Energy Transition: Challenges to Grid Operation

by

S R Narasimhan

FIE India, Senior Member IEEE, Distinguished Member CIGRE

Former Chairman & Managing Director, Grid-India

6th Feb 2026

IIT Kanpur Outreach Centre, Noida

Outline

- Energy Transition a multi-dimensional issue
  - Human Development Index (HDI)
  - Sustainable Development Goals (SDGs) 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

Human Development Index (HDI) published by UNDP

- Dimensions
  - Life Expectancy at Birth
    - 20-85 years for normalization in the range 0-1
  - Education (average of)
    - Expected years of schooling (0-18 years for normalization)
    - Mean years of schooling (0-15 years for normalization)
  - Standard of living
    - Gross National Income per capita ($$ Purchasing Power Parity or PPP)
    - Natural logarithm of 100-75,000 USD used for normalization
- HDI is Geometric Mean (GM) of above three indices

Very high human development	0.800 and above
High human development	0.700–0.799
Medium human development	0.550–0.699
Low human development	Below 0.550

As per Human Development Report 2025

- Sri Lanka 0.776 (Rank 89)
- Bhutan. 0.698 (Rank 125)
- Bangladesh 0.685 (Rank 130)
- India 0.685 (Rank 130)
- Nepal 0.622 (Rank 145)

https://hdr.undp.org/system/files/documents/global-report-document/hdr2025reporten.pdf

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

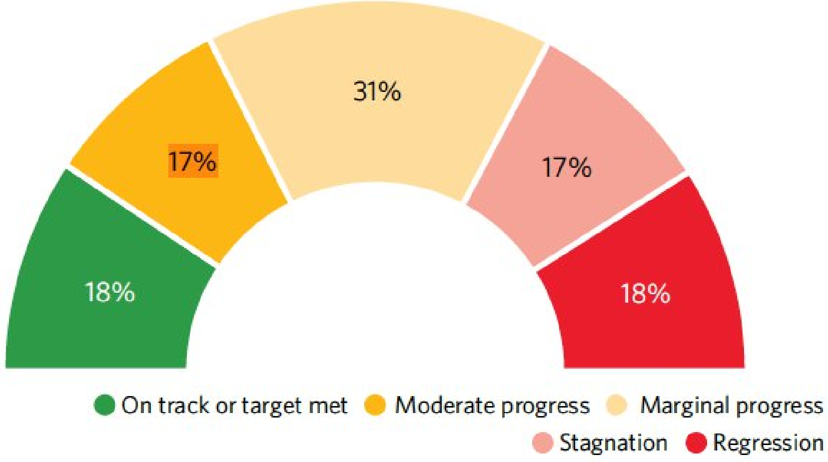
14 LIFE BELOW WATER

15 LIFE ON LAND

16 PEACE, JUSTICE AND STRONG INSTITUTIONS

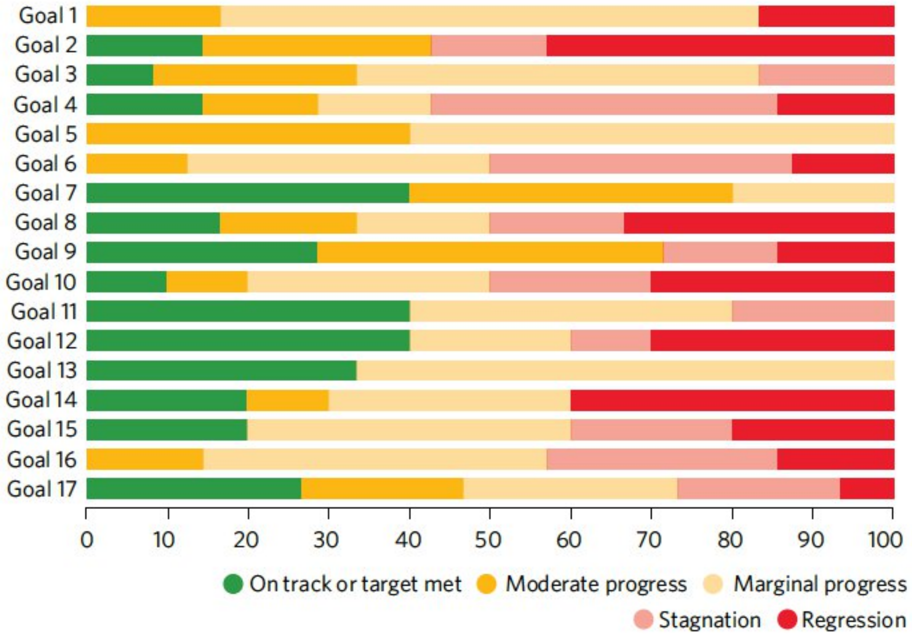
17 PARTNERSHIPS FOR THE GOALS

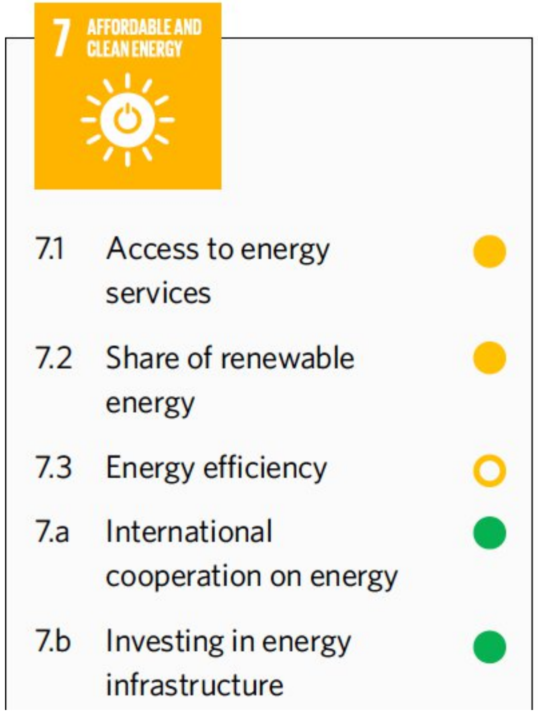
Overall progress across targets based on 2015-2025 global aggregate data



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)





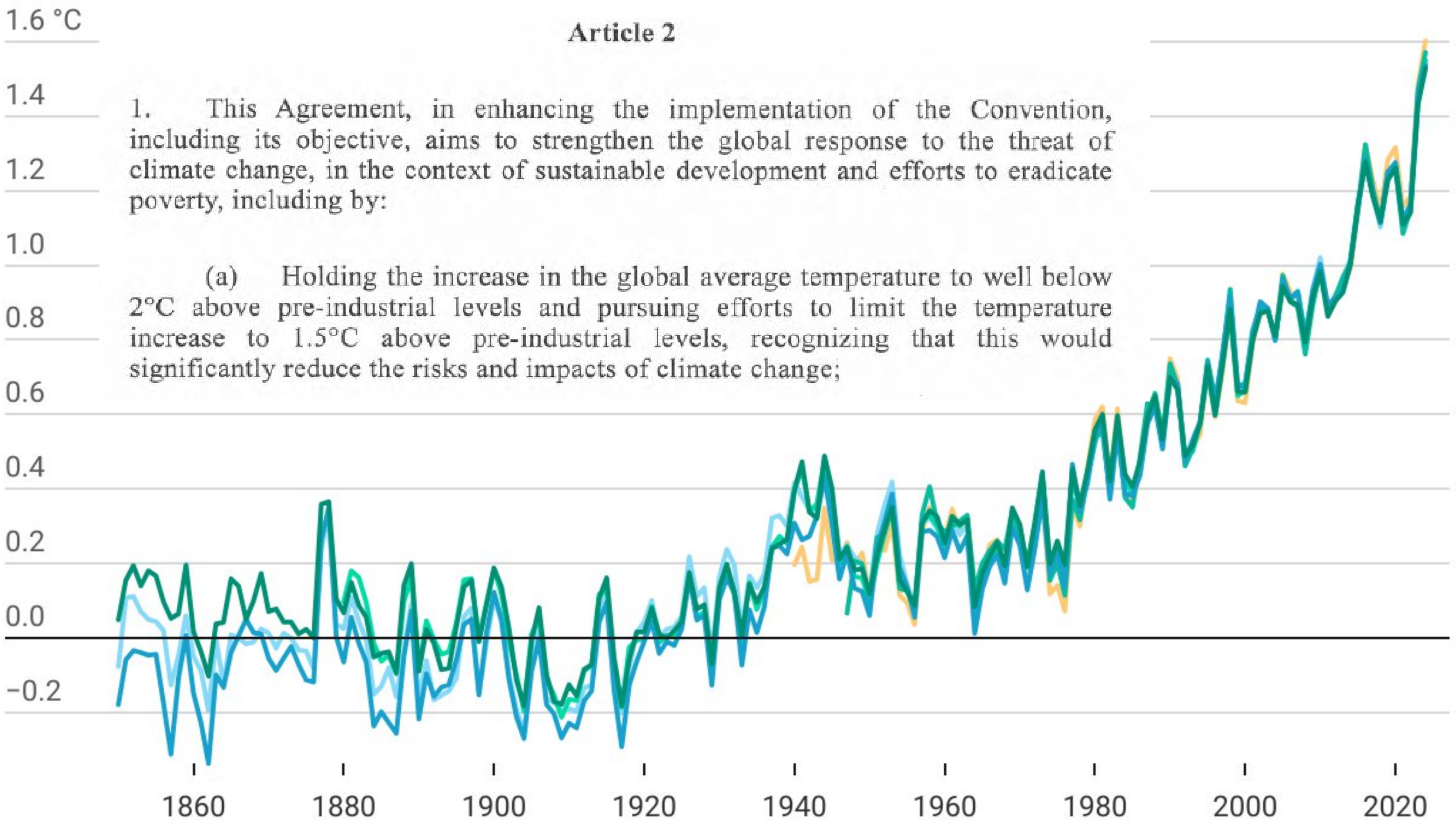
- 92% energy access (666 million without access)
- 17.9% share of Renewable Energy in Total Final Consumption (2022)
- Energy Intensity per GDP PPP; to reduce 4% every year from 2022 to 2030
- International financial flows in 2023 just 75% of peak 2016 USD 28.4 billion
- Per capita RE installed capacity 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) — NOAAGlobalTemp v6 (1850-2024.12)



