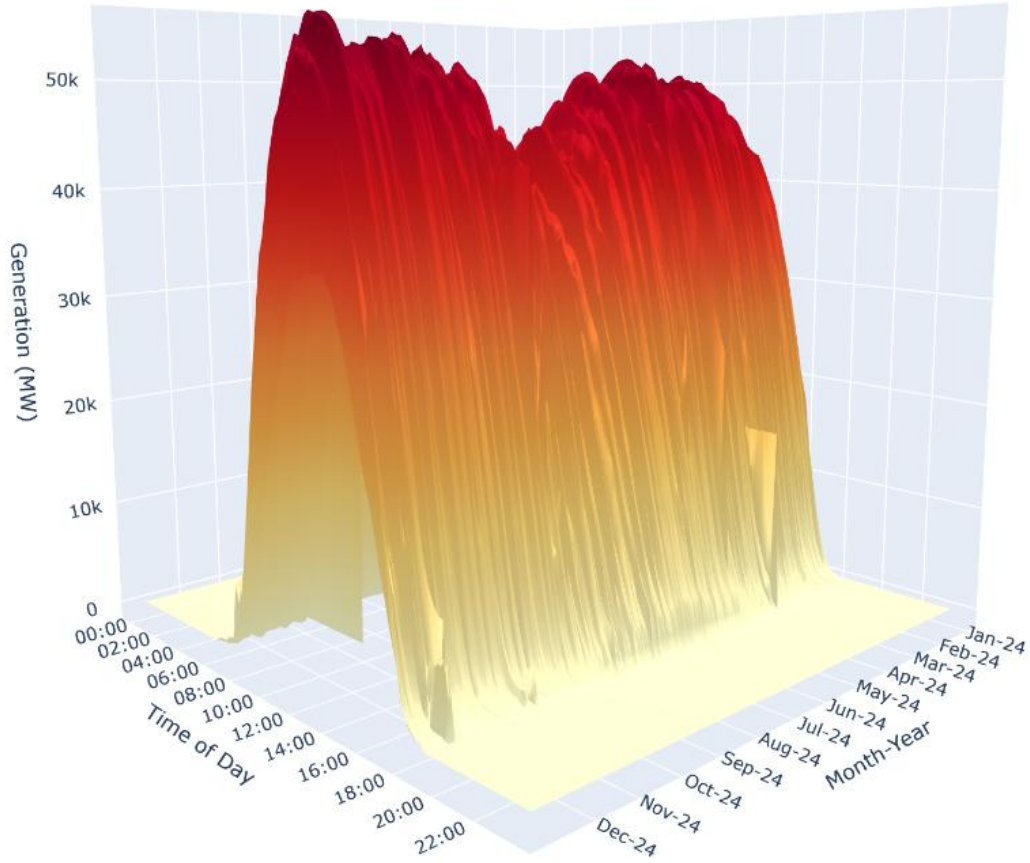
Predictability

- **How confident a particular outcome can be determined ahead of time**
- **Need for precise predictions of how much power will be fed into the grid**

2024 All India Wind Generation

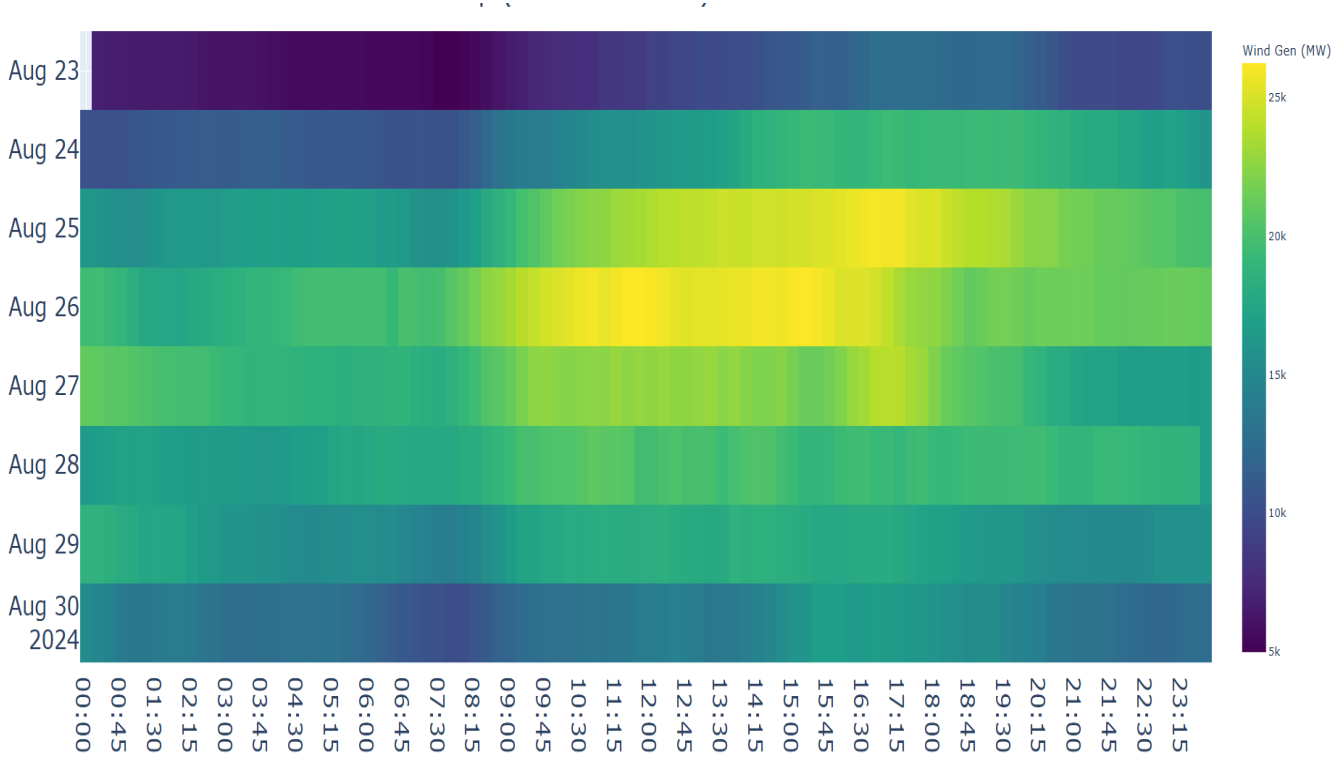


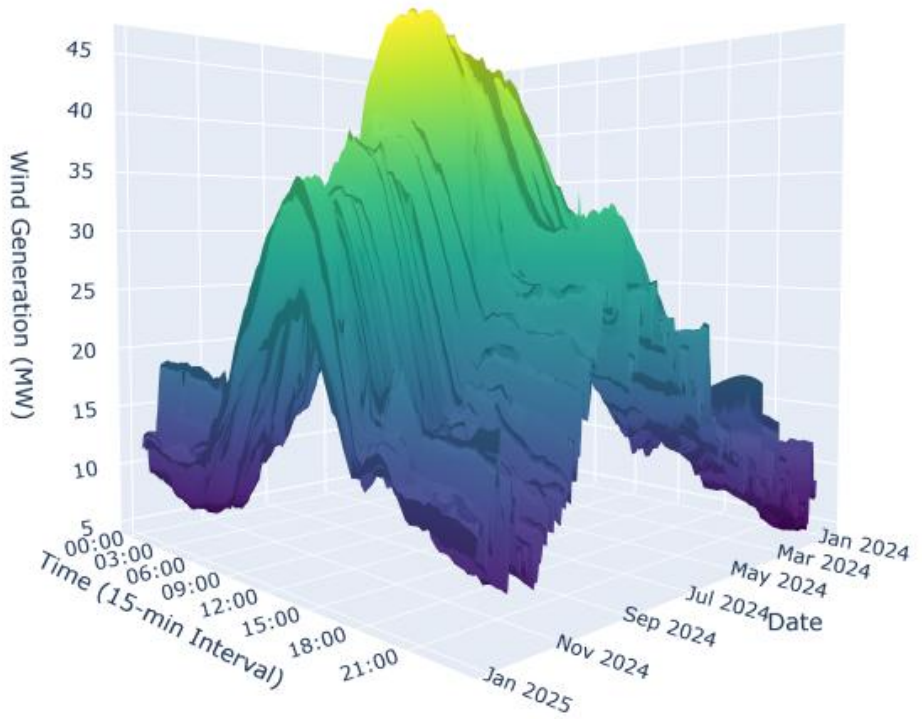
2024 All India Solar Generation



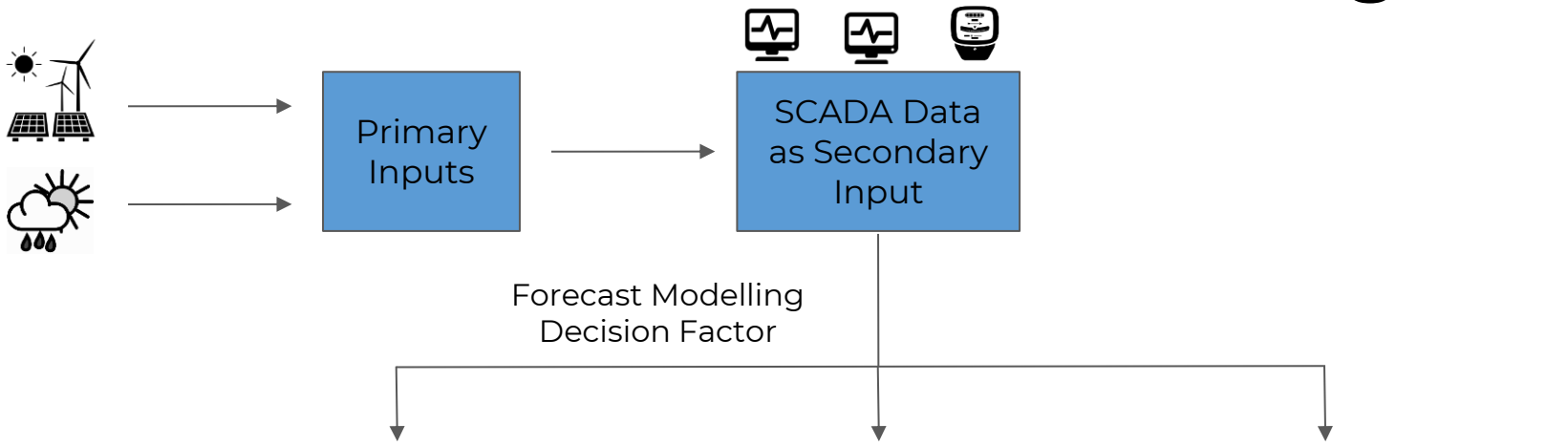
Wind Generation variation in August 2024

2024 RE Penetration





Forecasting



Real-Time Model

- Combination of weather to power correction, real-time power based correction for 16 revisions
- Highly advanced and can effectively capture real-time trends with high degree of accuracy
- extensive training required

Daily Adaptive Model

- Modelled to suite for sites with limited historical data with delayed transmission
- Works based on weather forecasts and past error-correlations between the weather forecasts and actual power generation
- works with limited data-sets

Base Model

- Modelled to suite for sites with no historical data and real-time data
- Weather forecast mapped with theoretical power curves to produce forecast
- accuracy completely relies upon quality of weather forecast data

