Grid Stability with RE Integration

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Indian Grid - Amongst the World's Largest & Complex

Source: GO15

1 National Synchronous Grid

3 Electricity Generation

Electricity Consumption

Installed Generation Capacity

Transmission System

Solar Generation

4 Wind Generation

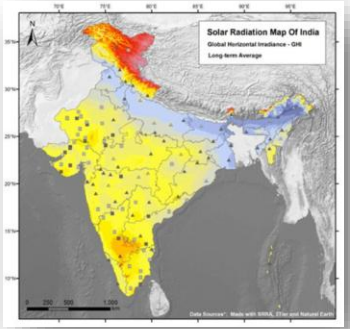
5 Pumped Storage Installed Capacity

6 Hydro Generation

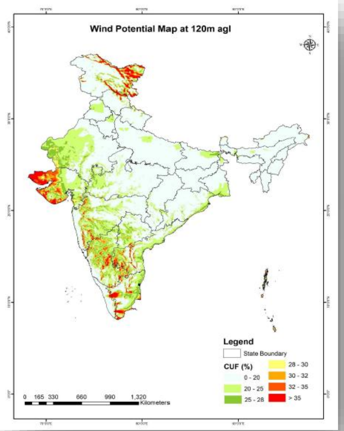
Source: IEA World Energy Outlook 2024 &
https://www.irena.org/Data/View-data-by-topic/Capacity-and-Generation/Country-Rankings

Characteristics of Regional Grids

Solar Radiation Atlas

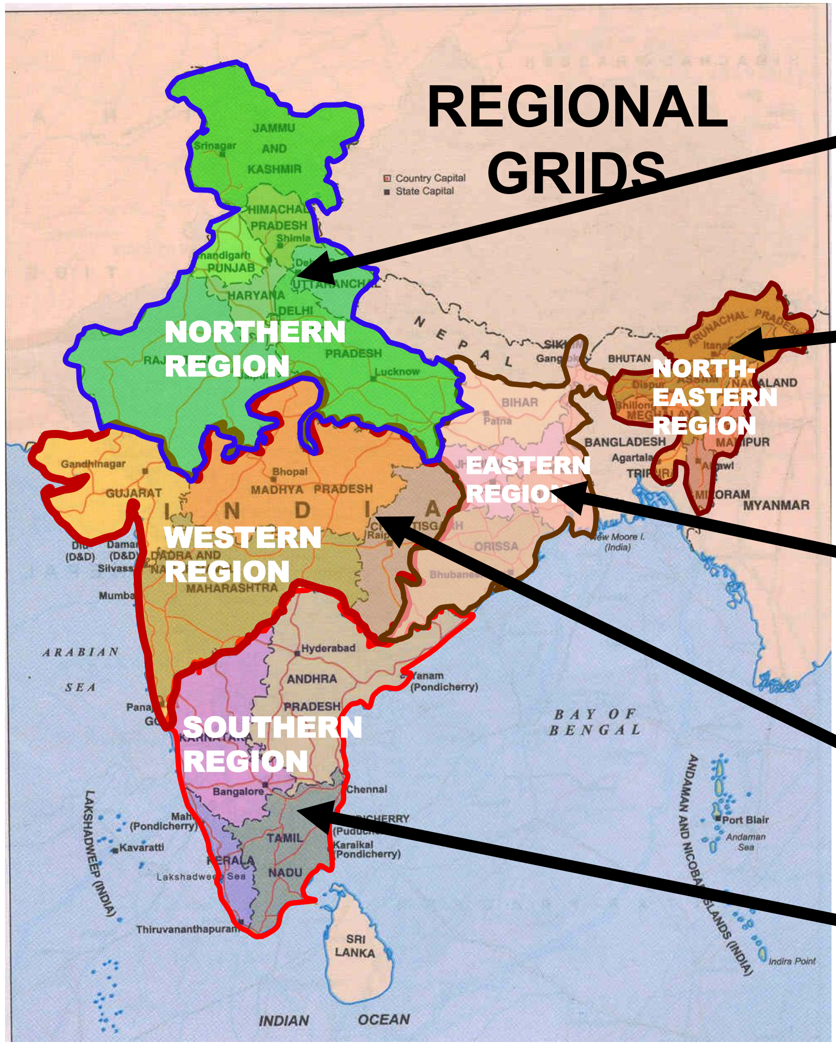


Wind Atlas



Offshore Wind

High Wind and Solar potential in Southern, Western, Northern Regions



- Snow fed – run-of –the –river hydro
- Highly weather sensitive load
- Adverse weather conditions: Floods, Fog & Thunderstorms
- High RE in Rajasthan

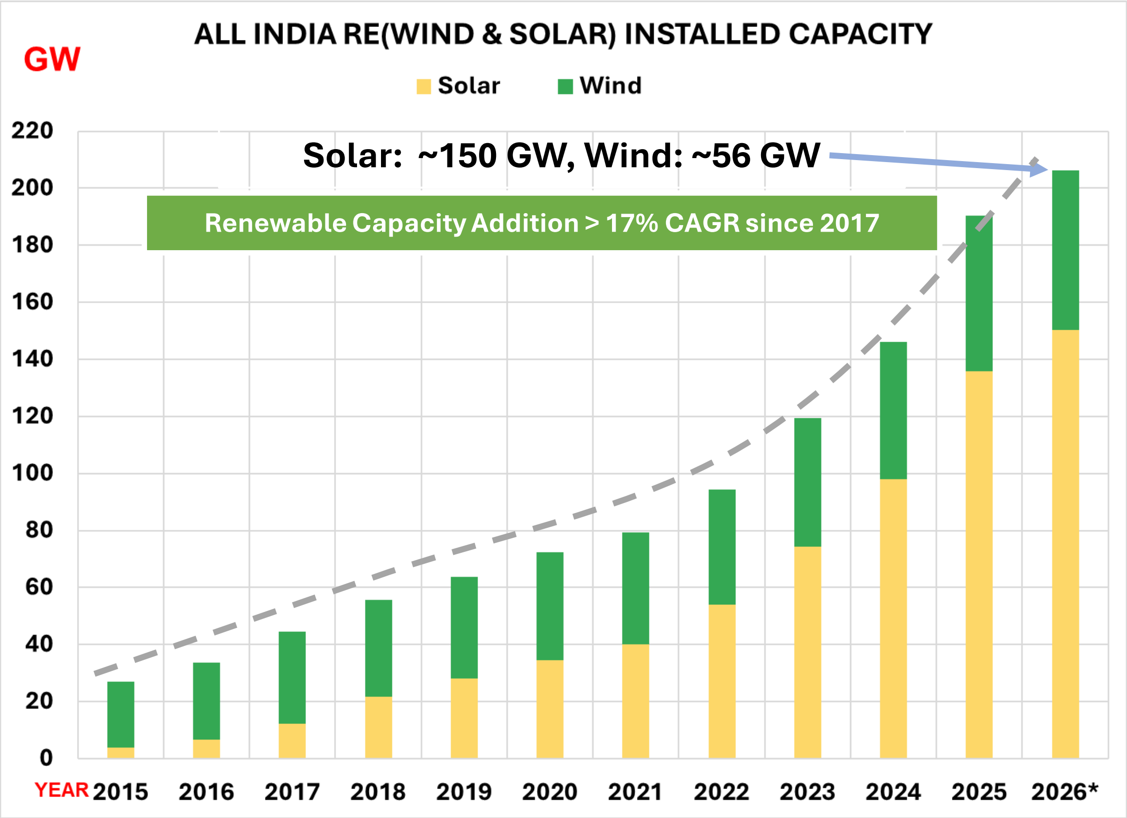
- High hydro potential
- Mountainous Terrain
- Power evacuation challenge

- High coal reserves
- Pit head base load plants

- Industrial and Agricultural load
- Renewable Rich States – Wind/Solar
- Large thermal generation capacity

- Industrial and Agricultural load
- Monsoon dependent hydro
- Renewable Rich States – Wind/Solar

India's Journey with Renewables

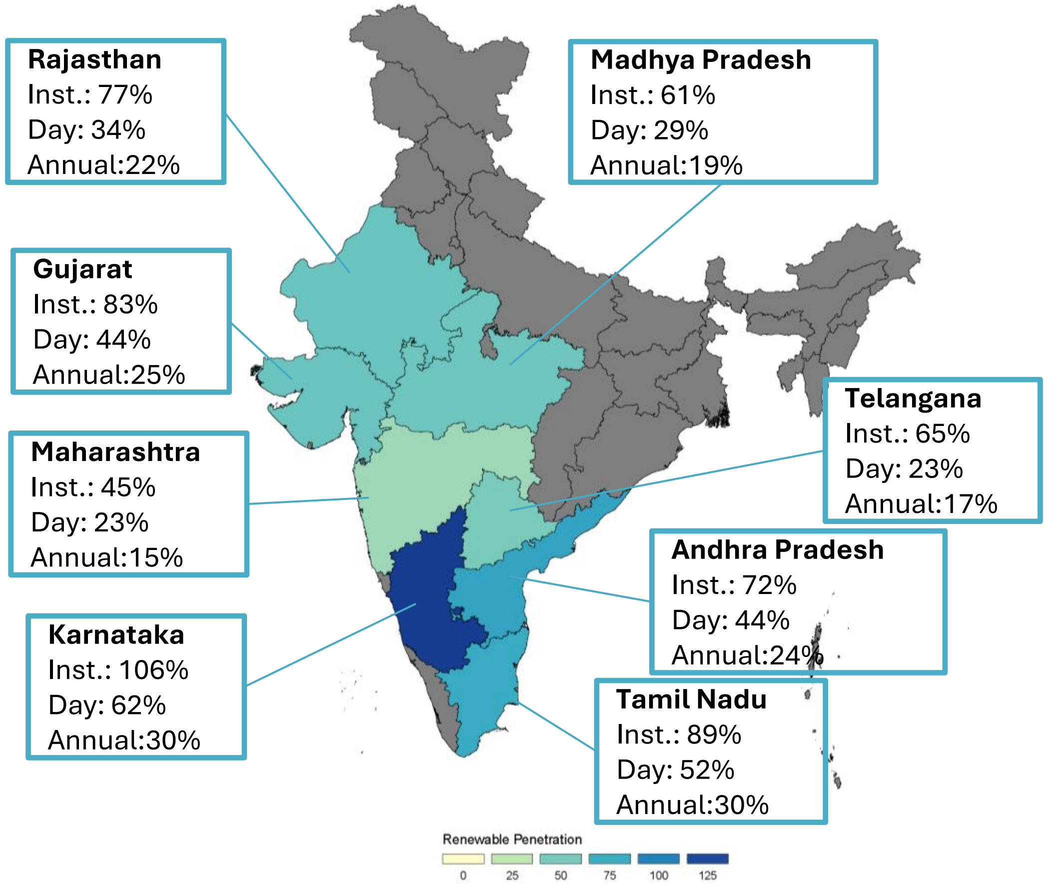


Source: CEA Installed Capacity Report (data as on Dec 2025)
[Installed Capacity Report - Central Electricity Authority]

Highest All India Instantaneous VRE (Solar + Wind) penetration of ~40.1% recorded - 2nd June 2025

Highest All India Instantaneous RE (Solar + Wind + Hydro) penetration of ~51% recorded – 6th Sep 2025

Maximum Wind + Solar penetration in instantaneous MW and energy (day/year) terms – FY 2025-26



500 GW non-fossil capacity by 2030
Including ~285 GW Solar & ~93 GW Wind

India's Energy Transition Roadmap

GRID-INDIA

Resource	Mar-2026	Mar-2030	Mar-2036
Hydro (including PSP)	51	81	**172**
Solar PV	150	**285**	**509**
Wind	56	**93**	**155**
Other RES	17	18	22
Nuclear	9	13	22
Coal + Lignite	229	260	315
Gas	20	20	20
Total	**533**	**770**	**1215**
BESS	-	**24**	**80**

All capacities in GW

Source: CEA LONG-TERM NATIONAL RESOURCE ADEQUACY PLAN (2026-27 to 2035-36)

Rooftop Solar I/C (as on Mar 2026): 25.73 GW

	till April 2026*	2030
Maximum Demand Met (GW)	~256#	334^
Electricity Consumption for preceding FY (BU)	~1707#	1949^
Total Generation Installed Capacity (GW)	533*	770
Non-fossil Fuel Based Generation Installed Capacity (GW)	283	500
Wind & Solar Installed Capacity (GW)	206	378

Source: # Operational Data of Grid-India
* As on Mar 2026, CEA Installed Capacity Report
^ 20th EPS Survey by CEA

Challenges with rising RE Penetration in India

1. Operational Challenges
- Non-compliance to standards leading to large disturbances
- Controller (PPC) Interactions
- Low System Strength (SCR) at RE Pooling Stations

2. Resource Uncertainty
- **Solar:** Cloud cover, seasonal variations, solar eclipse
- **Wind:** Wind speed fluctuations, weather patterns

3. Flexibility and Balancing Requirements
- Increasing flexibility requirement
- Additional reserve requirement

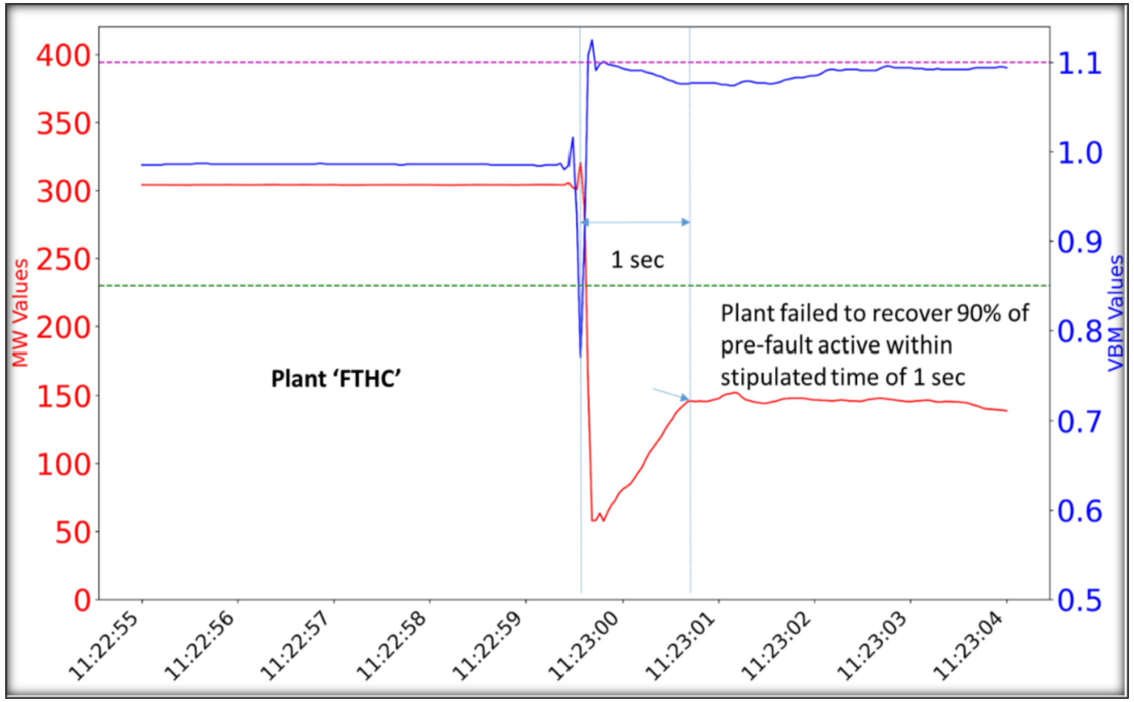
4. Transmission Planning
- Diurnal change in power flow patterns
- Challenges in ensuring adequate system strength

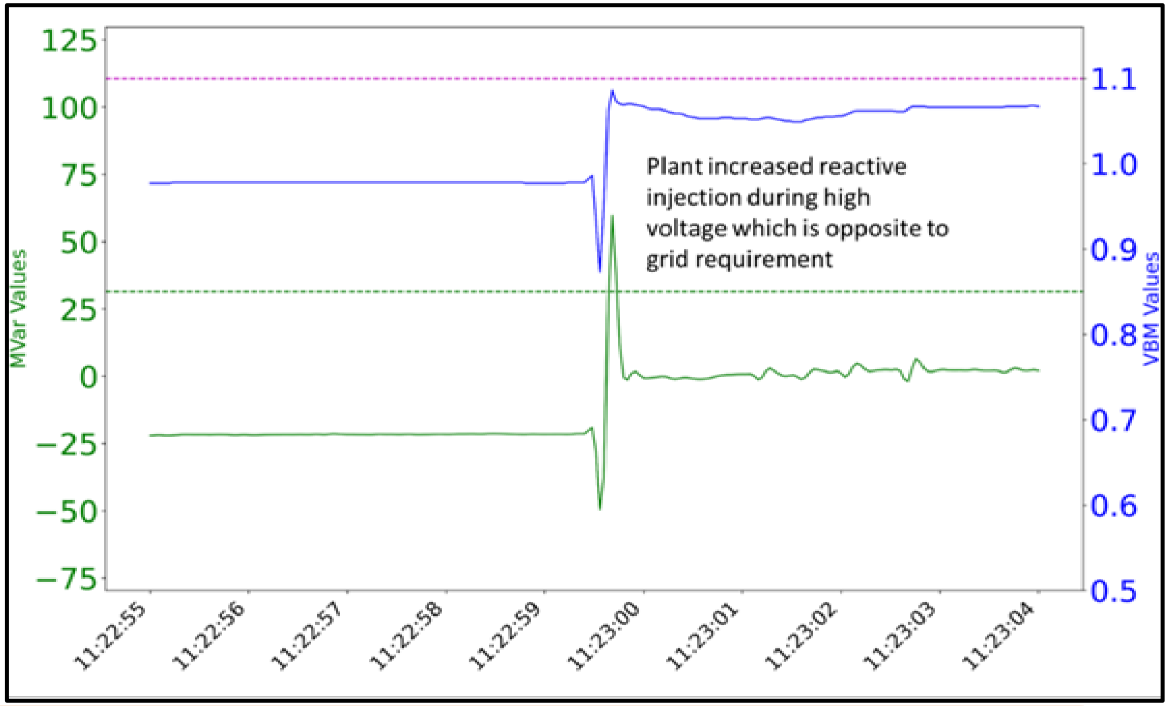
1. Operational Challenges – Impact on Grid Stability

Grid Events in RE Complex - Major Reasons

1. Non-compliance of RE Plants to specified CEA Standards – HVRT/LVRT

- Typical behavior of RE Plants during ride through events





- ➢ Reduction of active power by the RE plants during fault to accommodate reactive power injection
- ➢ Inadequate and delayed reactive power support during ride through conditions
- ➢ Delayed active power recovery post-fault-clearance
- ➢ High voltage post-fault clearance leading to tripping of inverters on HVRT and transmission lines on over-voltage