Article 2

1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

(a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

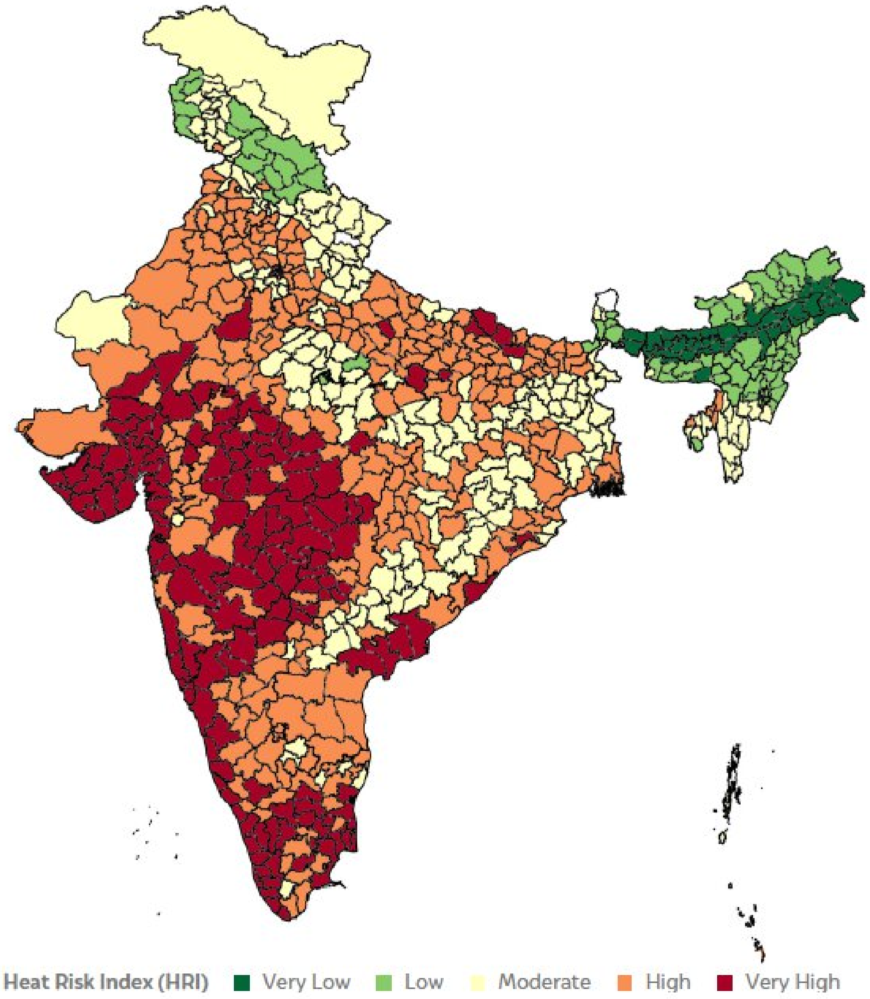
Annual global mean temperature anomalies relative to a pre-industrial (1850–1900) baseline shown from 1850 to 2024

Chart: WMO • Created with Datawrapper

- 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 Antartica sea ice
- Extreme weather events becoming frequent

Extreme Heat impacting livelihoods

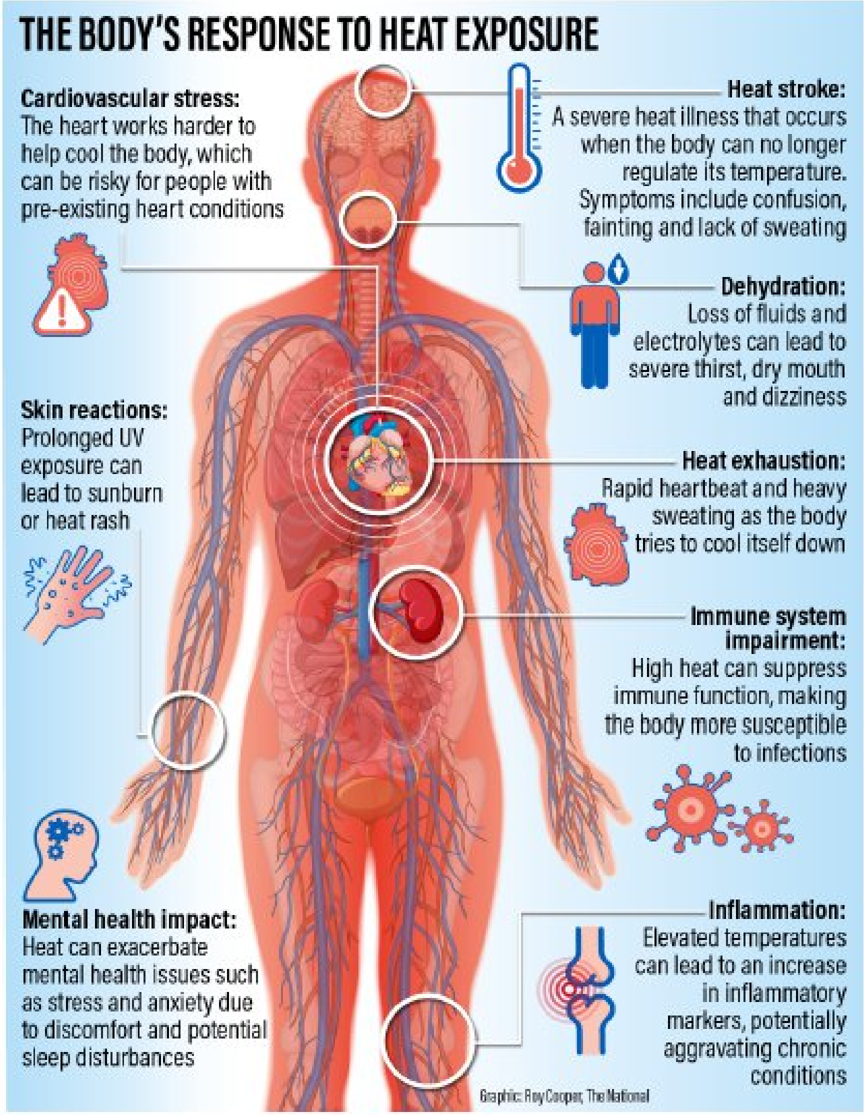
Figure ES3 More than 57% of districts are at high to very high heat risk in India



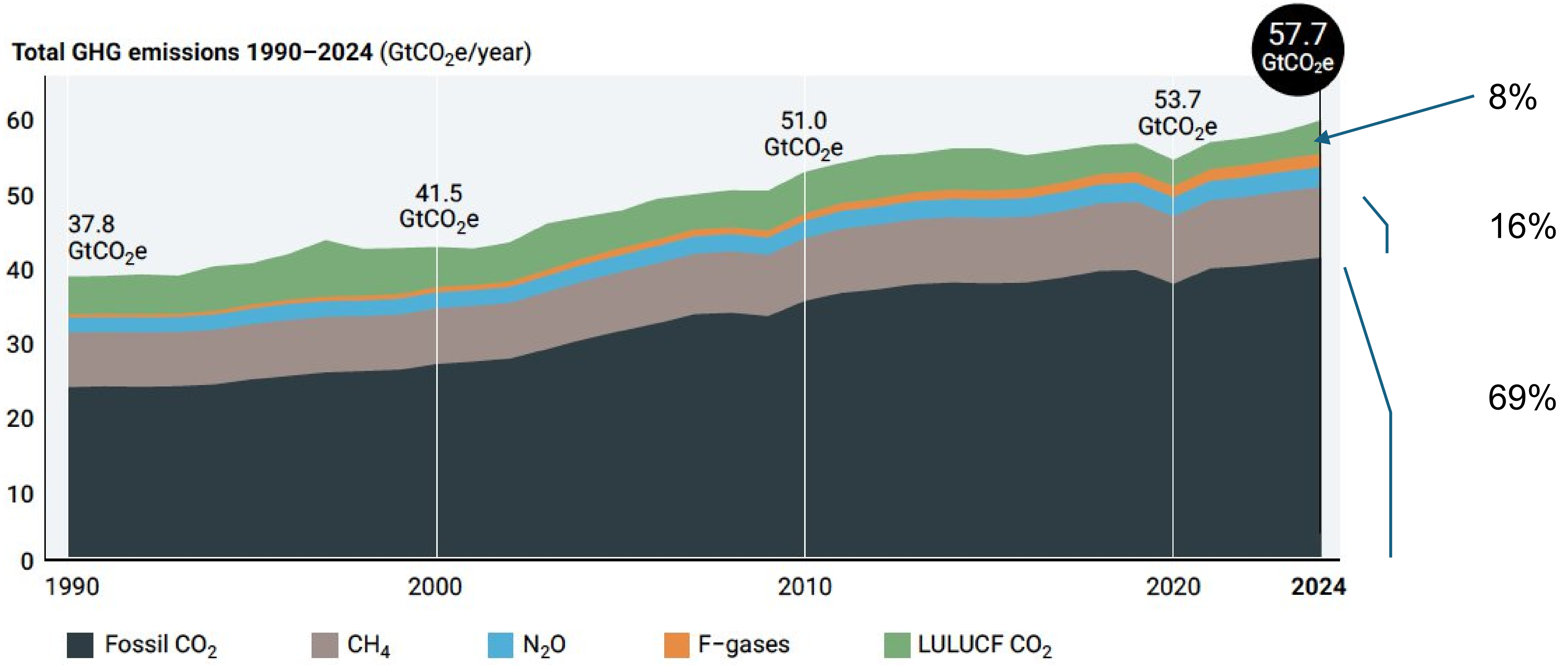
Source: Authors' analysis

Prabhu, Shravan, Keerthana Anthikat Sukesh, 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