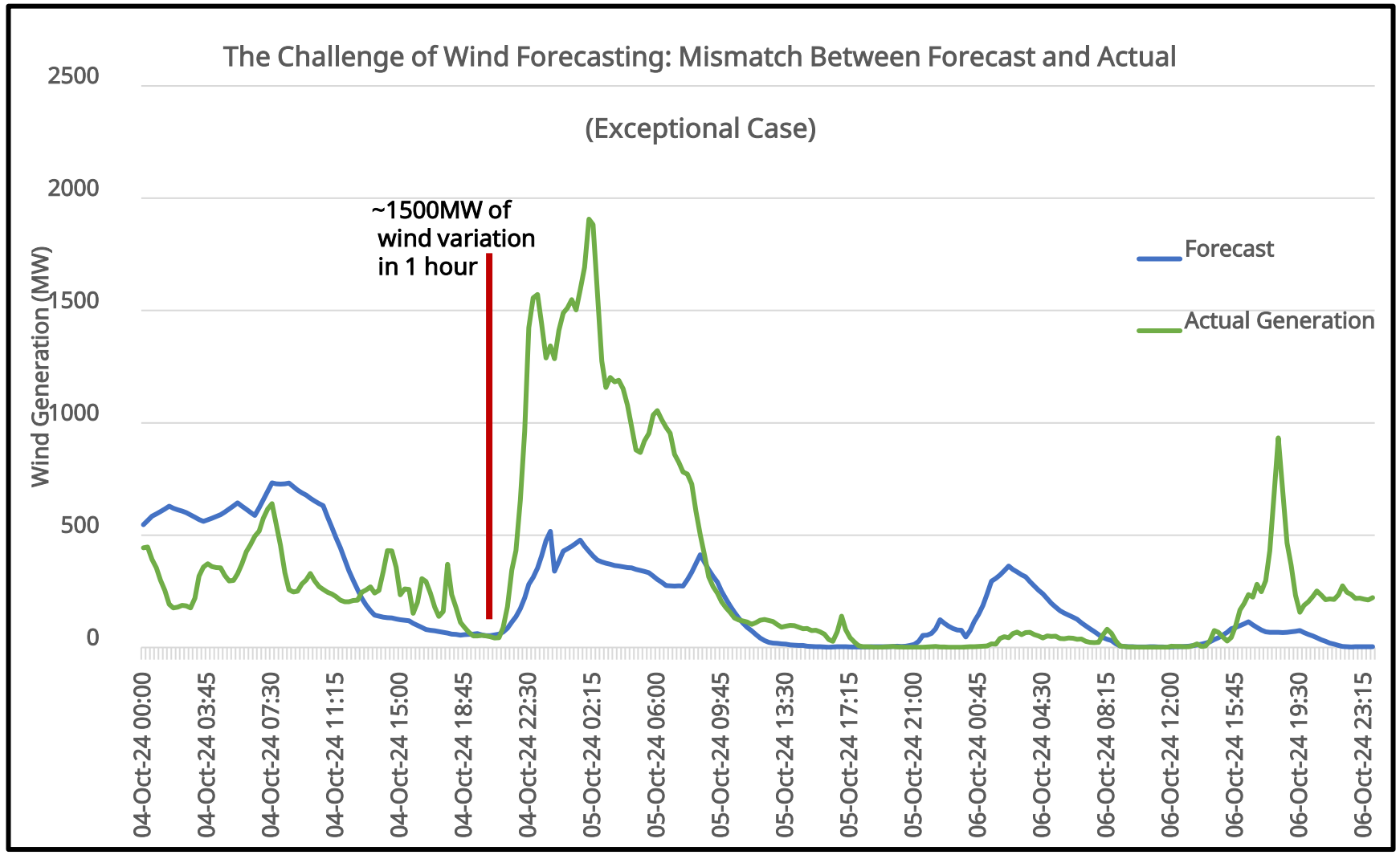
SCADA Data (Historical)

SCADA Data (Real-time)

ABT Data

Static Data (Wind, Solar)

Weather Forecast Data



All India Forecast error (RMSE) in 2024-25						
	Rev-0			Rev-16		
	Max	Min	Avg	Max	Min	Avg
Solar	9.8	1.38	4.19	7.49	1.14	3.16
Wind	20.08	0.92	7.65	9.47	0.44	3.14
Combined	13.3	0.93	4.93	6.41	0.81	2.39

Prediction is very difficult, Especially about future Neils Bohr
I think there is a world market for maybe 5 computers – Thomas Watson in 1943 (Chairman of IBM)

Initiatives for increasing accuracy of RE Forecasting

National Centre for Medium-Range Weather Forecasting (NCMRWF)

- **Enhanced Forecasting Capabilities**
- **High-Resolution Forecasts**: IMD/NCMRWF to deliver weather forecasts with high temporal and spatial resolution, updated hourly.
- **Satellite-Based Nowcasting**: Hyperlocal tracking of cloud, fog, and storm movements for precise, real-time insights.

Infrastructure Improvements

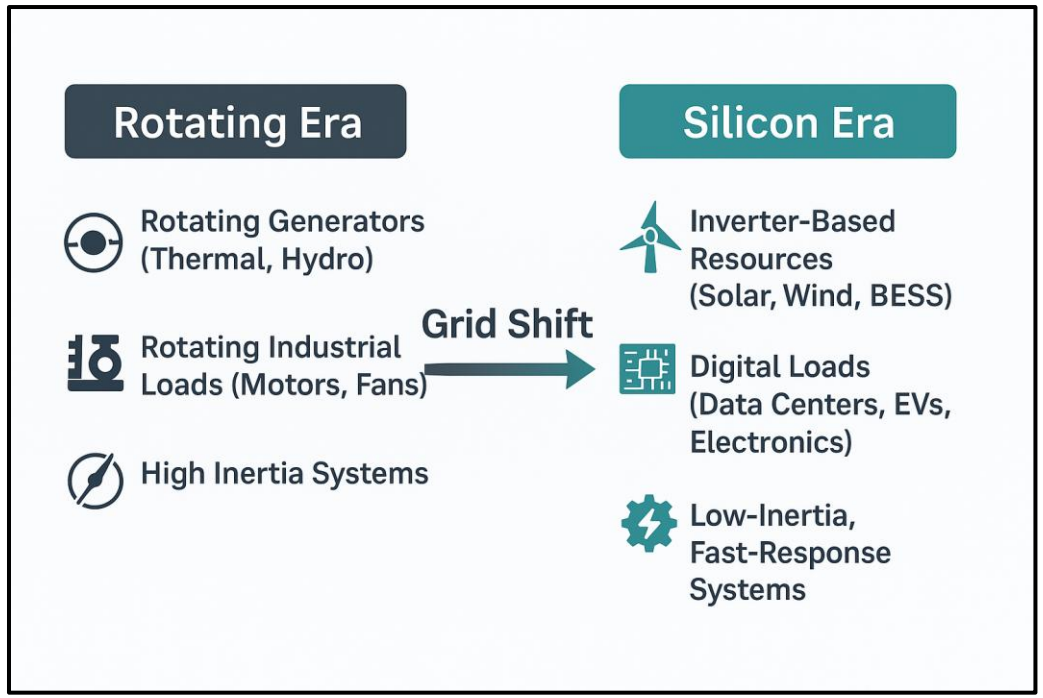
- **Automated Weather Stations (AWS)**: Installation at renewable energy (RE) plants to collect localized data.
- **Wind Profilers**: Deploying 21 profilers in RE-rich areas to provide input for Numerical Weather Prediction (NWP) models.

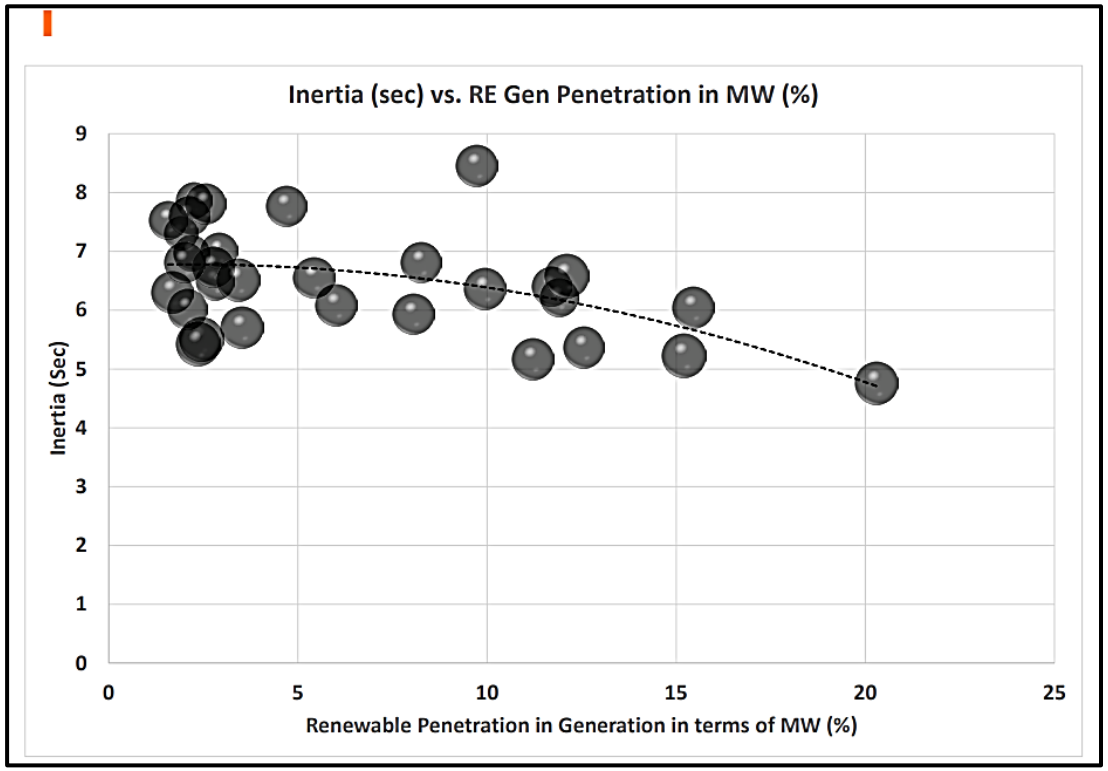
Research and Development

- **Indigenous RE Forecasting Model**: Grid-India R&D collaboration with IIT Bombay to develop a tailored forecasting solution.
- **AI/ML Integration**: Leveraging AI/ML on satellite data and weather/power generation measurements for hyperlocal, near real-time forecasting.
- **Comprehensive Power Forecasting**: Week-ahead, day-ahead, and intraday (15-min resolution) forecasts for individual plants, pooling stations, states, regions, and national aggregation.

Q&A !

