

# **Grid Operational Challenges in view of Energy Transition**

by

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# Outline

- Energy Transition a multi-dimensional issue
  - Sustainable Development Goals and the progress
  - Global warming and extreme weather conditions
  - Anthropogenic emissions and energy; building blocks to reduce emissions
  - Financing
  - Critical Minerals
  - Energy trilemma
- Impact of Next Generation Loads on the electricity demand
  - Space heating and cooling, electric cooking, EVs, Green Hydrogen, Data Centres
  - High Distributed Energy Resources (DERs) penetration
- Energy Transition and Reliability of Grids: the Conundrum!
- Building blocks for resilient and reliable grid operation

# SUSTAINABLE DEVELOPMENT GOALS

Adopted by UN member states in 2015 as Agenda 2030

**1** NO POVERTY



**2** ZERO HUNGER



**3** GOOD HEALTH AND WELL-BEING



**4** QUALITY EDUCATION



**5** GENDER EQUALITY



**6** CLEAN WATER AND SANITATION



**7** AFFORDABLE AND CLEAN ENERGY



**8** DECENT WORK AND ECONOMIC GROWTH



**9** INDUSTRY, INNOVATION AND INFRASTRUCTURE



**10** REDUCED INEQUALITIES



**11** SUSTAINABLE CITIES AND COMMUNITIES



**12** RESPONSIBLE CONSUMPTION AND PRODUCTION



**13** CLIMATE ACTION



**14** LIFE BELOW WATER



**15** LIFE ON LAND



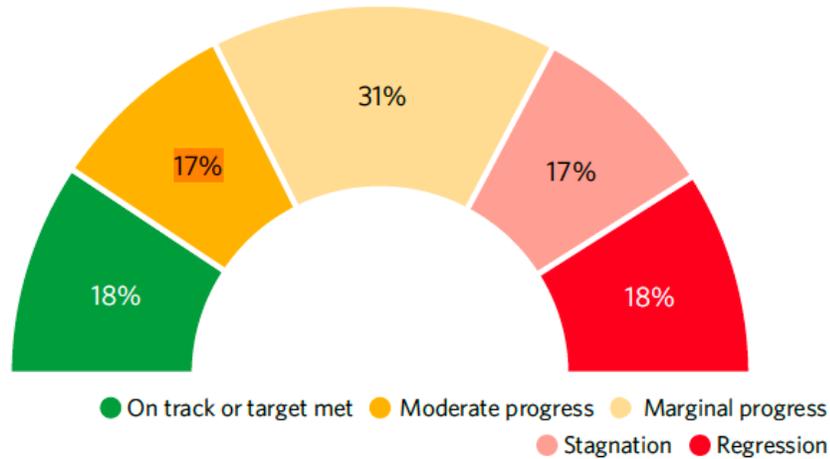
**16** PEACE, JUSTICE AND STRONG INSTITUTIONS



**17** PARTNERSHIPS FOR THE GOALS

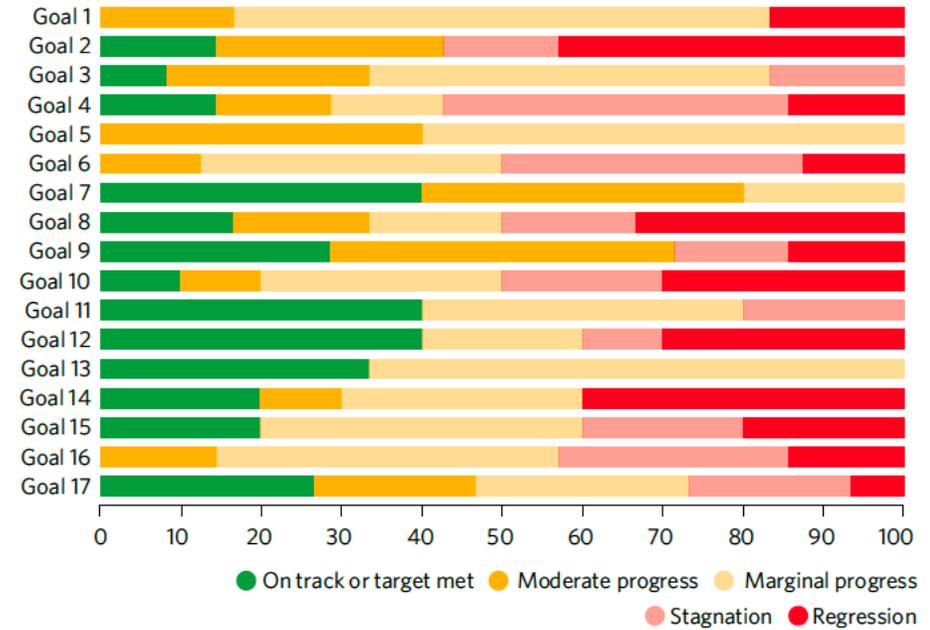


Overall progress across targets based on 2015-2025 global aggregate data



Note: Percentages do not add up to 100 per cent due to rounding.

Progress assessment for the 17 Goals based on assessed targets, by Goal (percentage)



- 7.1 Access to energy services ●
- 7.2 Share of renewable energy ●
- 7.3 Energy efficiency ○
- 7.a International cooperation on energy ●
- 7.b Investing in energy infrastructure ●

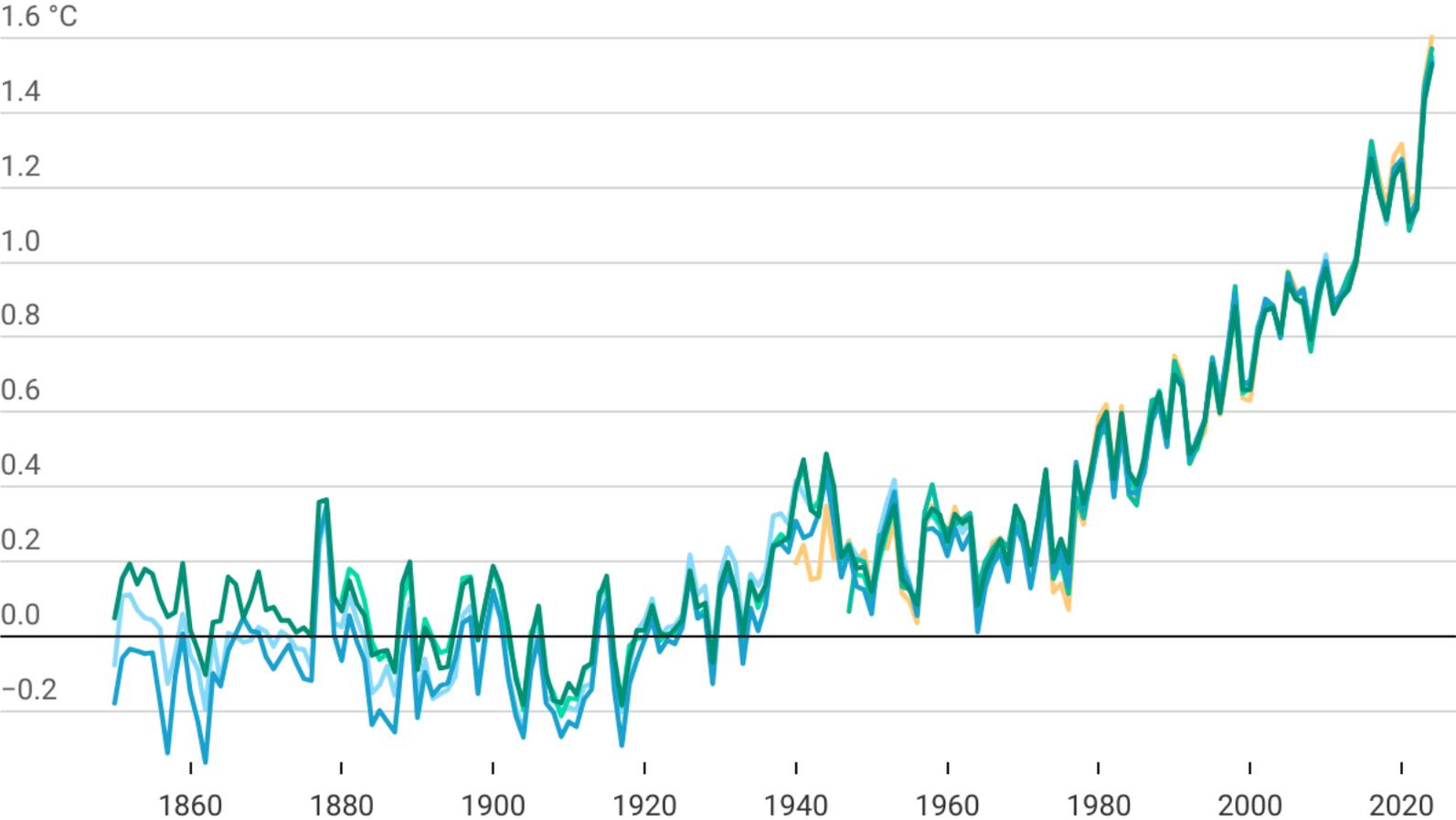
- 92% energy access (649 million without access)
- 17.9% share of Renewable Energy in Total Final Consumption
- Energy Intensity per GDP PPP; to reduce 4% every year from 2022 to 2030
- International financial flows in 2023 just 75% of peak 2016 USD 28.4 billion
- Per capita RE installed capacity 341 watts in developing countries>>> 1162 watts

**Source: UN Sustainable Development Report 2025**

# Global mean temperature 1850-2024

Difference from 1850-1900 average

— Berkeley Earth (1850-2024.12) — ERA5 (1940-2024.12) — GISTEMP (1880-2024.12) — HadCRUT5 (1850-2024.12) — JRA-3Q (1947-2024.12) — NOAA GlobalTemp v6 (1850-2024.12)

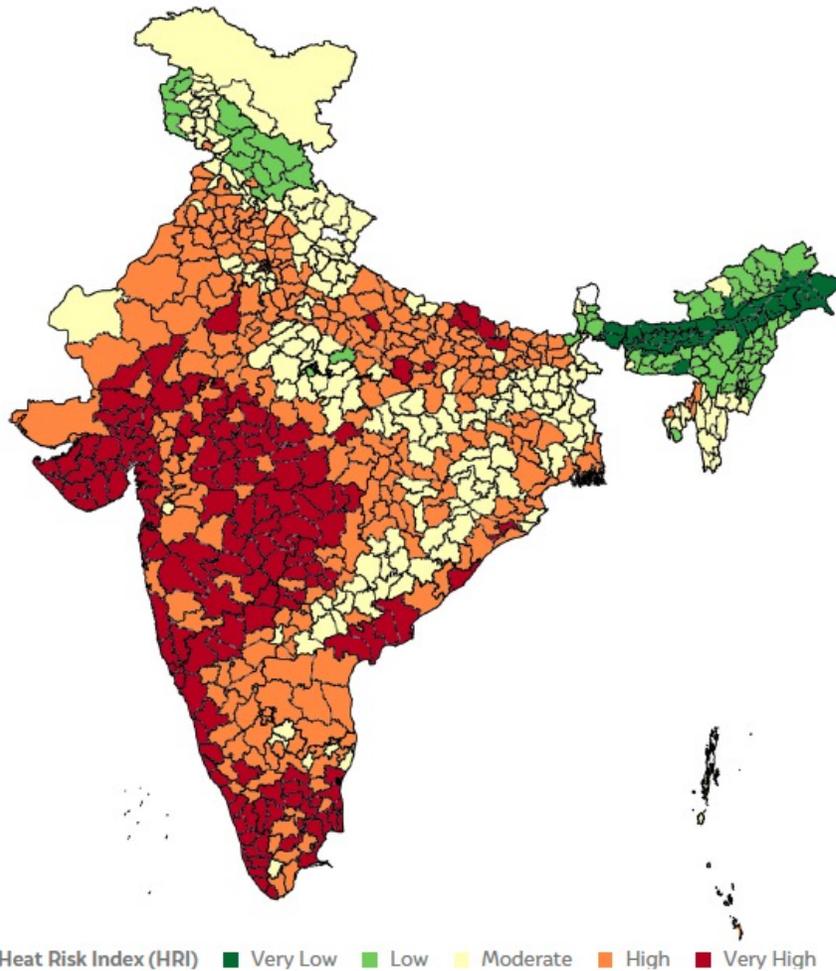


- 2024 global mean temperature rise over 1850-1900 pre-industrial levels highest on record
- 2010-2019 decadal increase in temperature 1.1 degree C
- Ocean warming, sea level rise, glaciers retreating, lowest Antarctica sea ice
- Extreme weather events becoming frequent

Annual global mean temperature anomalies relative to a pre-industrial (1850–1900) baseline shown from 1850 to 2024

# Extreme Heat impacting livelihoods

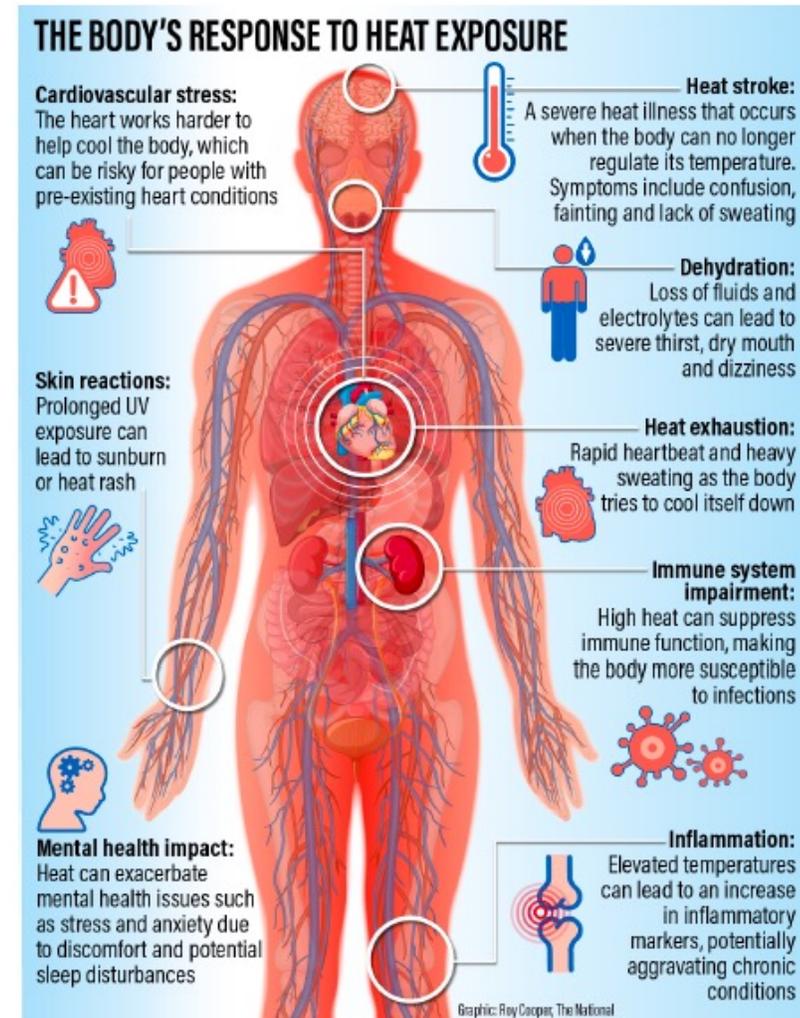
Figure ES3 More than 57% of districts are at high to very high heat risk in India



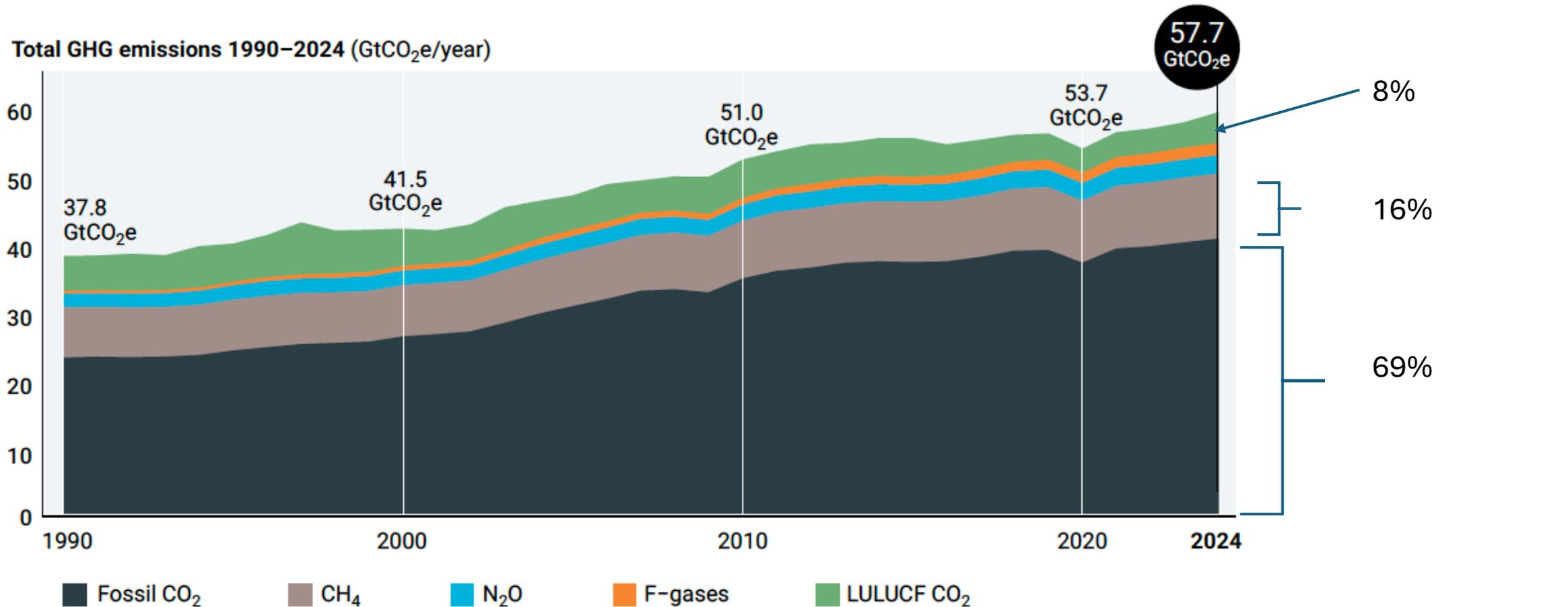
Source: Authors' analysis

Prabhu, Shravan, Keerthana Anthikat Suresh, Srishti Mandal, Divyanshu Sharma, and Vishwas Chitale. 2025. *How Extreme Heat is Impacting India: Assessing District-level Heat Risk*. New Delhi: Council on Energy, Environment and Water.