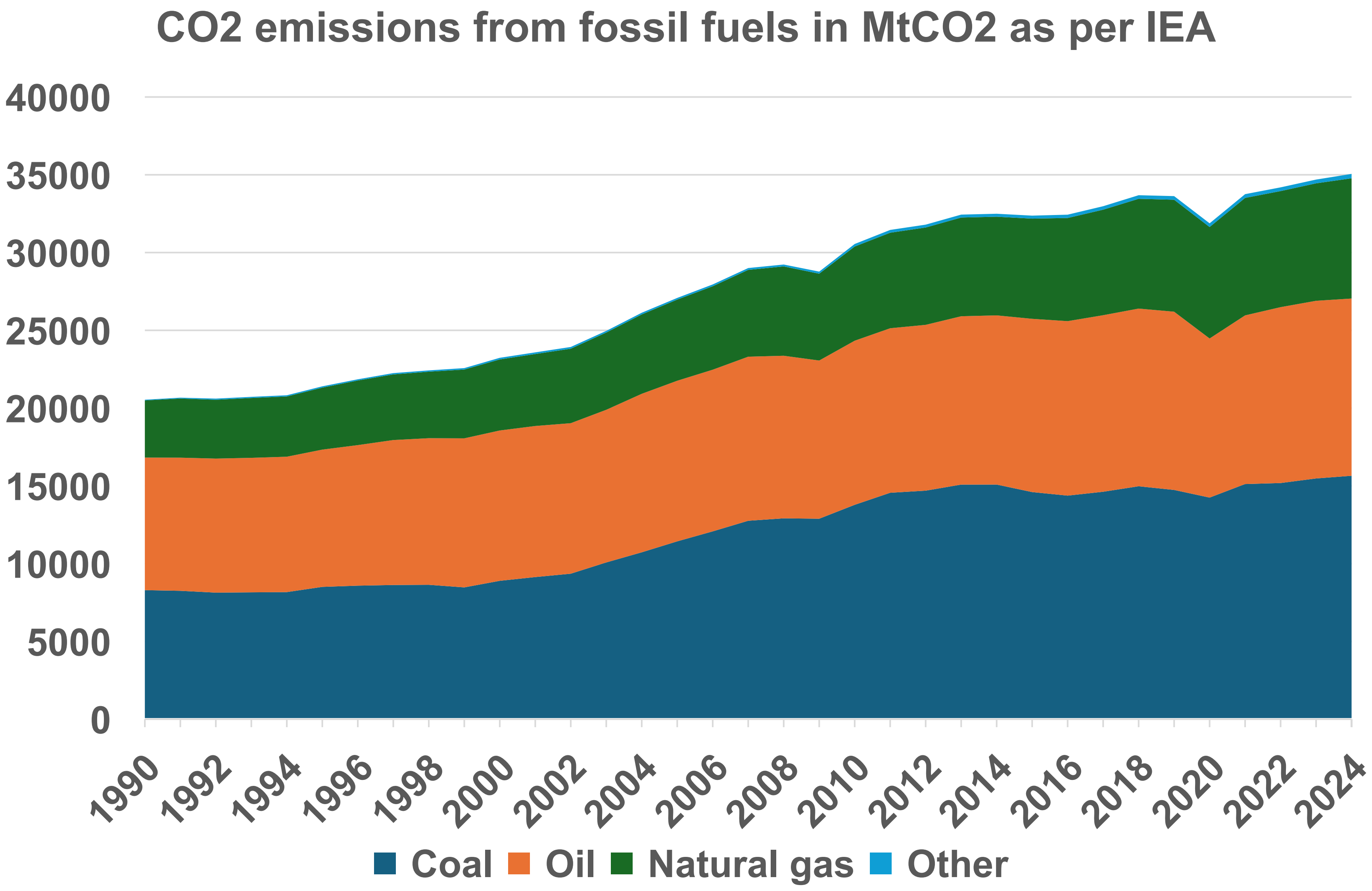
Total net Anthropogenic Emissions 1990-2024



LULUCF: Land Use Land Use Change and Forestry

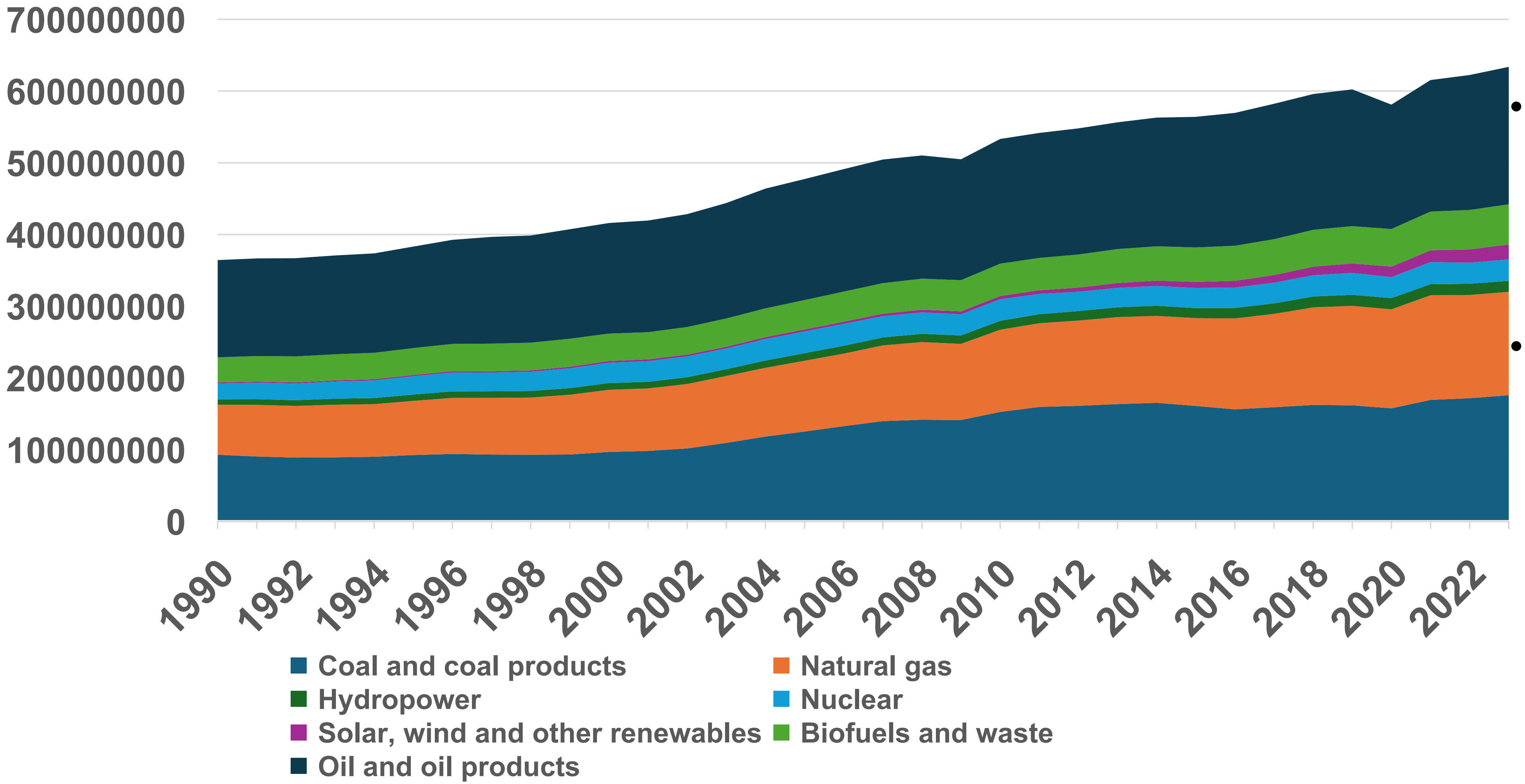
Note: The time series data sets used for the Emissions Gap Report are updated on an annual basis using the latest available statistical information on activities and emissions factors. These updates imply changes compared to prior reporting in the Emissions Gap Report. Accordingly, global GHG emissions in 2023 were adjusted to 56.2 $GtCO_2e$ from the 57.1 $GtCO_2e$ reported in the 2024 edition of the report.