Grid Events in RE Complex - Major Reasons

1. Non-compliance of RE Plants to specified CEA Standards – HVRT/LVRT

Compliance status of RE Plants vis-à-vis CEA Connectivity Standards during a grid event (15.12.24)

S.No	Connected at	Name of SPPD/Generator	Installed Capacity (MW)	Inverter/ WTG Make	Inverter/WTG Model	HVRT/LVRT Compliance	Reactive Power Support during fault condition (partially, fully, non-complaint)
1	400 kV Bhadla I (PG)	Essel Saurya Urja Company of Rajasthan Limited (ESURL)	300	SINENG	EP3125-HA-UD	Non compliant	opposite response
2		Azure Power Maple Pvt. Limited (AZRMP)	300	HUAWEI	SUN2000-200KTL-H2	Non compliant	opposite response
3		Clean Solar Power (Jodhpur) Pvt. Ltd.	250	SUNGROW	SG250HX-IN	Non compliant	opposite response
5	765 kV Bhadla 2 (PG)	Mega Suryaurja Private Limited (MSUPL)	250	SINENG	EP3125-HA-UD	Non compliant	opposite response
6		NTPC Kolayat_2	200			Non compliant	opposite response
7		Avaada Sunrays Pvt. Ltd.	320			Non compliant	opposite response
8	765 kV Bikaner (PG)	Avaada RJHN_240MW	240	SINENG	EP-3125-HA-UD	Non compliant	opposite response
9		Avaada sunce energy Pvt limited	350	SINENG	EP-3125-HA-UD	Non compliant	
10		Avaada Sustainable RJ Pvt. Ltd.	300	SINENG	EP-3125-HA-UD	Non compliant	
11		Renew Surya Ravi Private Limited Bikaner (RSRPL)	300	SUNGROW	SG250HX-IN	Non compliant	opposite response
12	765 kV Fatehgarh II (PG)	Adani Hybrid Energy Jaisalmer Three Limited (AHEJ3)	**300**	Suzlon WTG	TS208KTL-HV	Non compliant	opposite response
13		Adani Hybrid Energy Jaisalmer Three Limited (AHEJ3): Wind	**75**	TBEA	Suzlon S120		
14		ReNew Solar Urja Private Limited(RSUPL)	**300**	SUNGROW/TBEA	SG250HX-IN/TS208KTL-HV	Non compliant	opposite response

Grid Events in RE Complex - Major Reasons

2. Non-compliance of RE Plants to specified CEA Standards – No margins for reactive power support (1/2)

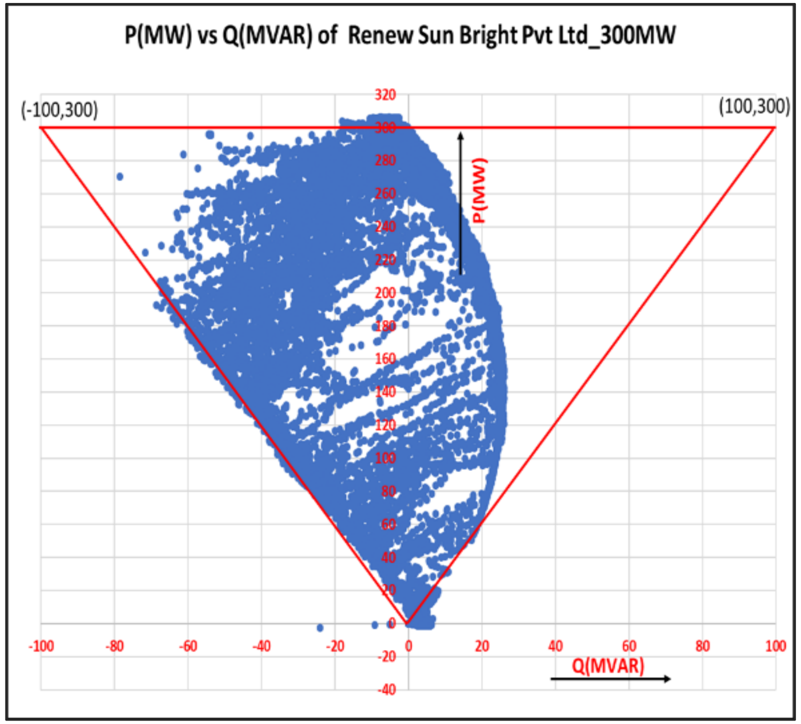
- In order to **inject/absorb 33% reactive power (MVAR) along with delivering rated active power (MW) at POI**, the MVA capacity of the RE plant shall be higher than the rated MW capacity of the plant i.e. **MVA Capacity > MW Capacity.**
- However, in most of the plants, **MVA = MW** has been installed, leaving no margin for reactive power support

User Name	Inverters/WTG Make	Inverter/WTG Model No	Inverter Rating in MVA @50 deg	Number of Inverters	Plant Capacity (MVA)	Plant Total Installed Capacity (MW)	Plant Registered Capacity(MW)
Azure Power Forty Three Private Limited	SUNGROW	SG3125HV	3.125	96	300	300	300
	SUNGROW	SG250HX-IN	0.2	1500	300	300	300
RENEW SOLAR POWER Pvt. Ltd. Bikaner	HUAWEI	SUN2000-185KTL-H1	0.16	1563	250.08	250	250
Renew Surya Ravi Pvt. Ltd.	SUNGROW	SG250HX-IN	0.2	1500	300	300	300
Avaada sunce energy Pvt limited	SINENG	EP-3125-HA-UD	3.125	112	350	350	350
Avaada Sustainable RJ Pvt. Ltd.	SINENG	EP-3125-HA-UD	3.125	96	300	300	300
Avaada RJHN_240MW	SINENG	EP-3125-HA-UD	3.125	44	137.5	240.1	240
	SINENG	SP-250K-INH	0.2	513	102.6		
Ayaana Renewable Power Pvt. Ltd.	SUNGROW	SG3125HV	3.125	96	300	300	300
Thar Surya Pvt. Ltd.	GAMESA	GAMESA E - 2.25MVA-SB-I	2.25	120	270	300	300
	GAMESA	GAMESA E - 2.5MVA-SB-I	2.5	12	30		
Tata Power Green Energy Ltd. (TPGEL)	SUNGROW	SG3125HV-32	3.125	72	225	225	225
SBSR Power Cleantech Eleven Private Ltd.	KEHUA	SPI3125K-B-H	3.125	96	300	300	300

Grid Events in RE Complex - Major Reasons

2. Non-compliance of RE Plants to specified CEA Standards – No margins for reactive power support (2/2)

- Further, there is **drop in the collector system and intermediate transmission network between IBRs and POI** which also needs to be factored in while designing the plant
- Also, **with rise in ambient temperature beyond a certain point, there is degradation in Inverter/WTG's rated MVA Capacity**. i.e. the IBRs have the margin to deliver/absorb reactive power at low ambient temp. (<40°C) but become non-compliant at higher ambient temp. (>50°C) as no margin is left.



2.4. GE 2.5 MW

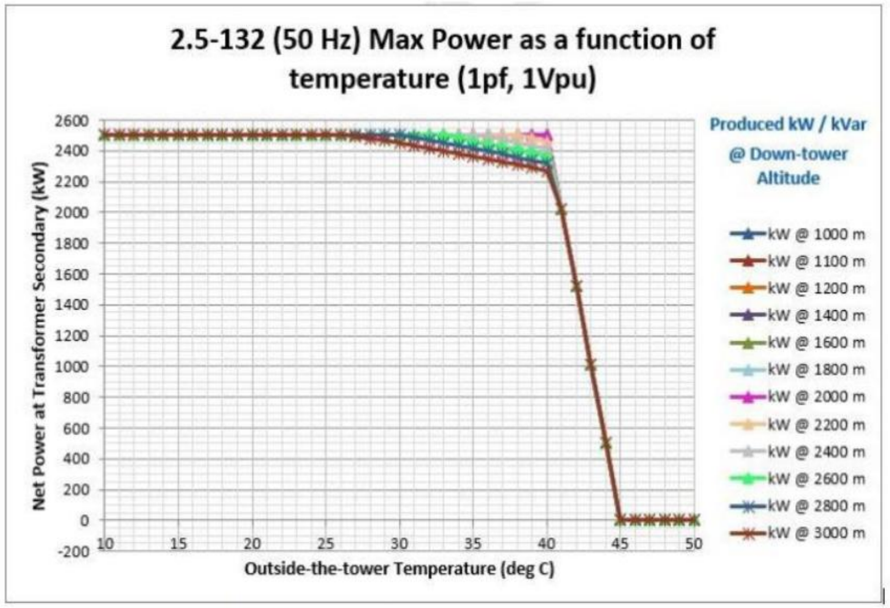
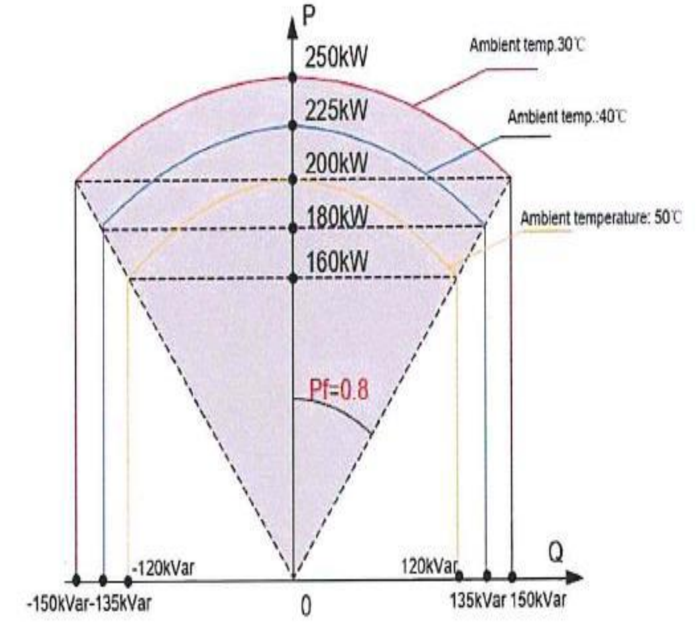
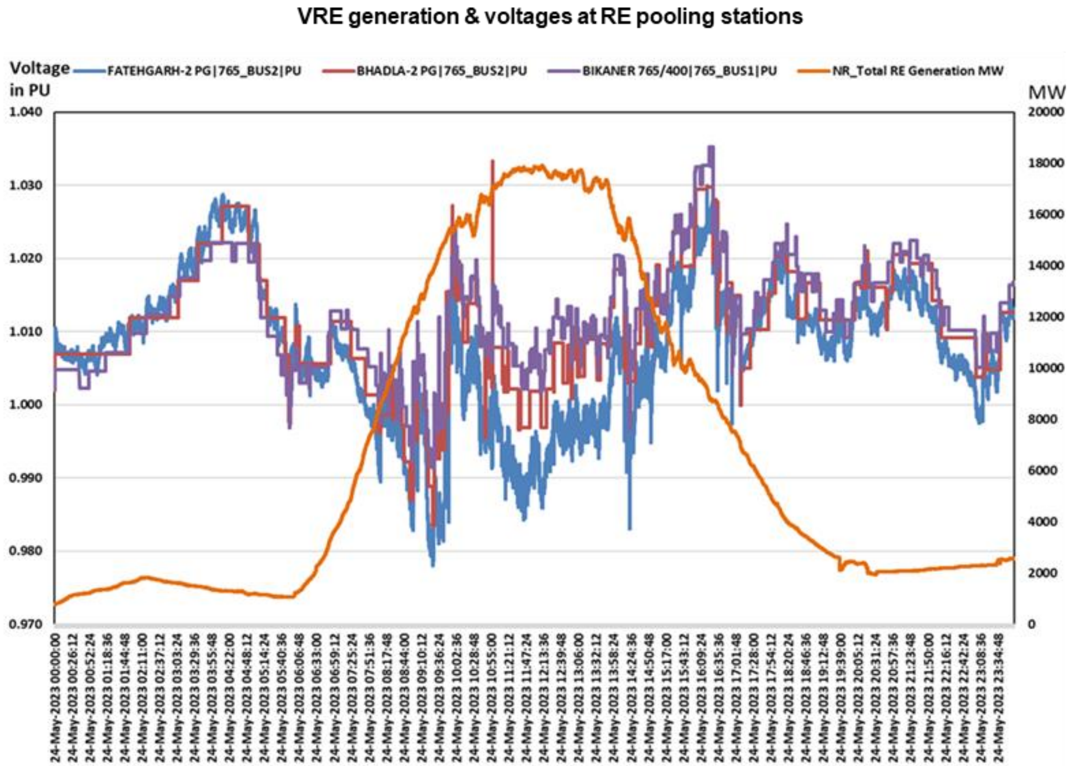


Figure 1: 2.5-132 Max power as a function of temperature (1pf, 1Vpu)



Single Inverter Capability Curve

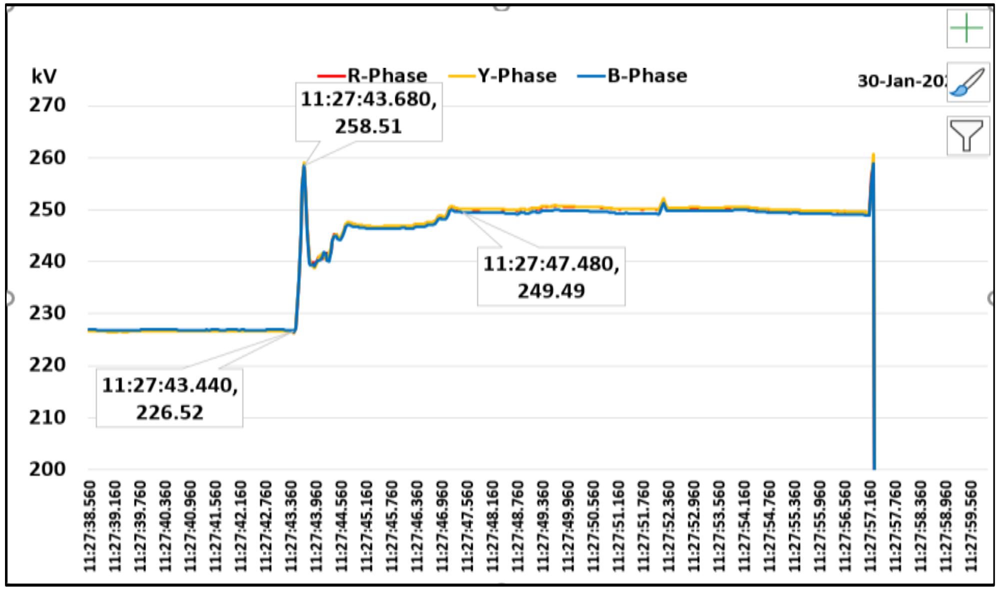
Challenges – Voltage Regulation at RE Pooling Stations



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

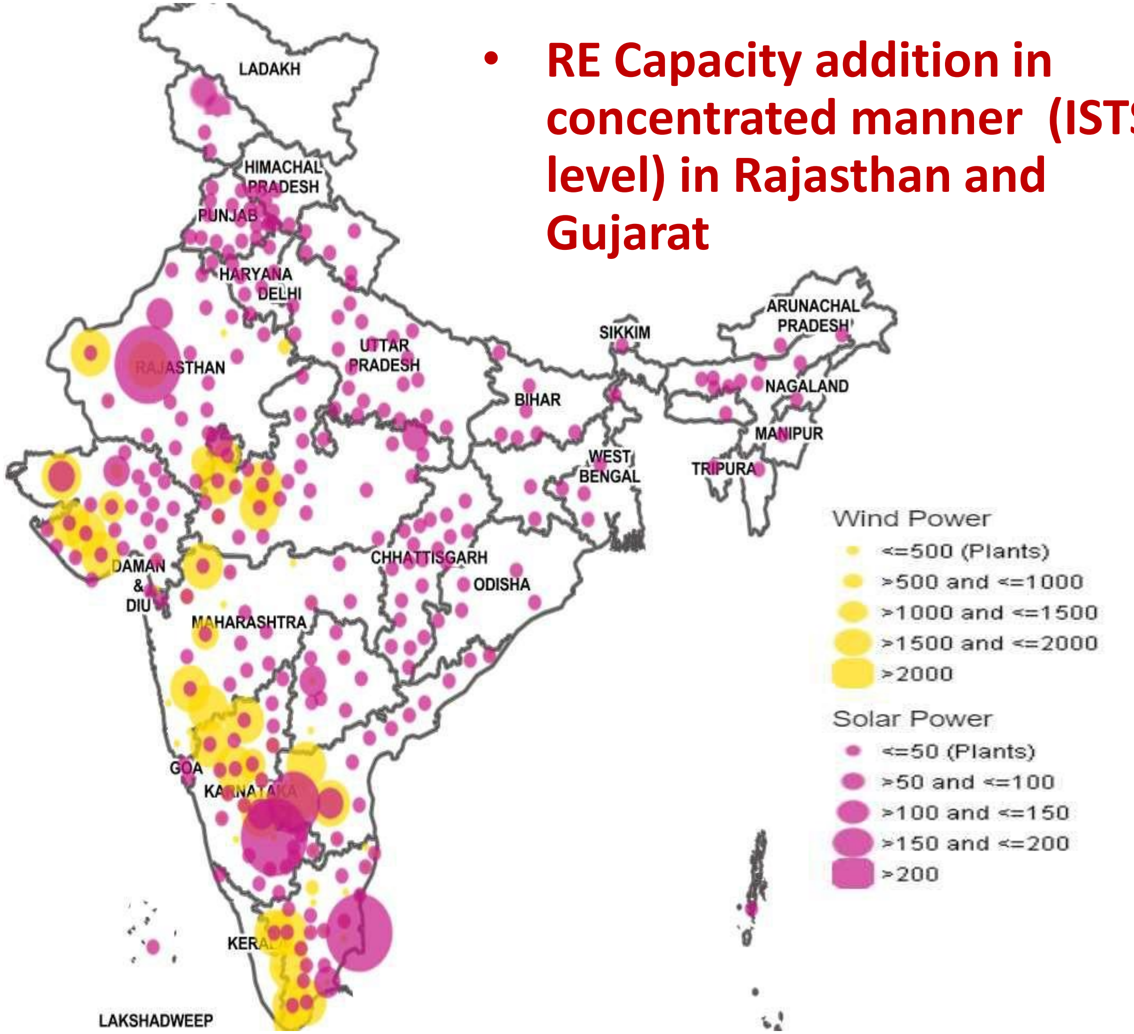
Reduction in SCR due to depleted network