Figure 2 How heat impacts the human body



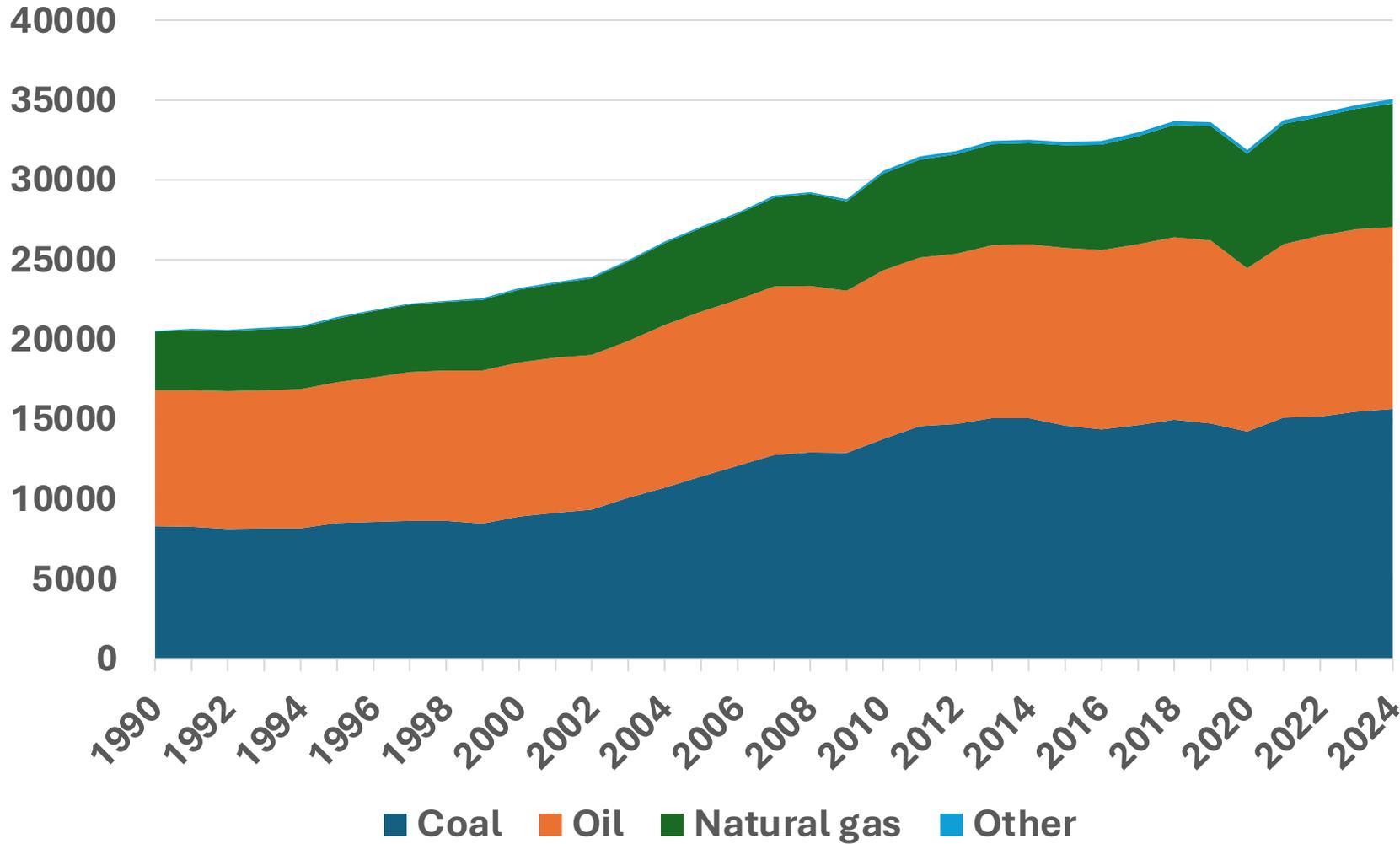
# Total net Anthropogenic Emissions 1990-2024



LULUCF: Land Use Land Use Change and Forestry

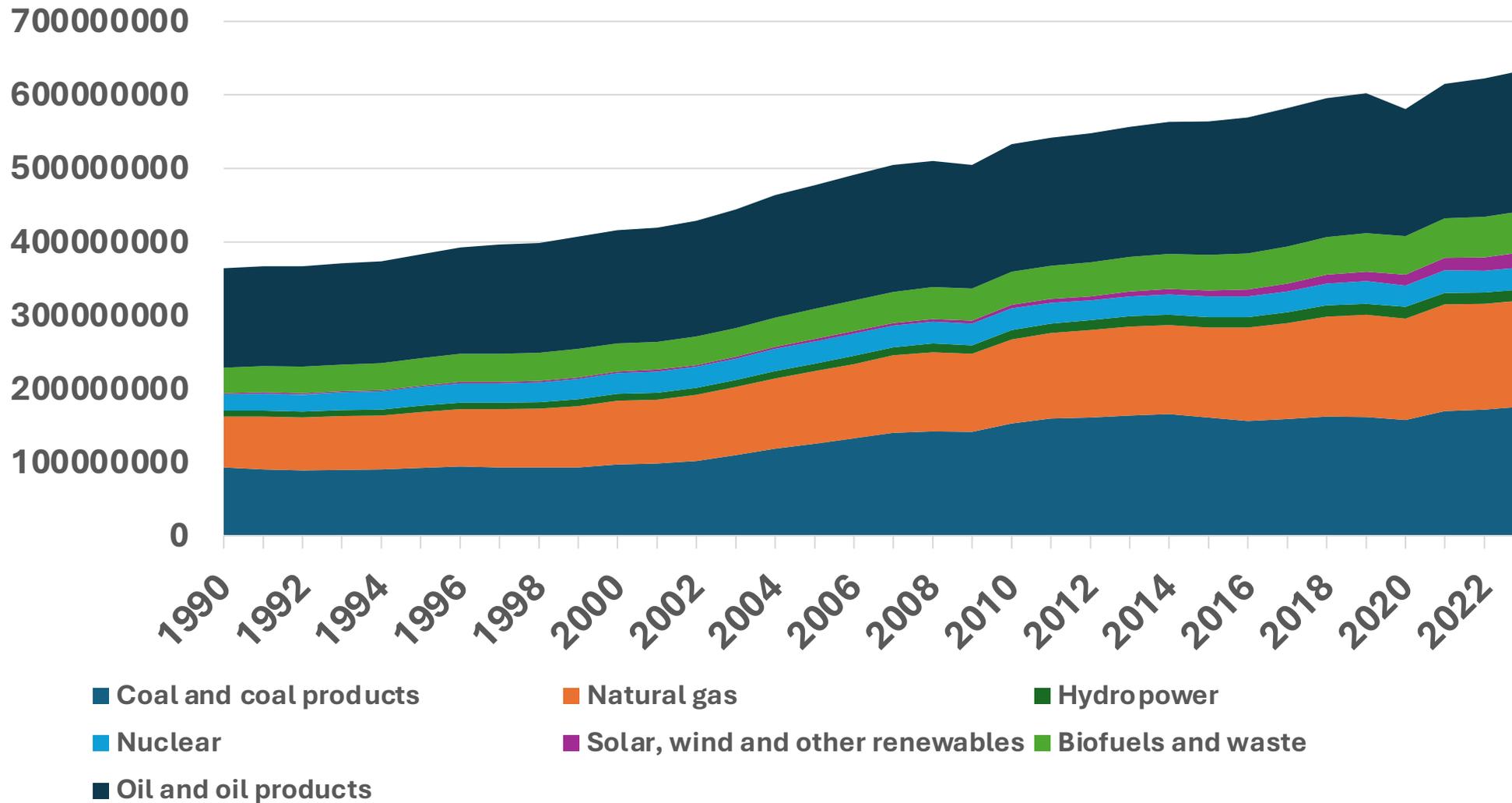
*Note:* The time series data sets used for the Emissions Gap Report are updated on an annual basis using the latest available statistical information on activities and emissions factors. These updates imply changes compared to prior reporting in the Emissions Gap Report. Accordingly, global GHG emissions in 2023 were adjusted to 56.2 GtCO<sub>2</sub>e from the 57.1 GtCO<sub>2</sub>e reported in the 2024 edition of the report.

## CO2 emissions from fossil fuels in MtCO2 as per IEA



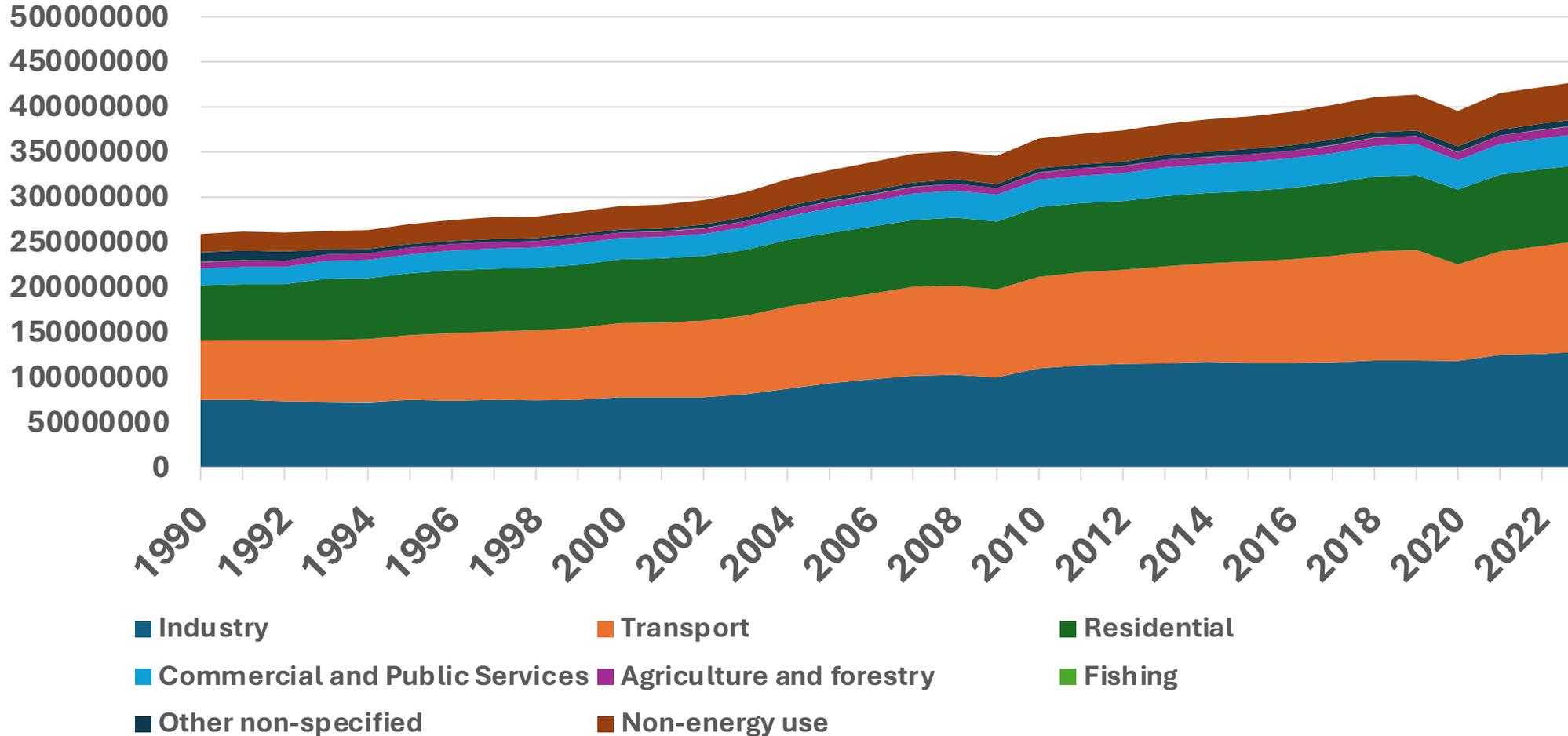
- Total CO2 emissions 38.15 Gt Including flaring & industrial process as per IEA's WEO 2025
- CO2 concentration increased from 355 ppm in 1990 to 424 ppm in 2024, as per WMO
- Massive surge of 3.5 ppm from 2023 to 2024

# Total Primary Energy Supply (TPES) in TJ from 1990-2023 as per International Energy Agency (IEA)



- In 2023, coal, oil and gas formed 81% of the TPES
- Electricity is a vector; only 30-35% of useful energy is extracted from coal, oil and gas used for power generation

## Total Final Consumption (TFC) in TJ across different sectors 1990-2023 as per IEA



- In 2023, electricity as a vector formed 21.2% of the TFC
- Lot of energy goes as waste in transport and other sectors
- Almost two thirds of TPES goes waste; energy efficiency a key imperative

## Key energy statistics (2024) from the World Energy Outlook 2025 by IEA

S no	Description	World	China	US	Europe	India	South East Asia	CAGR (2024-2035) in % in the Current Policies scenario
1	Population (million)	8091	1415	340	692	1441	690	0.8
2	Total Energy Supply (EJ)	654.2	174.5	93.0	74.9	48.4	34.0	1.2
3	Renewable Energy (RE) supply (EJ)	82.7	17.9	11.1	15.7	6.6	6.4	<b>5.5</b>
4	Total Energy Consumption (EJ)	452.7	113.0	65.6	55.8	33.1	21.0	1.3
5	CO2 emissions from energy (MT)	38153	12660	4521	3501	3113	1969	0.1
6	Electricity Demand (TWh)	27290	9102	4102	3487	1644	1317	<b>3.4(generation) 6.3(capacity)</b>

# Building blocks for pathways to a clean energy transition.....(1)

## i. Energy Efficiency

- Energy intensity (energy input per dollar output at PPP) needs to increase 1.3% improvement in 2024 to 4% by 2030 in the Net Zero by 2050 scenario by IEA
- Buildings, industry and transport the key areas

## ii. Life Style for Environment

- Responsible consumption and Production (SDG 12); avoiding energy obesity
- Food waste, food loss, electronic waste, rising material footprint a concern

## iii. Electrification

- Electricity share in final consumption 21% in 2024 to 26% (2030) and 33% (2035) as per Net Zero by 2050 scenario by IEA
- Electric Vehicles, Clean Cooking, Heat Pumps, Green Hydrogen

# Building blocks for pathways to a clean energy transition.....(2)

## iv. Renewable Energy (RE) plus Energy Storage including DERs

- RE capacity from 4900 GW (2024) to 11600 GW (2030) to 19600 GW (2035)
- Battery Energy Storage System (BESS) to go up from 86 GW (2023) to 1200 GW (2030)

## v. Nuclear Energy

- Capacity up from 420 GW (2024) to 520 GW (2030) and 710 GW (2035)