UNEP Emissions Gap Report 2025

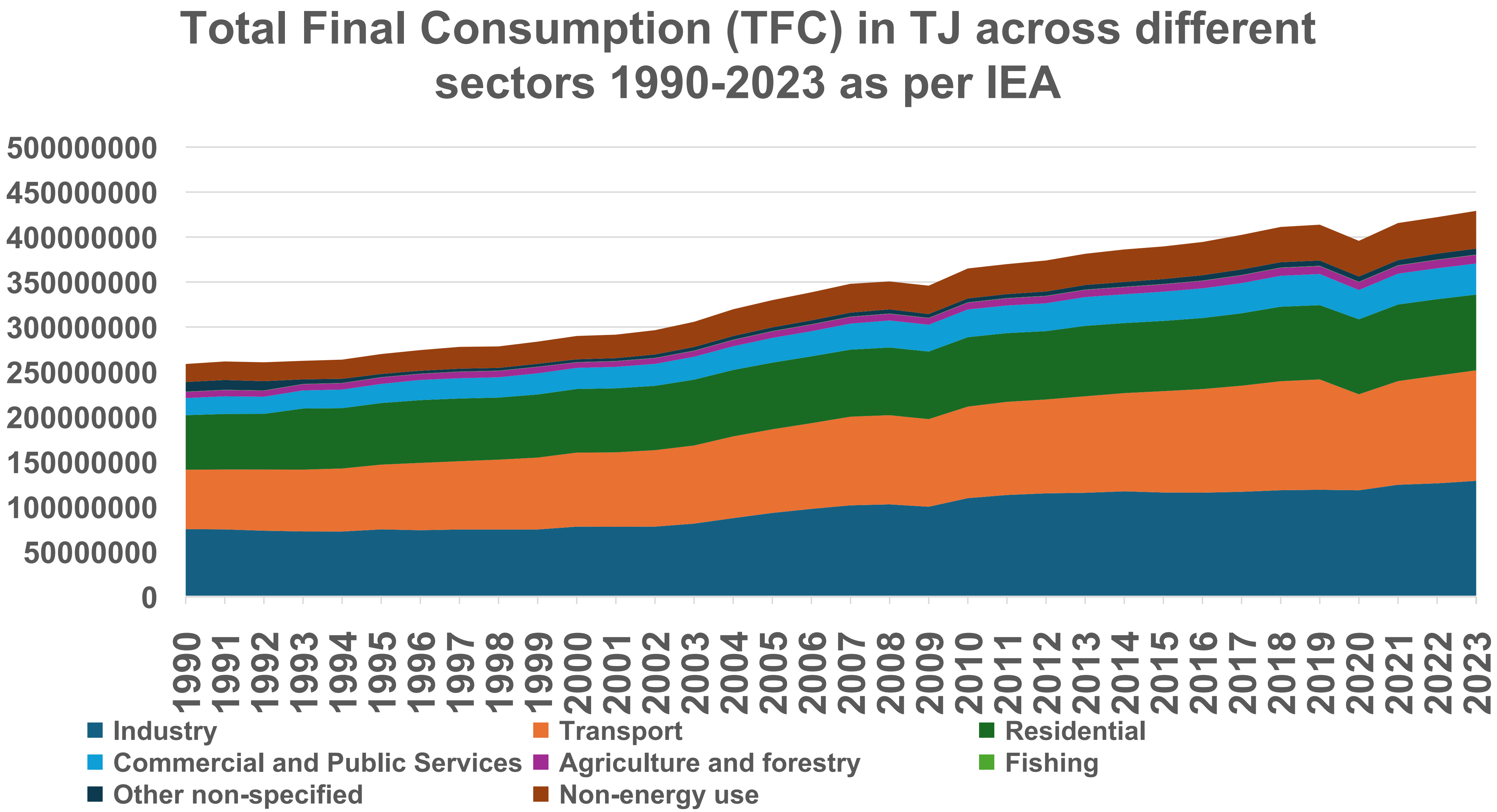


- Total CO_2 emissions 38.15 Gt Including flaring & industrial process as per IEA's WEO 2025
- CO_2 concentration increased from 355 ppm in 1990 to 424 ppm in 2024, as per WMO
- Massive surge of 3.5 ppm from 2023 to 2024

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



- 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 I

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	**5.5**
4	Total Energy Consumption (EJ)	452.7	113.0	65.6	55.8	33.1	21.0	1.3
5	CO_2 emissions from energy (MT)	38153	12660	4521	3501	3113	1969	0.1
6	Electricity Demand (TWh)	27290	9102	4102	3487	1644	1317	**3.4(generation) 6.3(capacity)**

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 2885 GW (2035)

v. Nuclear Energy

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

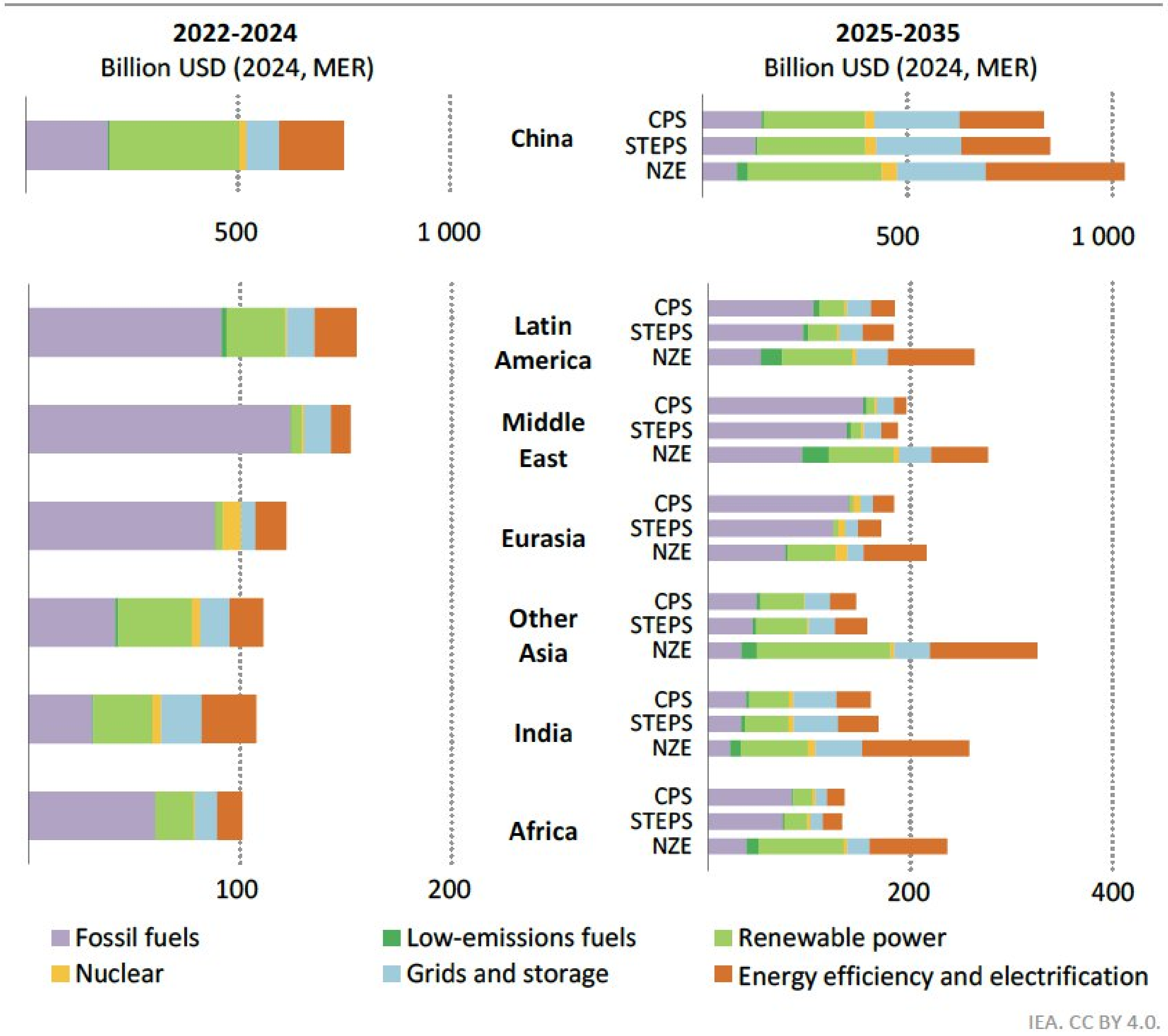
vi. Electricity Grids strengthening and digitalization

- 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)

- CO_2 removal 45 Mt (2024) to 690 Mt (2030) to 2260 Mt (2035)