Switching of 240 MVAR Line reactor

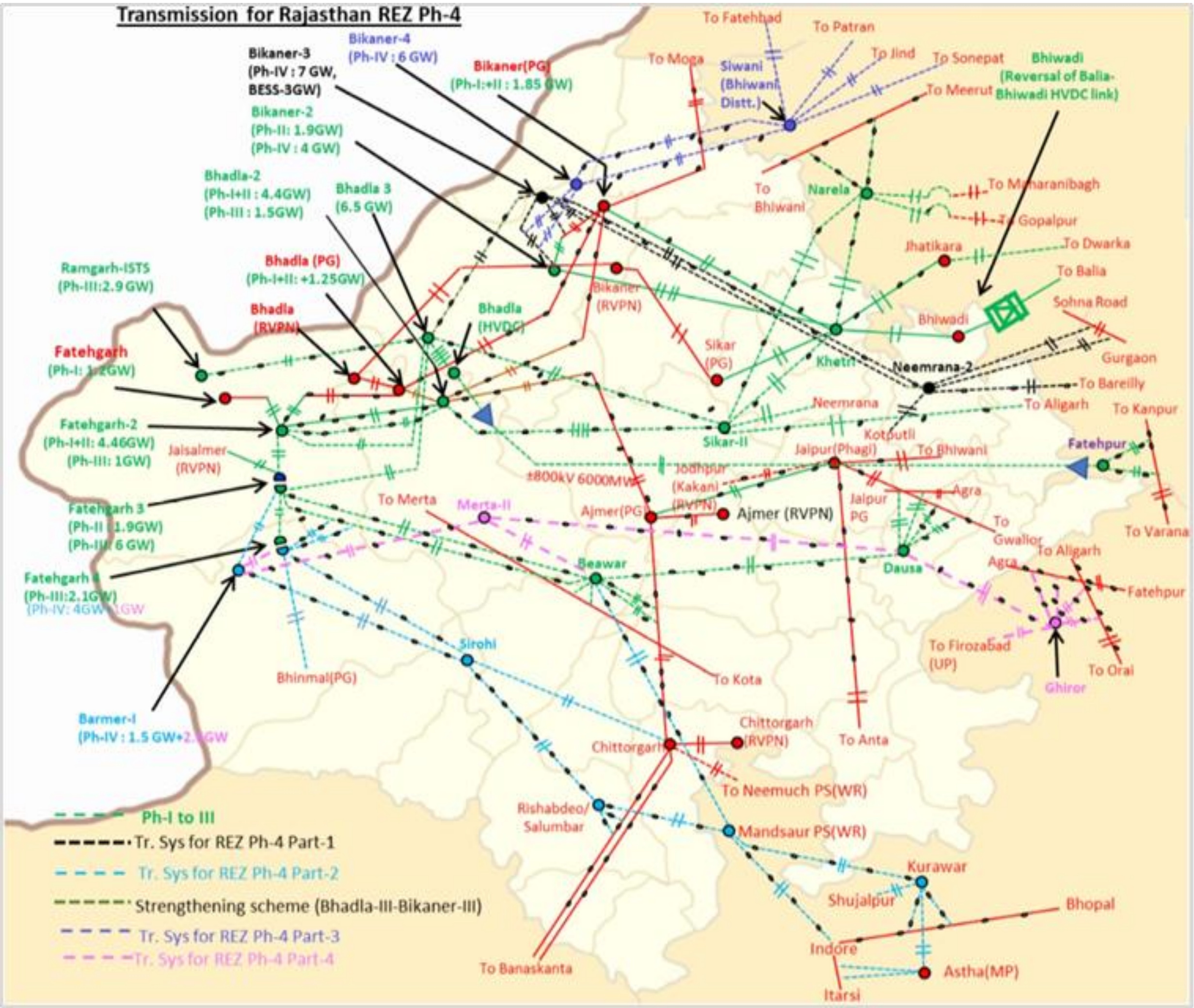
- Depleted network before event
- 32 kV Voltage rise in phase to neutral
- EHV Lines tripped on Overvoltage
- Triggered HVRT and consequent loss of 2000 MW generation

Concentrated RE Zones



Source: VEDAS portal of ISRO and NITI Aayog
https://vedas.sac.gov.in/energymap/view/powergis.jsp#

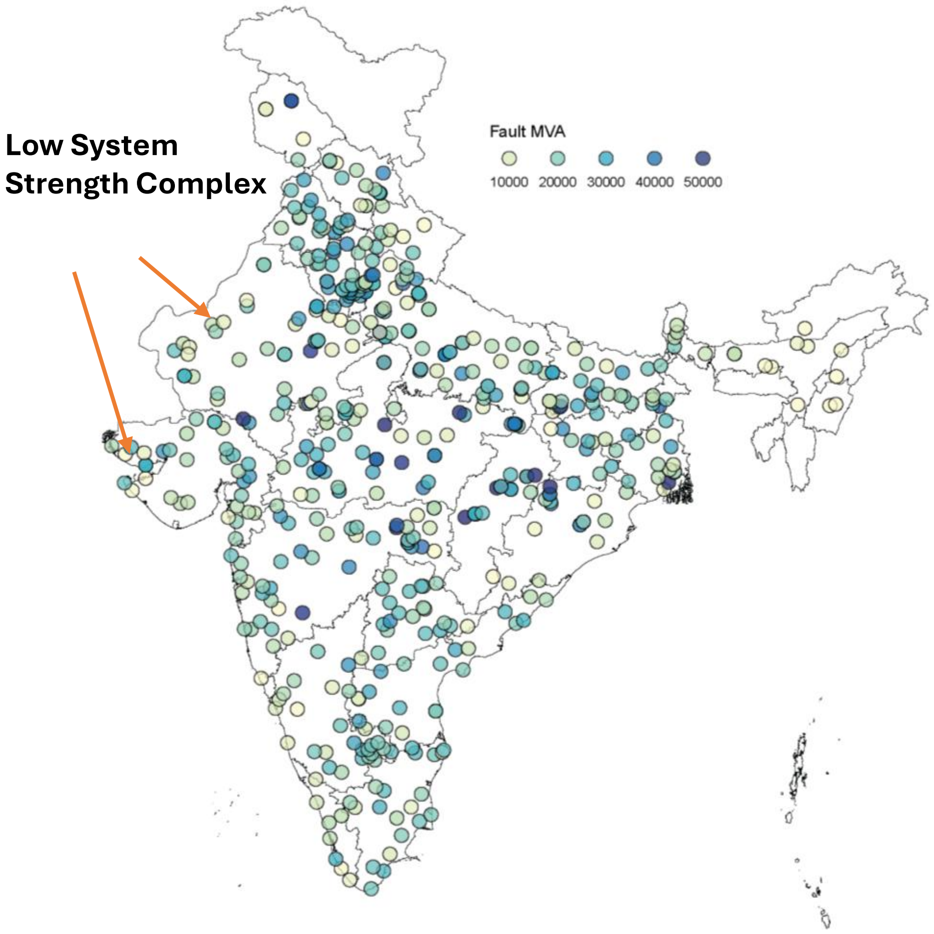
- **RE Capacity addition in concentrated manner (ISTS level) in Rajasthan and Gujarat**



- **Large RE Pooling stations at EHV level - vulnerable to large gen loss at single location**
- **Remotely located RE pockets, far from load centres**
- **Long Transmission lines to evacuate the intermittent/variable power from RES**

Operational Challenges: Low System Strength

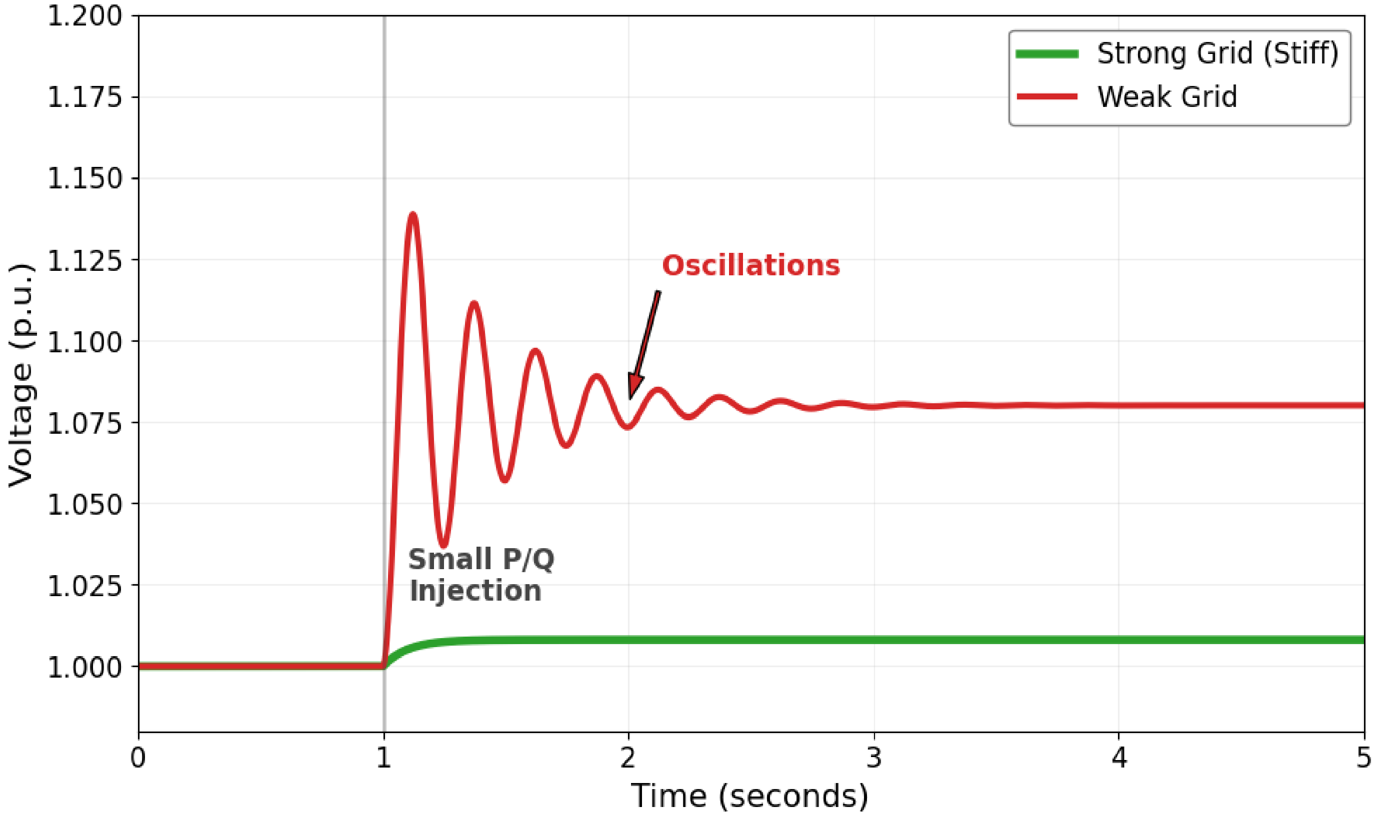
Low System Strength (SCR) at RE Pooling Stations



If the Grid is...	Then Voltage Sensitivity is...	Result
Strong (High Strength)	**Low**	The voltage is **"stiff".** Large changes in active or reactive power result in minimal voltage fluctuations.
Weak (Low Strength)	**High**	The voltage is **"sensitive".** Small changes in active or reactive power result in significant voltage swings.

Operational Challenges : Low System Strength

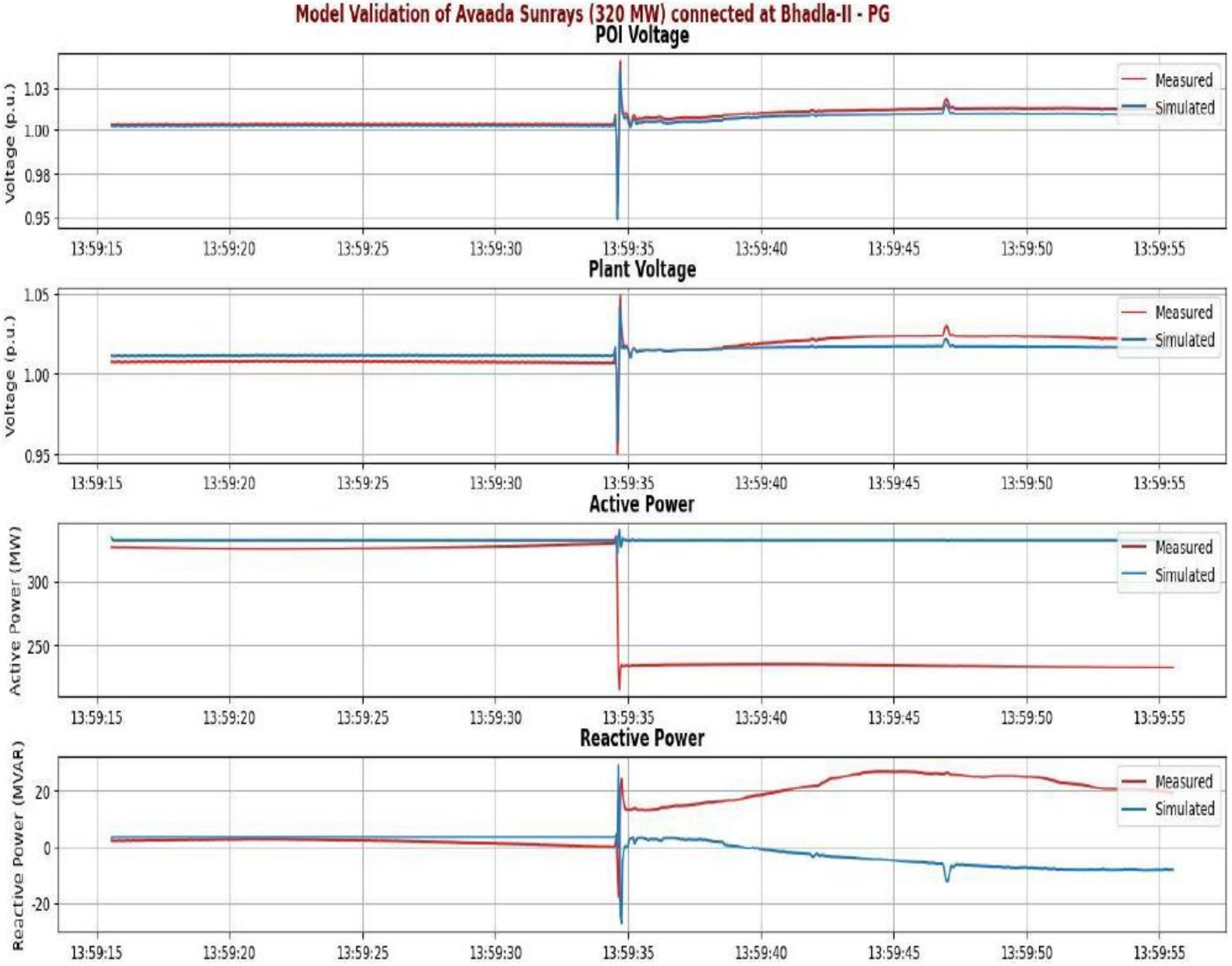
Voltage Sensitivity: Strong versus Weak Grids



In weak grids, for small active or reactive power injection:

- magnitude of voltage change can be large
- rate of change of voltage can be large
- frequency of change can be high
- **fast control loops of inverters can become unstable**

Discrepancies in IBR Models Submitted by Developers



- **Inaccurate models submitted by OEMs :-** Mismatch in performance of **submitted dynamic models** by RE developers for ISTS-connected plants in Rajasthan vis-à-vis actual performance of plants in real-time during faults

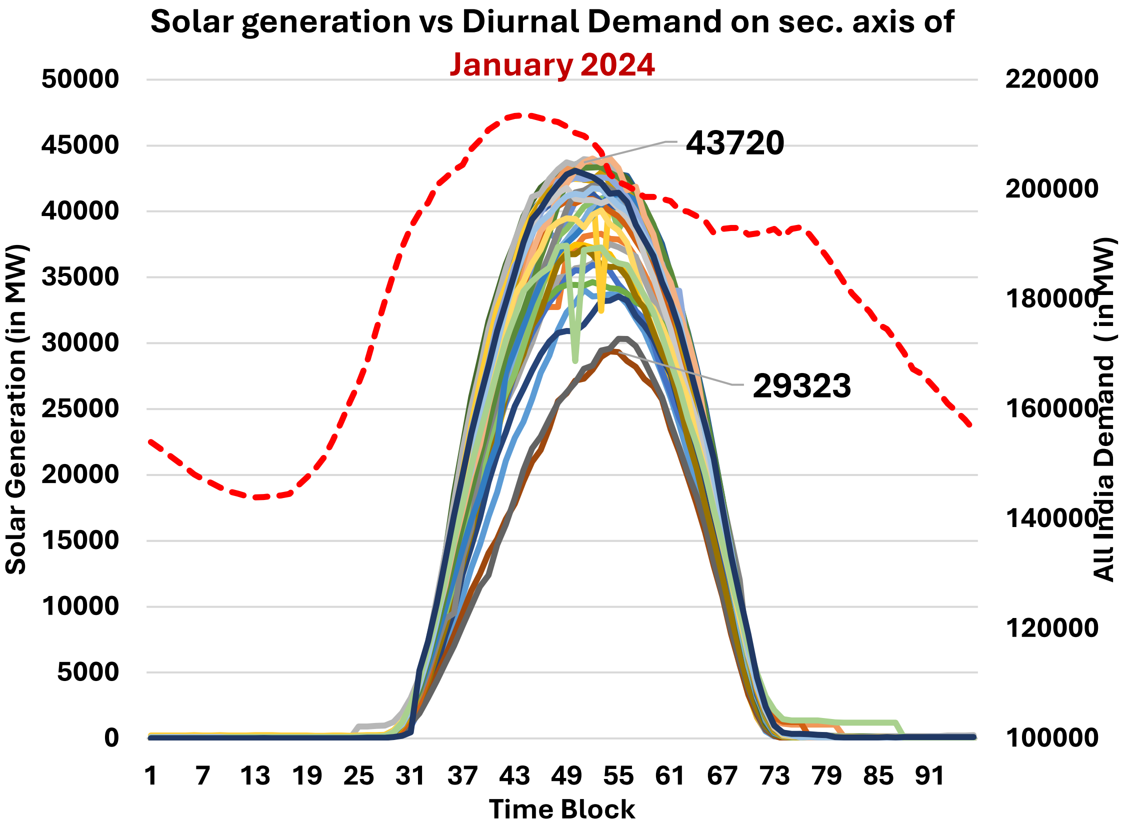
Observed deficiencies in submitted models