## vi. Electricity Grids strengthening and digitalization

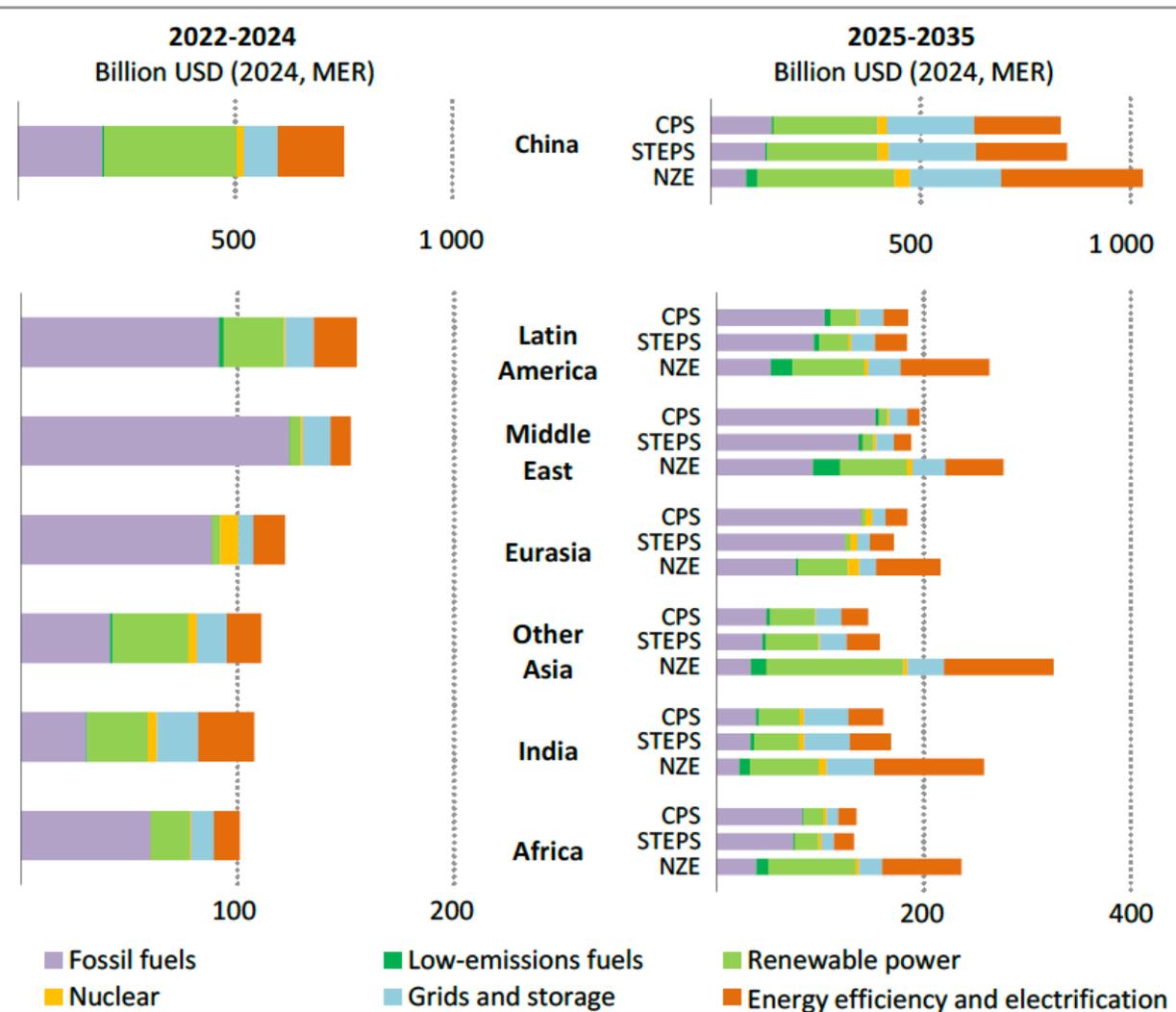
- Transmission grid 5.3/7.2/12.7 million circuit kms 2021/2030/2050
- Distribution grid 71.7/86.1/153.7 million circuit kms 2021/2030/2050

## vii. Carbon Capture, Utilization and Storage (CCUS)

- CO2 removal 45 Mt (2024) to 690 Mt (2030) to 2260 Mt (2035)

Figures as per IEA reports

# Clean Energy Financing Requirements



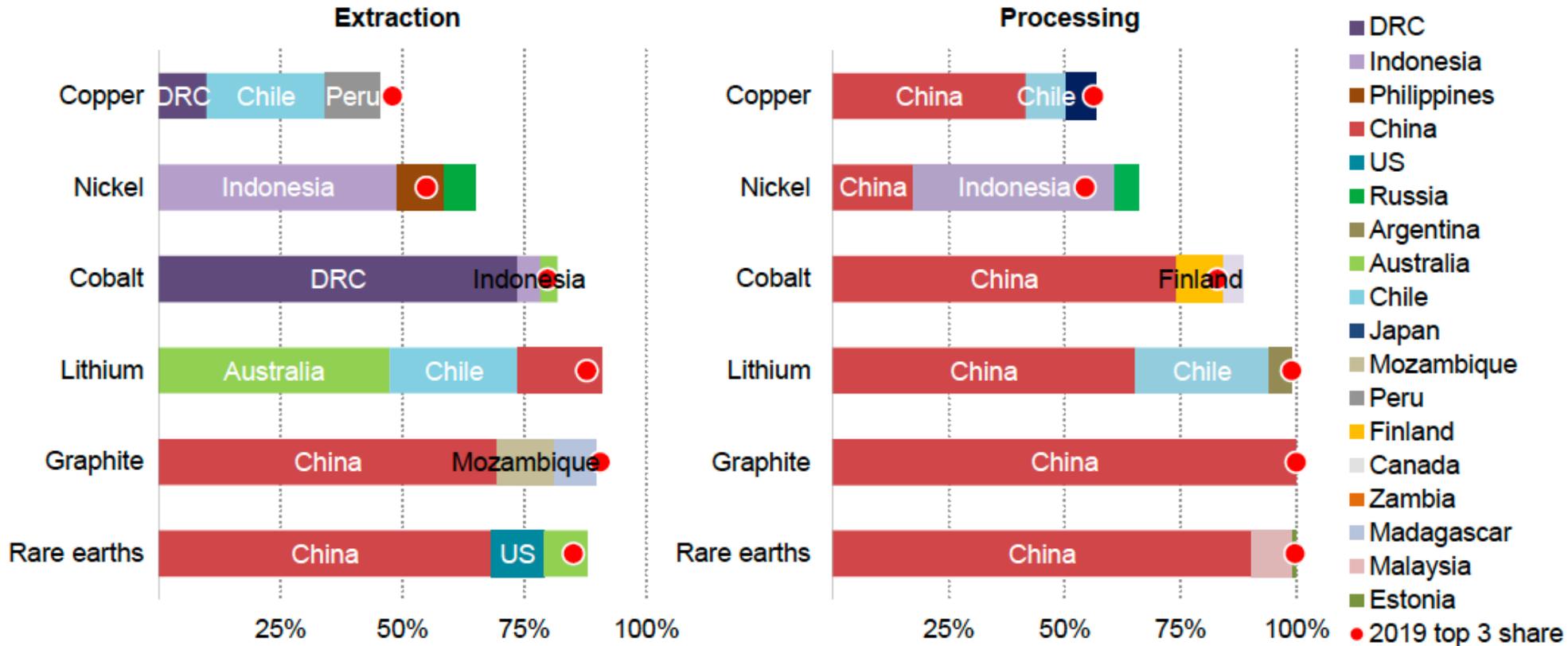
Average annual investments required would go up from 3.3 trillion USD today to 4.8 trillion USD per annum as per the Net Zero Energy by 2050 scenario as per IEA's World Energy Outlook 2025

IEA. CC BY 4.0.

Note: MER = market exchange rate; CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario.

# Critical Minerals

Share of top three producing countries in total production for selected resources and minerals, 2022



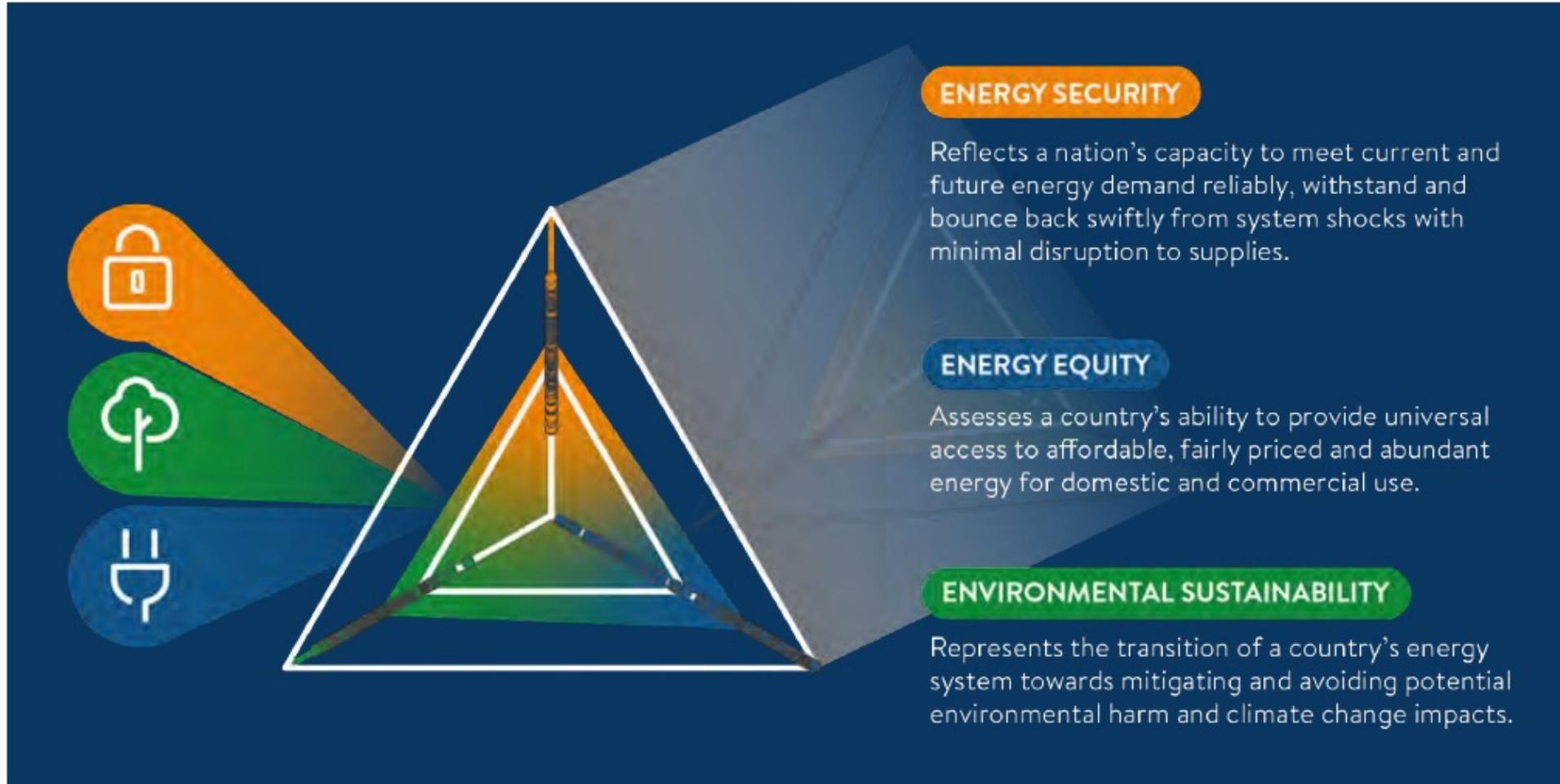
- Grain Oriented Electrical Steel for transformers
- HVDC and subsea cables
- High purity silicon for chips used for data servers
- Gallium for optical memory

IEA. CC BY 4.0.

Notes: DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. Graphite processing is for spherical graphite for battery grade.

Sources: IEA analysis based on S&P Global, USGS (2023), [Mineral Commodity Summaries](#) and Wood Mackenzie.

# So, what is Energy Transition?

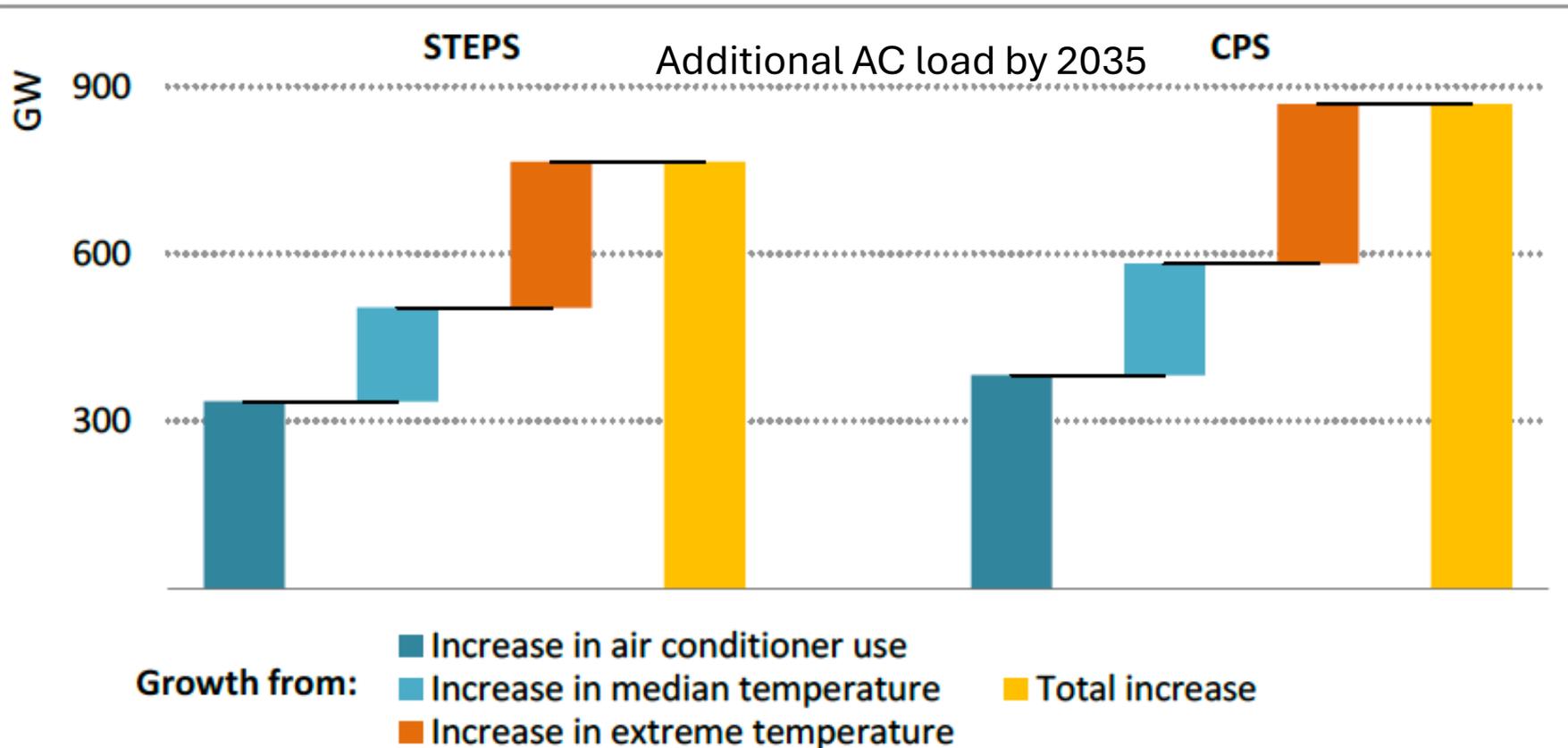


- **Decarbonized**
- **Decentralized**
- **Digitalized**

# Impact of Next Generation loads on electricity demand

- Airconditioning and heat pumps
- Electric cooking
- Electric Vehicles
- Green Hydrogen
- Data Centres