Clean Energy Financing Requirements

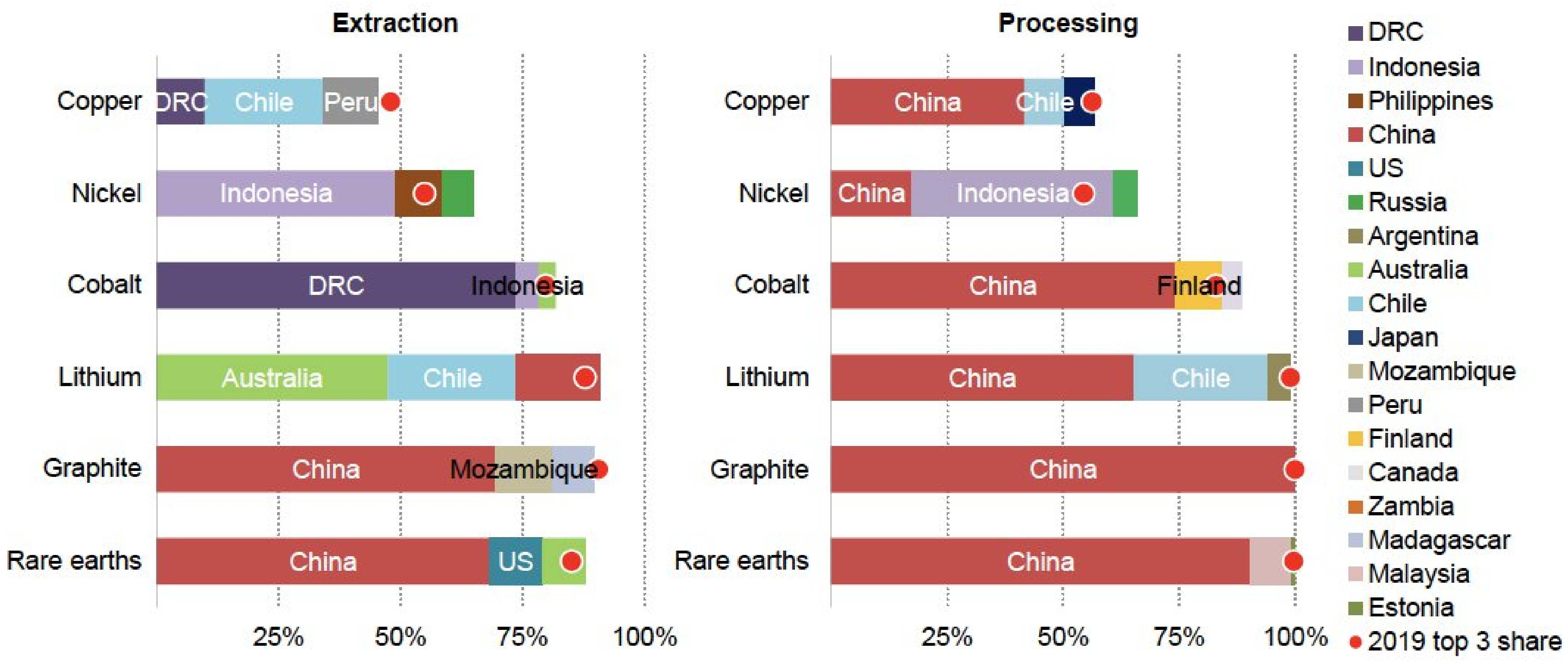


Note: MER = market exchange rate; CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario.

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

Critical Minerals

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

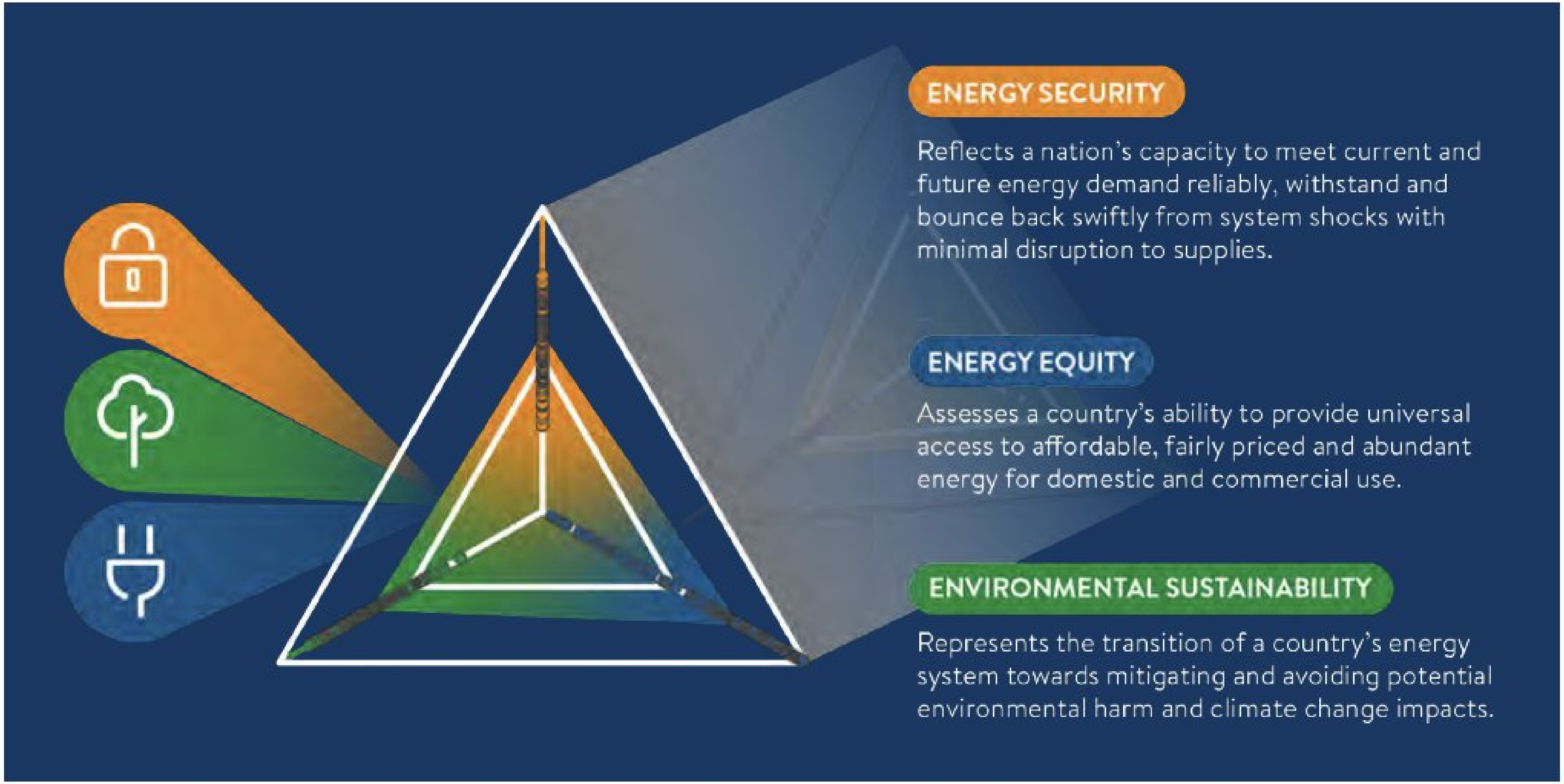


IEA. CC BY 4.0.

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.

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

So, what is Energy Transition?



World Energy Trilemma framework by the World Energy Council

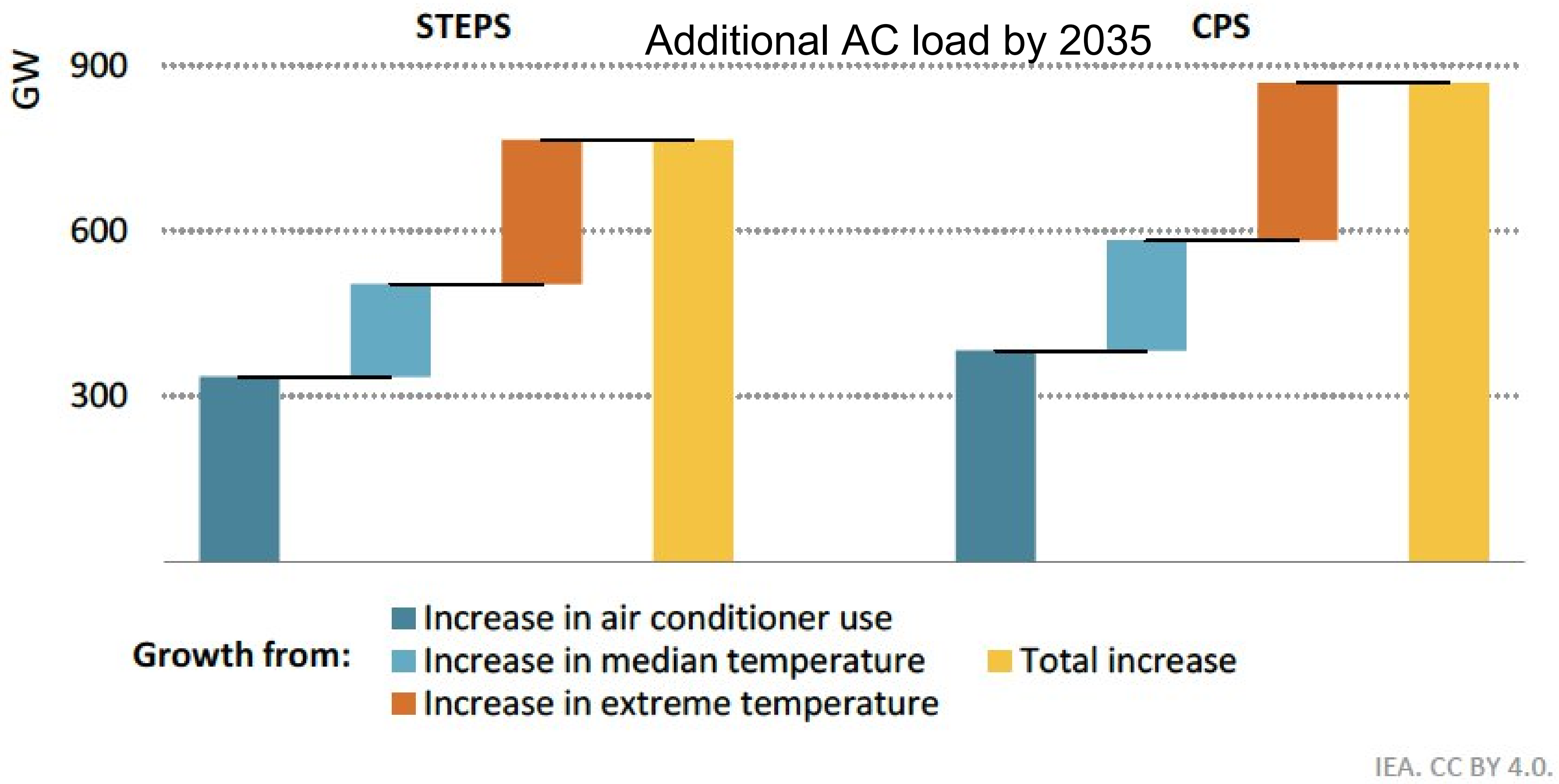
- **Decarbonize d**
- **Decentralized**
- **Digitalized**