Indian Grid Inertia





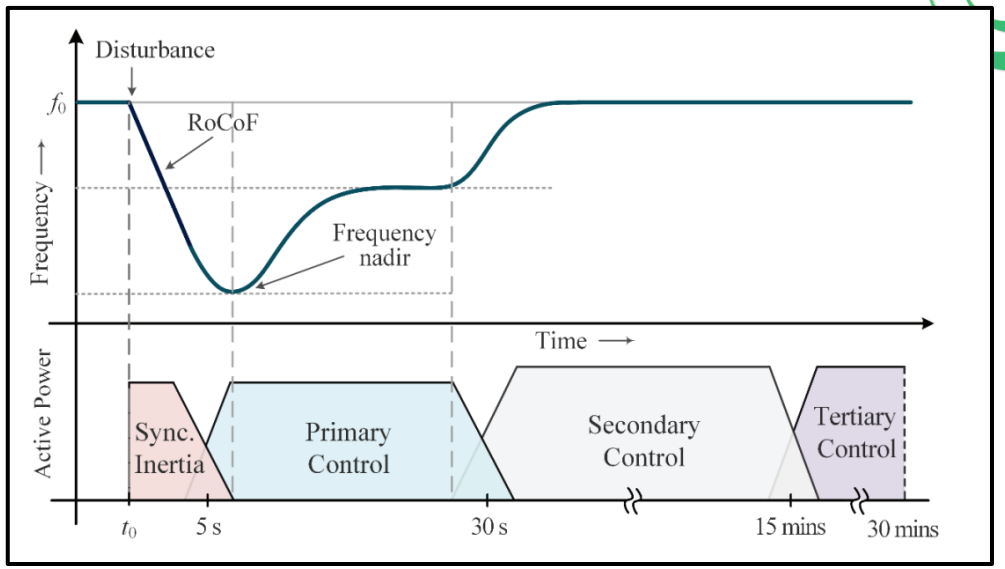
Note: Inertia of the power system(H) is measured in Seconds

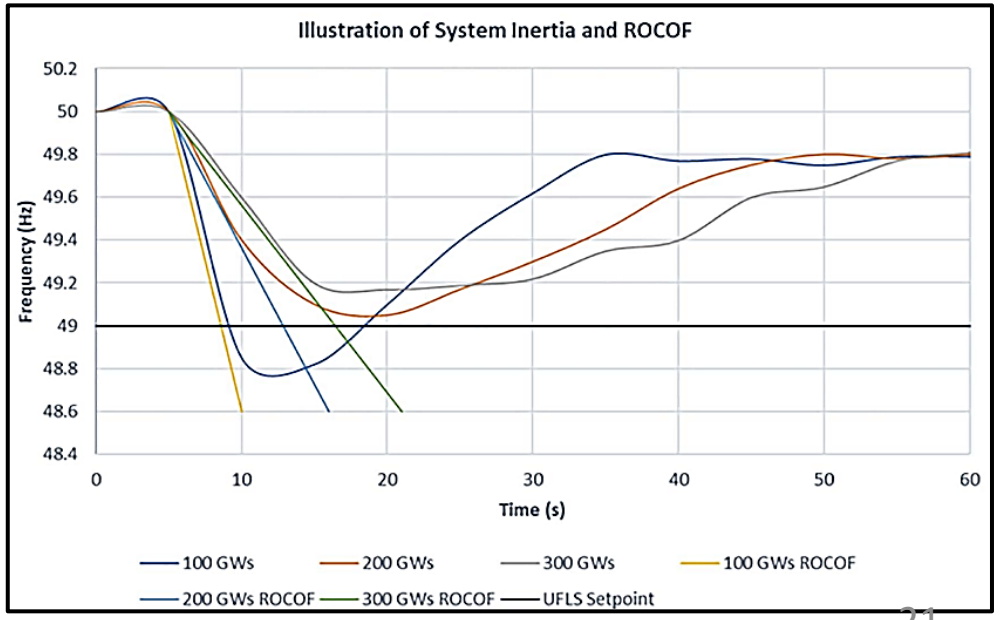
Courtesy : Grid-India

Impact on Frequency Stabi

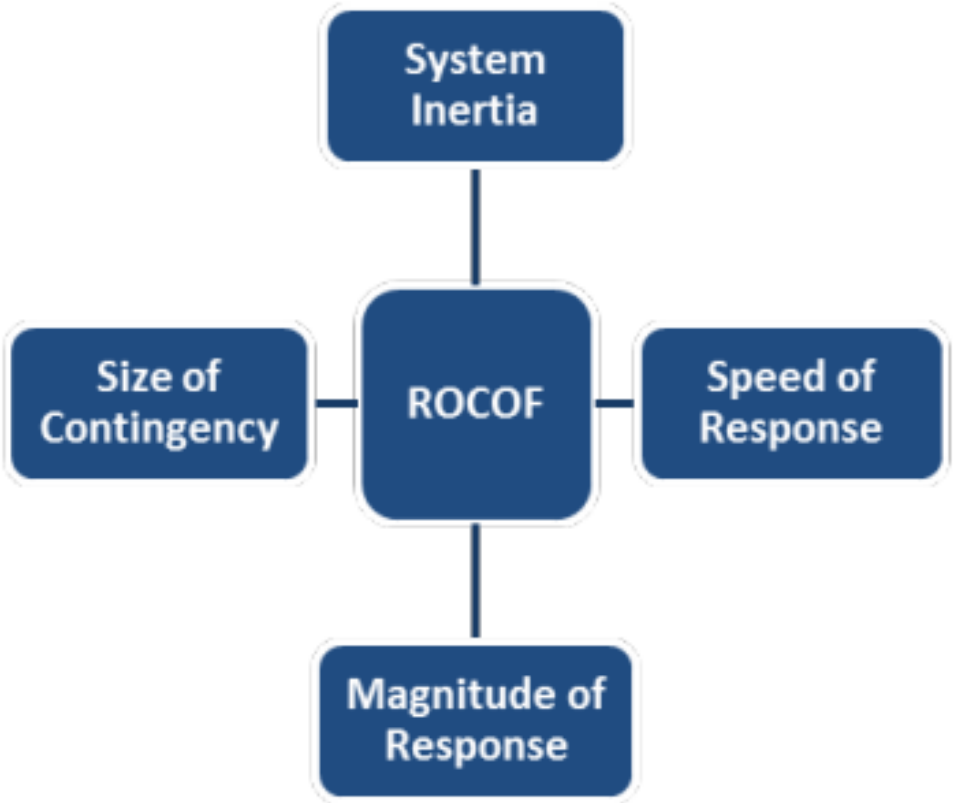
- **Diminishing Synchronous Inertia on Frequency**
  - **Extended frequency excursions with lower nadirs** can lead to cascaded failures in the system, posing risks to grid stability.
  - As the aggregate governor response diminishes, it negatively impacts primary frequency control, resulting in **reduced system recovery** following an event
- **IBR resources challenge in providing response**
  - Can Support the grid during over frequency events by reducing output
  - Frequency support for under frequency may not be feasible as need to be curtailed in advance **(economical, policy, and regulatory reasons)**

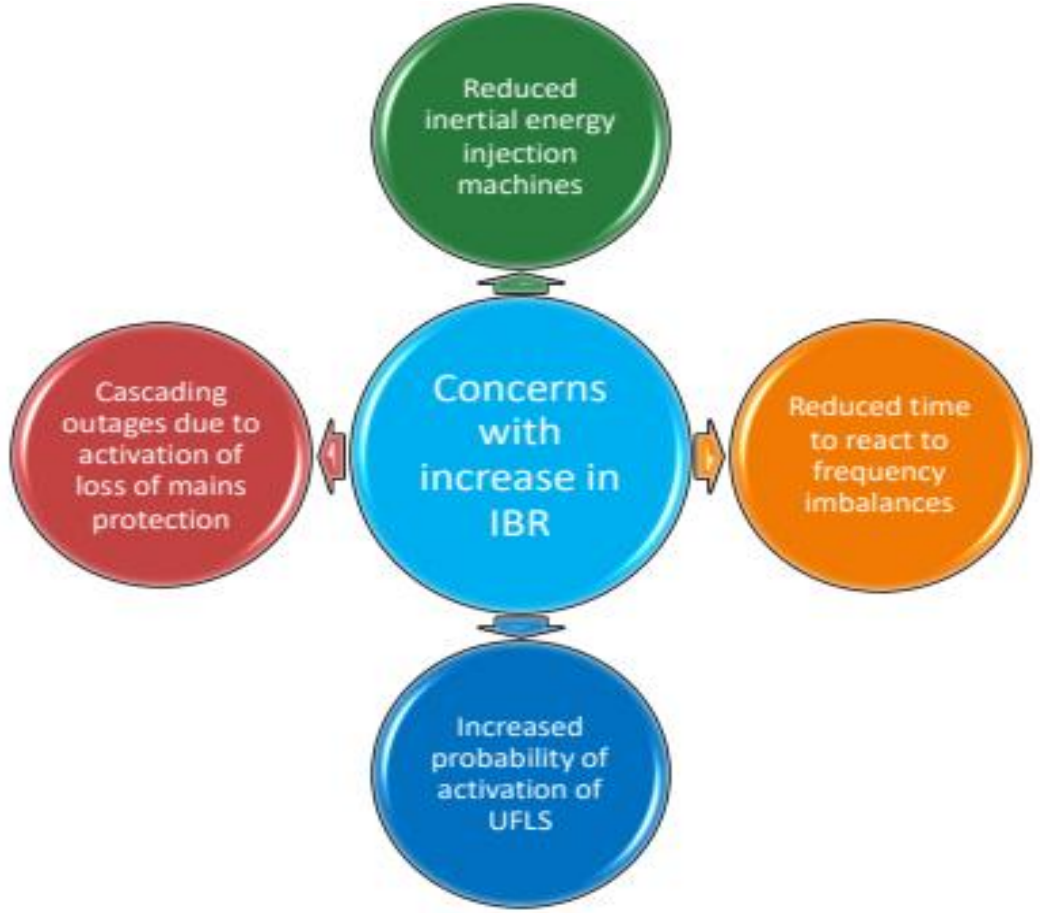
More IBR → Greater RoCoF





Declining trend of Power System Inertia…





Power system inertia is the collective **kinetic energy** stored in the rotating masses of **synchronous generators** connected to the grid, providing resistance against changes in grid frequency

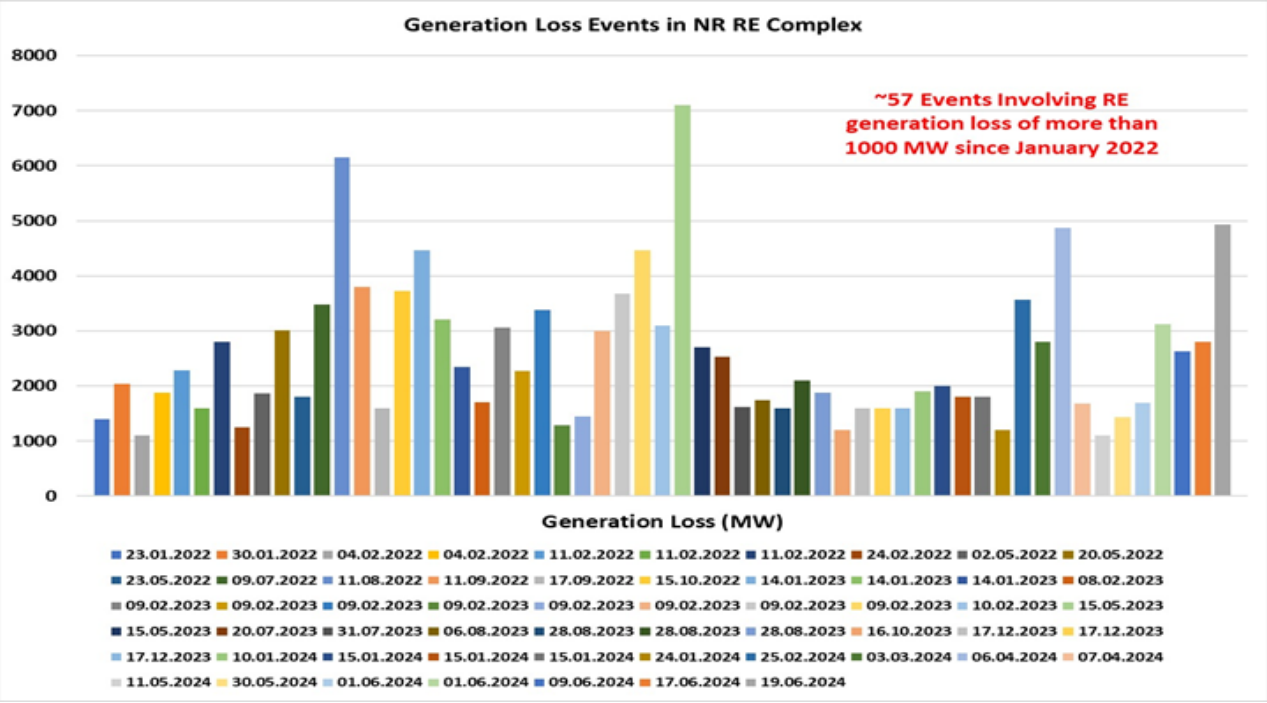
IBR: Inverter Based Resources
RoCoF: Rate of Change of Frequency
UFLS: Under Frequency Load Shedding