# Impact of Air Conditioning (AC) load



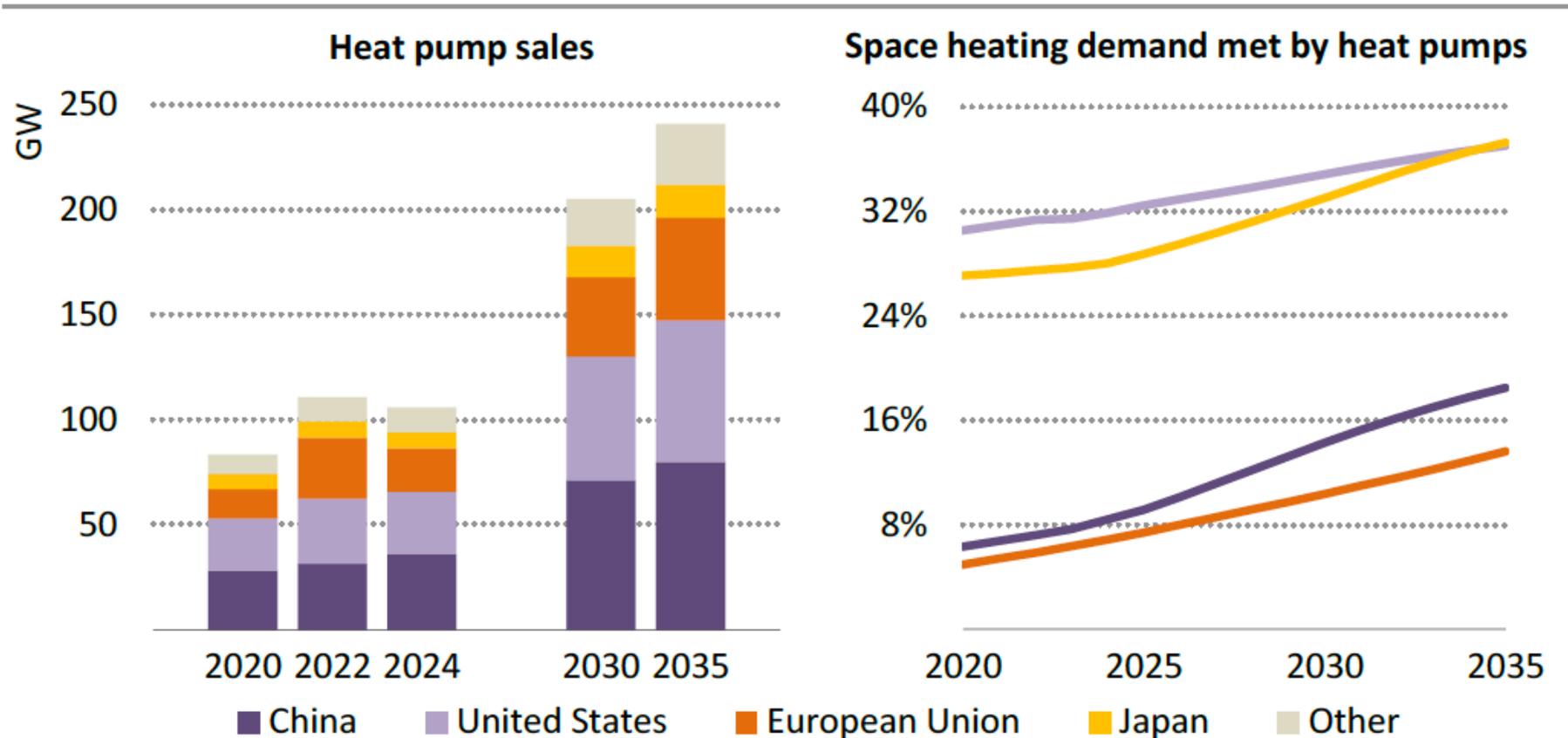
IEA. CC BY 4.0.

Notes: GW = gigawatt; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario.

- Sustained heat wave in May 2024 in India led to a 15 GW higher demand than forecasted
- BIMSTEC countries would see an increase in AC penetration
- Minimum Energy Performance Standards (MEPS) tightening can lead to 64 GW/118 TWh reduction as compared to BAU in India. (LBNL study 2025)

# Impact of Heat Pumps on electricity demand

**Figure 4.11** ▶ Global heat pump sales and contribution to space heating demand in selected regions in the STEPS, 2020-2035

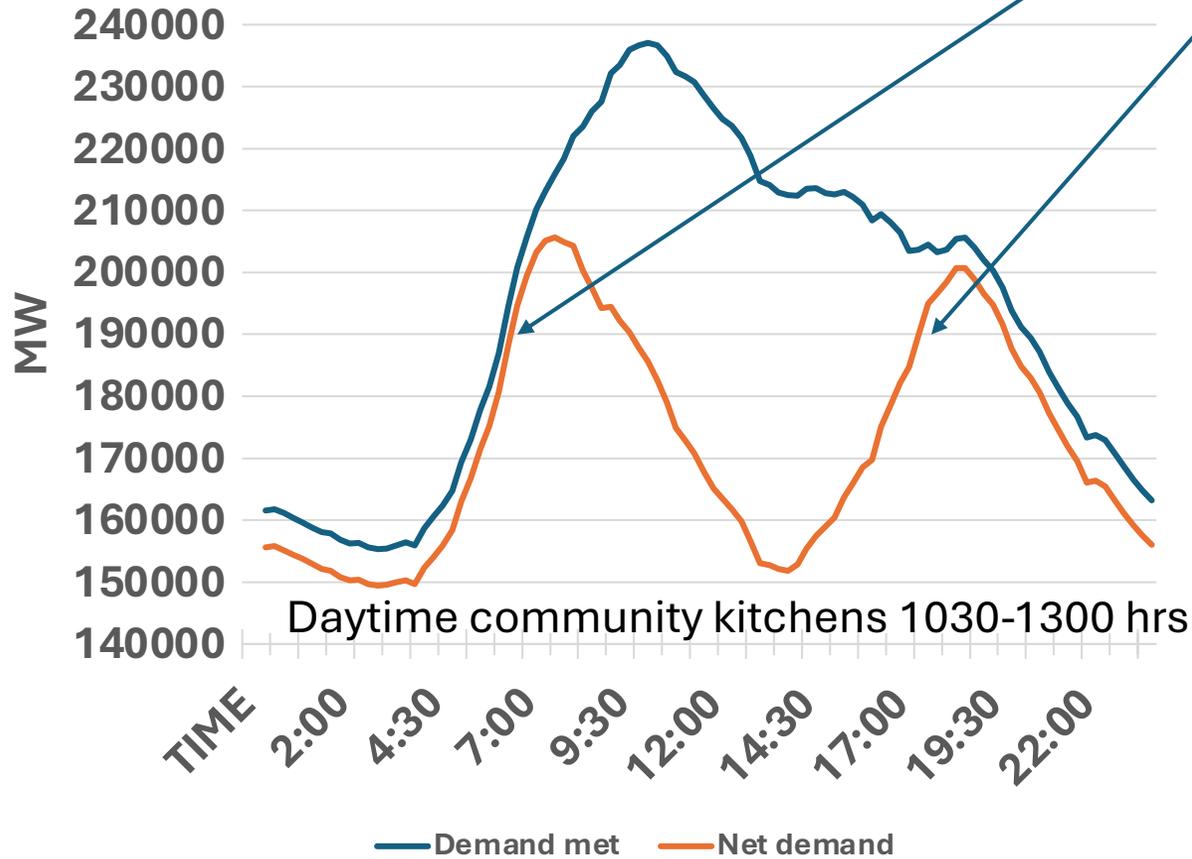


IEA. CC BY 4.0.

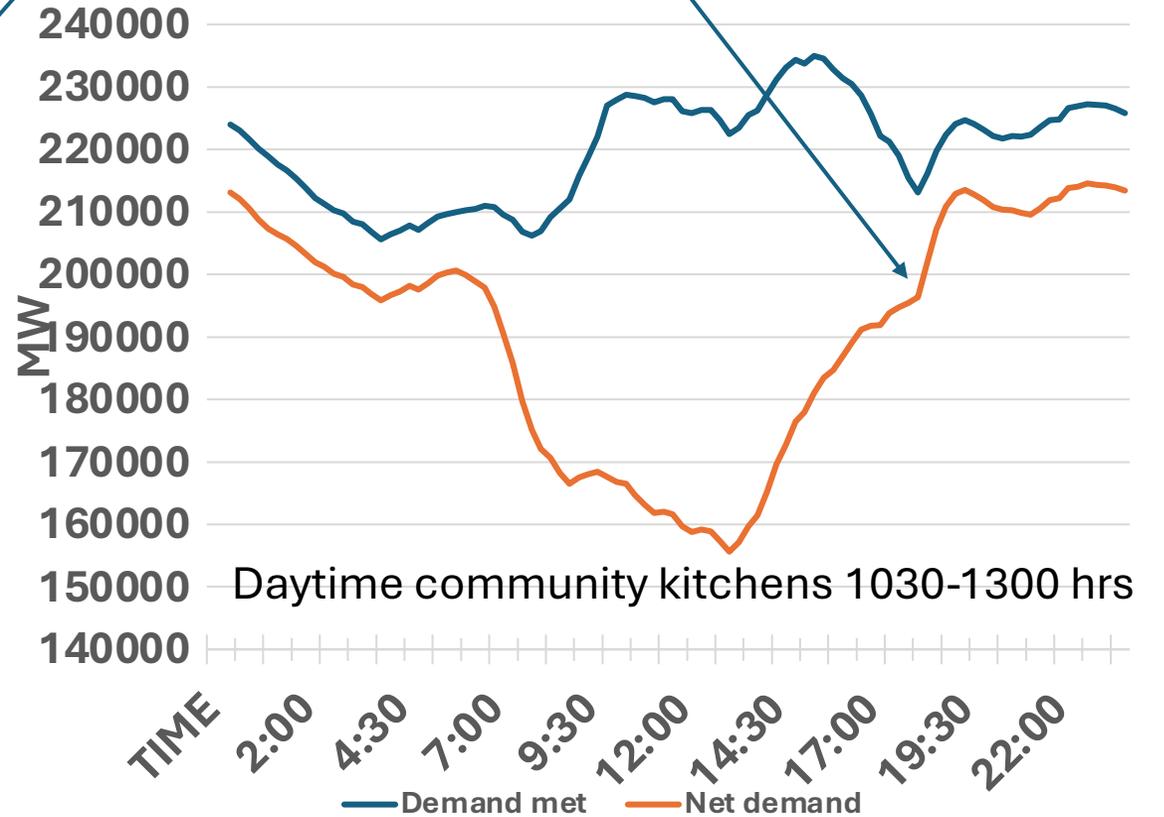
- 40% space heating requirements possible through Heat Pumps by 2035
- 40 BCM natural gas would get substituted by 2035
- Gas price vs electricity price dynamics create some resistance to adoption
- Bhutan, Nepal and Northern India candidates for Heat Pumps

# Impact of Electric Cooking

All India typical 2025 winter load curve



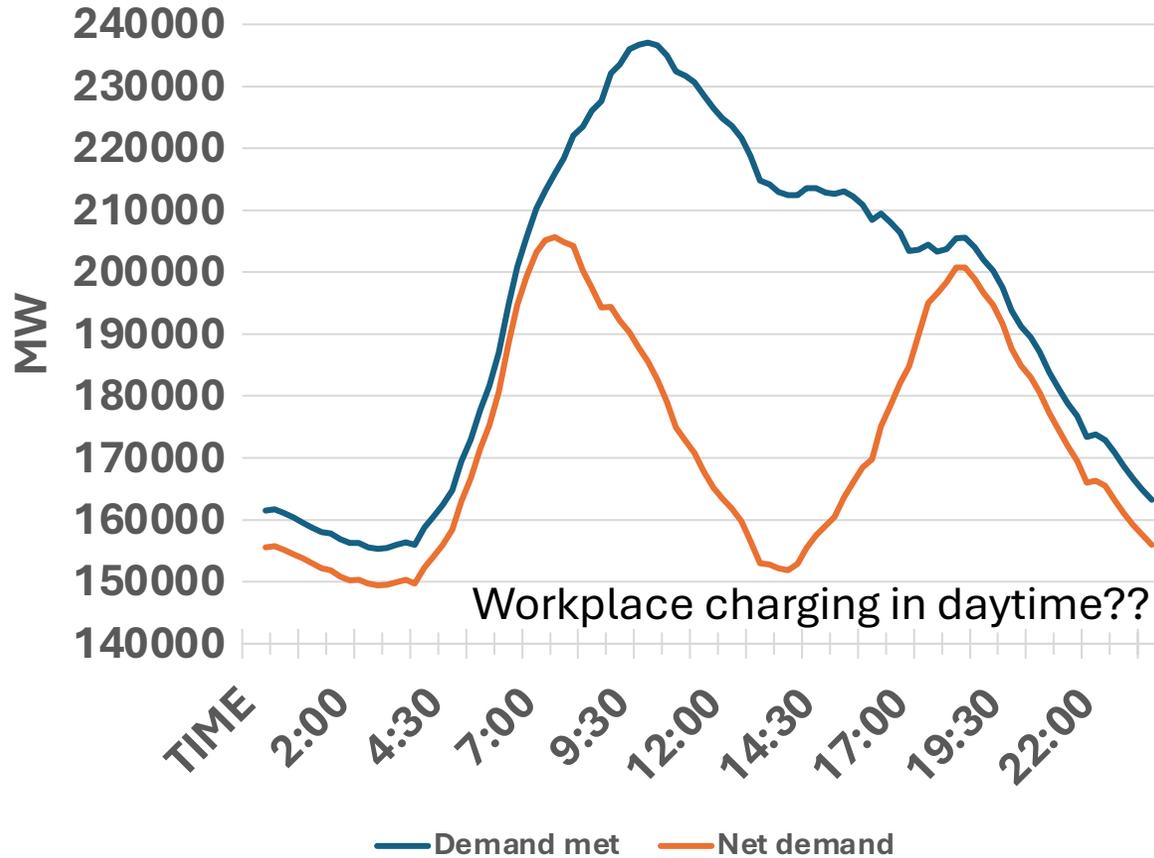
All India typical 2025 summer load curve



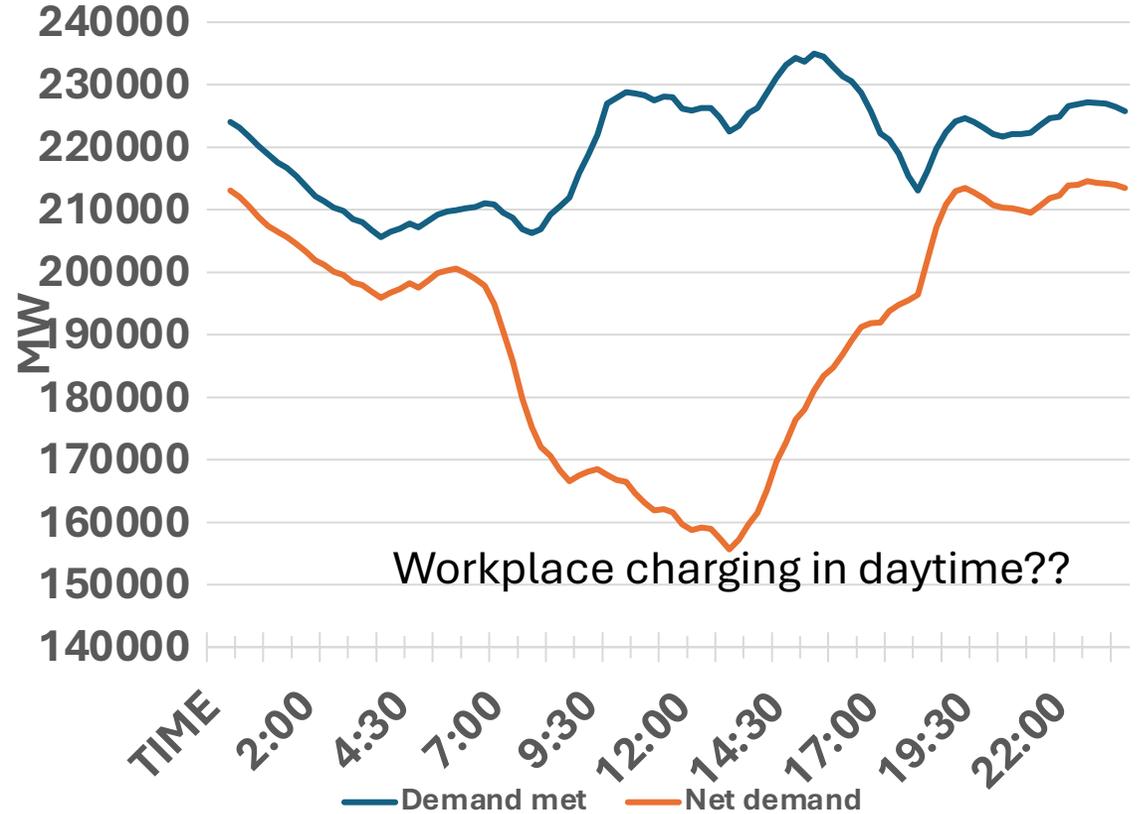
100 million households; 1.5 kW load; 70% simultaneous.....105 GW load.....Distribution system augmentation

# Impact of Electric Vehicles

All India typical 2025 winter load curve



All India typical 2025 summer load curve



Night time. Charging 1900-0300 hours;

no problem during winters.....coal generation increase?  
real stress during summers.....7-8 hours BESS required