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

Additional AC load by 2035

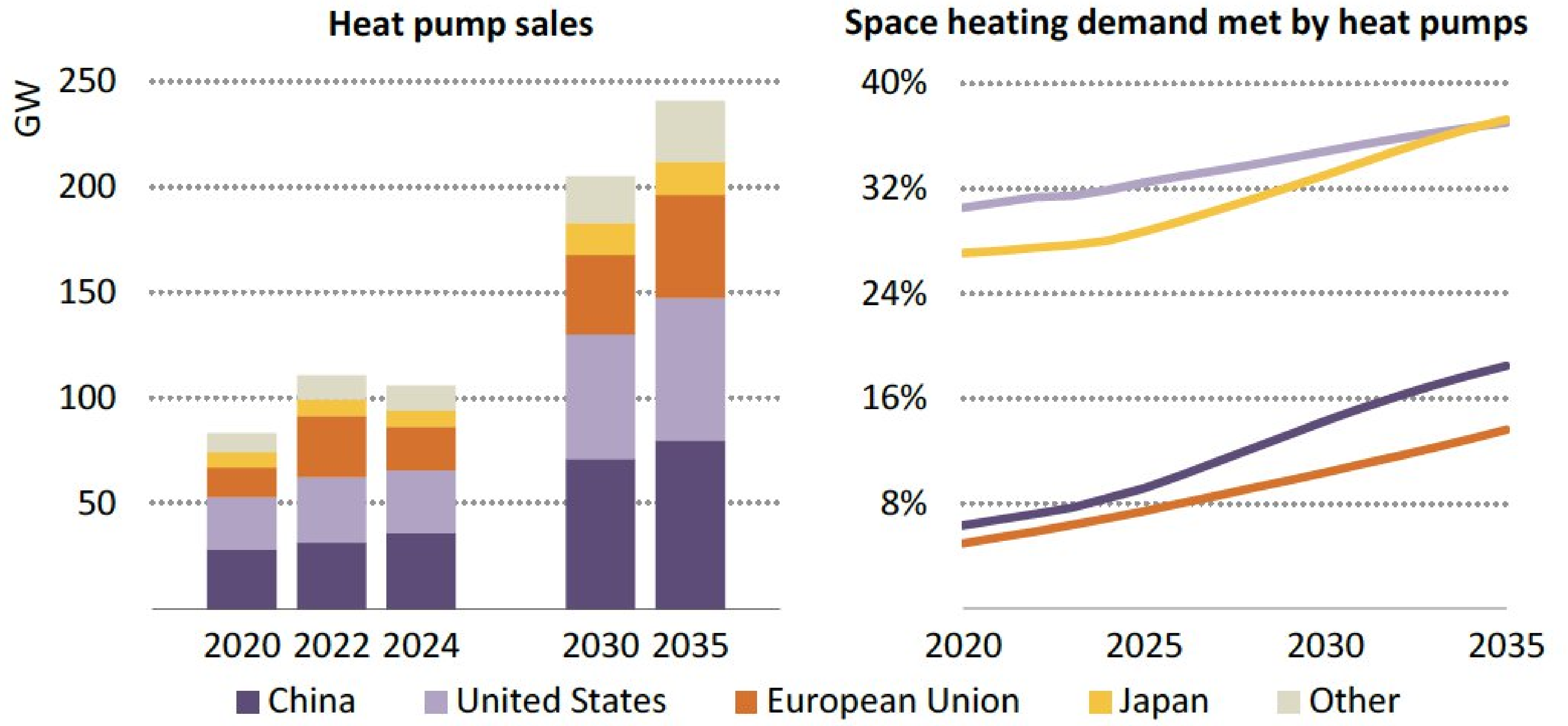


Notes: GW = gigawatt; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario.

- Sustained heat wave in May 2024 in India led to a 15 GW higher demand than forecasted
- South Asian countries would see an increase in AC penetration
- Minimum Energy Performance Standards (MEPS) tightening can lead to 64 GW/118 TWh reduction annually by 2035 as compared to BAU in India. (LBNL study 2025)

Impact of Heat Pumps on electricity demand

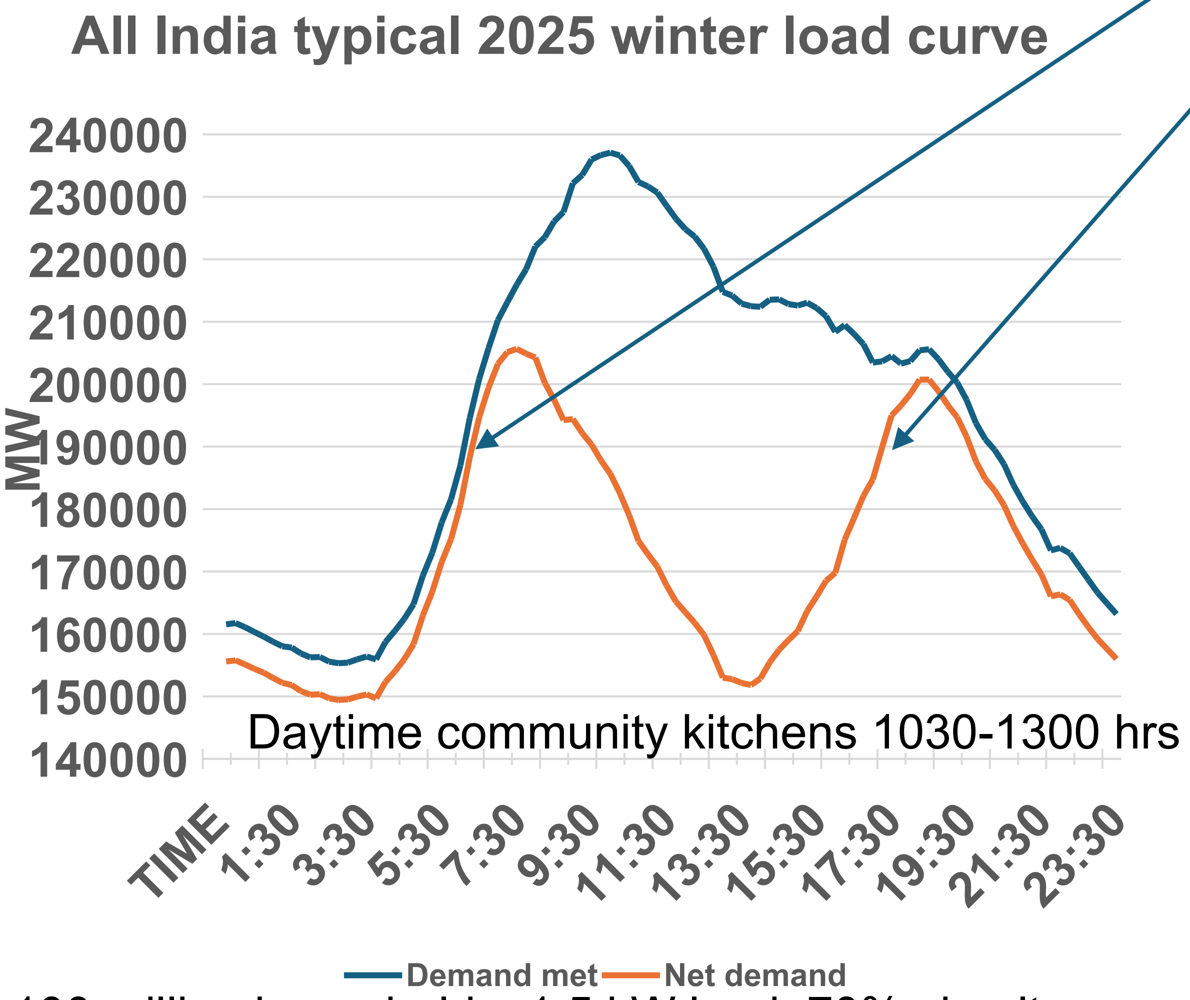
Figure 4.11 ▹ Global heat pump sales and contribution to space heating demand in selected regions in the STEPS, 2020-2035