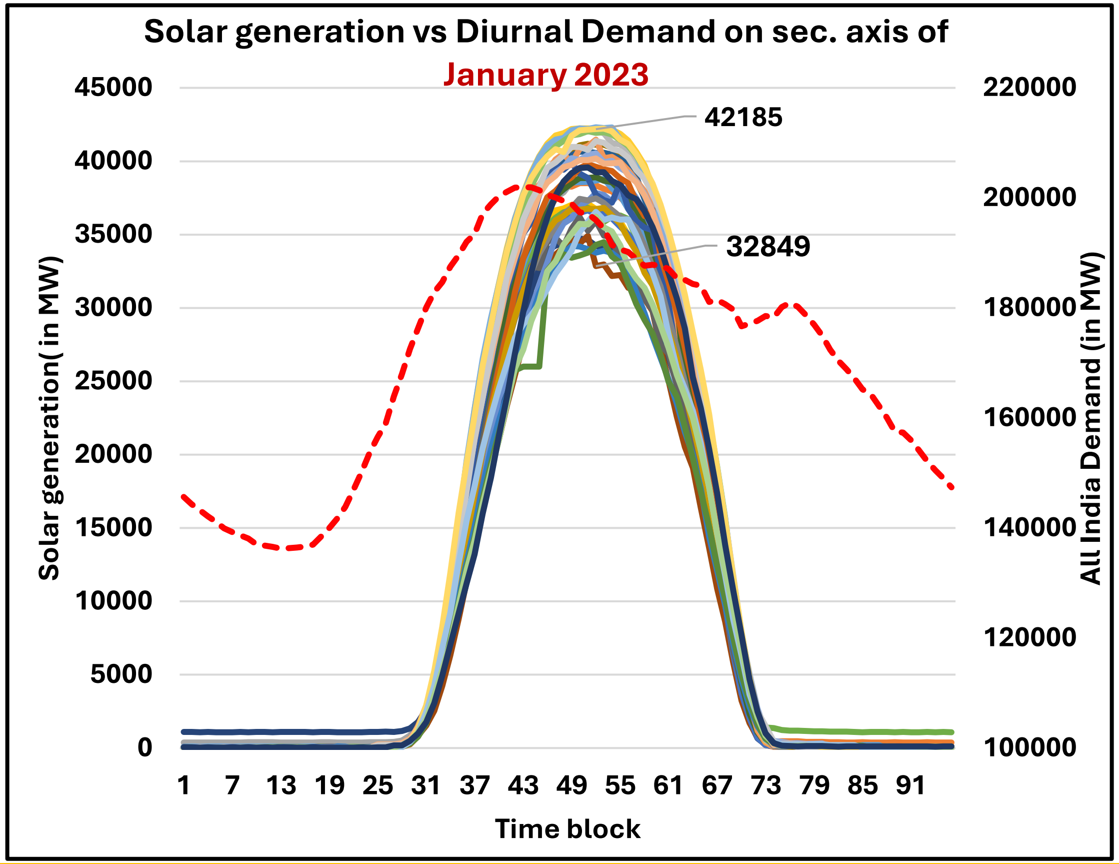
- High consideration of Short Circuit ratio (SCR) by RE Developers.
- Improper modelling - Post fault characteristics, Collector System Network etc.
- Consideration of different LVRT/HVRT K-factors in models in place of implemented value at site.
- No/incorrect modelling of relay in simulation model for IBRs, Collector system etc.
- Non-consideration of communication delays, polling rates/update rates of equipment in modelling

2. Resource Uncertainty – Adequacy Issues

Resource Uncertainty – Solar generation

- Effect of fog on Solar generation during Jan 24

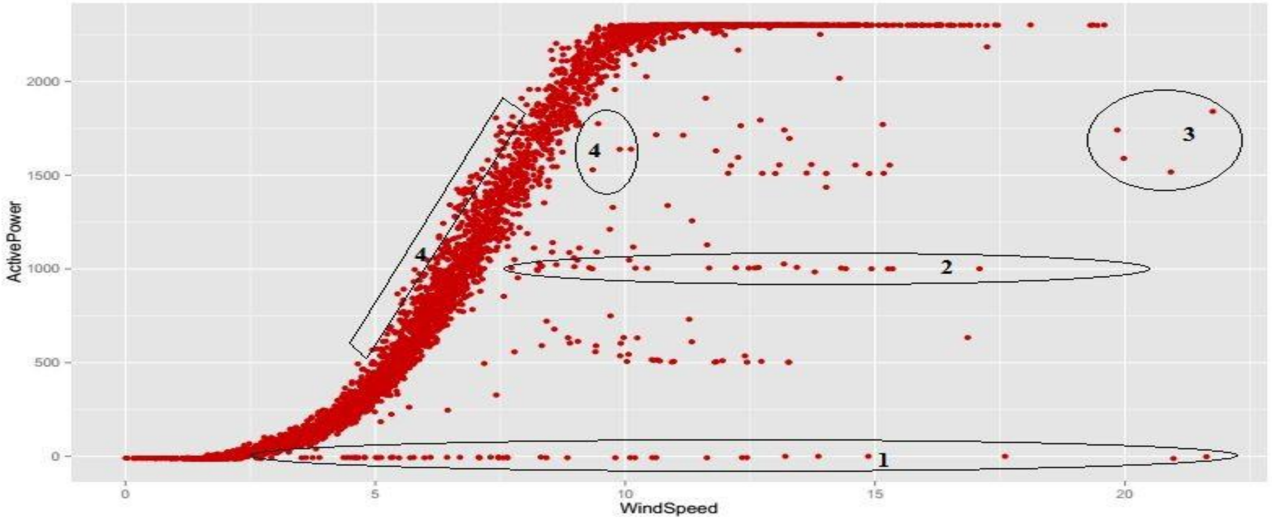


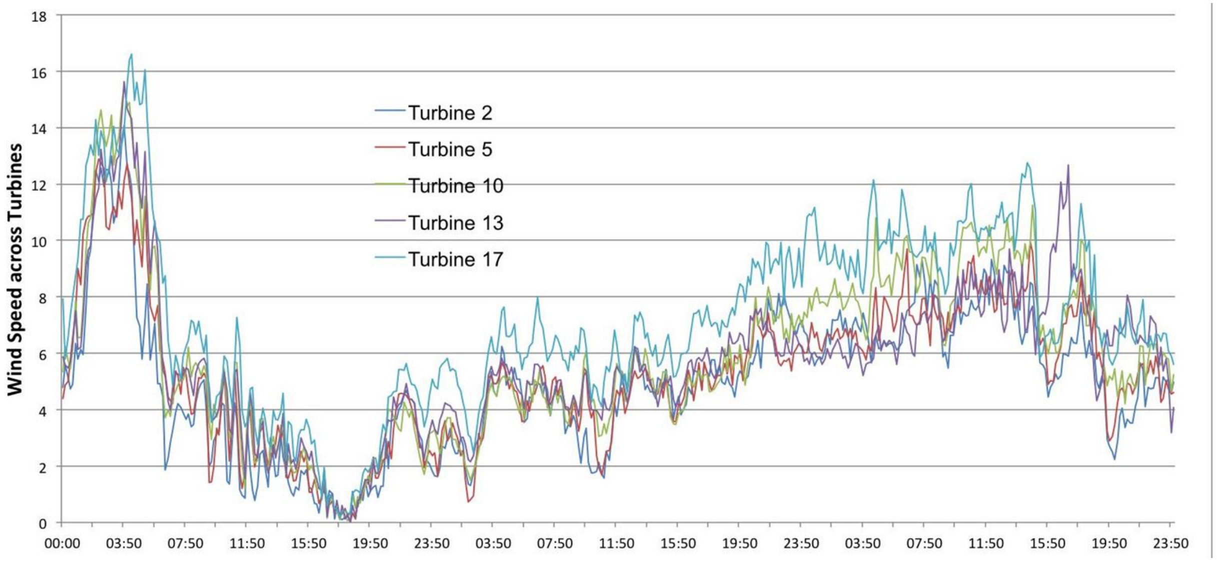


- Ramp up of demand & solar generation starts from around 4:30 hrs and 07:30 hrs i.e. **gap of around 3 hrs especially during winter**
- Despite increase in Installed capacity by 7 GW (from 53.4 to 60.4 GW) of solar generation, average All India Solar generation in Jan'24 (267 MU/day) was **3.4% lower** than in Jan'23 (277 MU/day)
- Max solar generation was on lower side **~ 29 GW** (08.01.24)

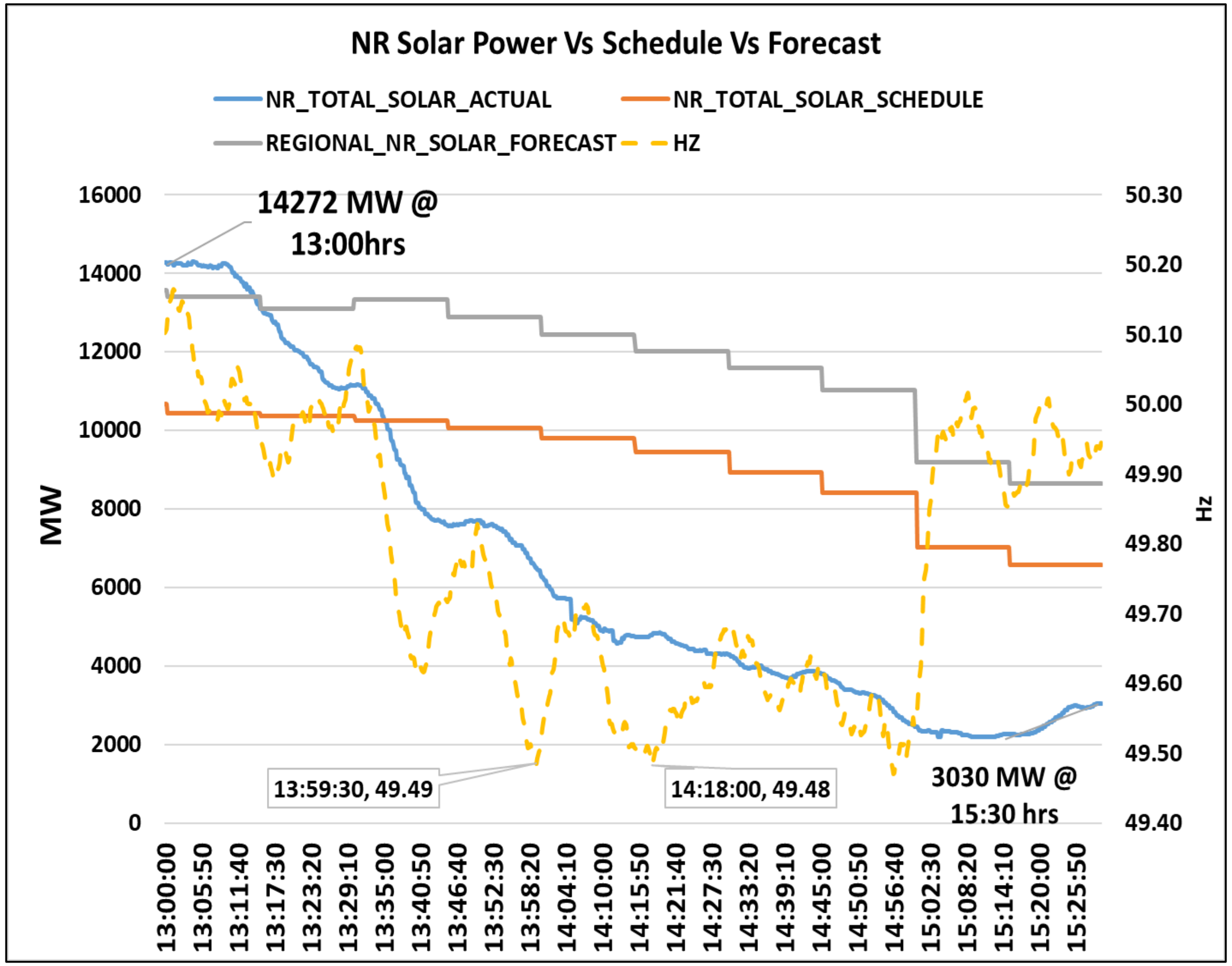
Resource Uncertainty - Challenges with Wind Forecasting

- Non-linear power curves lead to high errors in power output for small wind speed deviations.
- Wind speed is highly variable over time and space;
- Data unavailability, measurement errors, may lead to inconsistencies;
- Site specific features may not be captured accurately in weather models;

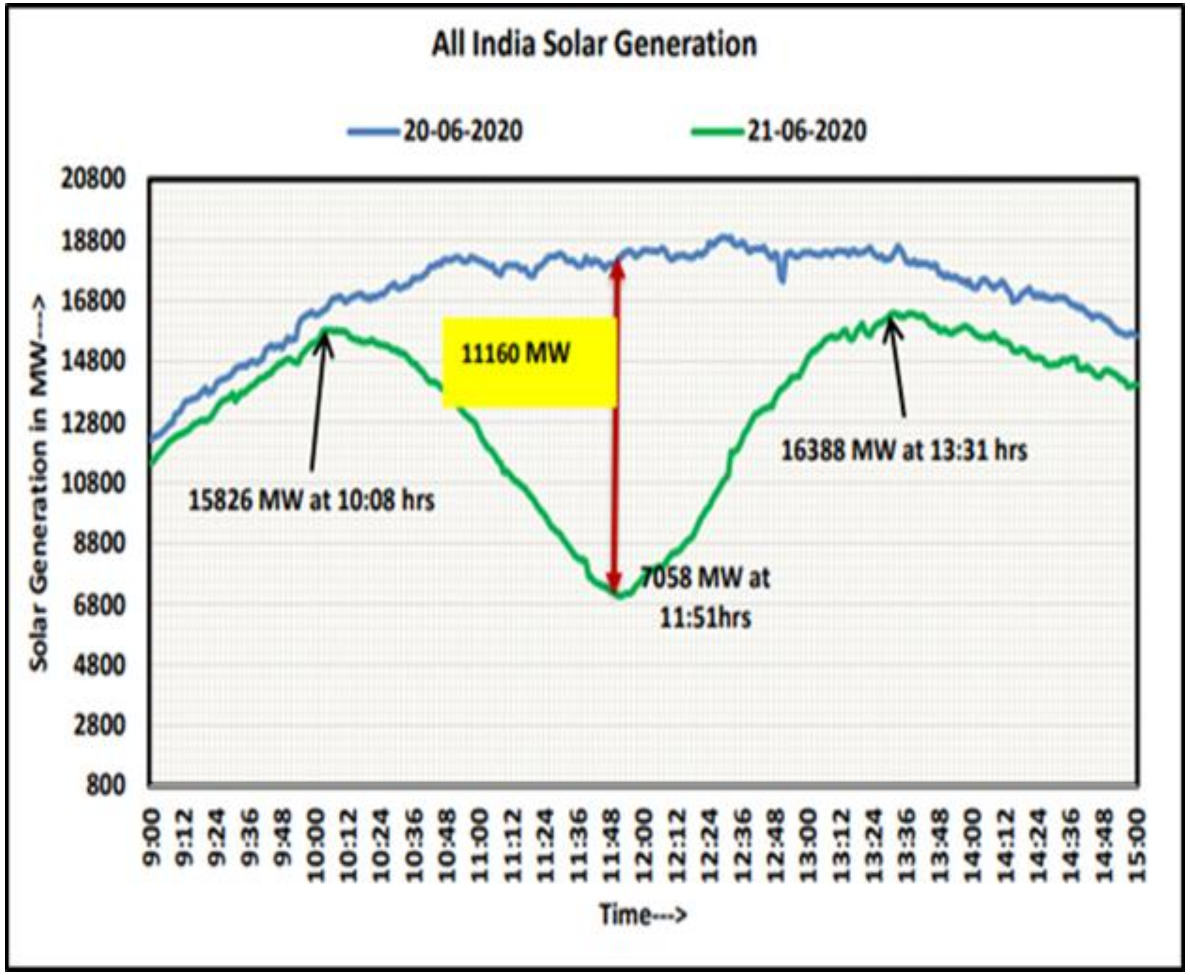




Impact of cloud covers and extreme weather events !!



Approx. 10 GW reduction in Solar Generation in 01 hour due to Large Cloud Cover on 16.10.23 (1300 to 1500 hours)