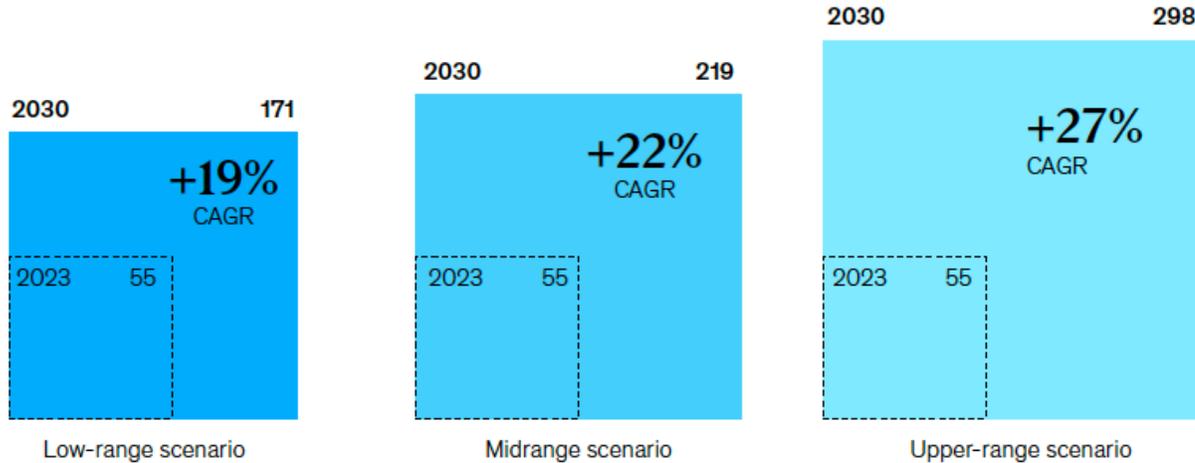
# Impact of Green Hydrogen

- 1 kg of hydrogen through electrolysis  $\sim\sim$  50 kWh electricity required  
1 T production /day  $\sim\sim$  2.1 MW electrolyser at 100% load factor (2.5 MW at 84% load factor)
- Practical case in India  $\sim\sim\sim$ 90,000 MT per annum green hydrogen plant
  - $\sim$ 650 MW round the clock contract provided by 2400 MW RE (wind plus solar) plus 350 MW, 6 hours Battery Energy Storage System (BESS)
  - Anticipated annual load factor of electrolyser.....80-85%
  - Hourly matching of RE generation and electrolyser load
- IEA WEO 2025 for low emission hydrogen for 2050 Net Zero
  - 1 Mt in 2024 to 35 Mt in 2035 to 125 Mt in 2035.  $\sim\sim$ 800-900 GW electrolyzer capacity?
- Inverter Based Large Loads and their interaction with grids, Demand Response

# Impact of Data Centres (DCs).....(1)

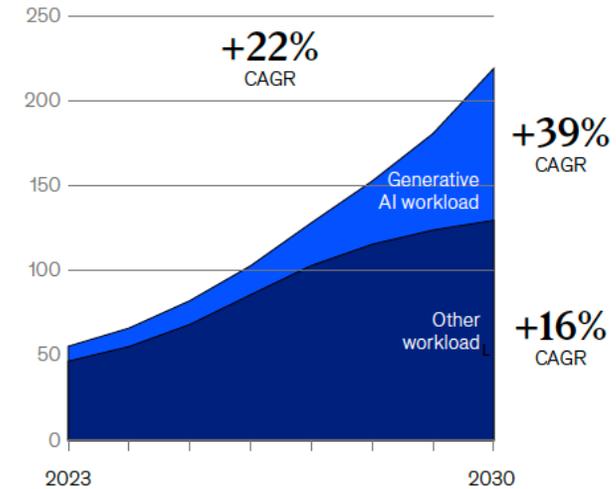
Global demand for data center capacity could more than triple by 2030.

Demand for data center capacity,<sup>1</sup> gigawatts

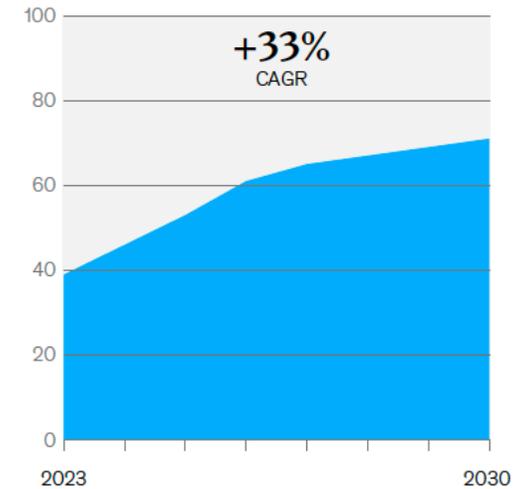


AI is the key driver of growth in demand for data center capacity.

Estimated global data center capacity demand,<sup>1</sup> gigawatts



Demand for advanced-AI capacity,<sup>1</sup> % of total data center capacity demand



Source: McKinsey Oct 2024 paper

- As per IEA WEO 2025; ~950 TWh consumption by data centres in 2030; 82% new DCs in US, China and Europe
- Average rack power densities doubled in 2 years to 17 kW per rack; 30 kW by 2027
  - NVIDIA GB200 chip; rack densities of upto 120 kW required
- Cooling effectiveness; liquid cooling and Power Usage Effectiveness (PUE) of data Centres

# Impact of Data Centres (DCs).....(2)

AI Training Data Center (50 MW)  
Demand Curve

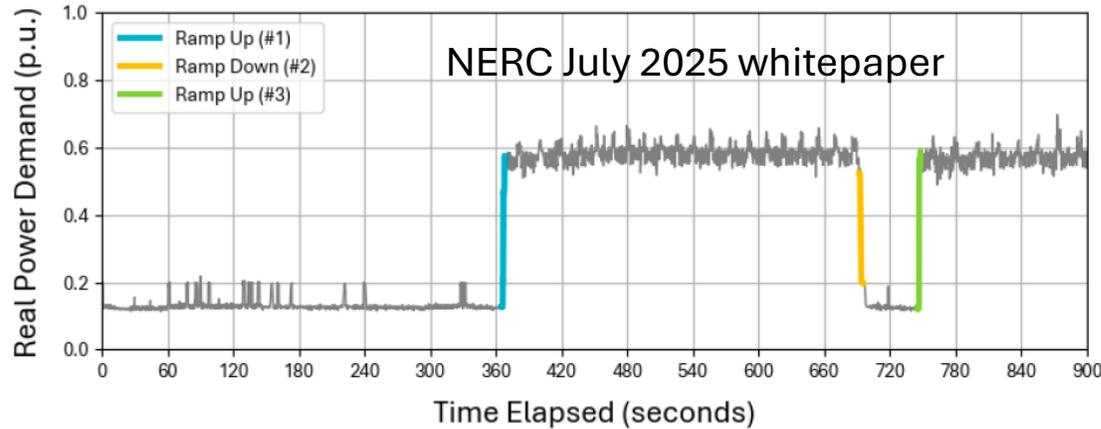
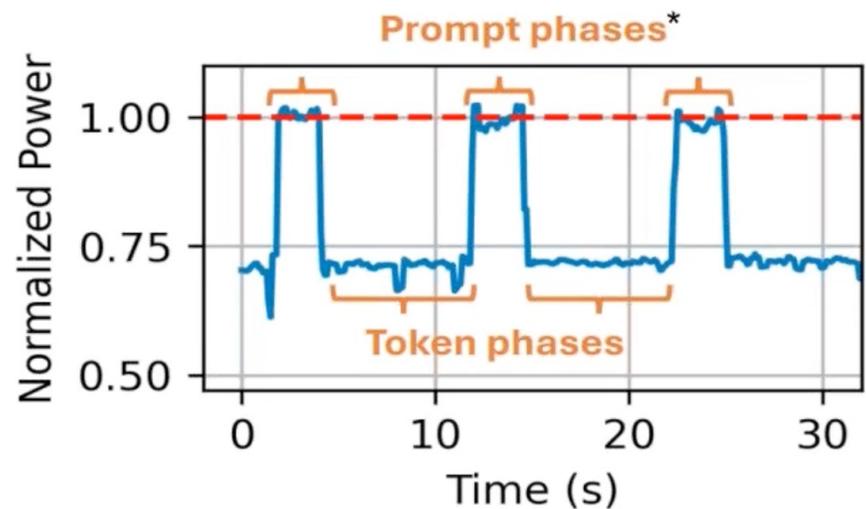
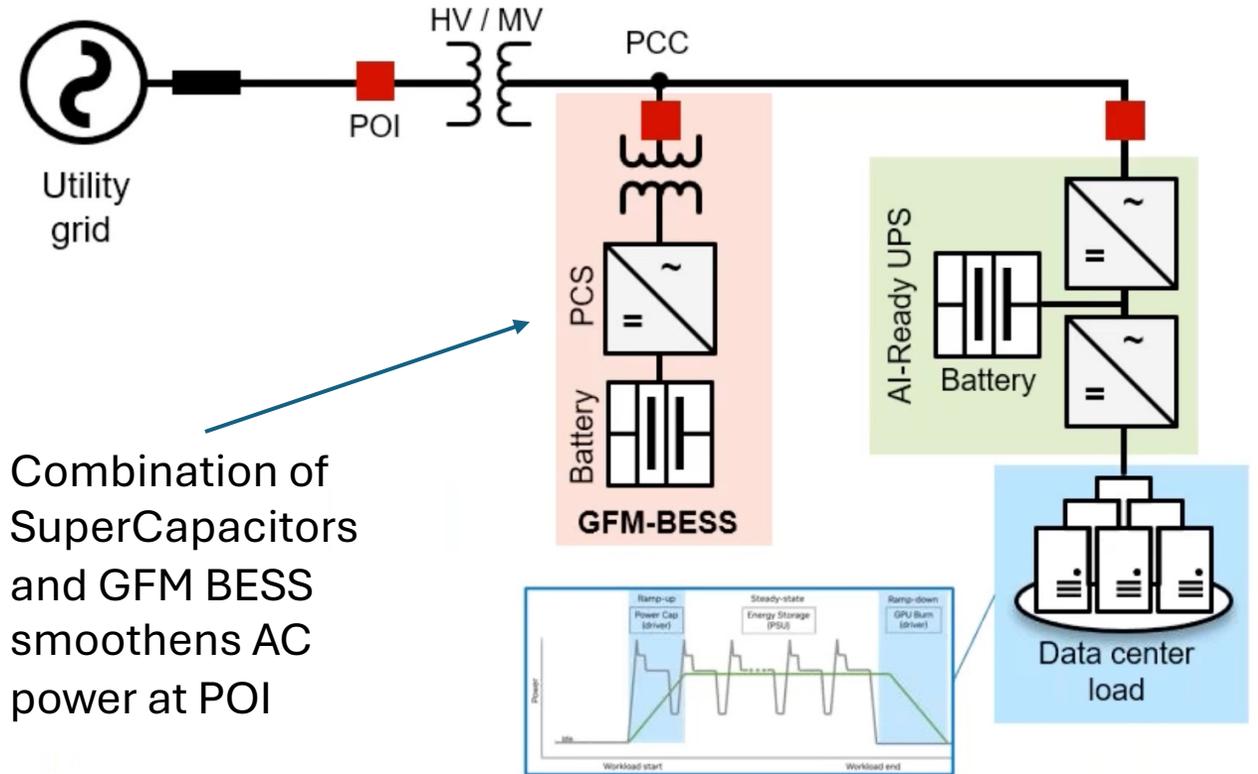


Figure 2.2: An AI Training Data Center Begins a Training Run (EdgeTunePower)



\*Image taken from P. Patel et al. "Characterizing Power Management Opportunities for LLMs in the Cloud", Association for Computing Machinery, April 2024.

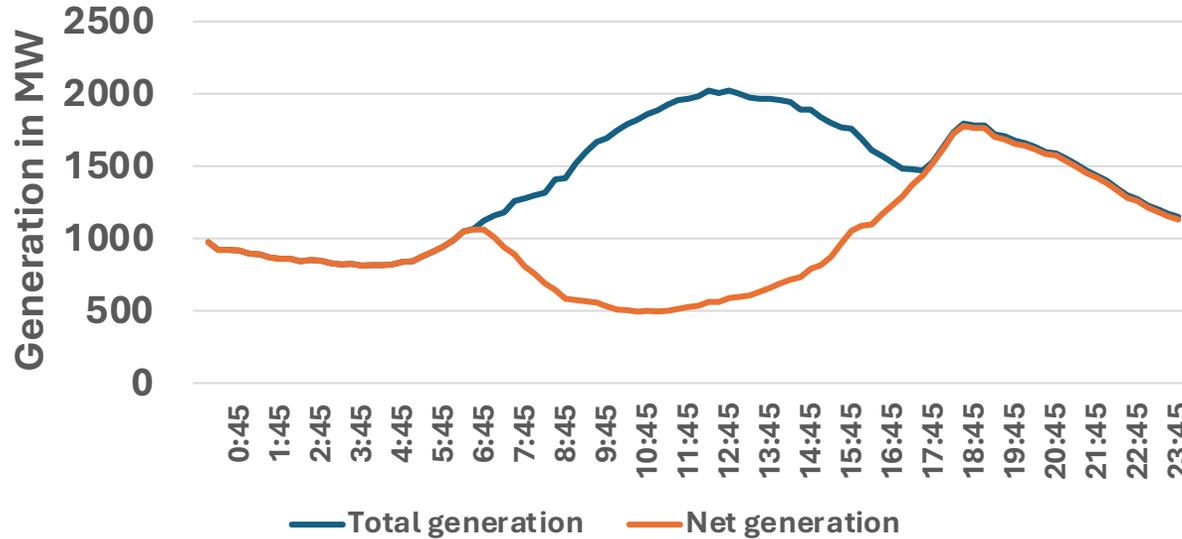


Combination of SuperCapacitors and GFM BESS smoothens AC power at POI

Source: Quanta Technologies webinar

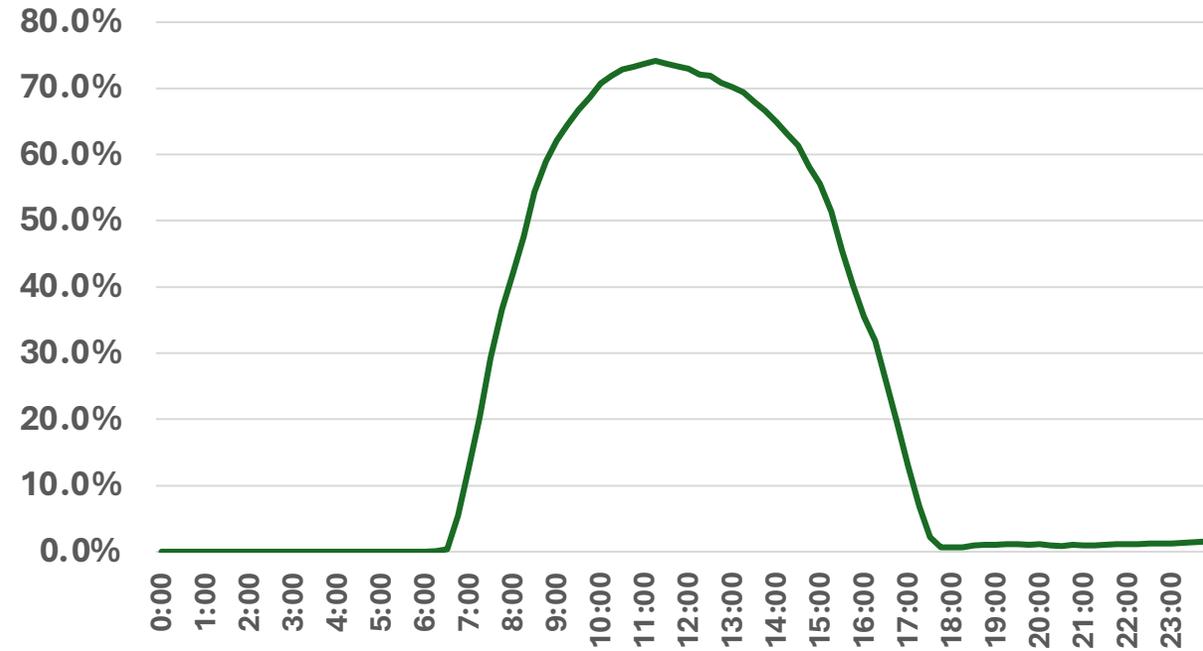
# Sunny Sunday on an island

Sri Lanka generation profile 30th Nov 2025  
(Sunday)



Total generation includes estimated rooftop solar  
 Net Generation is Total generation less wind and solar  
 Source: Public Utilities Commission of Sri Lanka