Operational Uncertainty – Impact on Grid Stability

Concentrated RE Capacity Addition - Possibility of a large disturbance/generation loss in case of any non-compliance

- **~57 events involving RE generation loss of above 1000 MW between January'22 to June'2024**

- **Fault ride through failure one of the primary reasons for these events**

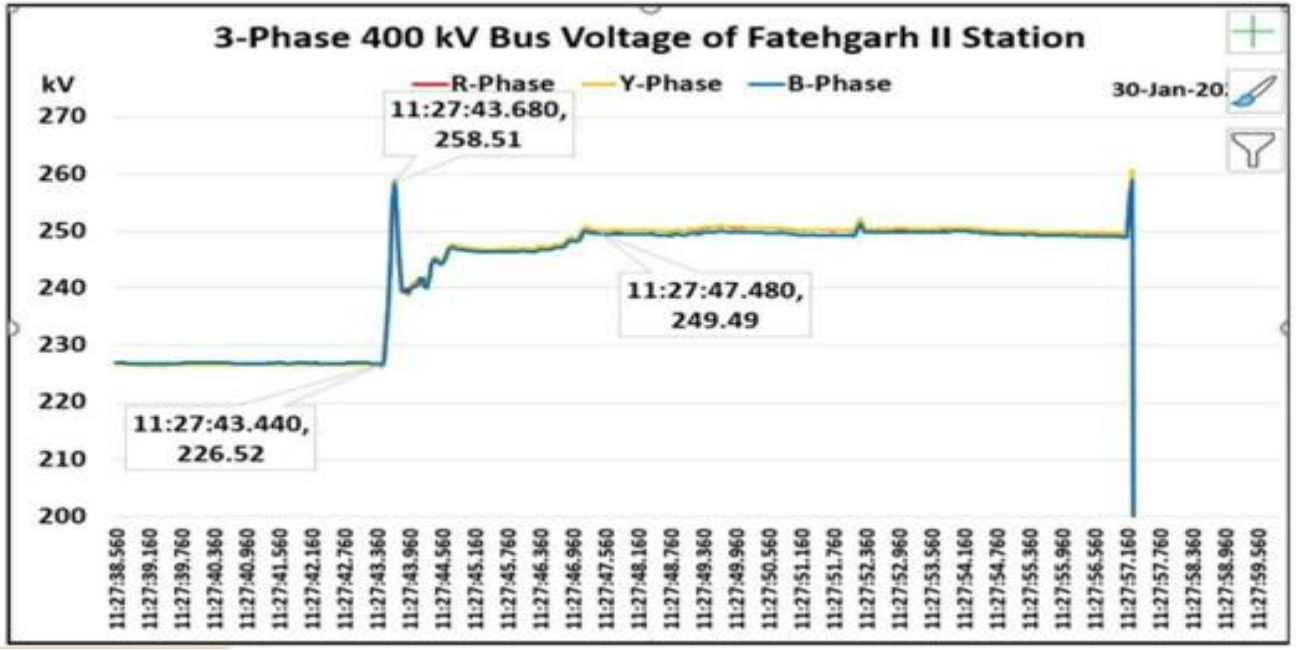


Fault Classification

- a. Transmission system faults external to RE plant
- b. Transmission system faults within the RE plant
- c. Over voltage during line or reactor switching
- d. Forced oscillations in reactive power and voltage

Fault level challenges at RE pooling stations

SCR of ISTS RE pooling station								
Sl. No.	Region	Voltage level	Station Name	3-ph fault current (kA)	3-Ph fault MVA	Generation being pooled (MW)	SCR	Min desirable SCR
1	NR	220	Fatehgarh-II_A	21	7850	2490	3.15	5
2		400	Fatehgarh-II	21	14150	4180	3.39	5
3		220	Bhadla	33	12636	3080	4.10	5

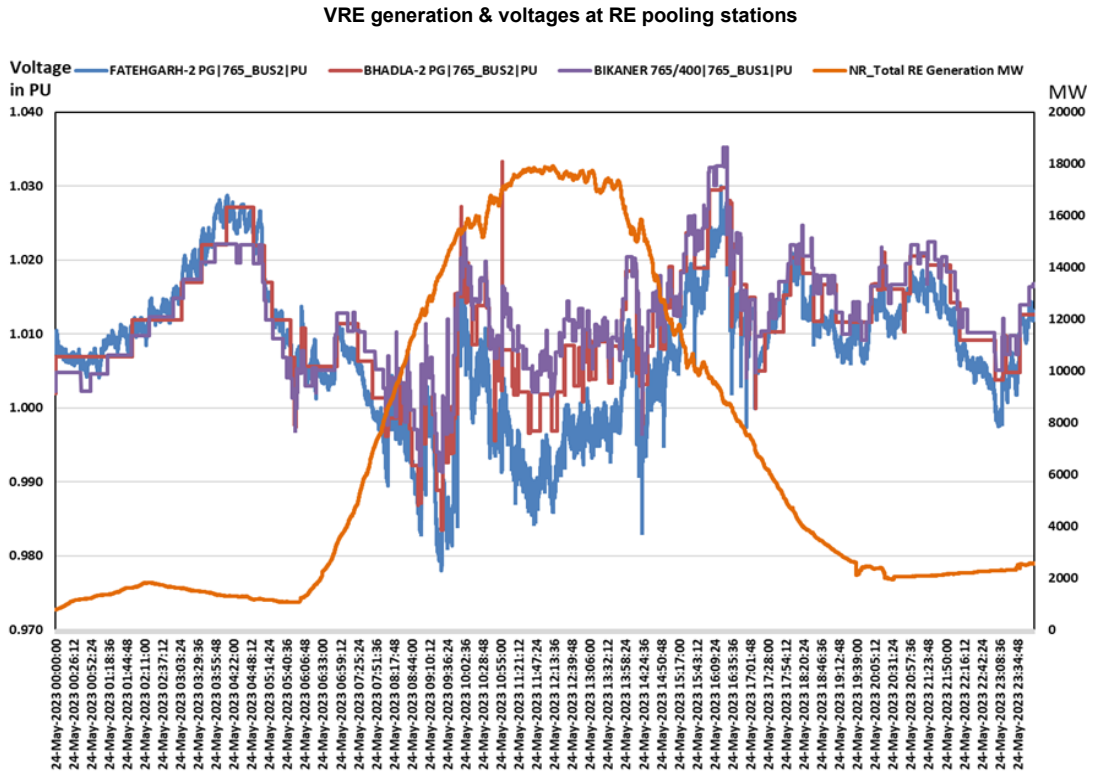


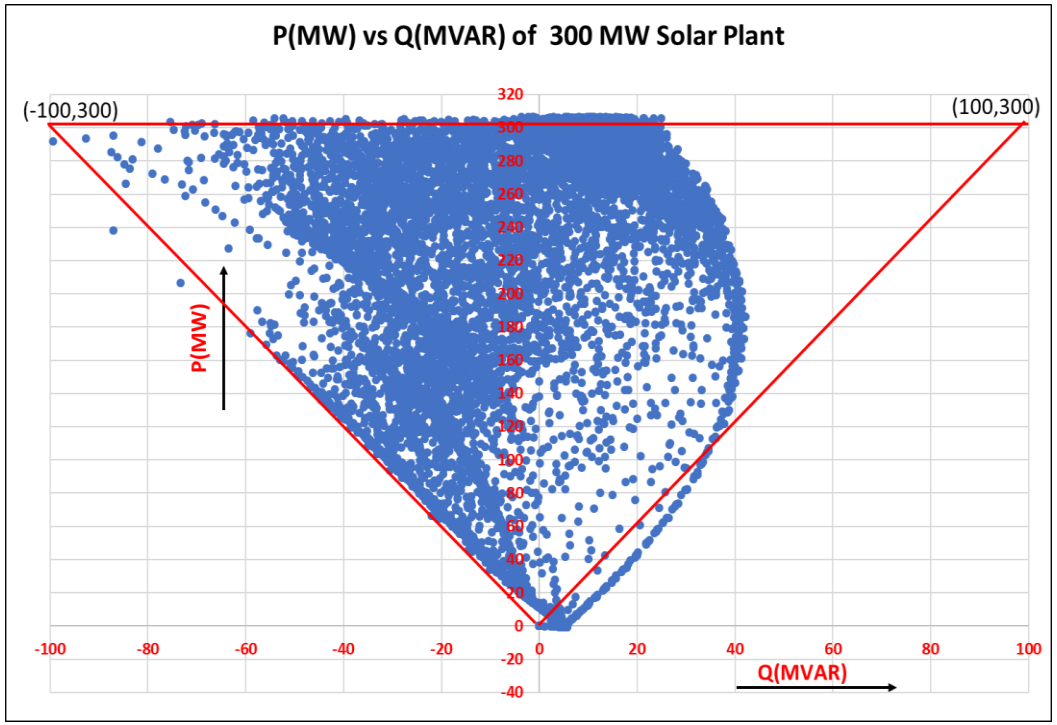
- The short circuit ratio (SCR) is a measure of the strength of the electrical grid at the substation
- With Integration of RE, SCR is getting reduced leading to lesser resilient buses to faults

Depleted Network on 30 Jan 2022

- 240 MVAR Line reactor switching
- 32 kV Voltage rise in phase to neutral
- EHV Lines tripped on Overvoltage
- Triggered HVRT and consequent loss of 2000 MW generation