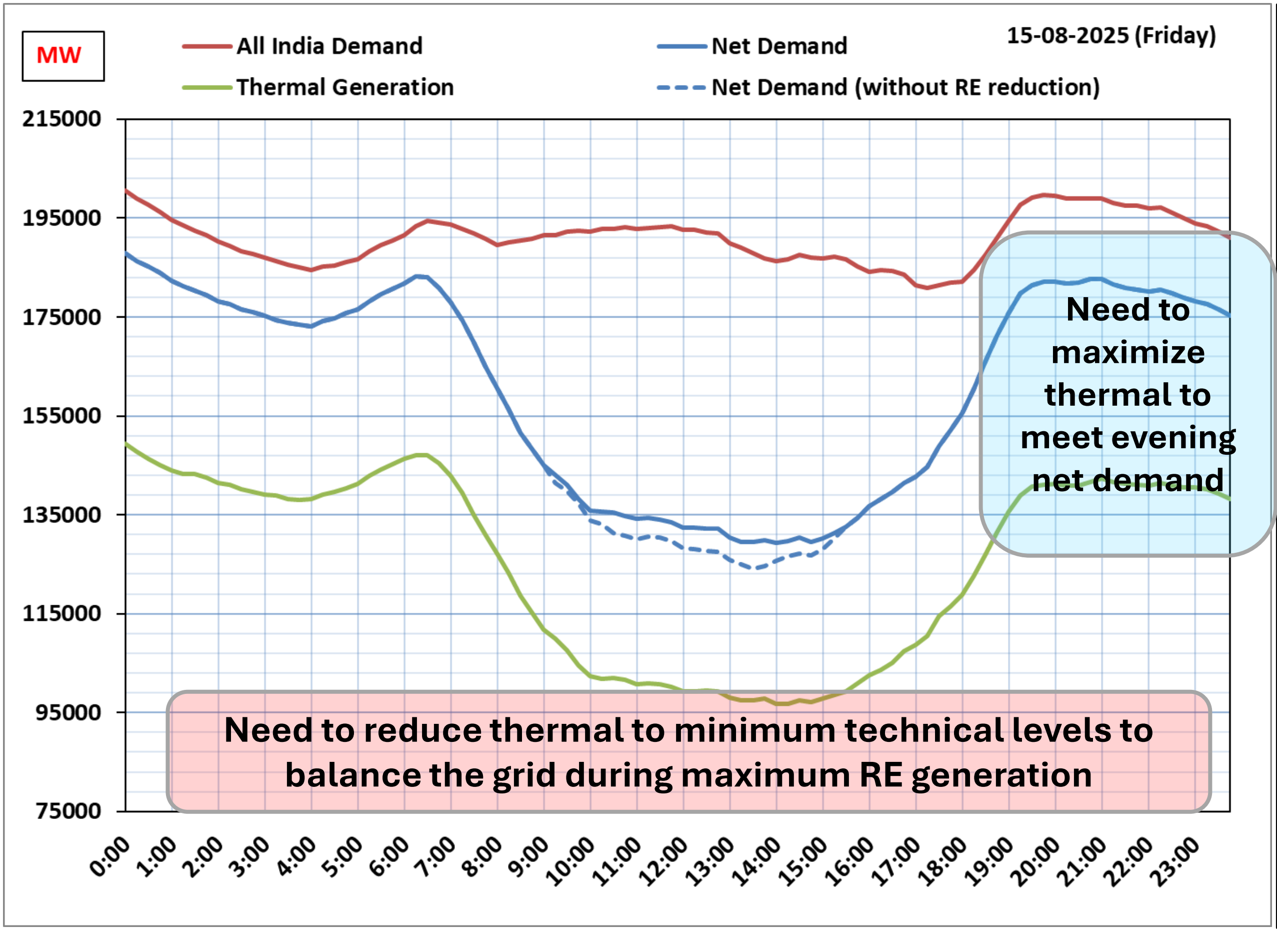


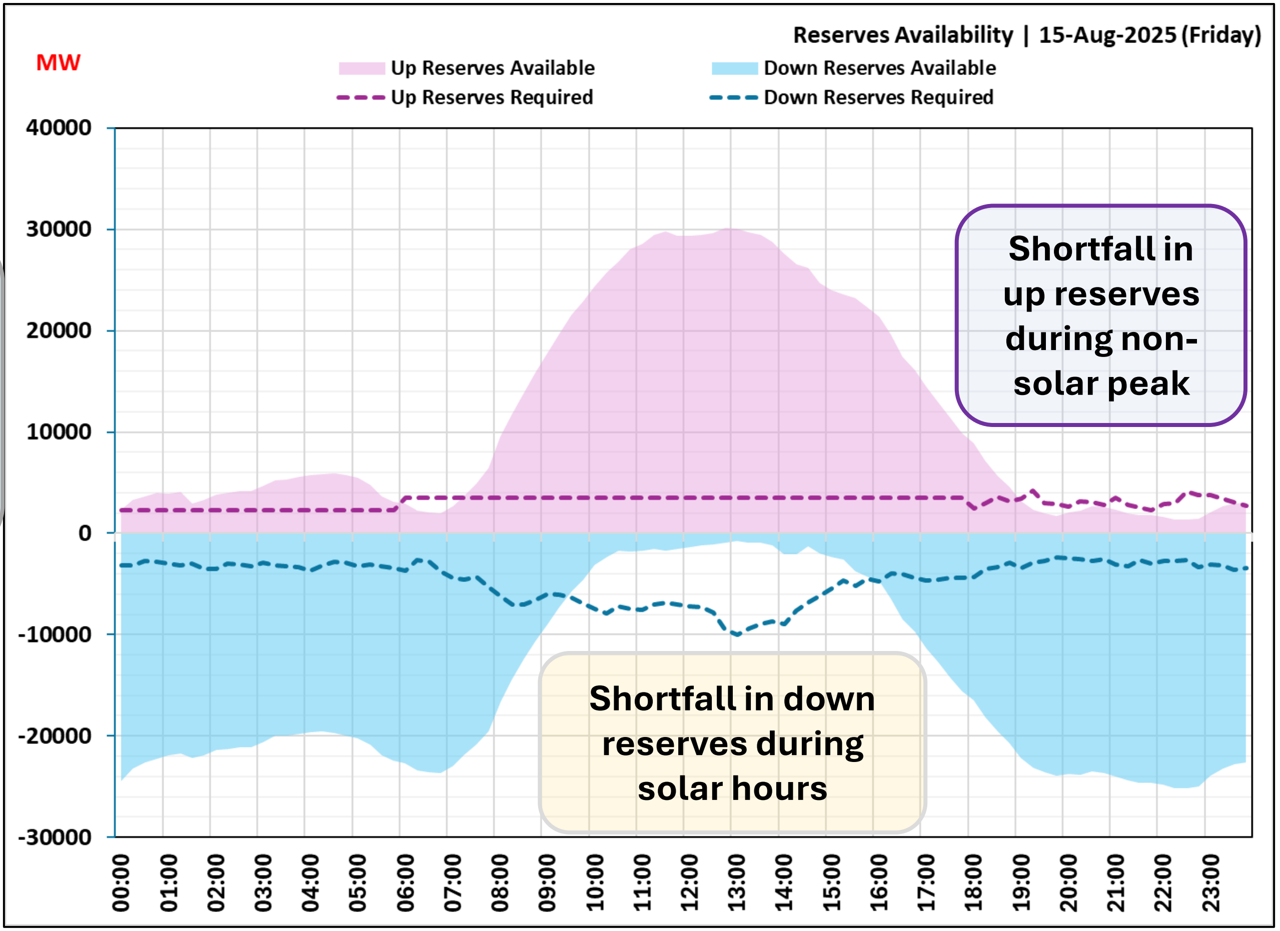
All India Solar Generation Reduction during Solar Eclipse on 21st June 2020

3. Flexibility and Balancing Requirements

Flexibility and Balancing Requirements

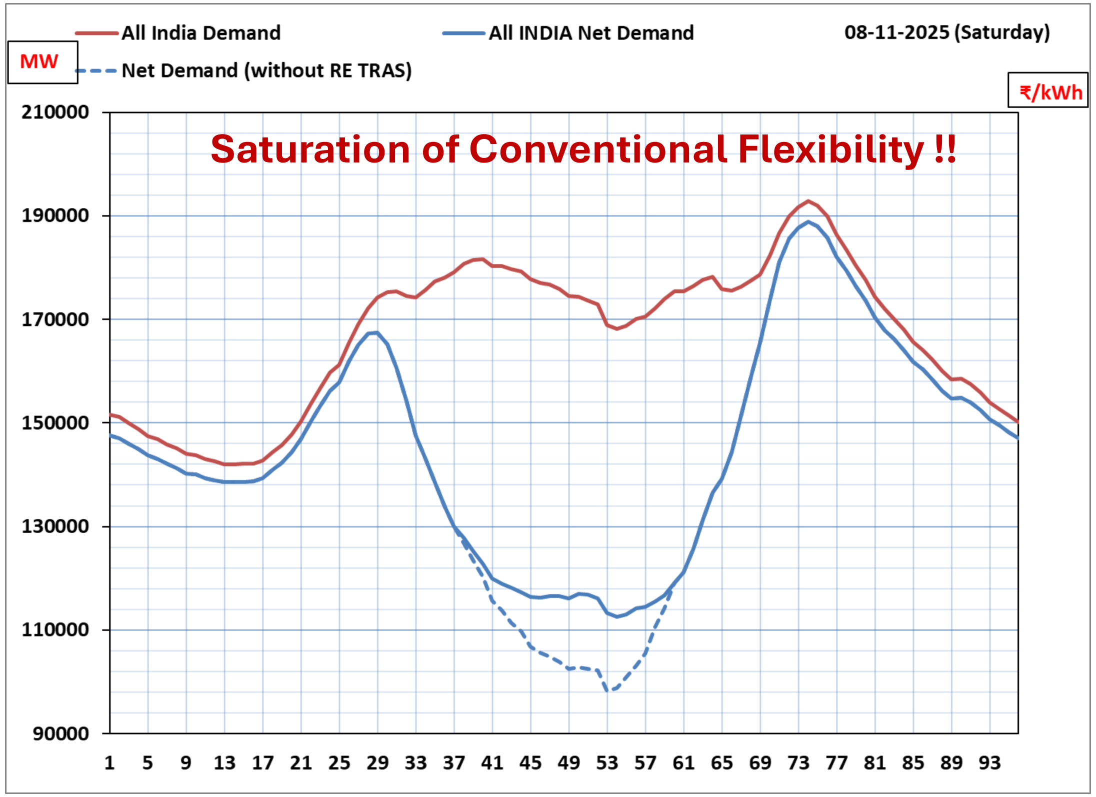
Divergent challenges - Flexibility in solar hours and adequacy in non-solar hours !!

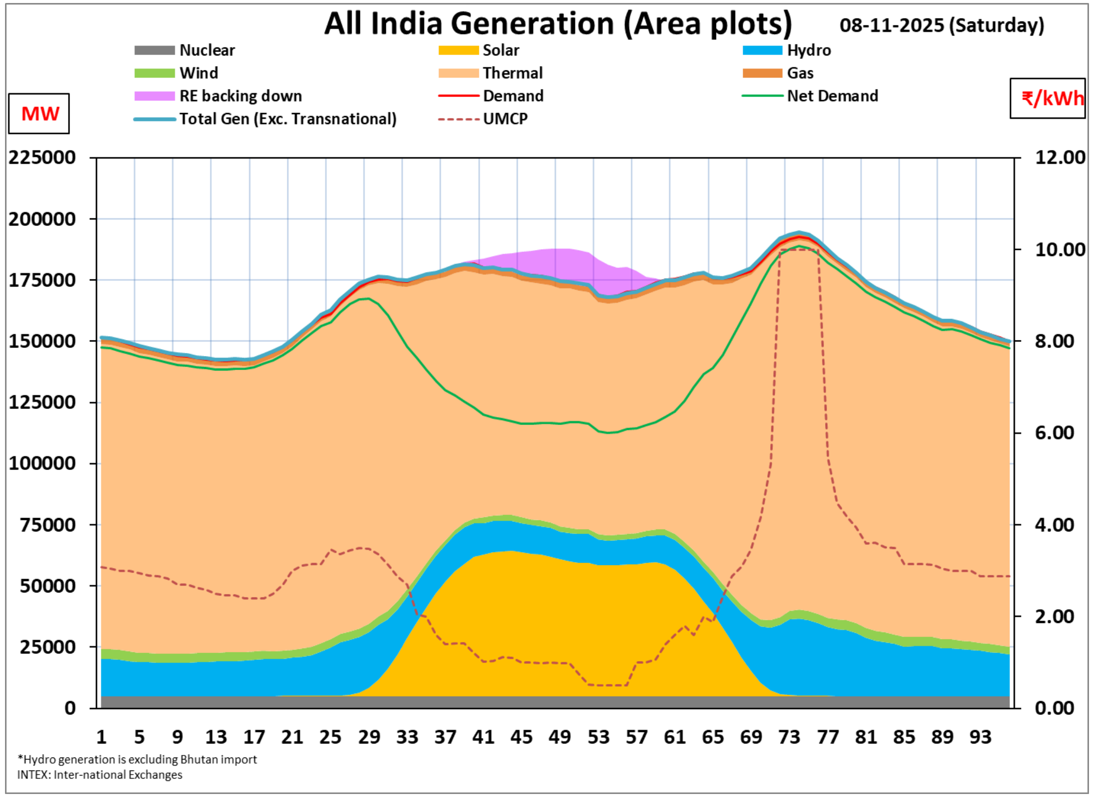




Availability of reserves is critical for secure grid operation !!

Net load curve - Evolution from “Duck” to “Giraffe”





- **Total net load flexibility required – 90 GW** – from 98179 MW (53rd block) to 188837 MW (74th block)

- **Flexibility obtained from different sources:**
  - Thermal: 56 GW
  - Hydro: 20 GW
  - Gas: 1 GW
  - RE backing down: 15 GW

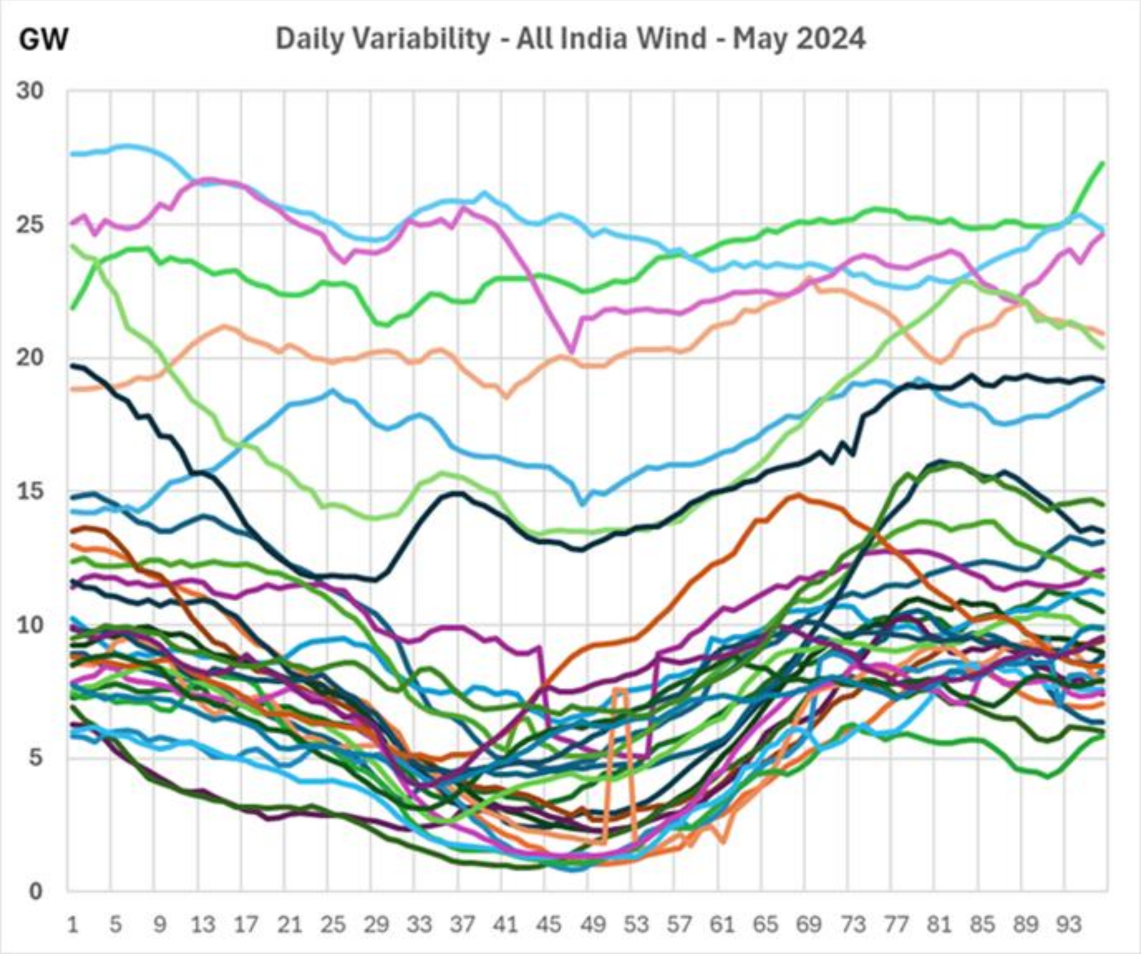
Change in Load Shape

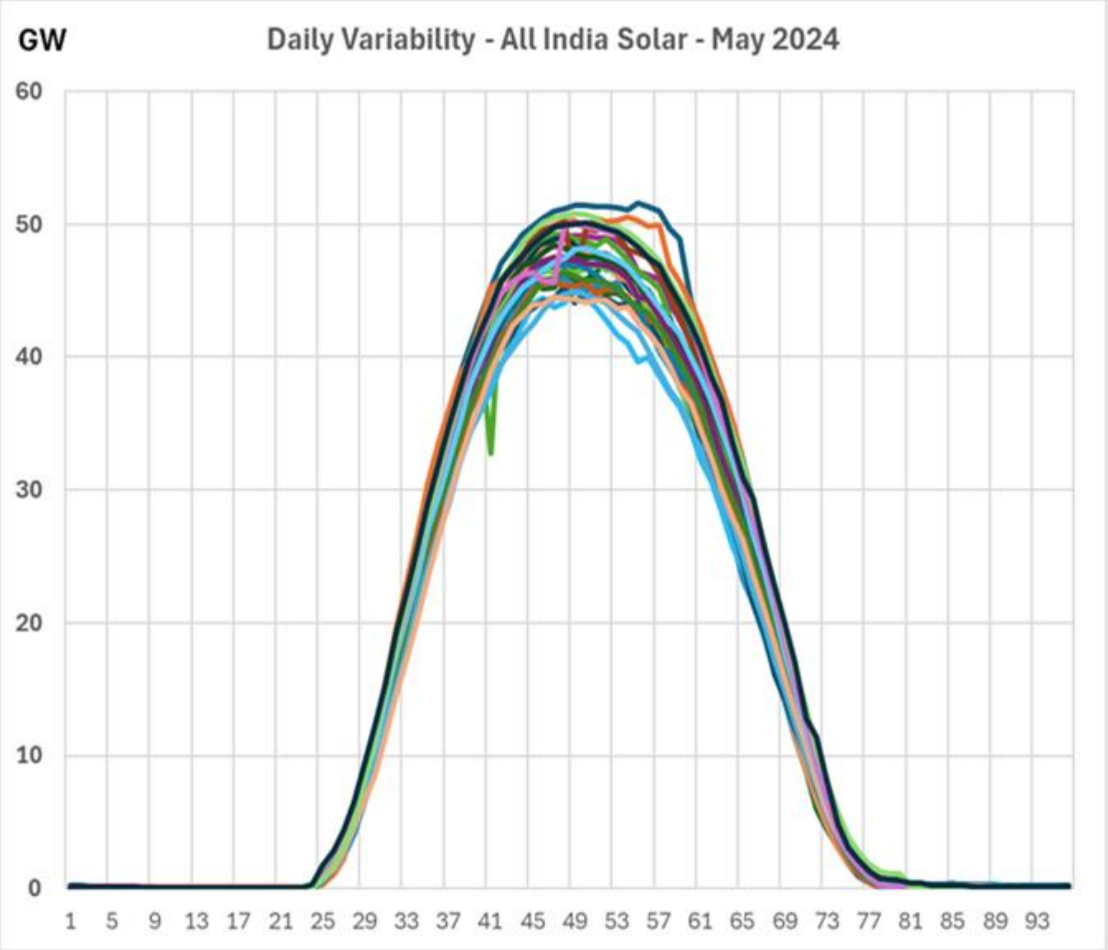
Increasing uncertainty on demand side

New Age Loads - EV Charging, Induction Cooking, Data Centers

Flexibility and Balancing Requirements

Large diurnal variation in wind & solar generation with steep ramp rate – Need for additional reserves for balancing and ramp management