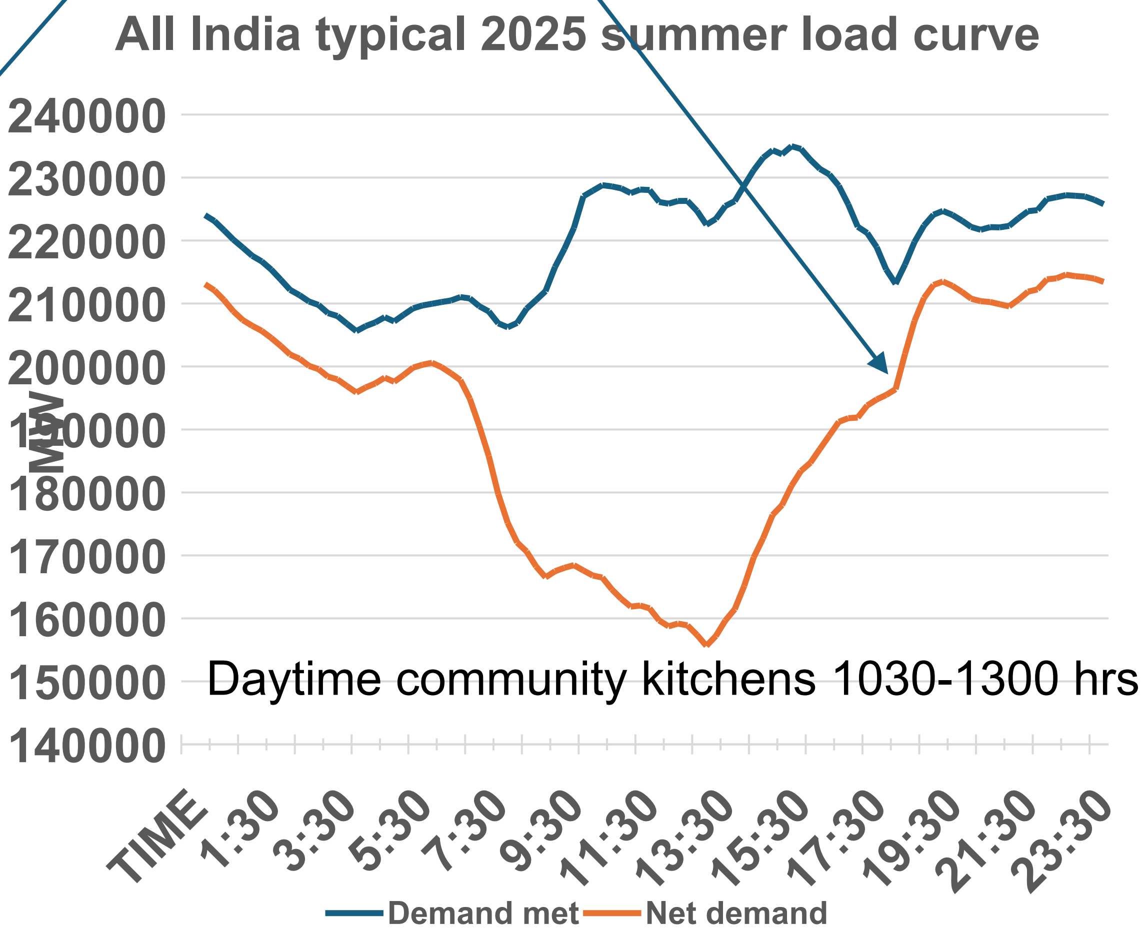


- 40% space heating requirements possible through Heat Pumps by 2035
- 40 BCM natural gas would get substituted by 2035
- Gas price vs electricity price dynamics create some resistance to adoption
- Bhutan, Nepal and Northern India candidates for Heat Pumps

Impact of Electric Cooking

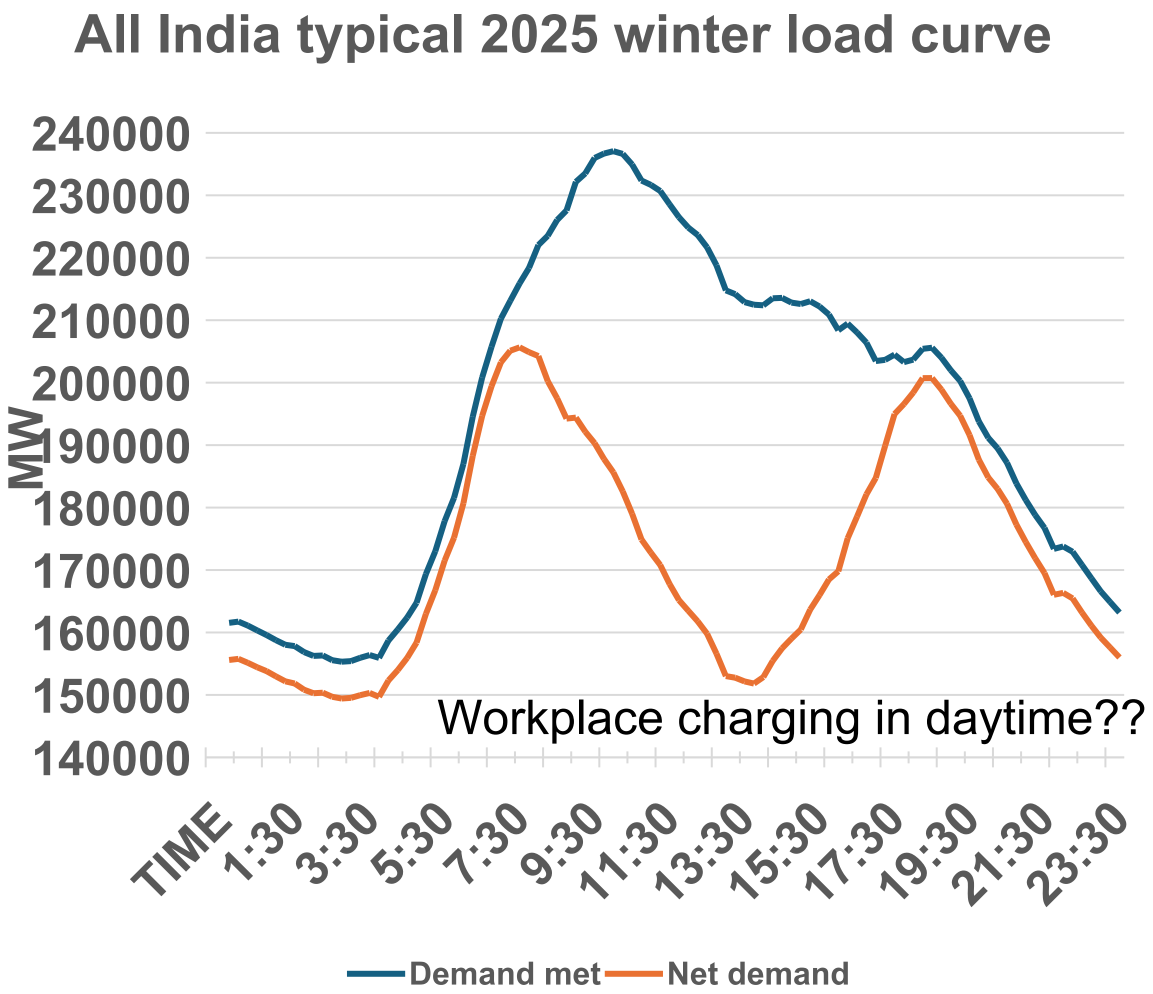
Cooking load between 06-08 and 18-20 hours will increase ramping requirements

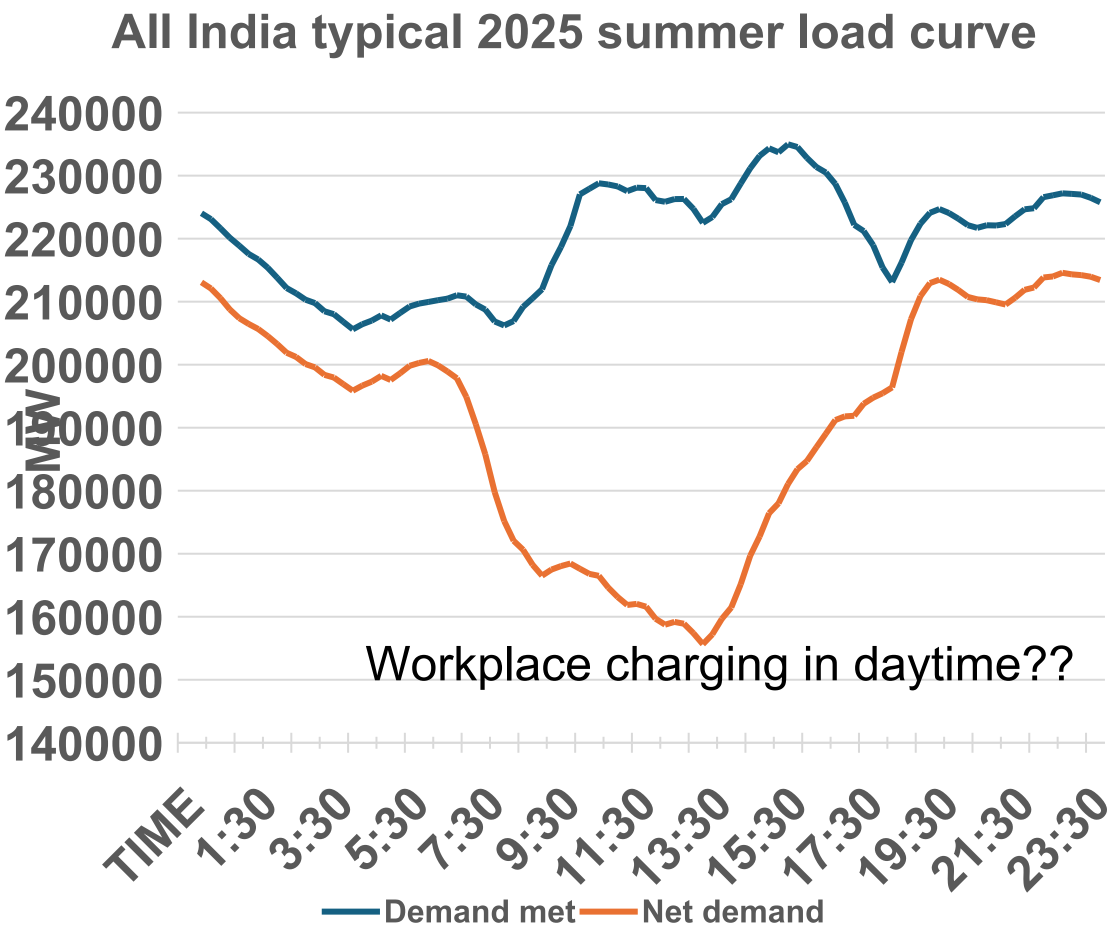




100 million households; 1.5 kW load; 70% simultaneous…..105 GW load……….Distribution system augmentation