IMPACT ON Voltage Stability



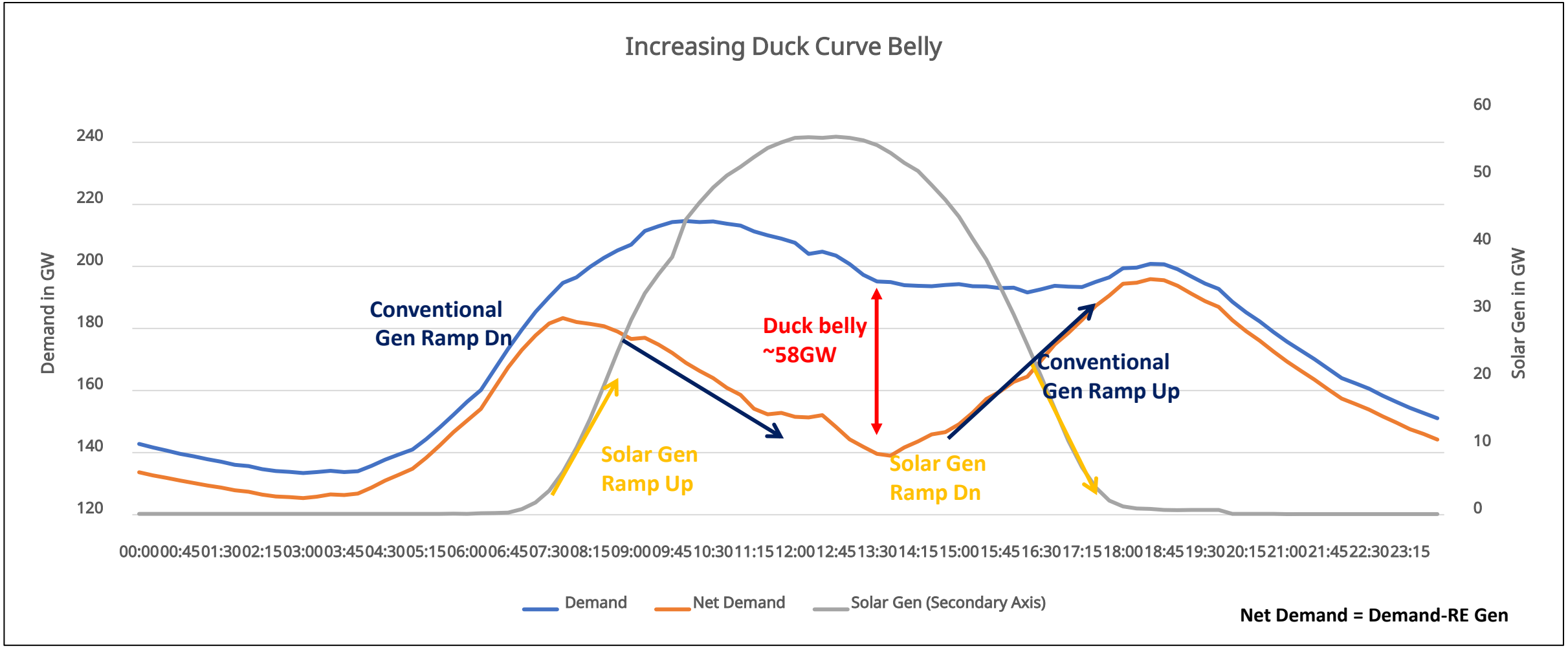


Large Fluctuation in Voltages (High v/s Low RE Period) – 8-10% voltage variation within same day

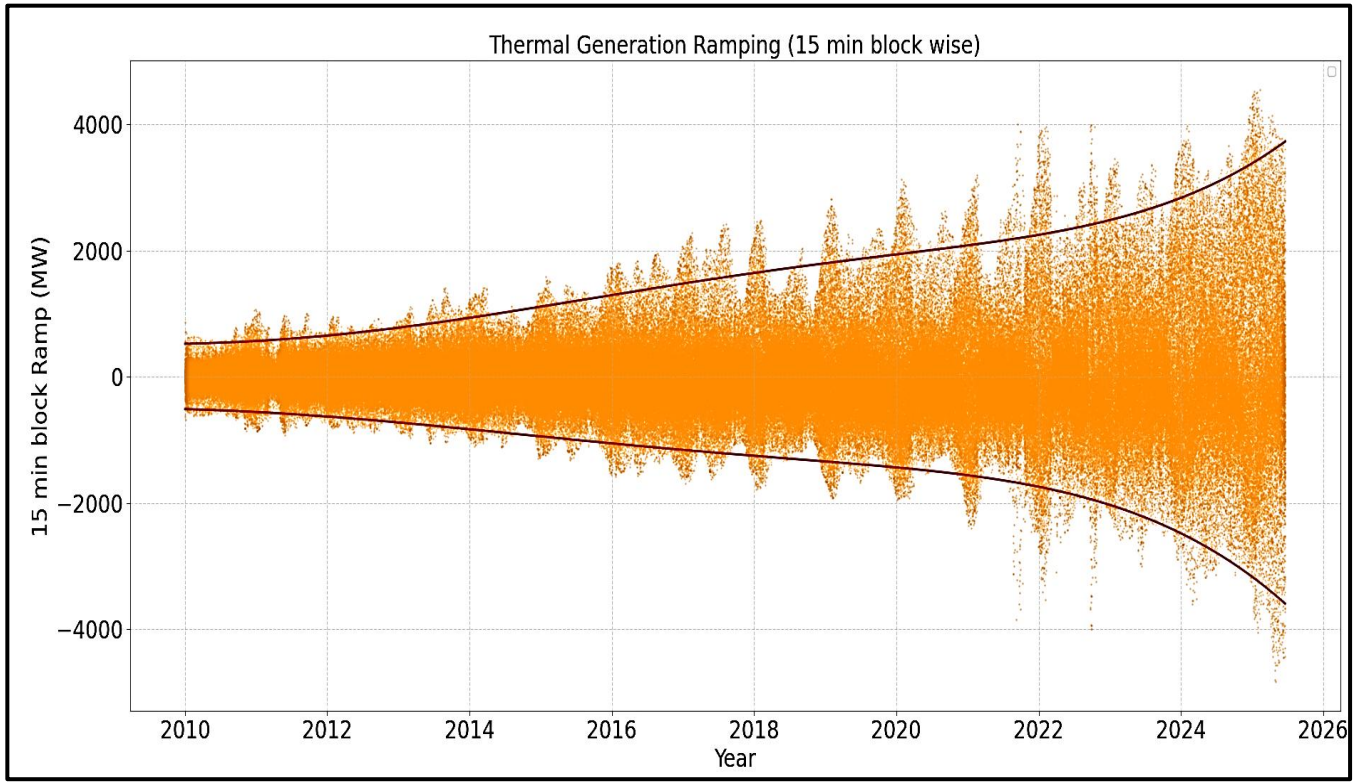
Several 765 kV lines opened daily for voltage regulation as last resort

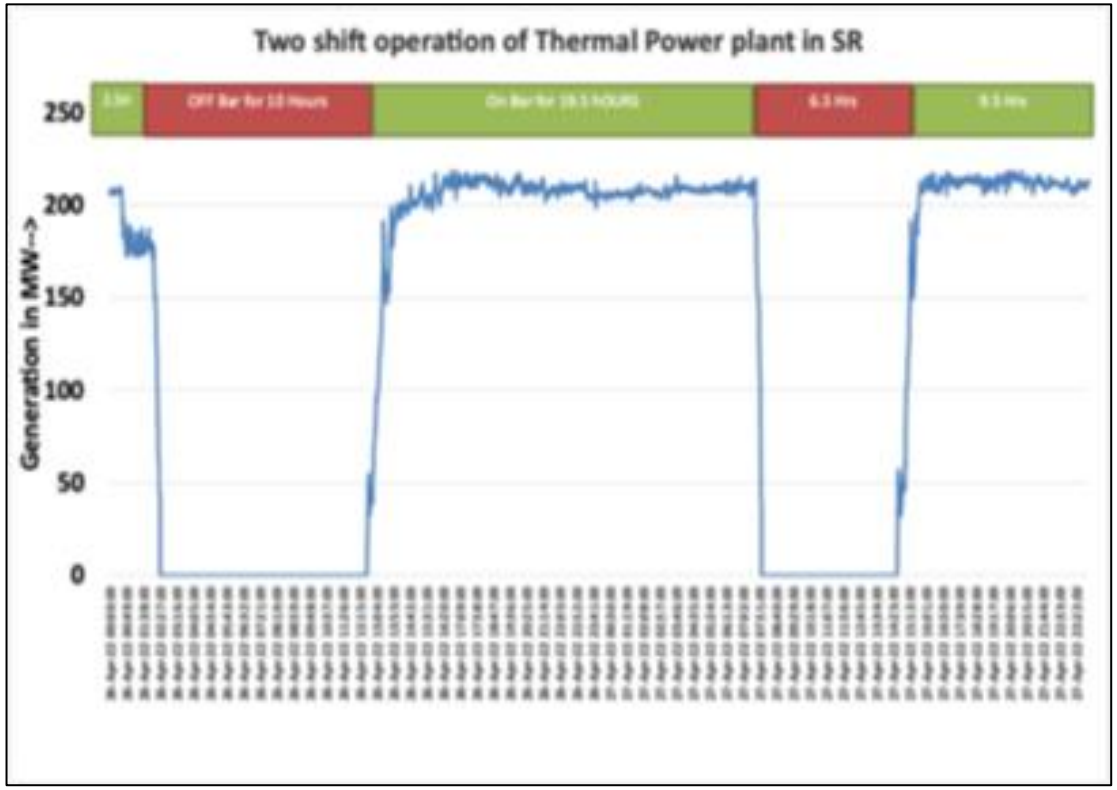
Inadequate Reactive Power Support from RE Plants

Flexibility and Balancing Requirements



Increasing Thermal Flexibility

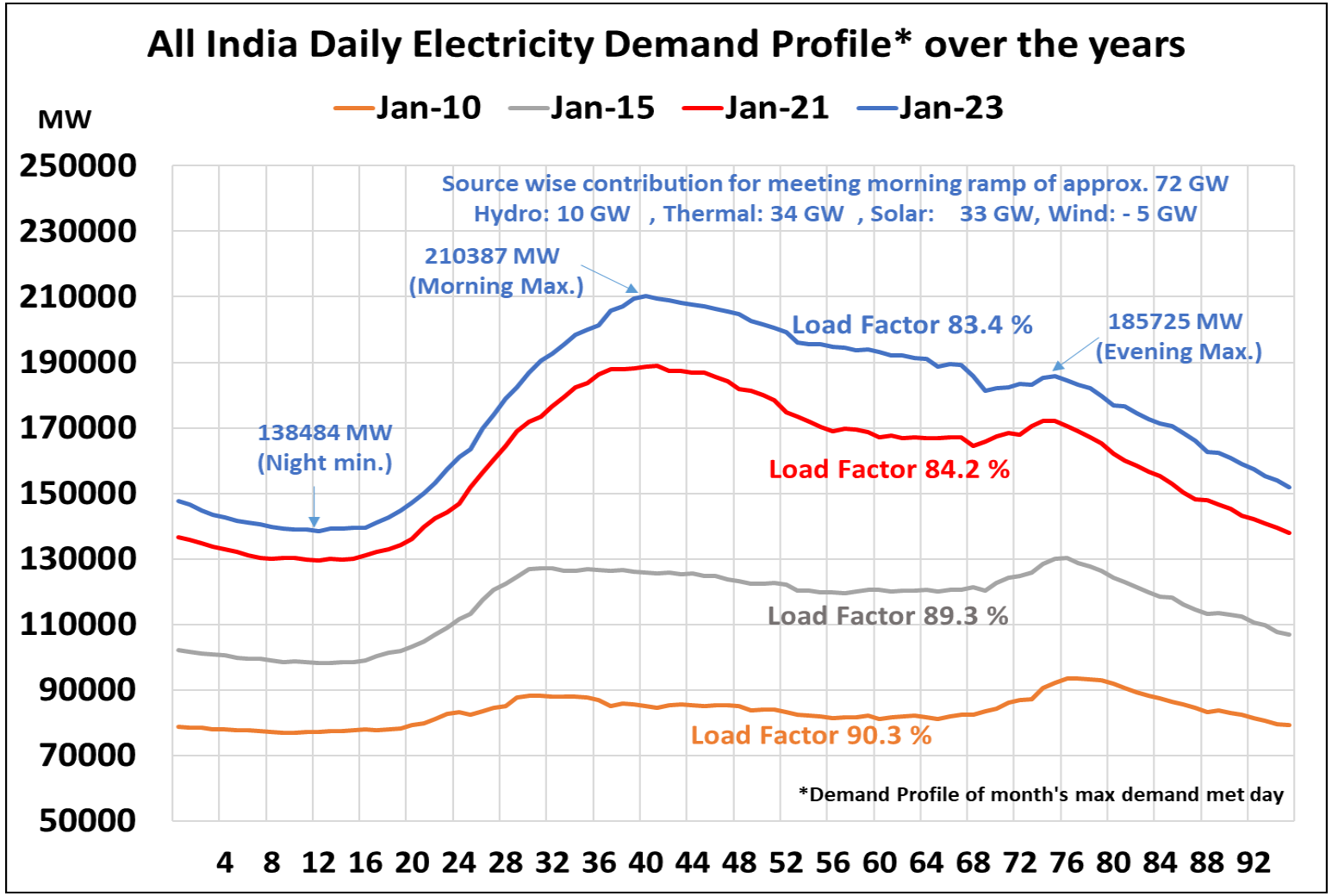




As the level of RE integration in the grid raises, thermal generating stations have increased their ramping abilities to accommodate RE