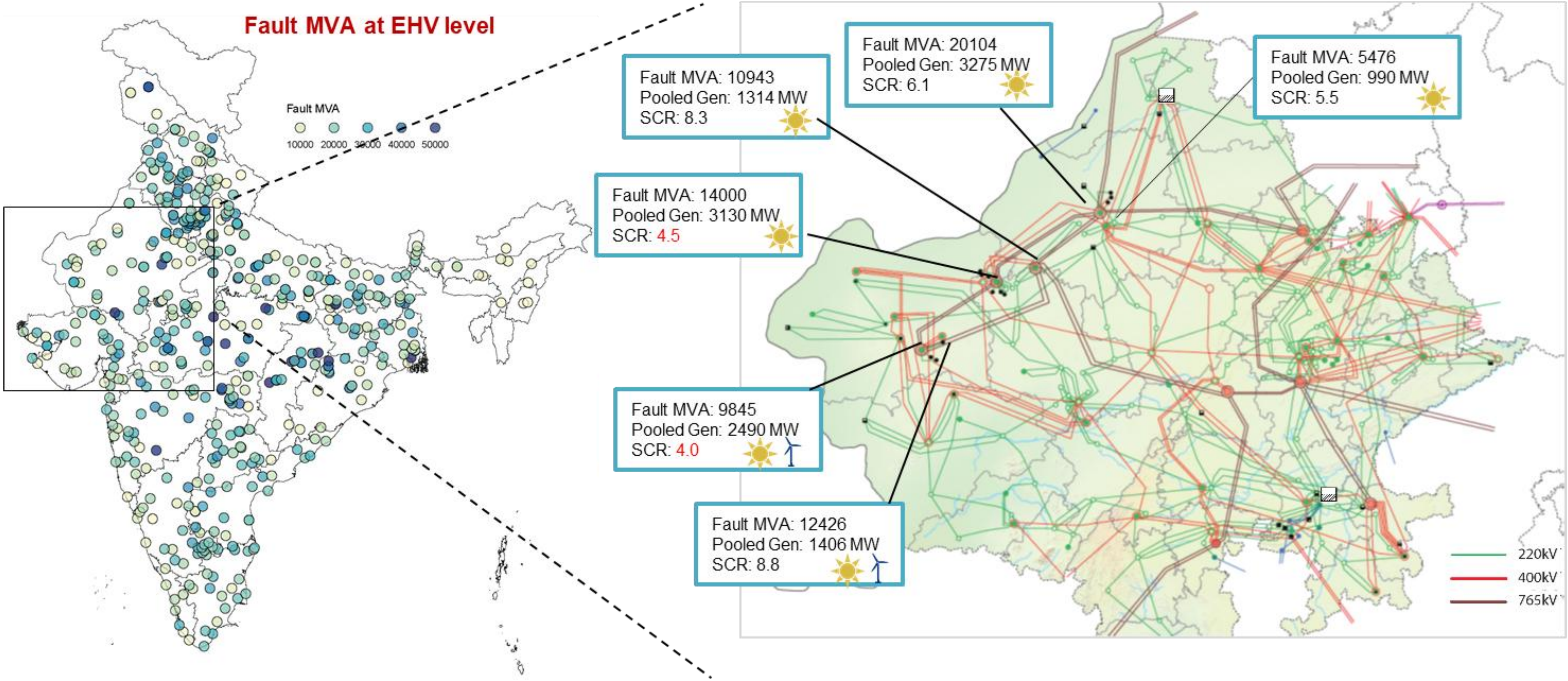




4. Transmission Planning

Transmission Planning

System Strength Concerns !! Low Fault level (SC MVA) – More susceptible to voltage instability

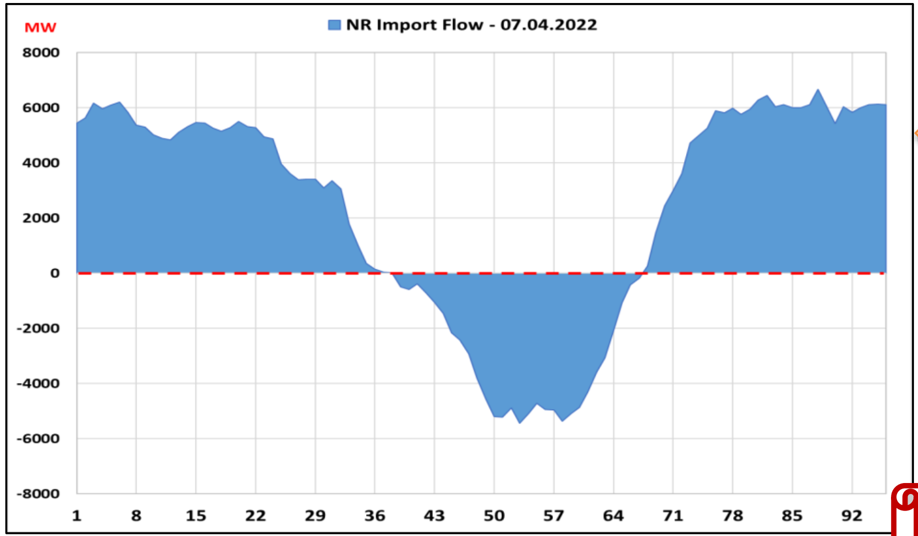


- **Challenges in ensuring sufficient system strength (short circuit ratio) at remotely located RE pockets**
- **CEA Technical standards mandates a min SCR of 5.0 at the point of interconnection for RE**

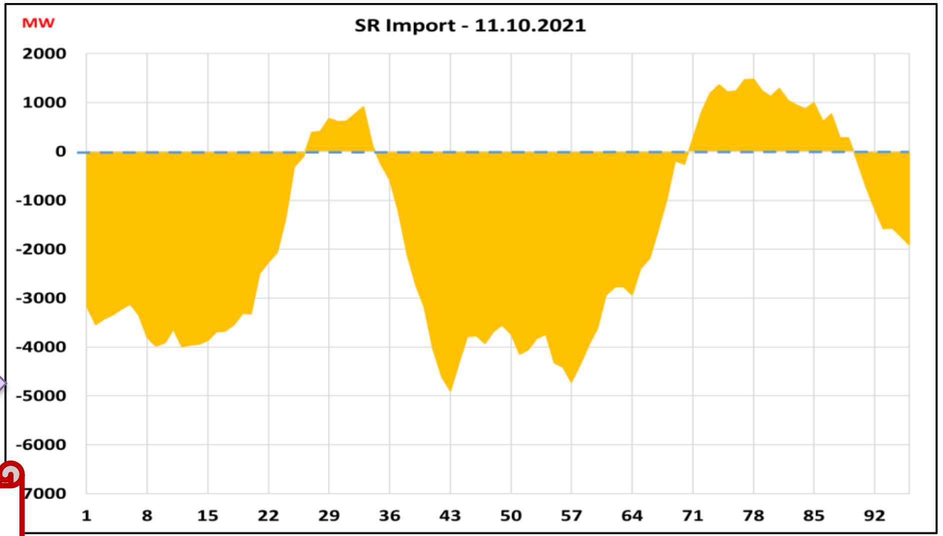
Transmission Planning

Increasing Uncertainty in Corridor Flows !!

Bidirectional inter-regional power flows due to variable RE generation throughout the day

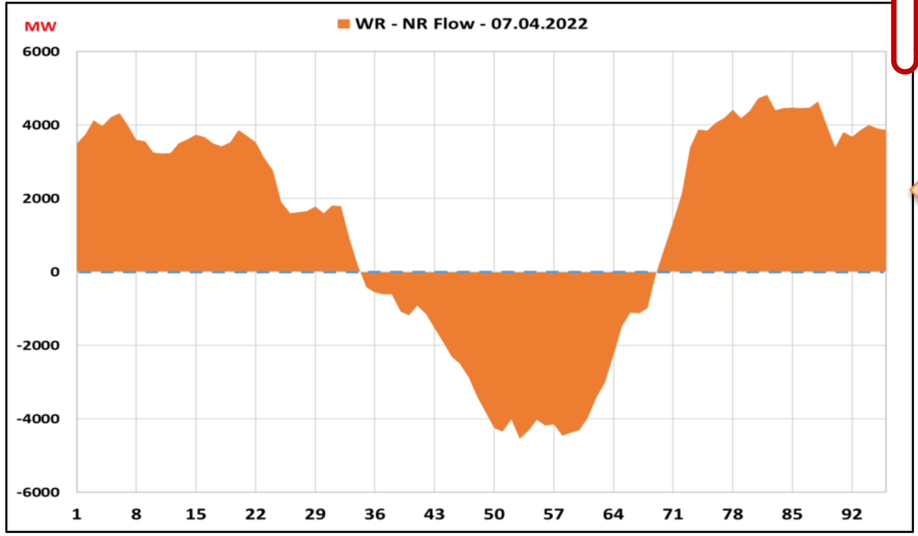


NR Import

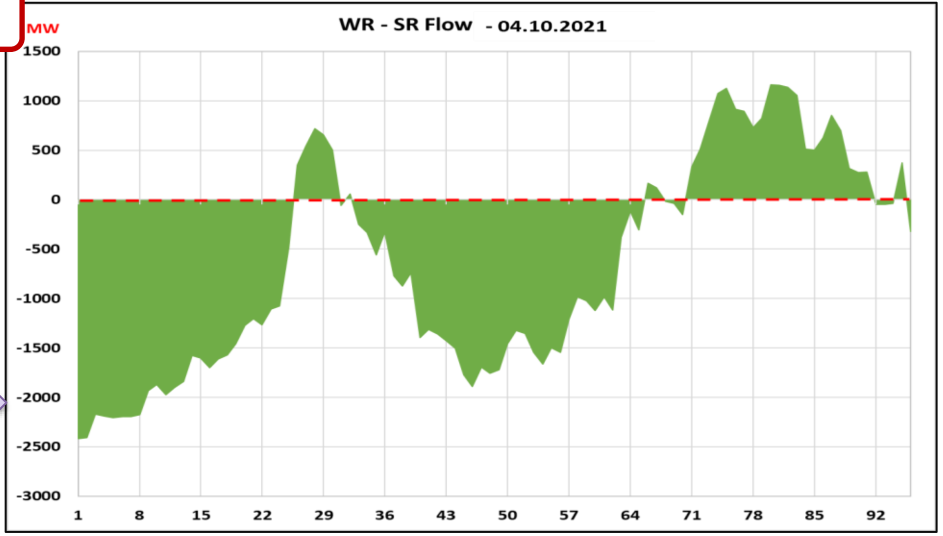


SR Import

Bi-directional Flows
The New Normal !!



WR - NR



WR -SR

Emerging Challenges for future

Ambitious VRE Integration Targets

500 GW Renewable Capacity by 2030

Intermittency, Compliance Issues, Grid Support and Grid Forming (Black start) Capability from RE

Integration of New Loads

EVs, Electrolyzers, Data Centers

Increasing Uncertainty on Demand Side

Constant shifts in Consumer Behavior

Demand Response Programs

Climate Change

Increasing frequency of extreme weather events;

Solar eclipses

Need for more simulation studies and benchmarking to ensure strict compliance of the current and evolving technical standards w.r.t Fault Ride Through capability , Power Quality, Harmonics etc.

Way Forward

Strengthen the transmission system to increase short circuit strength

- Long term solution - High gestation period of new transmission
- Increase in system strength is not significant if pocket is far away for synchronous generators

Re-tune the fast control loops of inverters for weak grid conditions

- May not provide desired performance under all conditions
- Capacity building at developer end required

Addition of synchronous condensers

- Green field projects approved at Fatehgarh-II and Barmer-II. Additional requirement is being assessed.
- Brown field projects under deliberation

Deployment of Inverters which can perform stably under weak grid conditions

- Pilot projects required to ascertain effectiveness
- Standardization required to ensure consistent performance

Thank You

Operational Challenges : Low System Strength

1. **System Strength** is:

    - Represented by **“Short Circuit MVA”** or **“Short Circuit Ratio (SCR)”**
    - Dependent on number of Synchronous Generators in the vicinity

2. Pockets far away from Synchronous Generators have **low system strength**

3. In weak pockets, high sensitivity can lead to voltage instability, causing control systems to oscillate

$$SCR = \frac{Short\ Circuit\ MVA}{IBR_{MW}}$$

SCR in Rajasthan

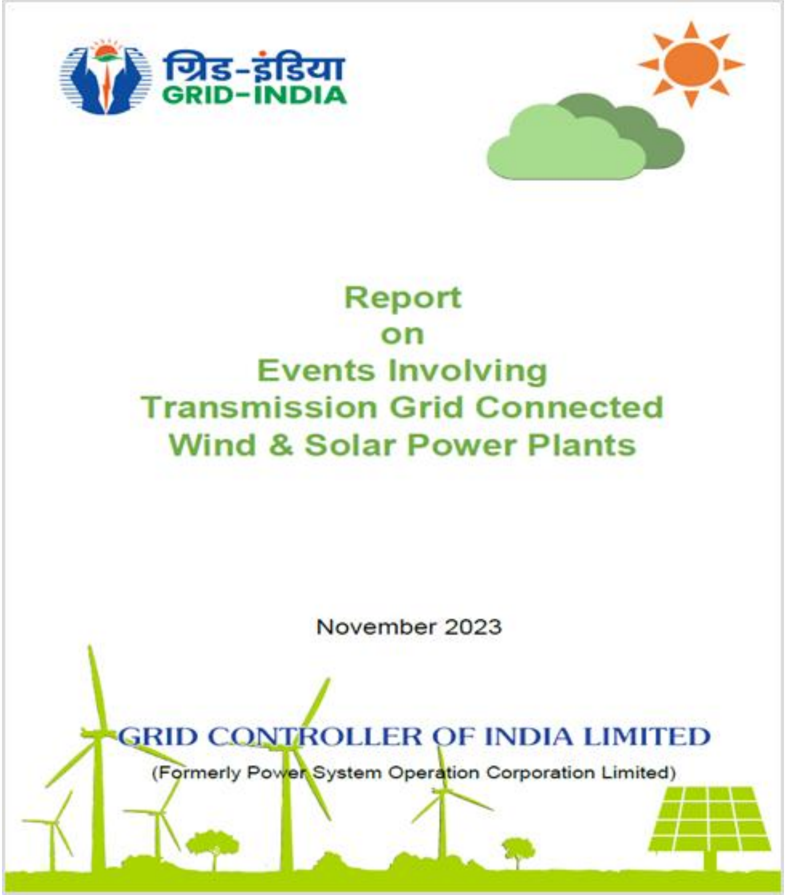
SCR in Gujarat

Not much increase in system strength with commissioning of planned lines

Details

Compliance to Technical Standards – Impact on Grid Stability

Concentrated RE Capacity Addition - Possibility of a large disturbance/generation loss in case of any non-compliance to the CEA Technical Standards on LVRT, HVRT, Power Quality, PQ Capability etc.



57 Grid-Events/Disturbances in RE Complex Jan-22 to Jun 2024:

- **RE generation loss of above 1000 MW in each of these grid events**
- **Fault ride through (LVRT) failure one of the primary reasons**

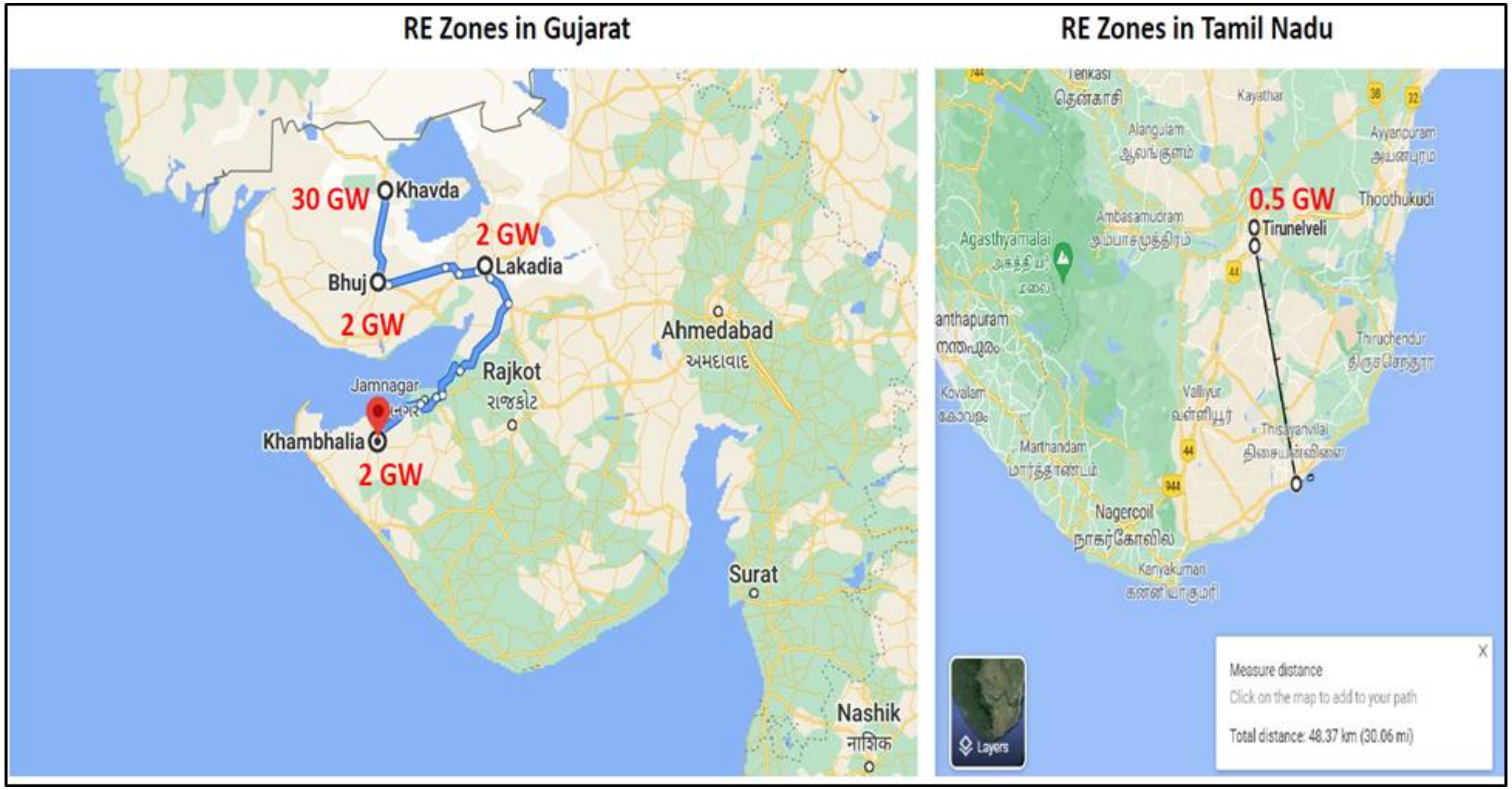
Voltage Oscillations in large RE complex

- Low Freq Oscillations during peak solar period & low voltage scenario
- Triggering events (Reactor switching, line charging, etc.)
- Oscillation is predominantly observed in voltage and reactive power
- Maximum voltage variation during these oscillations is observed in pooling stations with low fault level
- **Potential Reasons: Delay in communication from PPC to IBRs; Improper tuning of controllers**