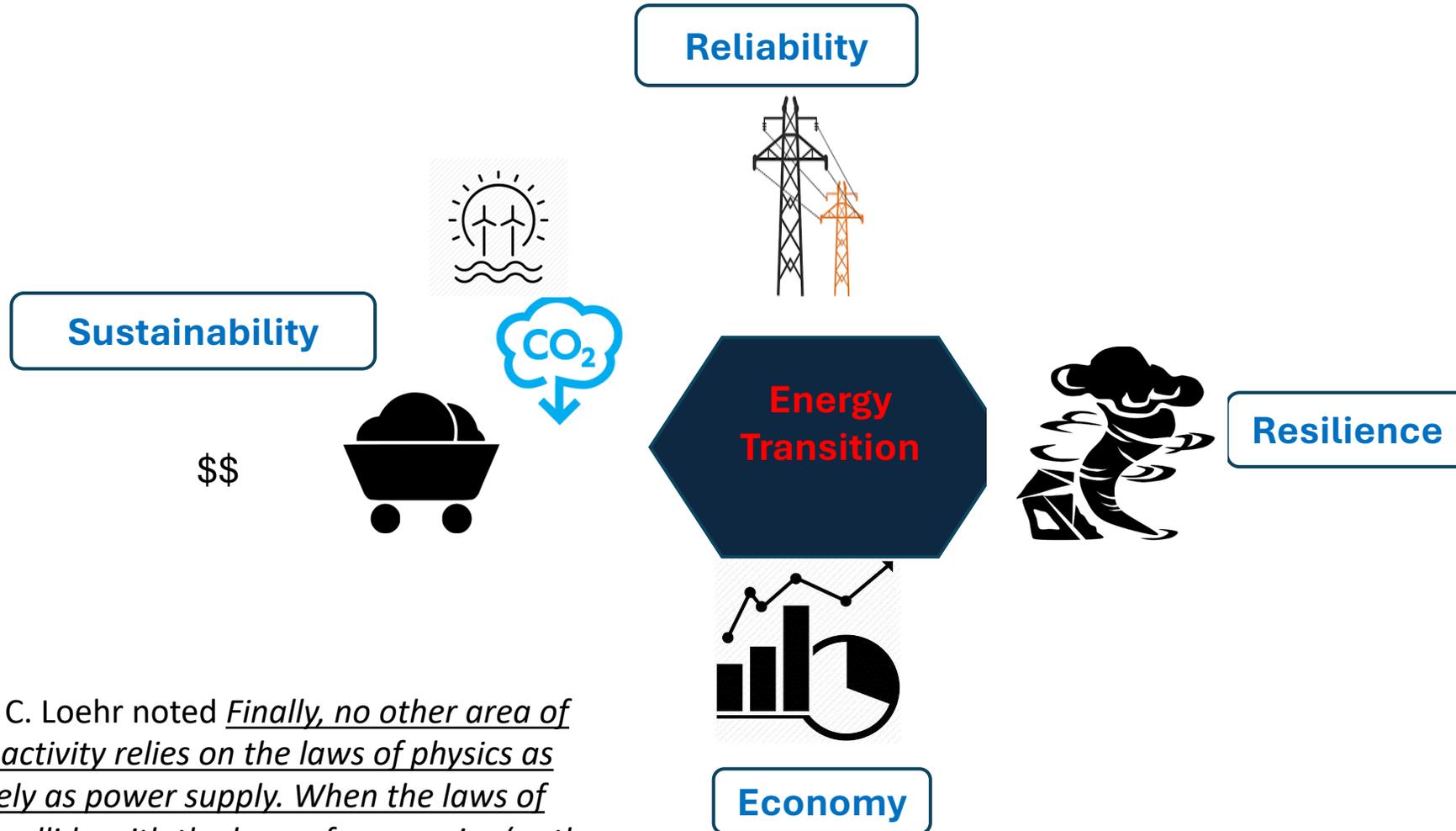
Penetration of Variable RE on 30th Nov 2025



Includes rooftop solar

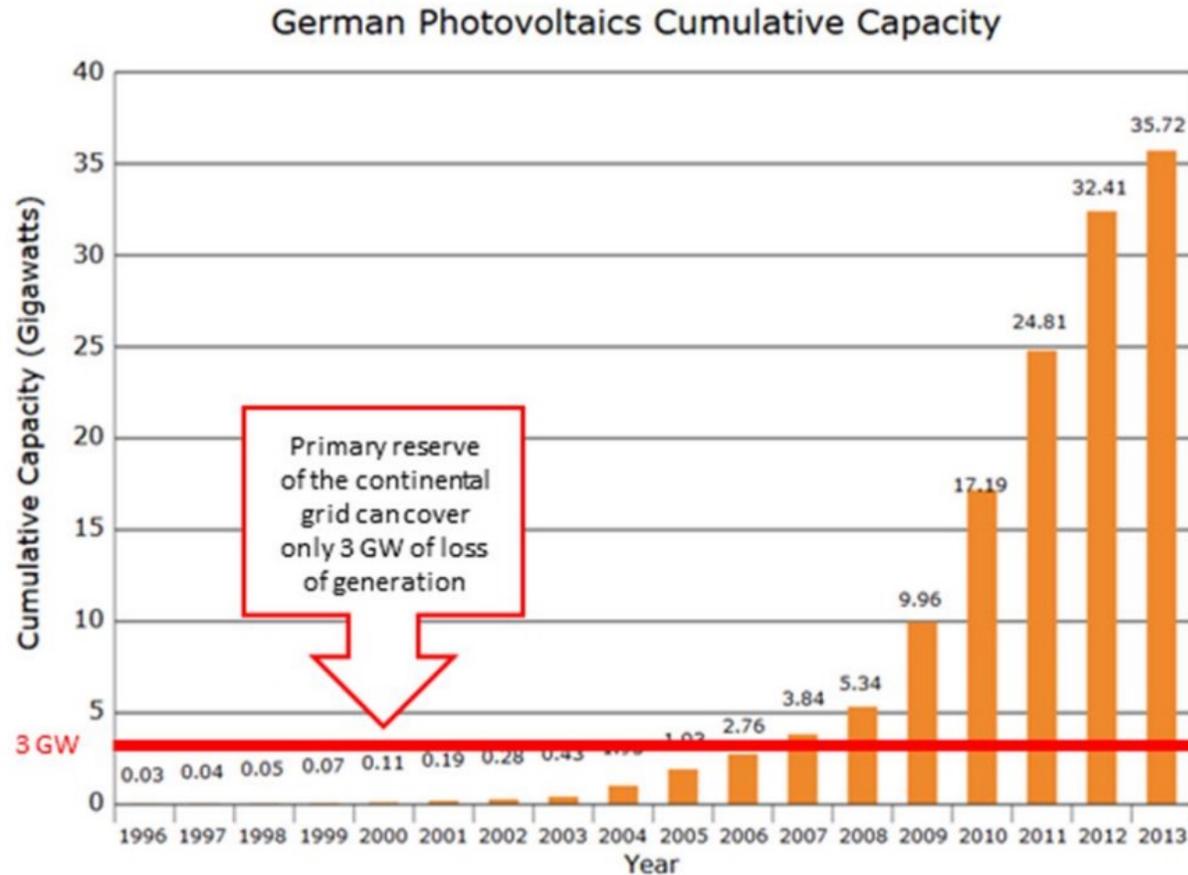
- System becomes vulnerable in case of any contingency
- System strength, Inertia, Frequency Control, Voltage control the key
- Adoption of relevant standards like IEEE 1547:2018

# Energy Transition and Reliability of Grids: The Conundrum!



George C. Loehr noted Finally, no other area of human activity relies on the laws of physics as intimately as power supply. When the laws of physics collide with the laws of economics (or the laws of society), physics wins, always.

# 50.2 Hz problem in Germany



ENTSOE April 2012 report red flagged this issue

Extensive retrofits in Germany solar PV

PV capacity in Germany, reaching 43 % of peak load in 2014 and exceeding primary reserve capabilities from 2007 onwards.

Source: [https://regridintegrationindia.org/wp-content/uploads/sites/3/2017/09/10A\\_1\\_GIZ17\\_xxx\\_paper\\_Ackermann\\_170808.pdf](https://regridintegrationindia.org/wp-content/uploads/sites/3/2017/09/10A_1_GIZ17_xxx_paper_Ackermann_170808.pdf)

# Power outage on 9th Aug 2019 (16:52 hours) in UK

## Major Highlights

1. 892 MW (approximately 4% of national demand )of loads lost in distribution networks as a result of UFLS, affecting 1.15 million customers. 1990 MW of cumulative generation loss connected to TSO.
2. Event started with lightning strike on a 400 kV line causing a fault which was cleared in 80 msec
3. **150 MW of distributed generation tripped on vector shift protection**
4. **A windfarm became unstable and got deloaded by approx 737 MW, a steam generating unit of 244 MW got tripped due to discrepancy in speed sensor**
5. Distributed generation tripped due to loss of mains protection/or embedded generation as a part of load in UFLS
6. System frequency fell below 48.8 Hz activating Stage-1 load disconnection.
7. **Significant disruption to the rail network (not due to power supply), with 371 services cancelled and 220 part cancelled**



## Key Findings:

- Inadequate performance of fast frequency, primary and secondary control
- Wind turbine controllers behaved incorrectly following a fault
- Steam turbine tripped due to discrepancy in speed sensor
- Non compliance of Grid code requirements by Distributed generation
- Insufficient demand disconnection in UFLS

## Spain/Portugal blackout at 12:33 hrs. on 28<sup>th</sup> April 2025

- Oscillations in the system and low voltages in Spain
  - Transmission Lines were reconnected
  - Solar curtailed in Spain to reduce export to France
  - Spain to France HVDC mode changed to fixed power
- Oscillation mitigation steps led to high voltages in Spain
- Further tripping of solar generation on high voltage
- Spain started importing heavily from France
- Unstable conditions and the lines to France tripped
- Islanding and collapse of Spain/Portugal system

# Building Blocks for Resilient and Reliable Grid Operations



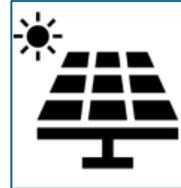
**Regulations and Standards** - future ready with regular updates for the future grid and compliance monitoring



**Resource Adequacy and Flexibility** – new avenues for ensuring adequacy and flexibility, harnessing existing flexibility etc.



**Forecasting and Scheduling, Reserves for frequency control, Voltage Control, Visualization and Situational Awareness**



**Sustainable ecosystem for equipment testing** – development of lab / field testing facilities, technical consulting, logistics etc.

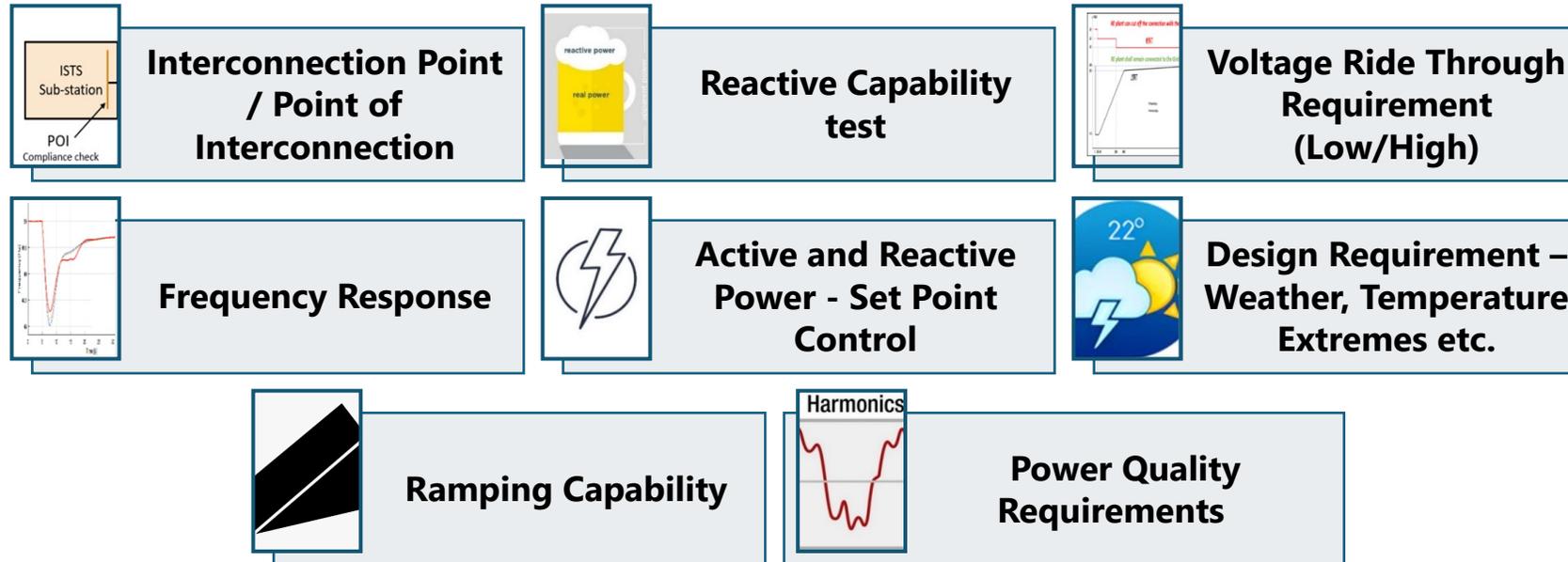


**Robust Transmission Planning** – factoring in energy storage, reactive power planning, resiliency aspects, new technologies etc.



**Big Data Analytics, AI/ML deployment and cybersecurity**

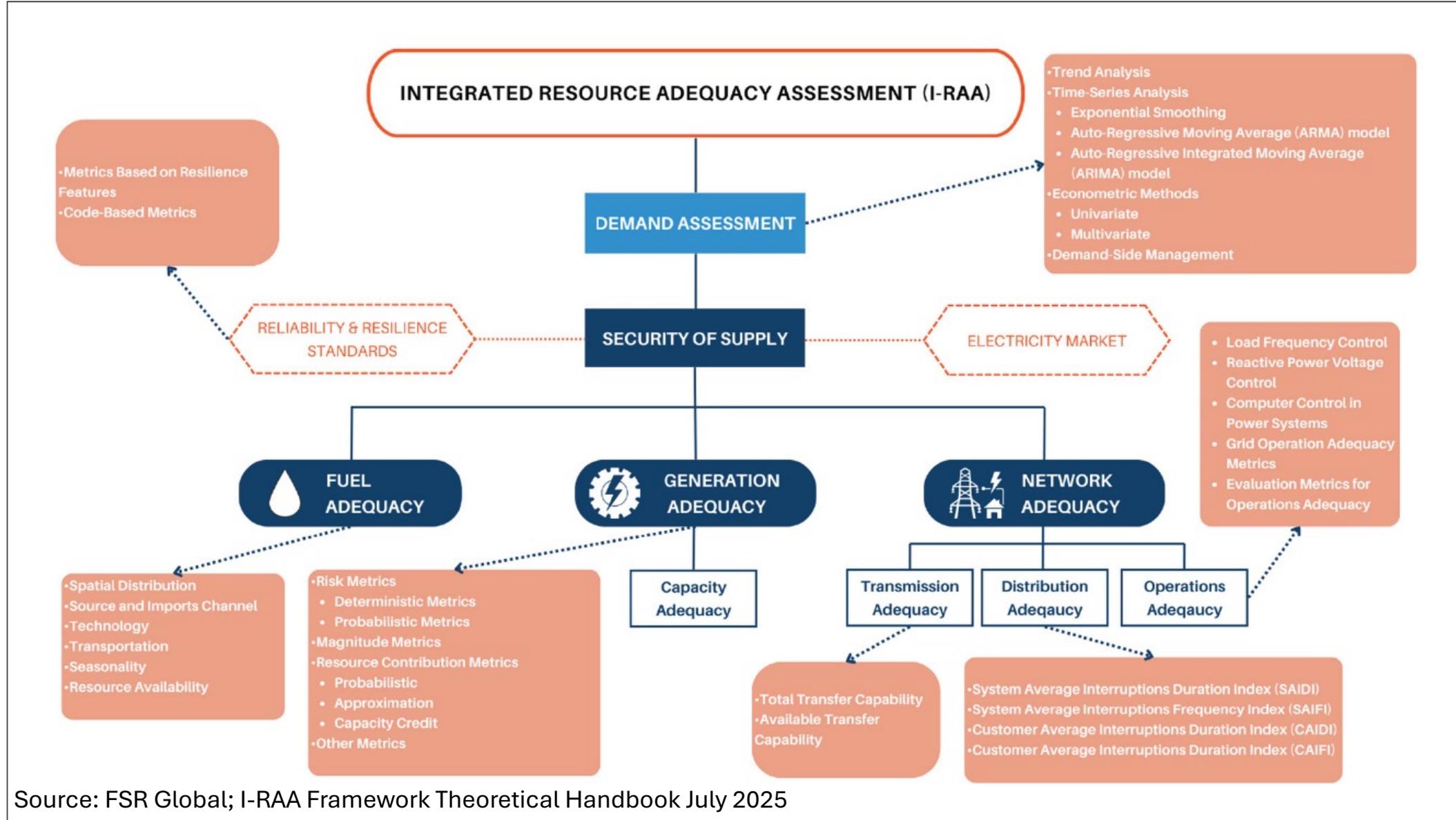
# Regulations and Standards



Standards and regulations to keep pace with the technological advancements through regular updates

- ✓ Applicability to Battery Energy Storage Systems (BESS)
- ✓ New Inverter Based Resources (IBRs) Large loads - GH2 Loads, EV Charging Stations, Data Centres etc. Demand Response
- ✓ IBR Tech – Grid Forming, Hybrid HVDCs etc.
- ✓ Behaviour of Distributed Energy Resources (DERs) and visibility at Control Centres
- ✓ Protective Relay Settings and Co-ordination