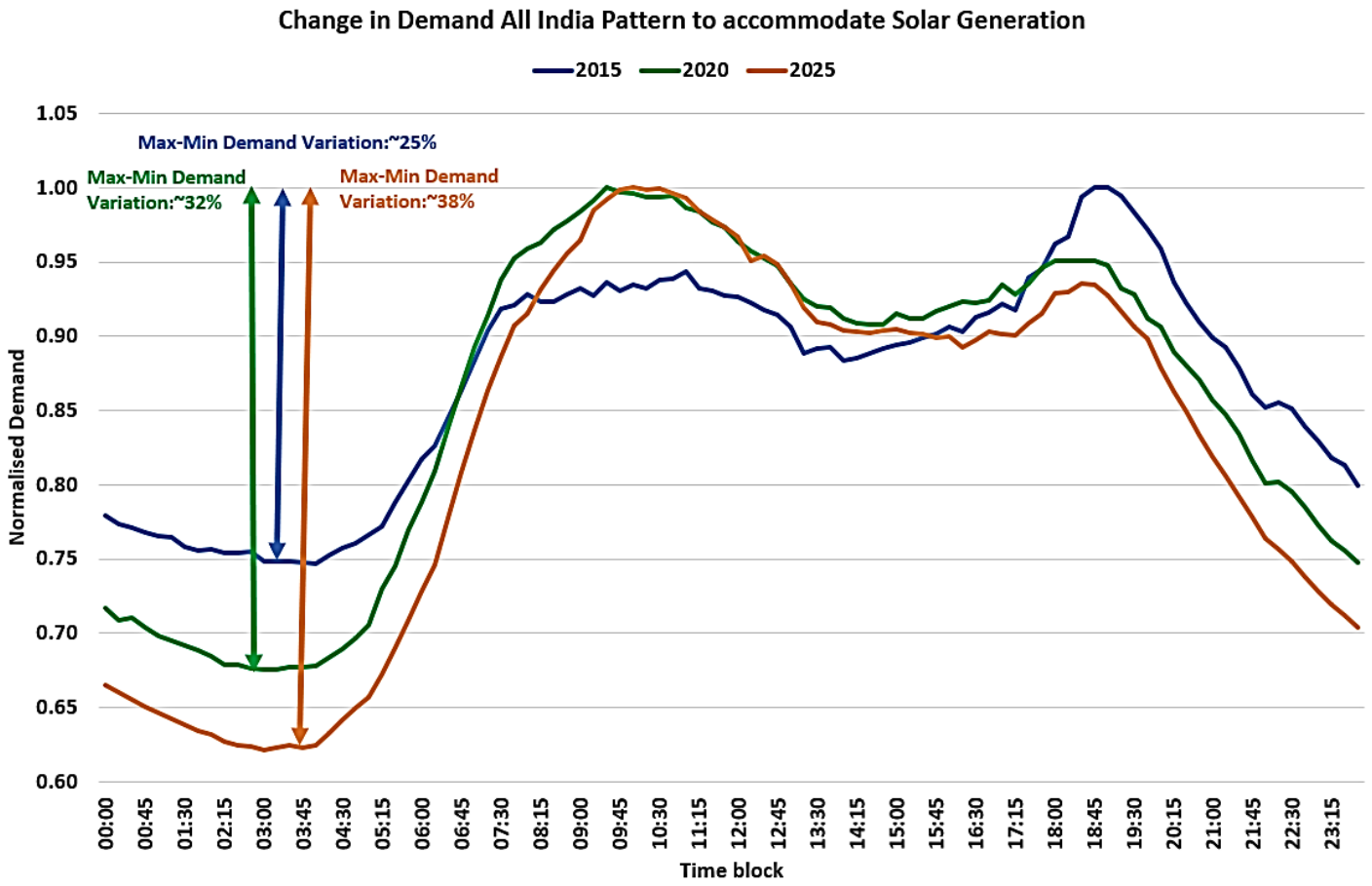
Thermal power plants running during high-demand periods (morning and evening peaks) and shutting it down during off-peak hours is one of the solution

Flexibility and Balancing Requirements



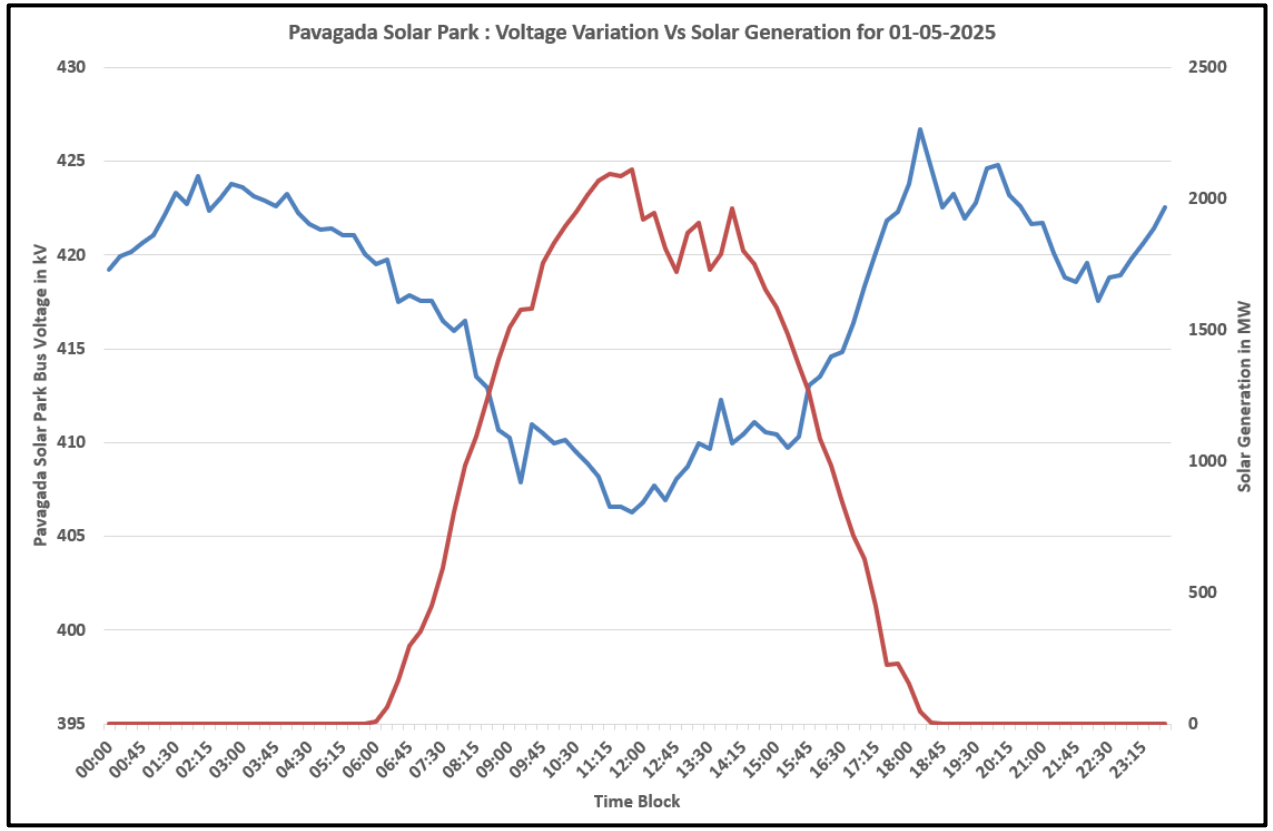
- ✓ Daily load profile becoming more variable
- ✓ Large swing between peak & off-peak demand

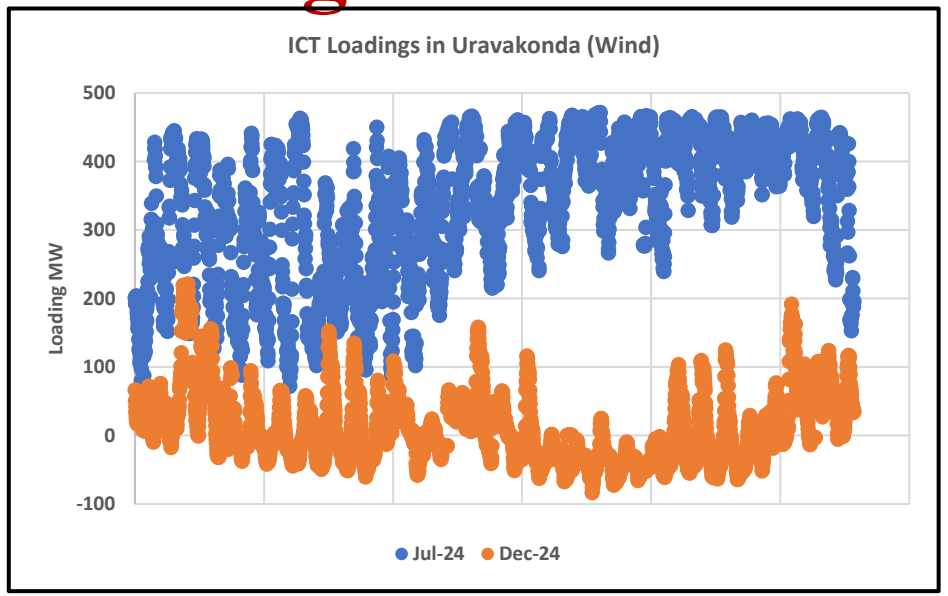
Demand Side Flexibility

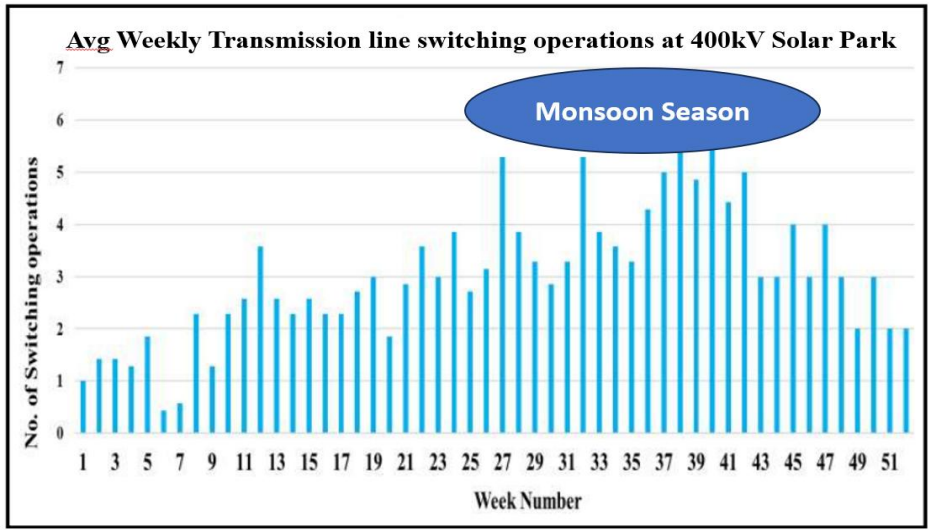


- ✓ Demand getting aligned to solar generation
- ✓ Difference in the Maximum and Minimum demand getting increased.
- ✓ Flexible loads (Agricultural loads) being shifted to Solar Hours.