Link to the Report: https://posoco.in/wp-content/uploads/2024/01/Report-on-Events-Involving-Transmission-Grid-Connected-Wind-Solar-Plants.pdf

Impact on Grid Stability

- **Disaster Management and Strategic Importance**



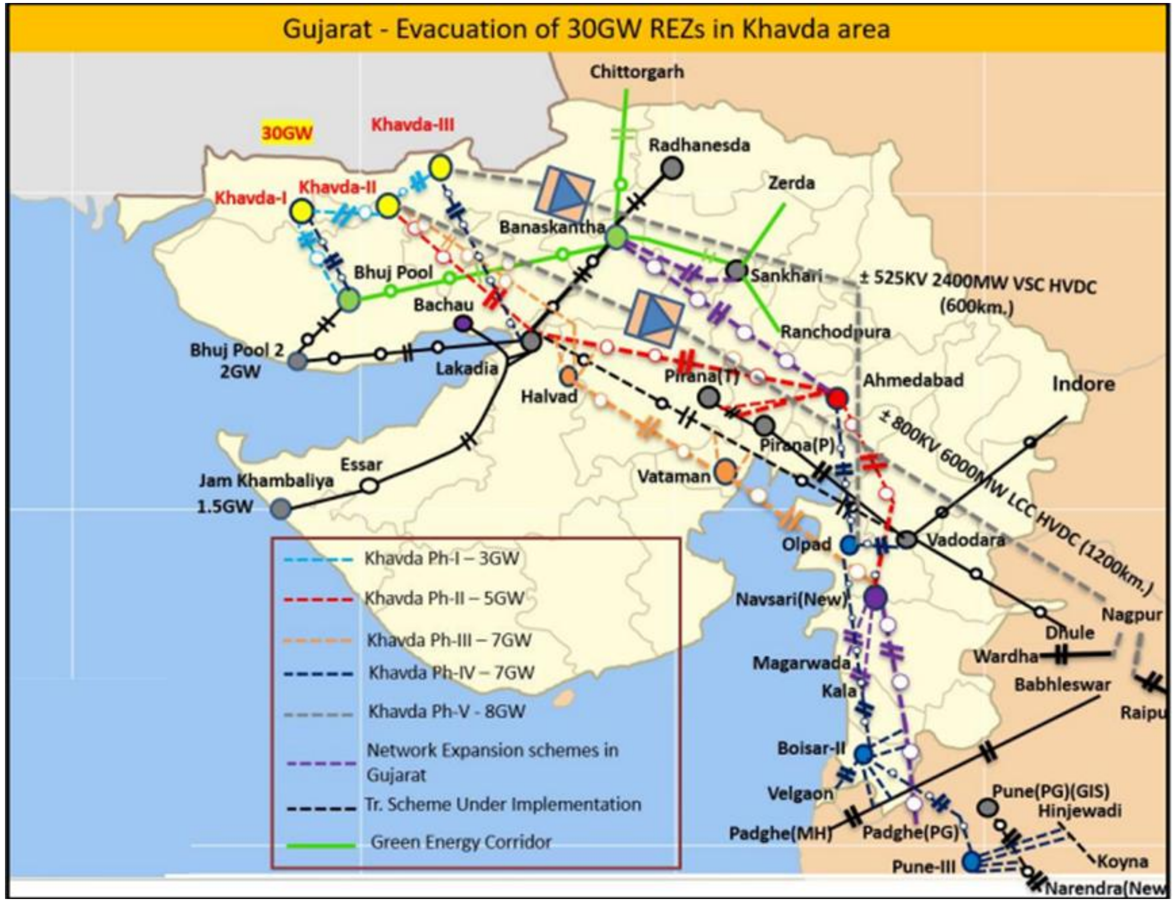
Cyclones

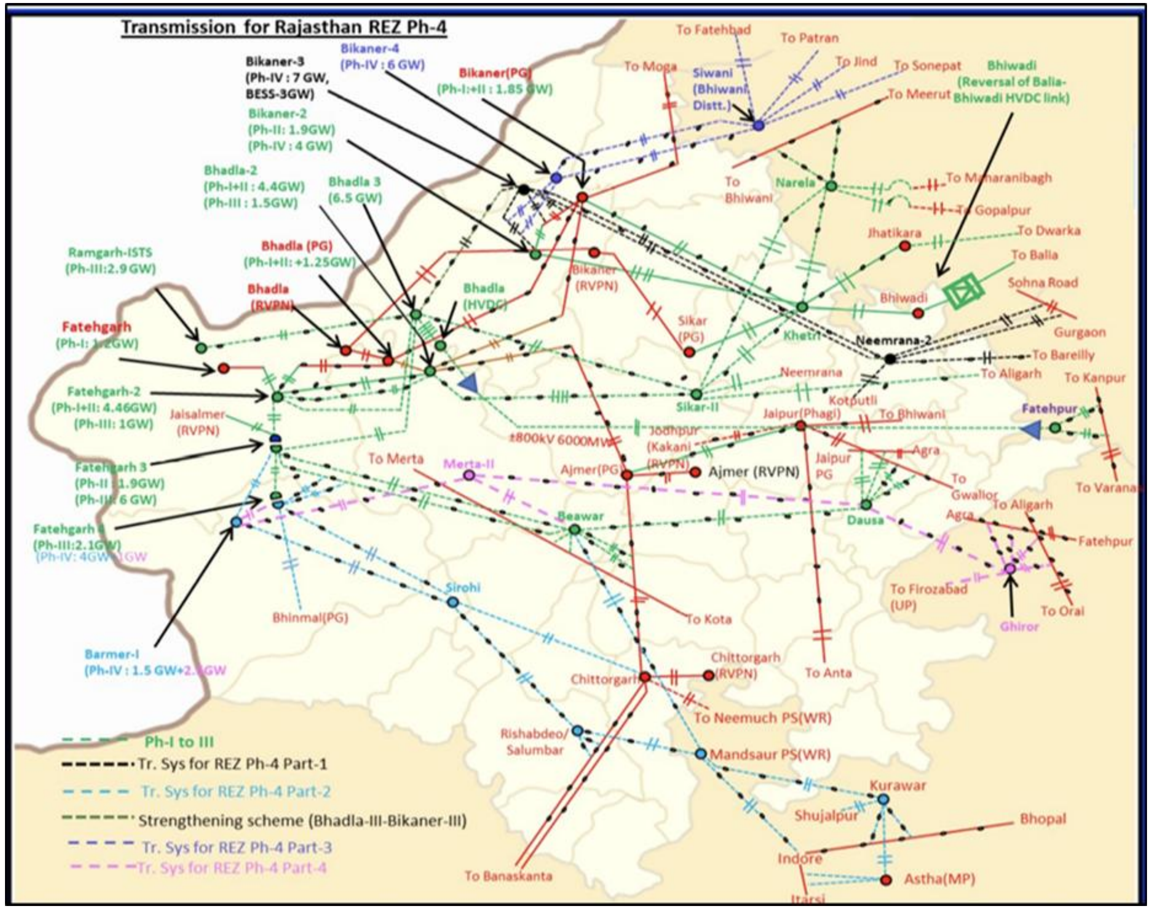
- **2024:** Remal, Dana
- **2023:** Biparjoy, Michaung
- **2022:** Asani , Mandous
- **2021:** Tauktae , Yass
- **2020:** Amphan, Nivar
- **2019:** Fani, Bulbul
- **2018:** Titli, Gaja
- **2016:** Vardah
- **2014:** Hud-Hud
- **2013:** Phailin

- ➢ Generation and Transmission Network Depletion due to Natural Disasters is a cause of concern !!
- ➢ Most of the RE capacity in Gujarat and Tamil Nadu is near coastal areas making it vulnerable to cyclones

Impact on Grid Stability

- **Disaster Management and Strategic Importance**





- ~30 GW RE generation within 30-40 kMs coming up at Khavda
- ~ 42 GW generation within 140-150 kMs in Gujarat
- ~70-80 GW solar generation in close vicinity in Rajasthan by 2030

Installation of Energy Storage Systems in the large RE complexes is essential to enhance resiliency (especially from black-start perspective) !!

Energy Transition : Operational Challenges

1. **Resource Adequacy and Balancing Requirements**

2. **Generation Flexibility**

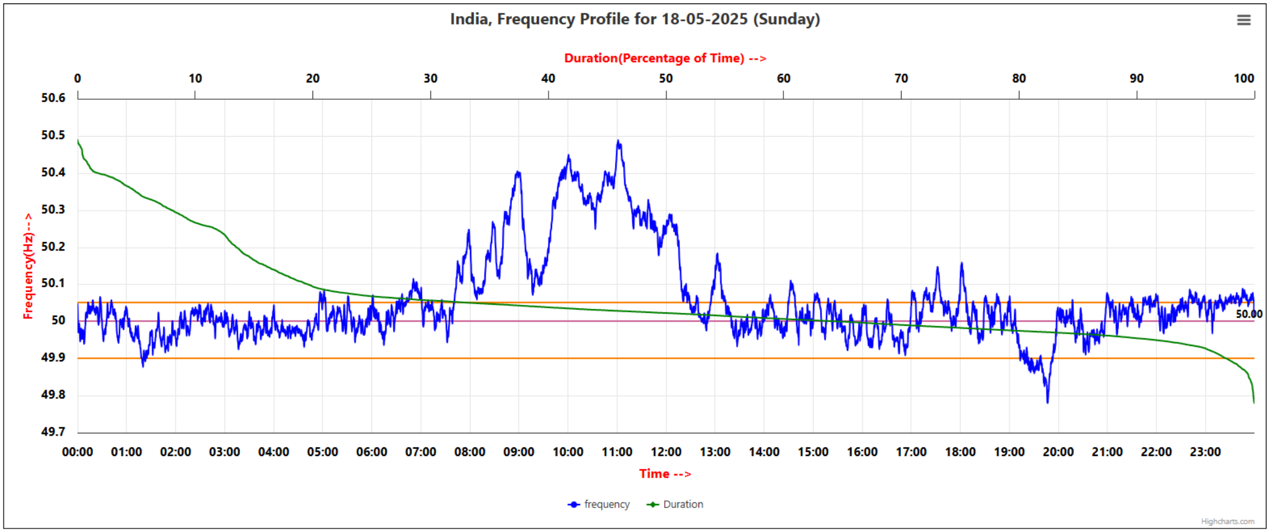
3. **VRE Forecasting**

Managing High frequency in solar hours

High Frequency observed on several days

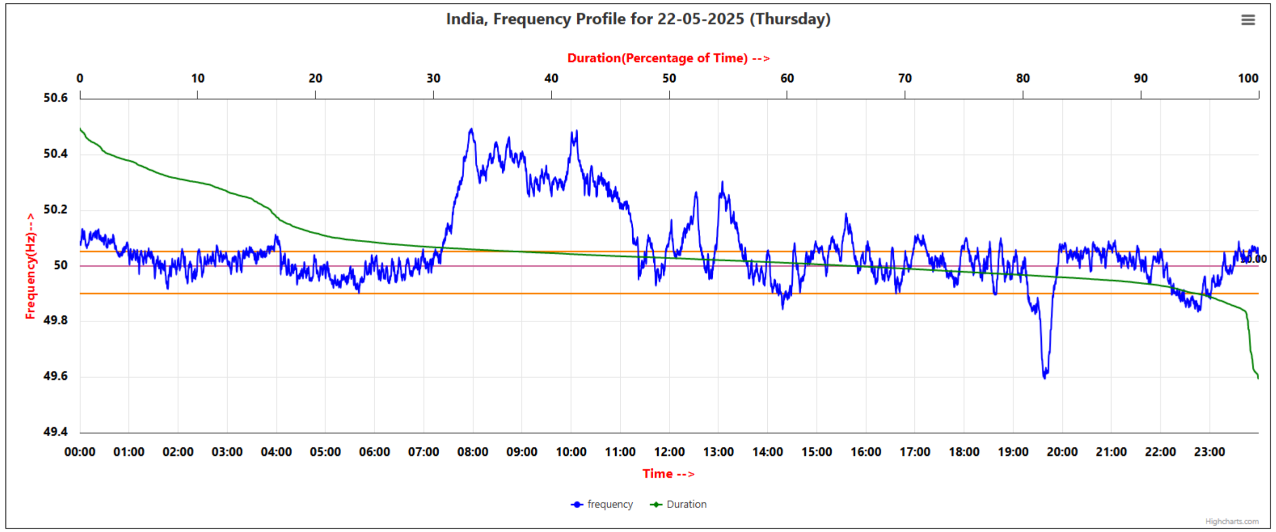
>50.05 Hz for about 33% of the time

18th May 2025



>50.05 Hz for about 37 % of the time

22nd May 2025



- Ref. Grid-India report on high frequency operation on 04th,11th & 25th Aug 2024
  https://webcdn.grid-india.in/files/grdw/2025/08/NLDC%20communication_High%20Frequency%20_%20August%202024_Final_699.pdf
- Hon'ble CERC in 2/SM/2025, has directed measures to contain high grid frequency and ensuring reliable grid operation (https://cercind.gov.in/2025/orders/2-SM-2025.pdf) – Ancillary from RE, Thermal Flexibilization (MTL, Two shifting,

ग्रिड-इंडिया GRID-INDIA

Dimensions of Indian Power System

~513 GW
generation capacity

250 GW+
peak demand

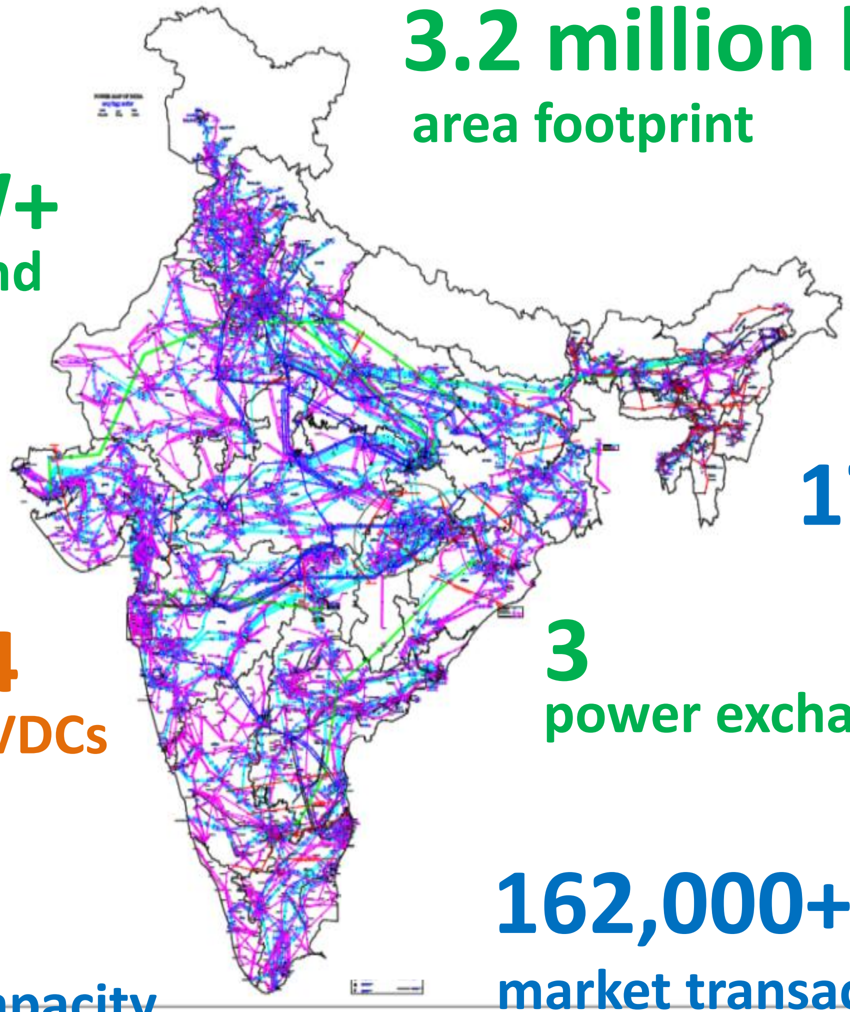
> 5 TWh
daily energy met

499000 ckm+
EHV transmission

~257 GW
renewables
(incl. ~49 GW large Hydro)