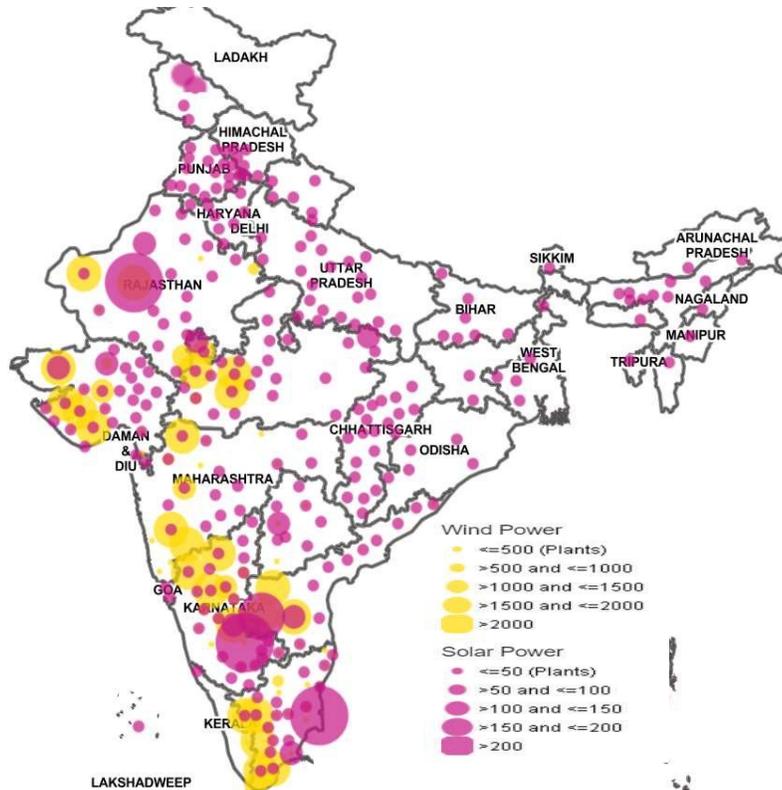
# Resource Adequacy



- All time horizons
- High Demand and Low RE
- Low Demand and High RE

Source: FSR Global; I-RAA Framework Theoretical Handbook July 2025

# Robust Transmission Planning



Proactive planning to keep pace with generation capacity addition (8670 hours)

Factor in energy storage, new technologies to optimize transmission planning

Address Reactive Power and System Strength Concerns

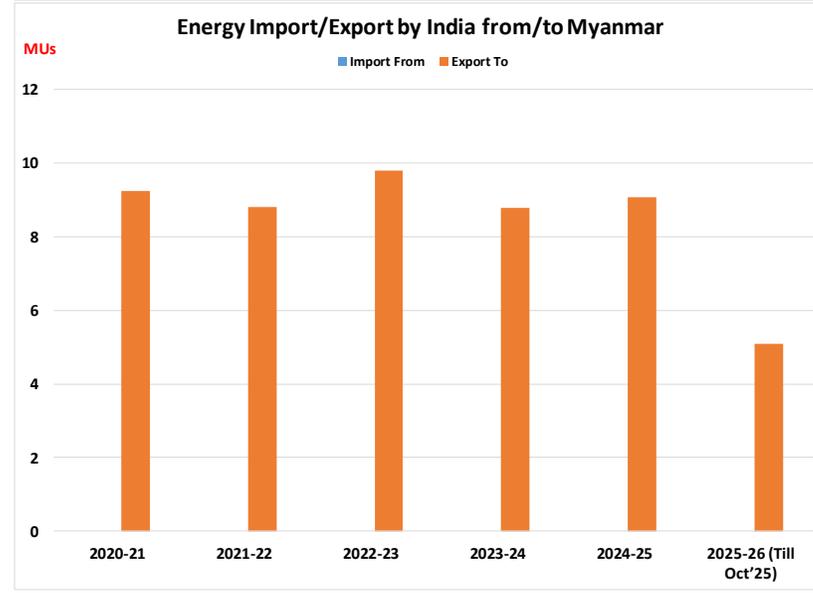
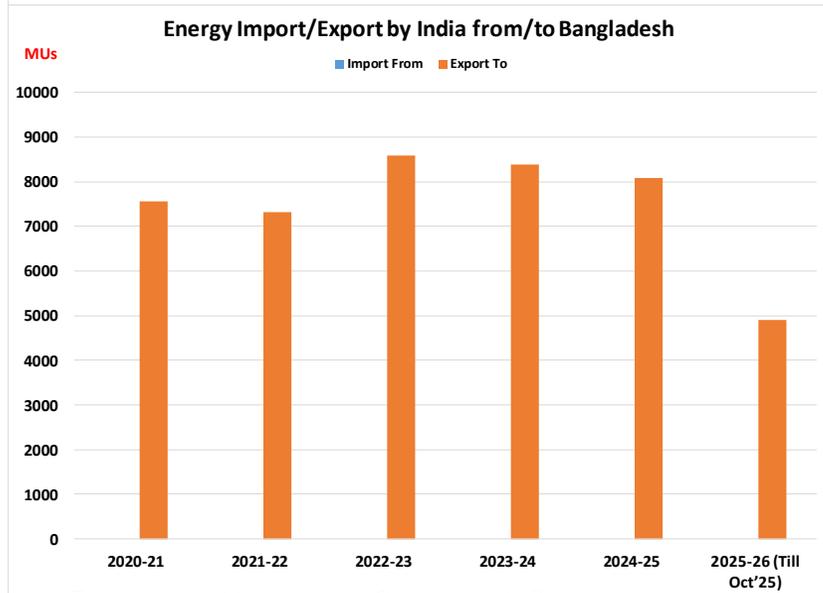
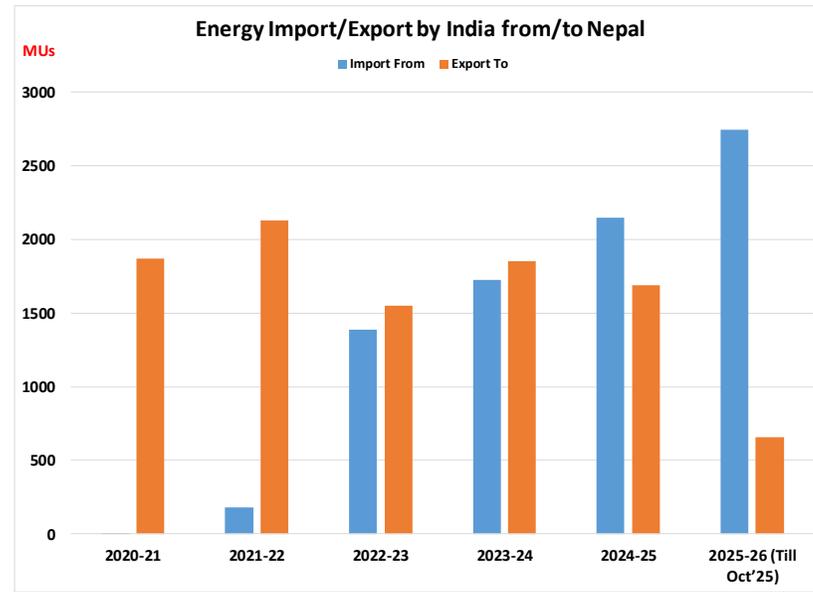
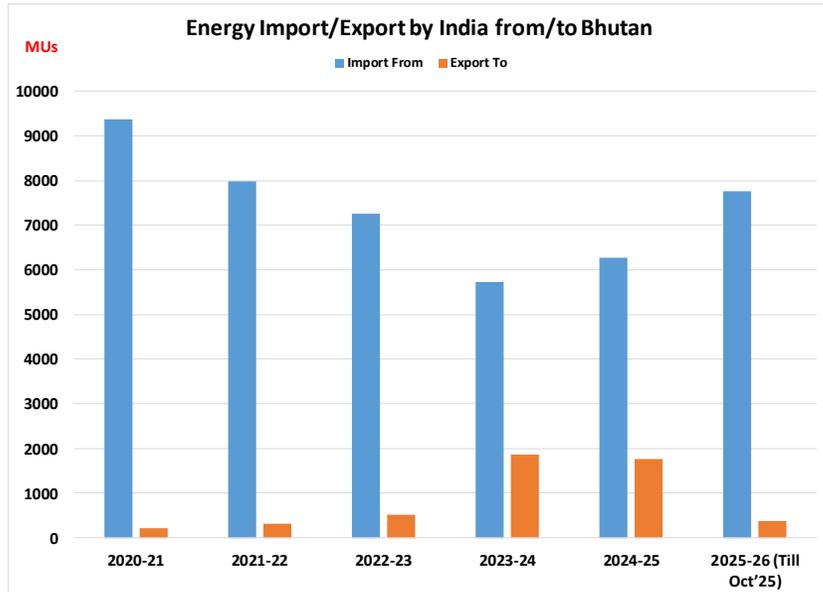
Disaster Management and Resilience

System Integrity Protection Scheme

Communication, cyber security etc.

- ✓ Concentrated RE zones
- ✓ Large RE pooling stations at EHV level for power evacuation; Remotely located, far from load centres
- ✓ Long UHV/EHV lines to evacuate bulk intermittent/variable power from IBR to the grid
- ✓ Energy storage, synchronous condensers, STATCOMs, Grid Forming Inverters (GFM) urgently in place
- ✓ System Integrity Protection Schemes (SIPS) for large contingencies much beyond N-1 or N-2

# Cross Border exchanges



Excludes direct transfer from Godda India to Bangladesh

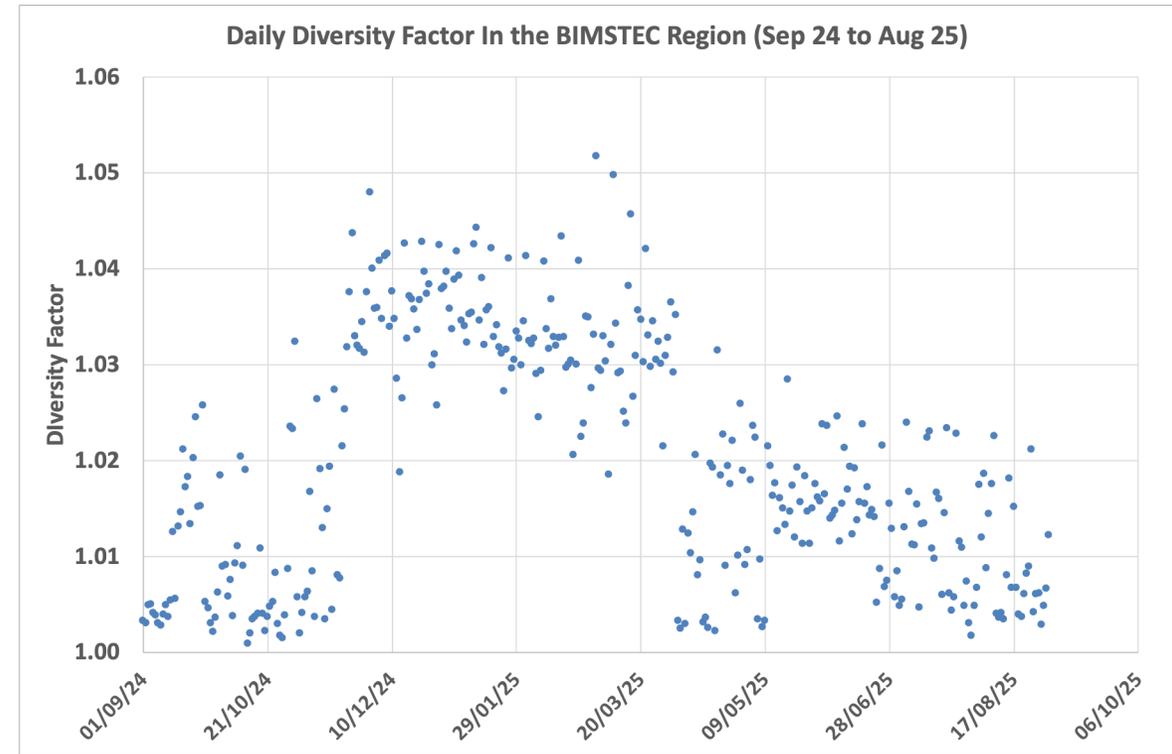
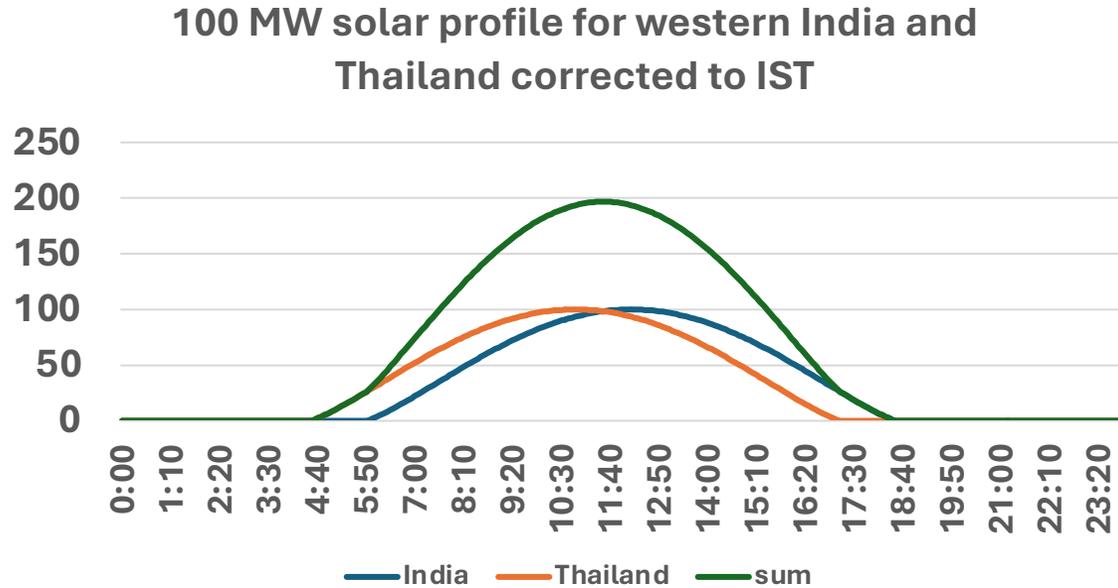
Participation in Indian energy markets –including power exchanges

Harnessing diversity in load and generation patterns

Help in balancing renewable-rich systems

Cooperation during exigencies

# BIMSTEC potential for interconnections



Courtesy: BIMSTEC Energy Centre

- 1.04-1.05 diversity factor during winter months
- 1.5 hour time difference between Thailand and India; solar generation smoothing if interconnected

# OSOWOG: Proposed Electricity Grids Interconnection



# Grid Resilience



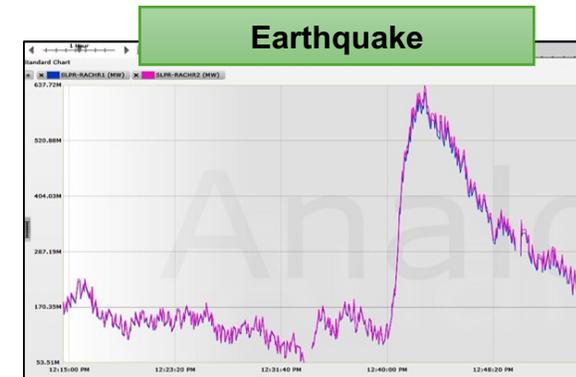
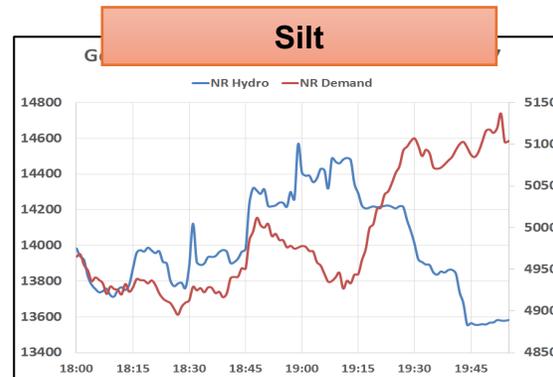
## Floods

- Gujarat (2017)
- Kerala (2019)
- Assam(2020)