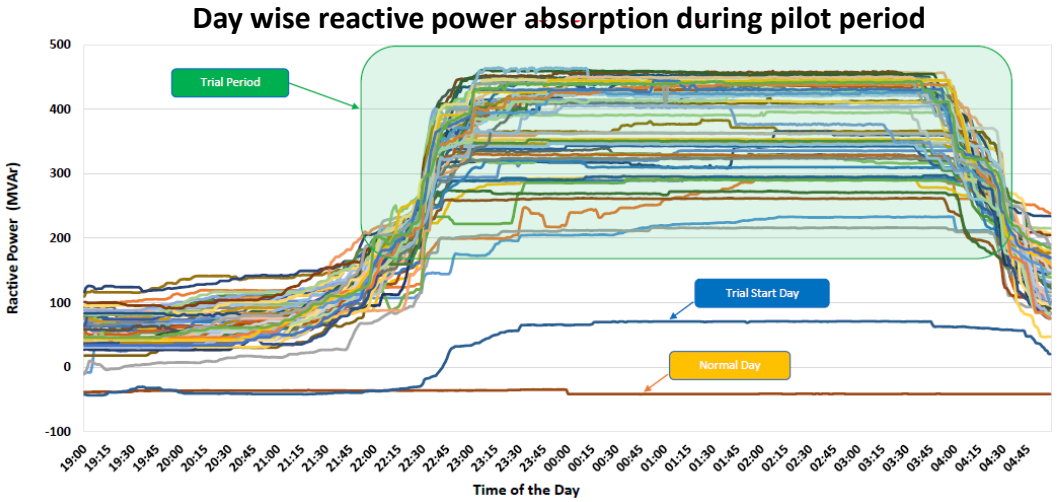
Power Flow Variations leading to Voltage issues

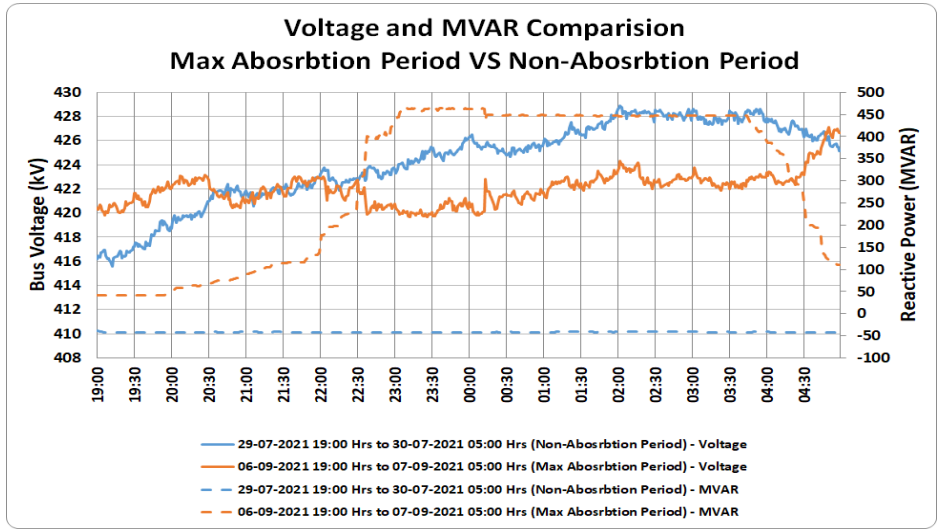




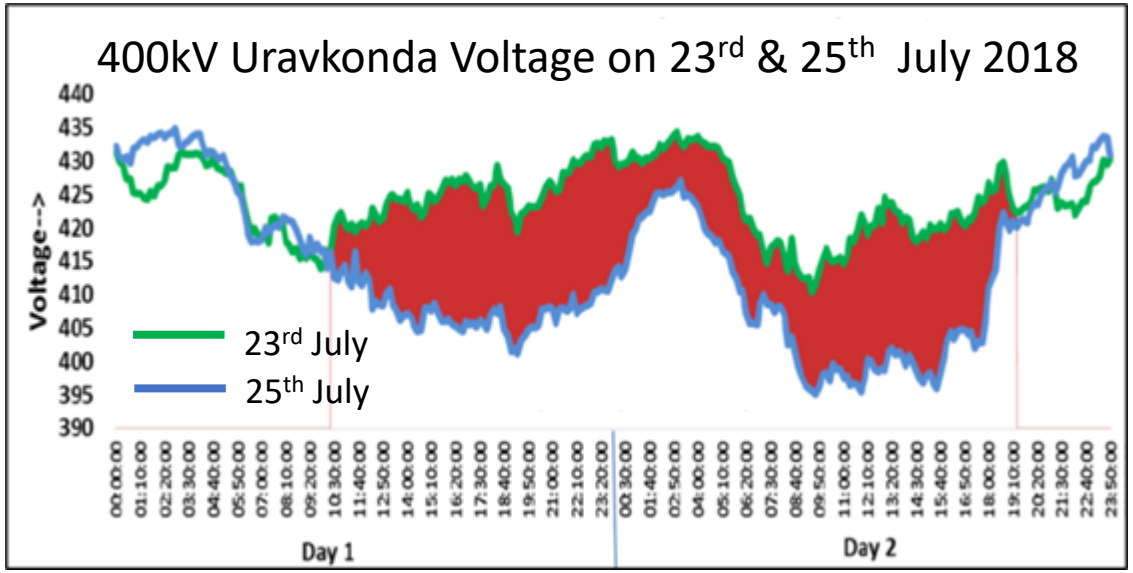


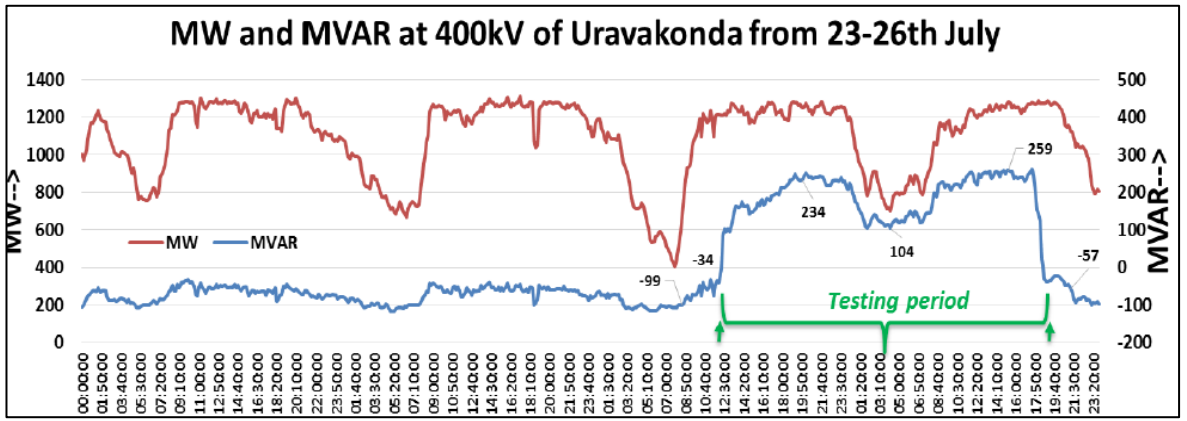
Using Solar & Wind Invertors for Voltage control





Positive MVAR is Absorption of MVAR
Negative MVAR is Generation of MVAR





Regulatory Reforms

MTDL of thermal stations to 55%

Mandating 1% ramping capability from thermal stations

Incentivising primary frequency response

- Forecasting Relaxations: Enhanced error band under Deviation Settlement Mechanism (+/- 15% for wind & +/- 10% for Solar and Frequency delink for RE
- Energy Storage Support: VGF-backed 1000 MWh BESS scheme
- Ancillary Services: RE + Storage can earn via frequency support
- Flexible Coal Operations: Incentives for retrofit and flexible dispatch

Incentivizing fixed cost during peak hours

Hydro Purchase Obligation & Energy Storage Obligation

Market Reforms (RTM, GDAM, GTAM, MBAS, GOAR)

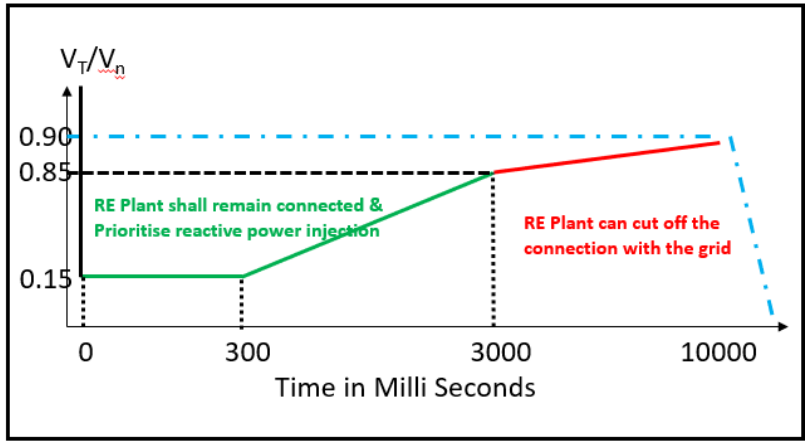
RTM: Real time market
GDAM: Green Day Ahead Market
GTAM: Green Term Ahead Market
MBAS: Market Based Ancillary Services
GOAR: Green Open Access Registry

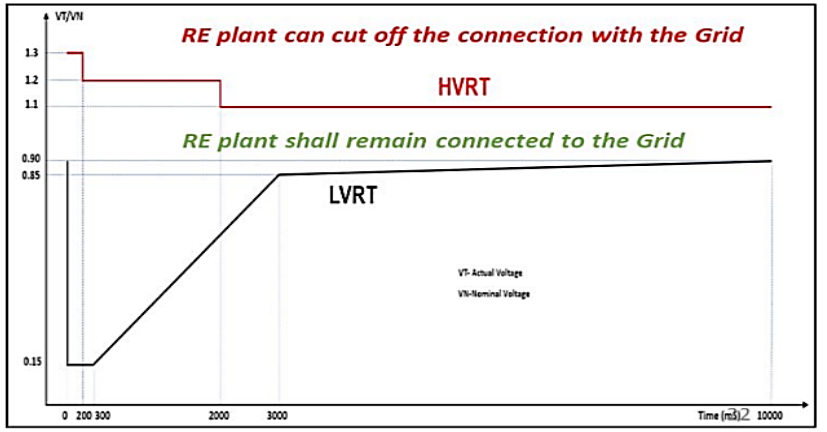
1. Connectivity Standards

Amendment to CEA's "Technical Standards for Connectivity to the Grid"

Notified on 8th Feb 2019; Effective from 6th Aug 2019

Frequency Response by RE Generators	Active Power – Set Point Control	Low Voltage Ride Through (LVRT) and High Voltage Ride Through (HVRT) Applicability
Provision to vary Active and Reactive Power*	Short Circuit Ratio – five or above	Rate of Change of Power < ±10% per minute





The generating station shall be capable of supplying dynamically varying reactive power support so as to maintain power factor within the limits of 0.95 lagging to 0.95 leading.