14
HVDCs

~ 120 GW
inter-regional capacity



3.2 million km²
area footprint

1.4 Billion+
people served

4.5 GW+
international exchanges

171 TWh+
annual market trades

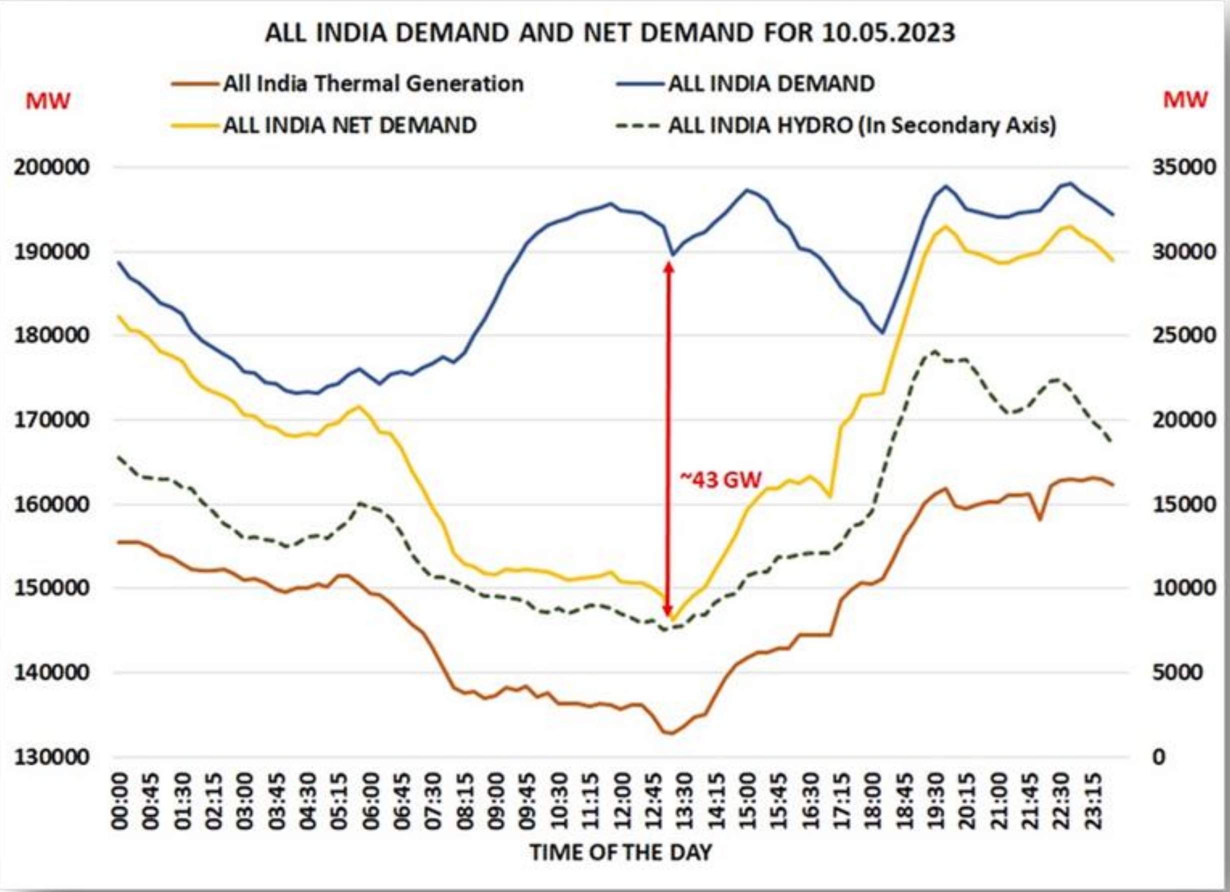
3
power exchanges

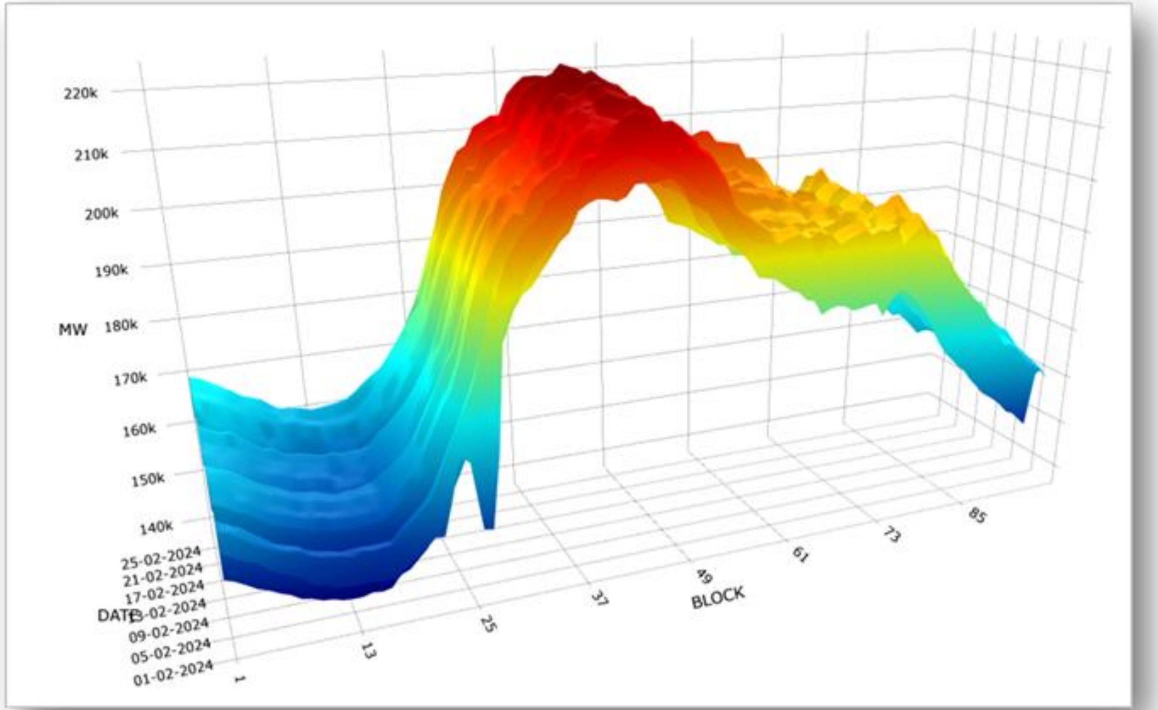
6000+
market participants

162,000+
market transactions

3. Flexibility and Balancing Requirements

Increasing "Duck Curve" Belly !!





Need for more flexible resources viz. energy storage, Gas Thermal Flexibilization, (Technical Min, Two shifting etc.)

Change in Load Shape

Increasing uncertainty on demand side

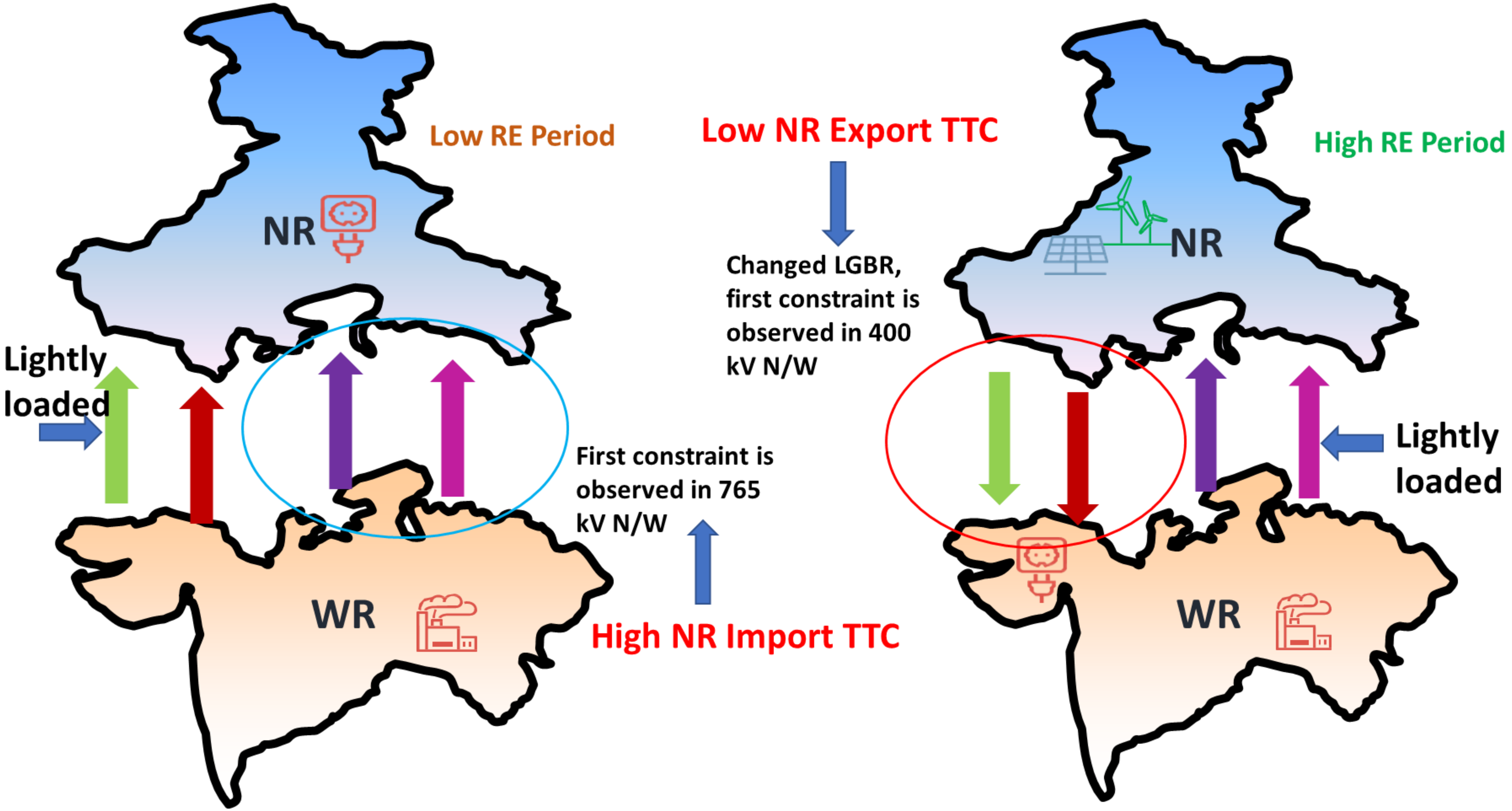
Near Future –

EV Charging?

Induction Cooking?

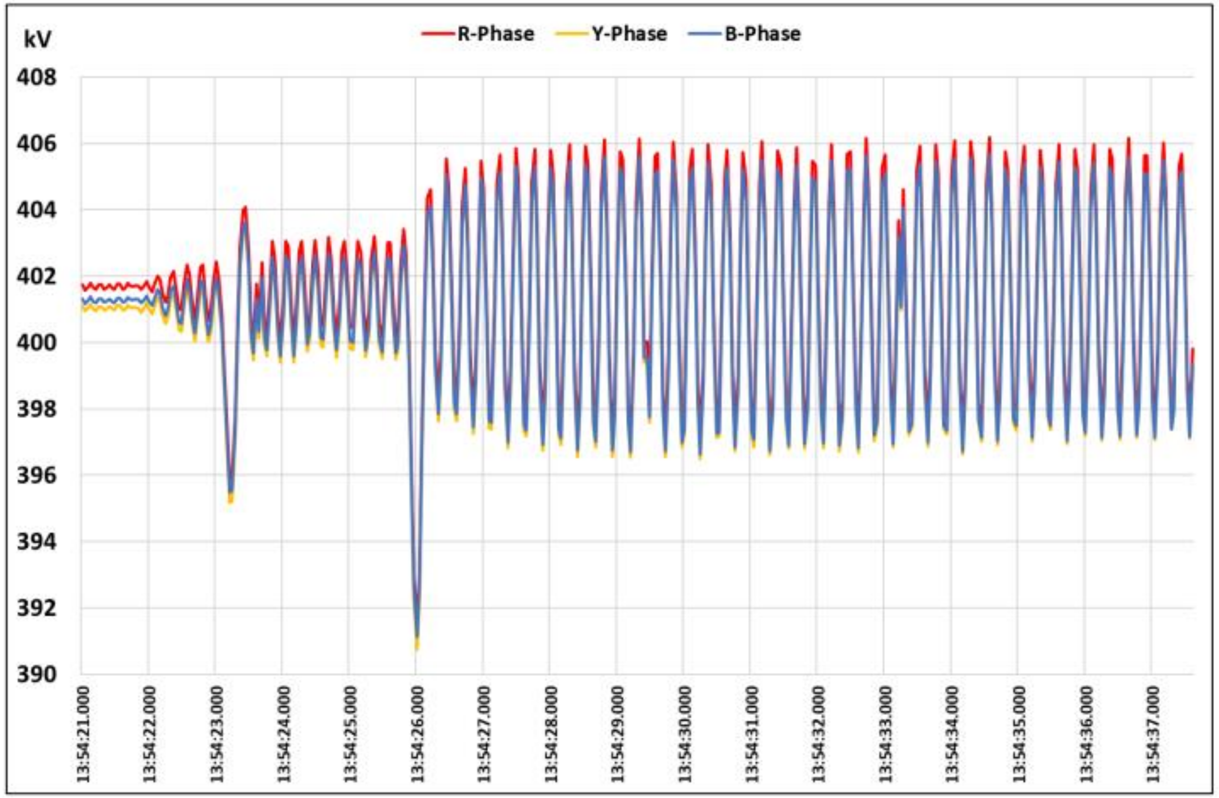
Data Centers?

Behavioural Changes in Power Flow Patterns



Low-Frequency Oscillations

- **LFO during peak solar period & low voltage scenario in RE complex**
- **No triggering events (Reactor switching, line charging, etc.)**
- **Oscillation is predominantly observed in voltage and reactive power**
- **Maximum voltage variation during these oscillations is observed in low short circuit strength pooling stations**
- **Suspected reasons - Delay in communication from PPC to IBRs, Improper tuning of controllers**



Voltage Oscillation Freq	Dominant Mode	Voltage oscillation magnitude (220 kV line)
Mode 1: 2-4 Hz	3.6 Hz	0.01-0.04 p.u. (2-4 kV)
Mode 2 : 0.03-0.1Hz	0.08 Hz	0.1 p.u. (20-22 kV)
Mode 3 : Multi mode	0.069 Hz	0.15 p.u. (30-35 kV)

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Resource Adequacy Challenges due to the variability of RE

All India Generation (Area plots) 06-07-2024 (Saturday)

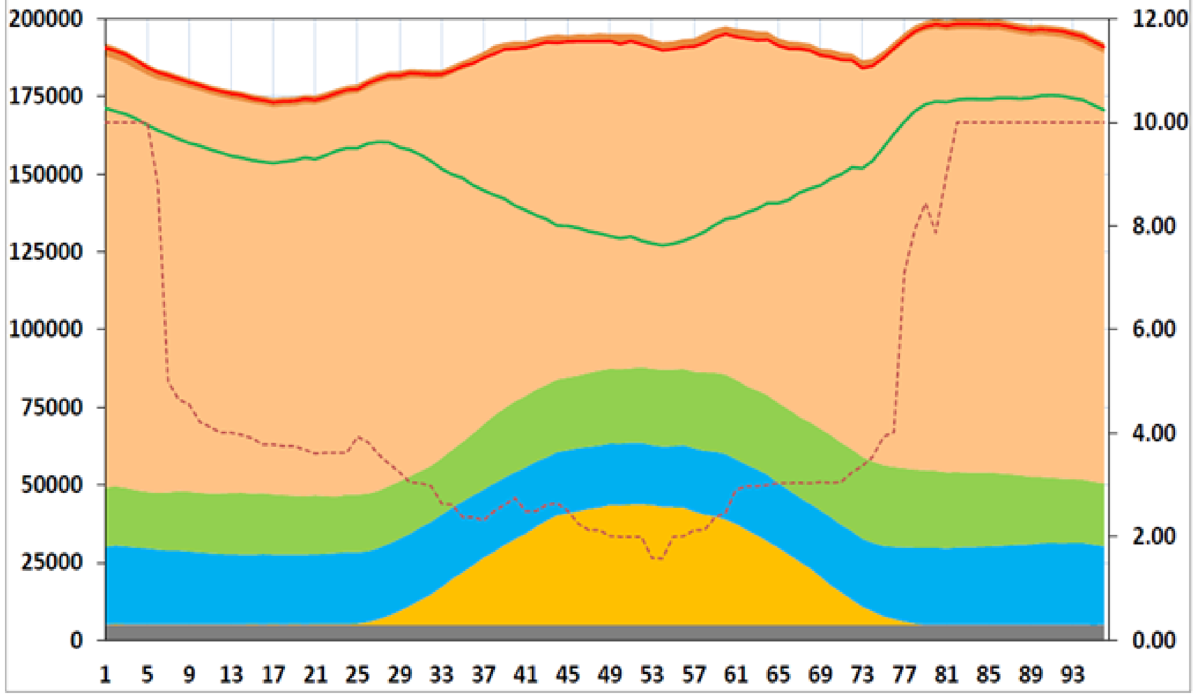
Nuclear · Solar · Hydro · Wind · Thermal · Gas · Demand · Net Demand · UMCP

MW

	AI Demand	⏱	Net Demand	Nuclear	Thermal	Gas	Hydro	Wind	Solar	% RE	Day Peak
Peak (solar hrs)	195402	14:49	135450	4922	109266	2697	21006	25609	34343	30%	✗
Peak (non-solar hrs)	198666	20:29	174334	4941	142630	3177	25013	24220	0	12%	✓

Demand & Genration values are in MW, Time in hh:mm   solar hrs : 0600-1800 non-solar hrs : 0000-0600 & 1800-2400

₹/kWh



All India Generation (Area plots) 31-08-2023 (Thursday)

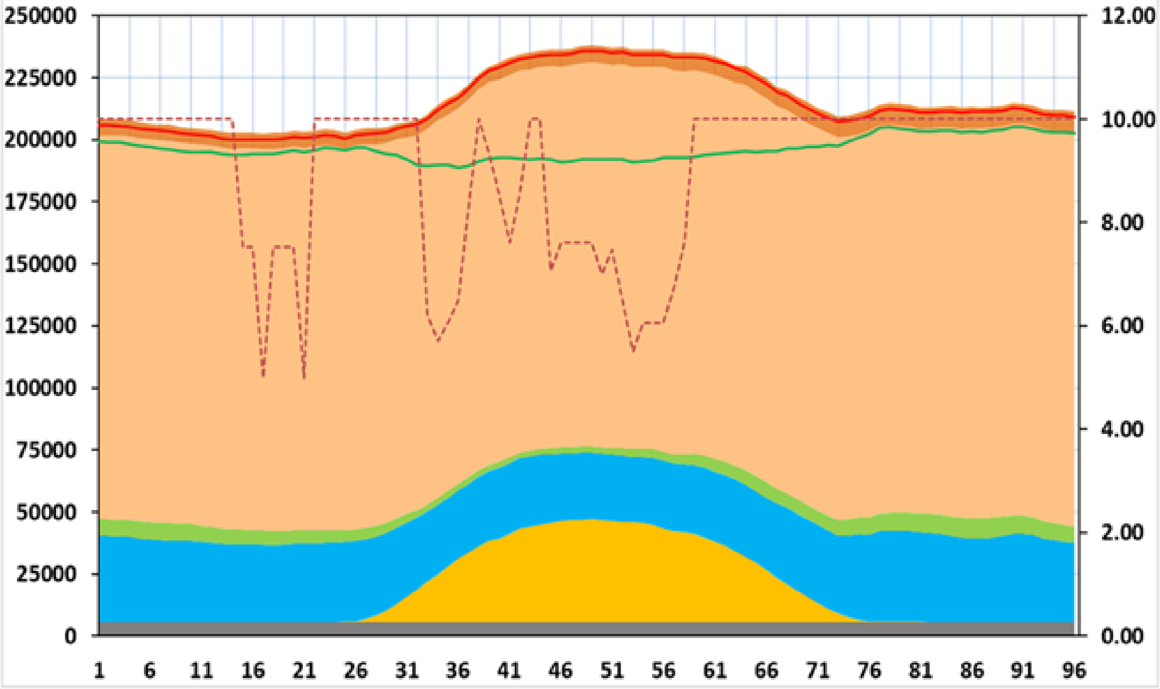
Nuclear · Solar · Hydro · Wind · Thermal · Gas · Demand · Net Demand · UMCP

MW

	AI Demand	⏱	Net Demand	Nuclear	Thermal	Gas	Hydro	Wind	Solar	% RE	Day Peak
Peak (solar hrs)	236598	12:11	192544	5626	154565	6894	27254	2622	41432	18%	✓
Peak (non-solar hrs)	212975	22:21	205399	5622	157834	8405	35541	7524	0	4%	✗

Demand & Genration values are in MW, Time in hh:mm   solar hrs : 0600-1800 non-solar hrs : 0000-0600 & 1800-2400

₹/kWh



High RE, Low Demand scenario:

- Higher net load ramp, Thermal Generation backed down
- Depleted Down Reserves, High Freq conditions

Low RE, High Demand Scenario:

- Resource adequacy issue (more acute in non-solar hours
- Shortage, Low freq. conditions, Section 11, Gas despatch