## Cyclones

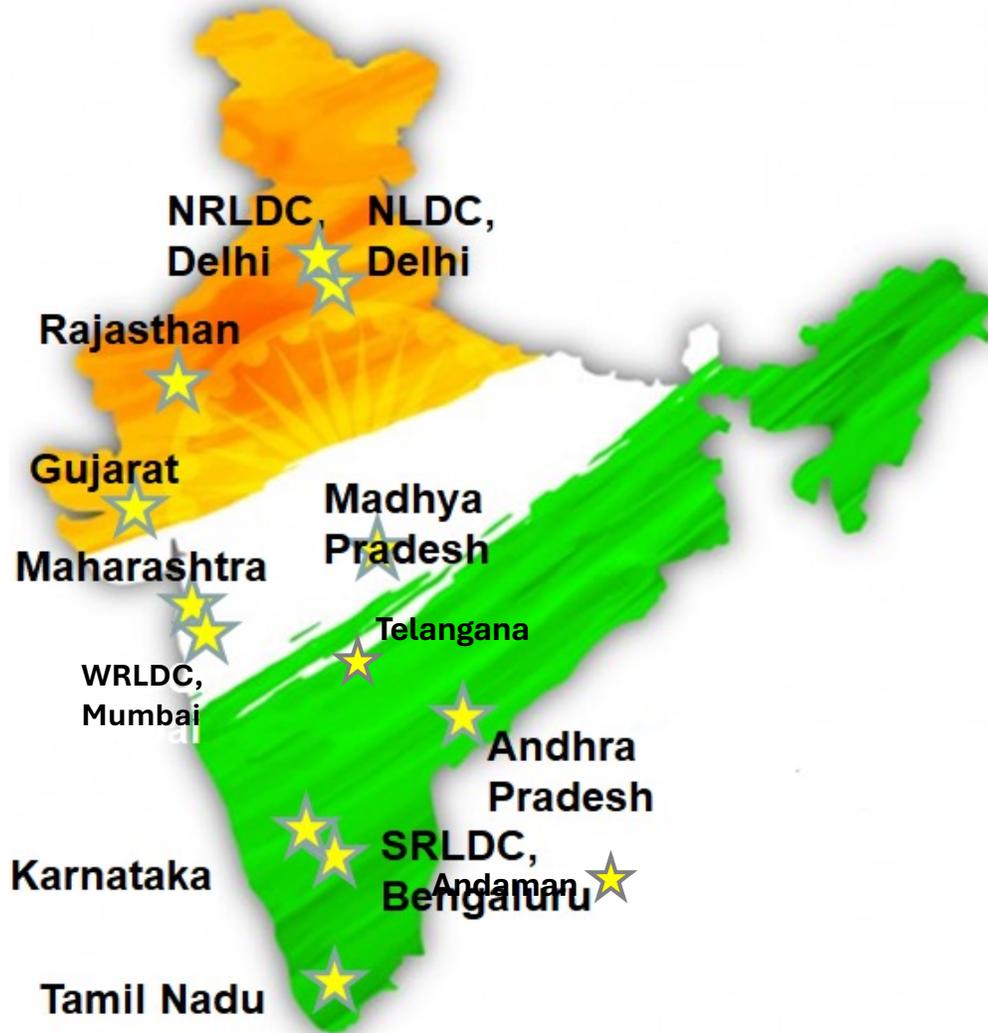
- Phailin (2013)
- Hud-Hud (2014)
- Vardah (2016)
- Titli (2018)
- Bulbul (2019)
- Amphan (2020)
- Nivar (2020)
- Biparjoy (2023)
- Dana (2024)
- Montha (2025)

## Natural Disasters in Recent History which impacted Electricity Grid in India



Resilience: means the ability to withstand and reduce the magnitude or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, or rapidly recover from such an event; and incorporate the learnings quickly

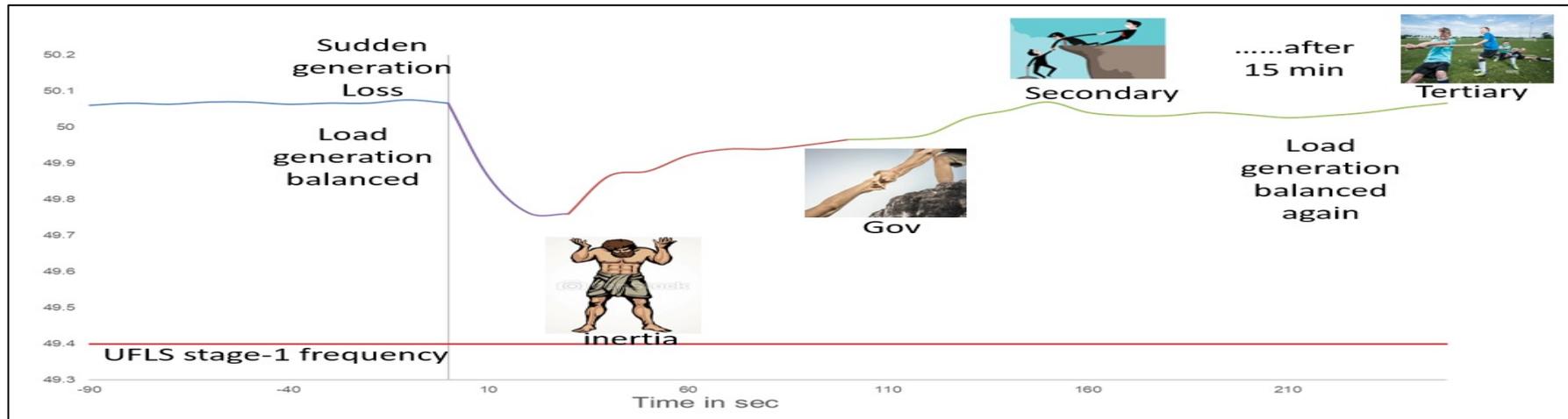
# VRE forecasting through Renewable Energy Management Centres (REMCs)



NCMRWF: National Centre for Medium Range Weather Forecasting

- 13 Nos. REMCs (State/Regional/National) Co-located with Load Despatch Centres
- Forecasting & Scheduling
- Forecast accuracy improvement through
  - Improving Numerical Weather Products (NWP) through NCMRWF in terms of faster updates (every 4-6 hours) and higher spatial resolution (4 x 4 kms square)
  - Improving weather model accuracy of NCMRWF through field data from RE plants
  - Cloud cover and wind gust forecast improvement
- Project with IITB; use of AI/ML

# System Balancing Continuum in India



Reserve	Start of activation	Full Availability/ deployment	Ability to sustain the full deployment	Providers
<b>Primary Response (Automatic)</b>	Instantaneous after frequency crosses dead band	Within 45 sec	5 min	All generators, Energy Storage
<b>Secondary Reserve Ancillary Service (Automatic)</b>	Within 30 sec	Within 15 Min	30 min or till replaced by Tertiary Reserves	All generators, Energy Storage, DR
<b>Tertiary Reserve Ancillary Service (Manual)</b>	Within 15 Min		60 min	All generators, Energy Storage, DR

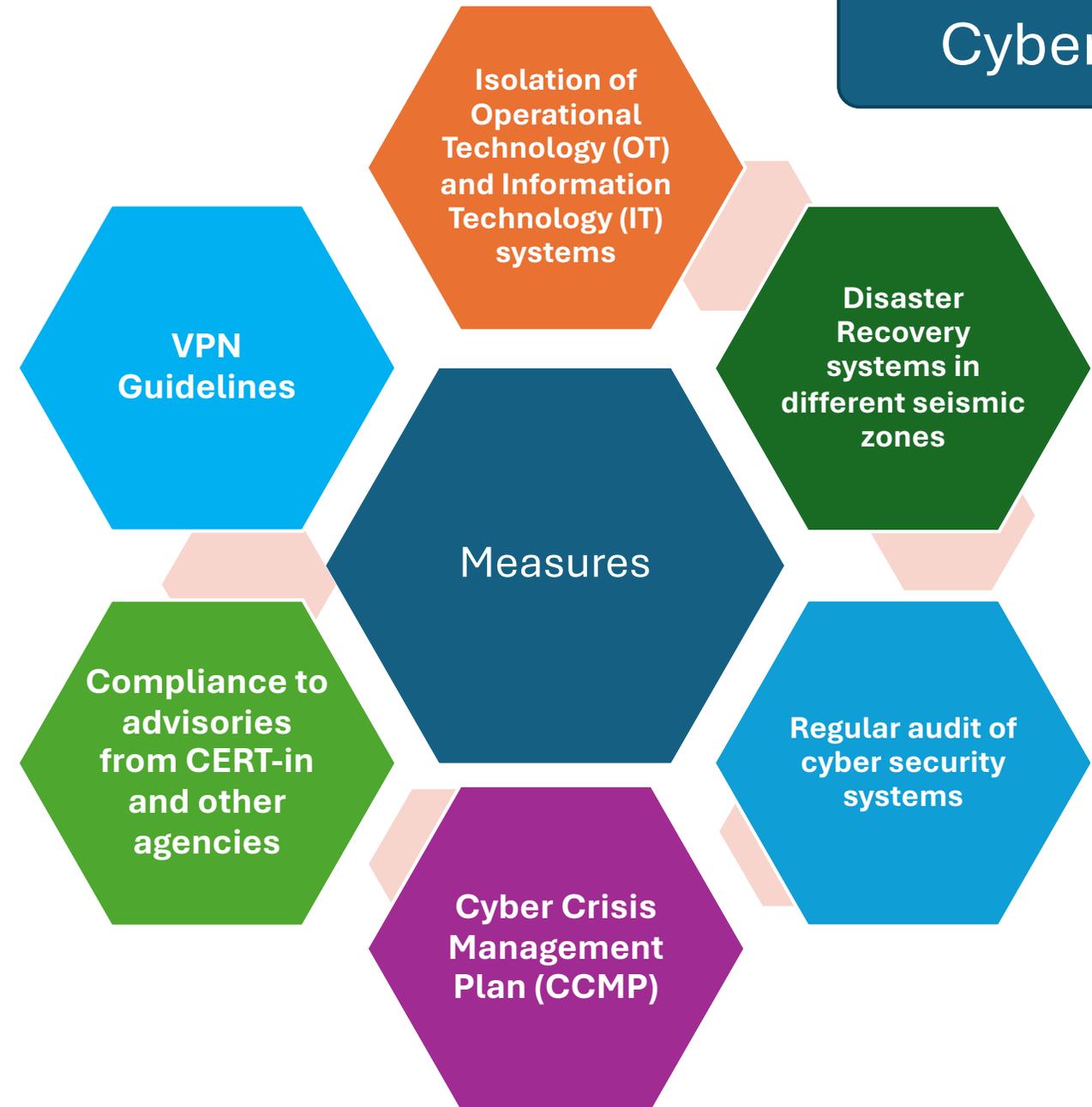
- Single largest contingency that the grid has to handle is important
- 4500 MW Ultra Mega Power Plant (UMPP) or cluster of Renewable Energy (RE) stations?

# Visualization and Situational Awareness in Control Centres

- Energy Management Systems (EMS), Synchrophasors
  - Many off-line tools and applications used by operators like Load and RE forecasting, weather portals, scheduling, Ancillary Services activation, Network applications like Dynamic Security Assessment (DSA) and so on
  - Huge Information Overload for the operators.
- How can AI/ML tools help the system operators ? Possible areas other than Load/RE forecasting\*
  - Alarm processing during events, summarizing and suggested actions
  - EMS and Planning Model validations
  - Anomaly detection
  - System Operator training
  - Report generation and Procedure Drafting (Large Language Models LLMs do it well)

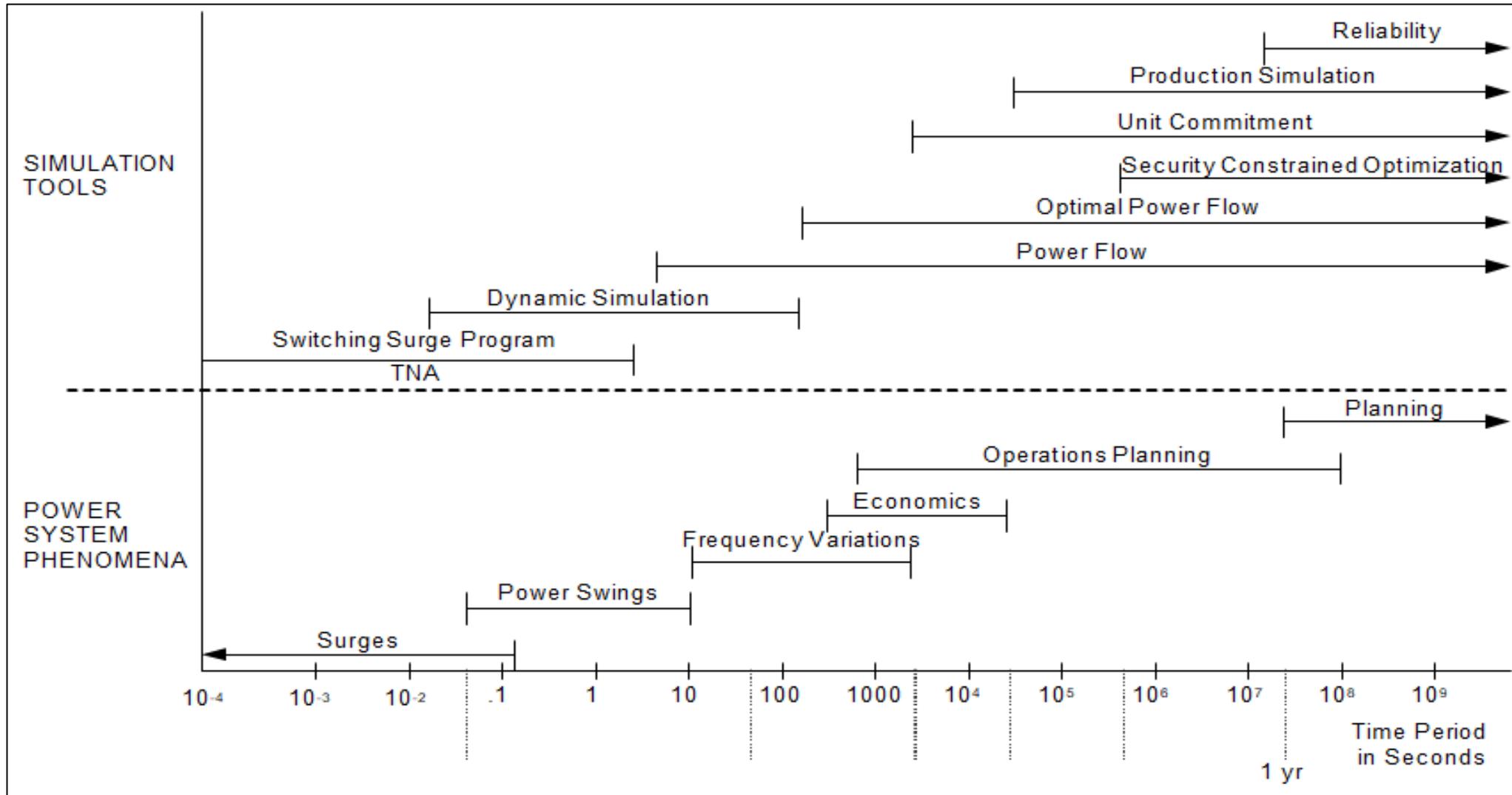
**\*NERC White Paper on AI and ML in Real Time System Operation; Nov 2024**

# Cyber Security Measures



- Need for a full fledged Security Operations Centre (SOC) with staffing
- Specialized discipline
- Legacy SCADA/EMS should be regularly updated with security patches besides upgradation before End of Life
- Vulnerabilities also arise from wind, solar and Battery Energy Storage Systems (BESS) which provide VPN access too for troubleshooting
- Remote access to transmission infrastructure also a vulnerability
- Pre-paid Smart Meters??

# Capacity Building in Modelling and Simulation



Developing inhouse capabilities in all the above areas important

# Electricity Markets to complement reliability of grids

- **Capacity Markets**
  - Ensuring Resource Adequacy in all time horizons
  - Adequate new build out of flexible resources
- **Energy Markets**
  - Ensuring competition and fair prices at the wholesale level
  - Social Welfare Maximization Or Security Constrained Economic Despatch (SCED)
- **Ancillary Services Markets**
  - Frequency Control (Primary, secondary and tertiary); Inertia??
  - Demand Response from bulk loads and through aggregators
- **Regulated prices for Voltage Control Ancillary Services (VCAS) and mandates in Grid Code for black start services**
- **Renewable Energy Certificates, EScerts and Carbon Markets**

# Prof Janusz Bialek Quotes

- Prof Janusz Bialek in his Nov 2014 posting on PowerGlobe

*"Generally, it is worth noting the obvious that blackouts happen even when (N-1) contingency rule is obeyed but more than one element fails. However N is quite general as power system is a complicated large-scale cyber-physical system so N contains not only power equipment failures (which are relatively easy to understand and deal with) but also people, communication, markets, other infrastructures (e.g. gas), weather and anything else that influences power system operation. Analysing those dependencies is fascinating and requires an interdisciplinary approach combining efforts of engineers, mathematicians, physicists, computer scientists, social scientists and economists. Concentrating only on power engineering is so much last-century..."*

- *From 'known unknowns' to 'unknown unknowns'.....Jan 2020*

# Discussions!

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