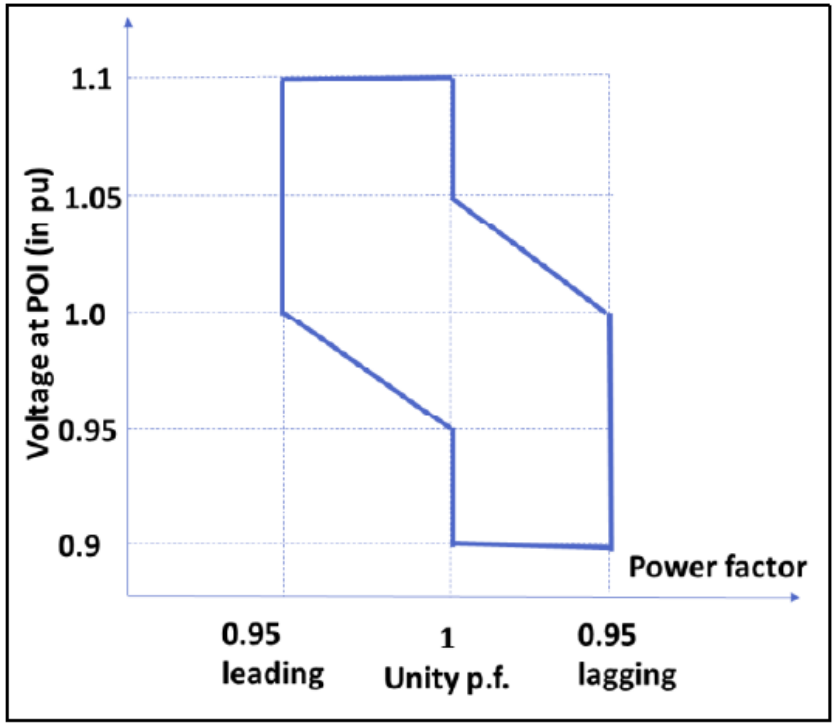
* Based on the signal from the State Load Dispatch Centre or Regional Load Dispatch Centre

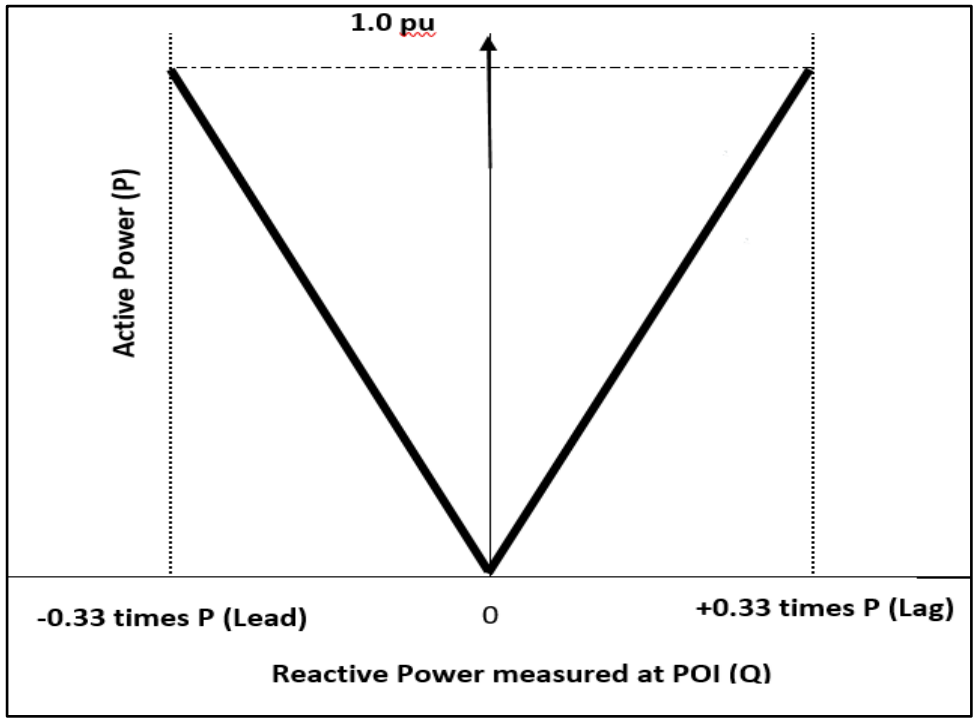
1. Connectivity Standards (…contd.)

d. Reactive Power Capability – <u>Existing Provision</u>

<u>Issues faced in Real time</u>

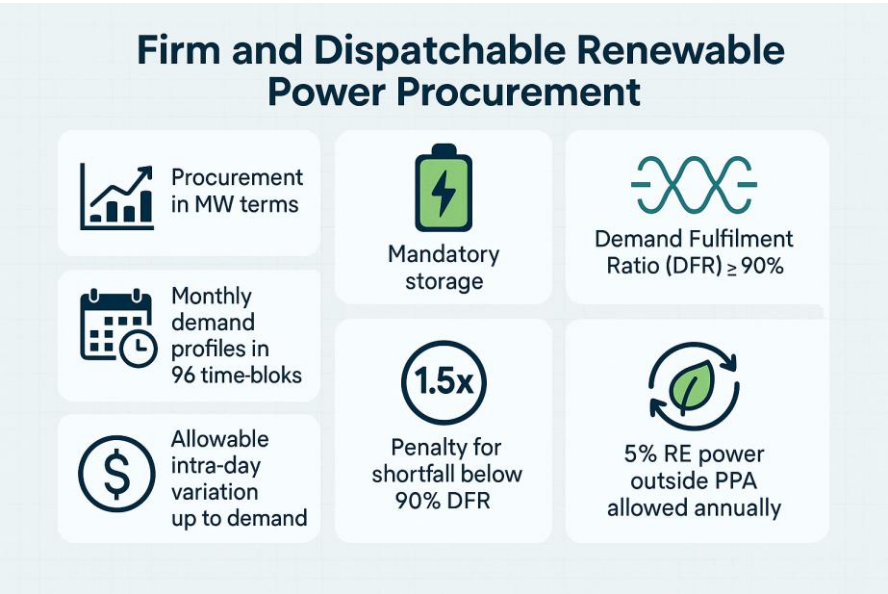
- Reference point to be specified as Point of Interconnection (POI)
- Operation in any control mode viz. voltage, power factor or Q control to be specified
- Voltage range for providing reactive power support to be specified

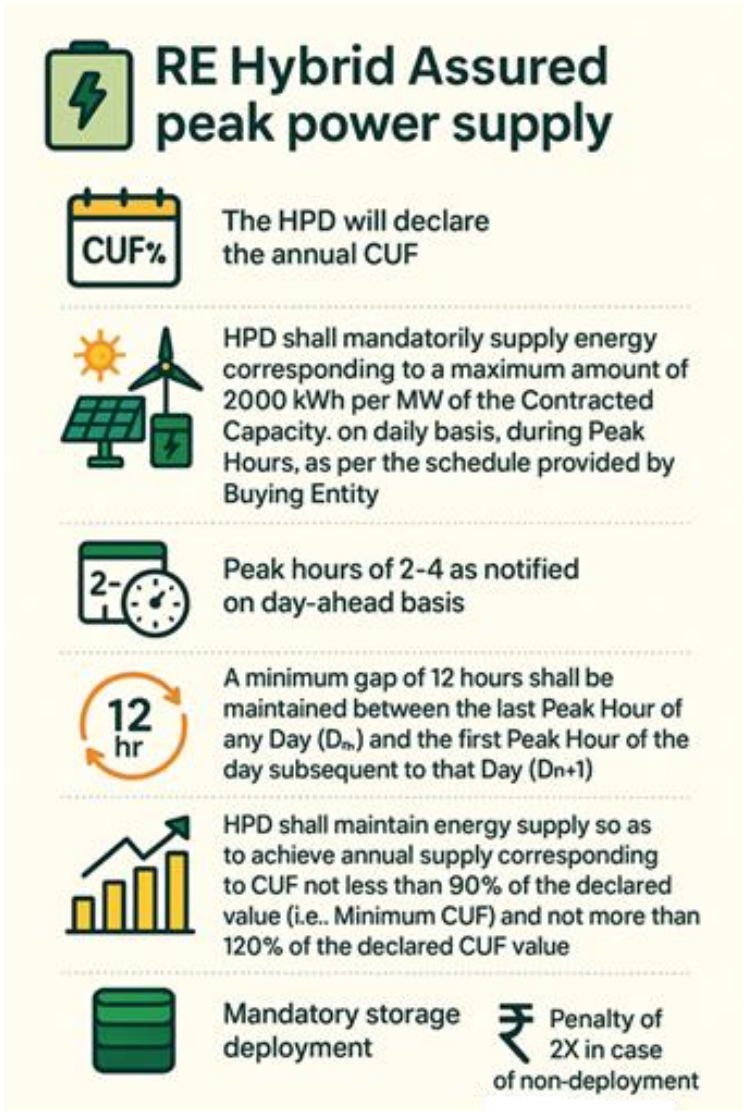


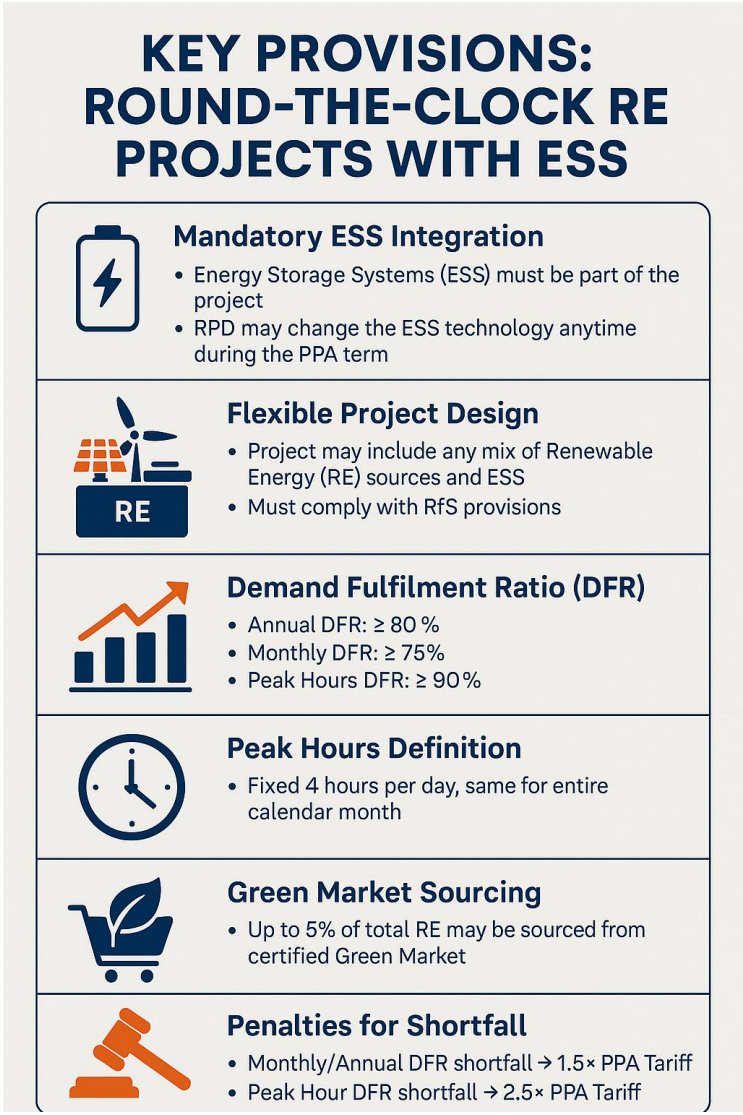


<u>International Practice</u>

Transformative Bidding Frameworks







"Engineers like to operate sophisticated power systems, economists like to think about optimal incentives, and lawyers like to write rules and agreements. Power sector reform brings all of them into close contact. But none of them can succeed at their chosen tasks unless they work together in designing sustainable institutions."

- World Bank Report: Transmission System Operators – Lessons From The Frontlines

Thank You!

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धन्यवाद

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धन्यवाद

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ขอบคุณ

For your valuable attention and commitment to a sustainable energy future across BIMSTEC nations!