Impact of Electric Vehicles





Night time. Charging 1900-0300 hours; no problem during winters……coal generation increase?

real stress during summers……..7-8 hours BESS re

Impact of Green Hydrogen

- 1 kg of hydrogen through electrolysis ~~ 50 kWh electricity required

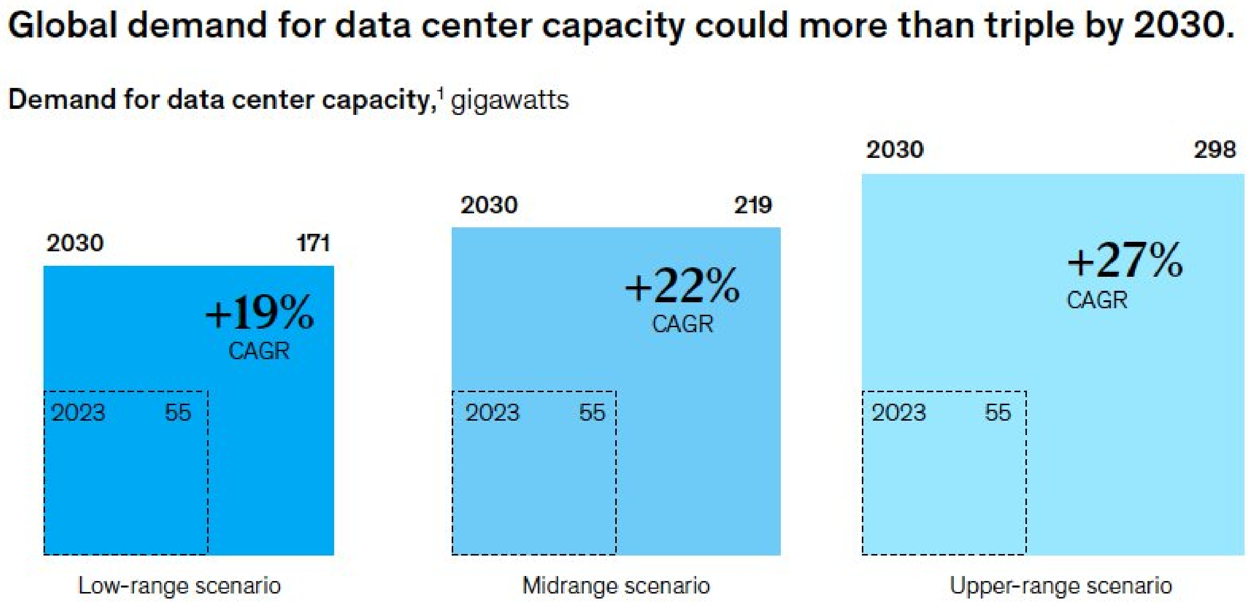
1 T production /day ~~ 2.1 MW electrolyser at 100% load factor (2.5 MW at 84% load factor)

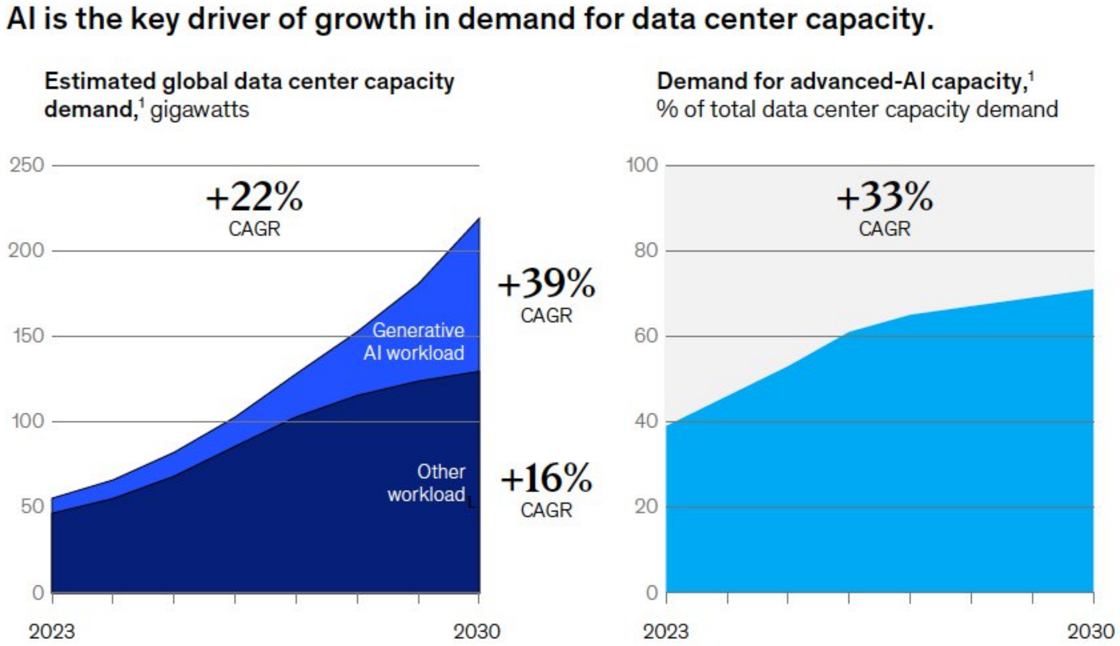
- Practical case in India ~~~90,000 MT per annum green hydrogen plant
  - ~650 MW round the clock contract provided by 2400 MW RE (wind plus solar) plus 350 MW, 6 hours Battery Energy Storage System (BESS)
  - Anticipated annual load factor of electrolyser…………80-85%
  - Hourly matching of RE generation 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. ~~800-900 GW electrolyzer capacity?

- Inverter Based Large Loads and their interaction with grids, Demand Response

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





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)

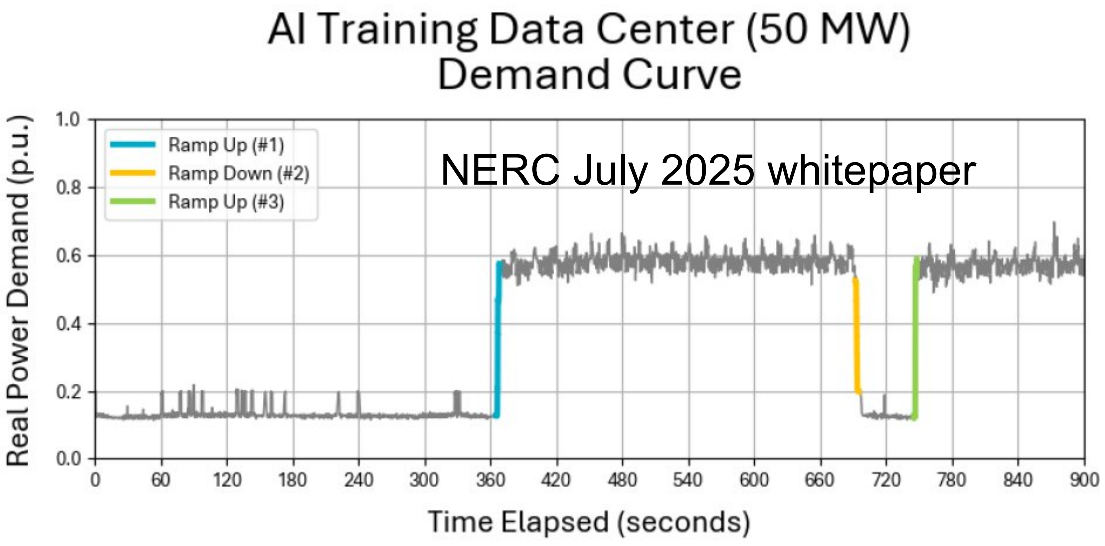


Figure 2.2: An AI Training Data Center Begins a Training Run (EdgeTunePower)

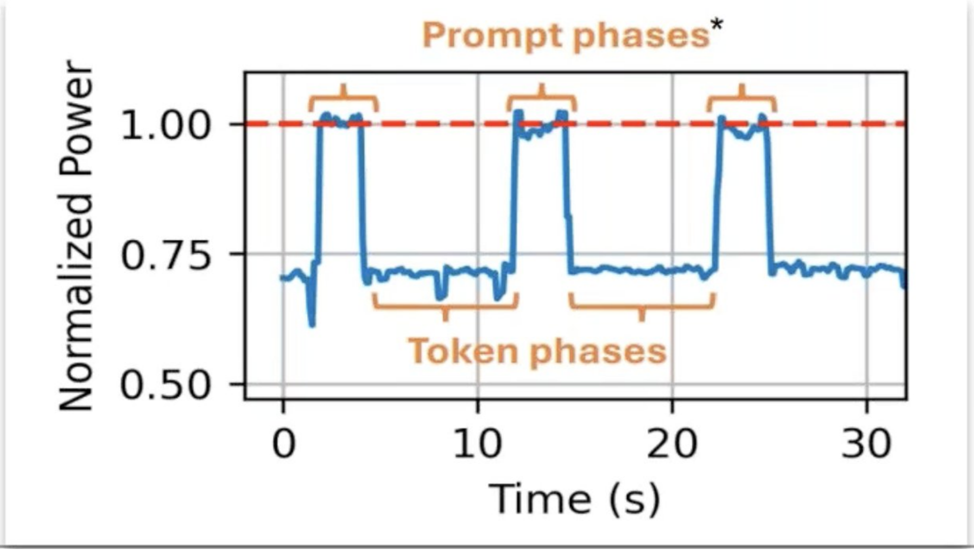
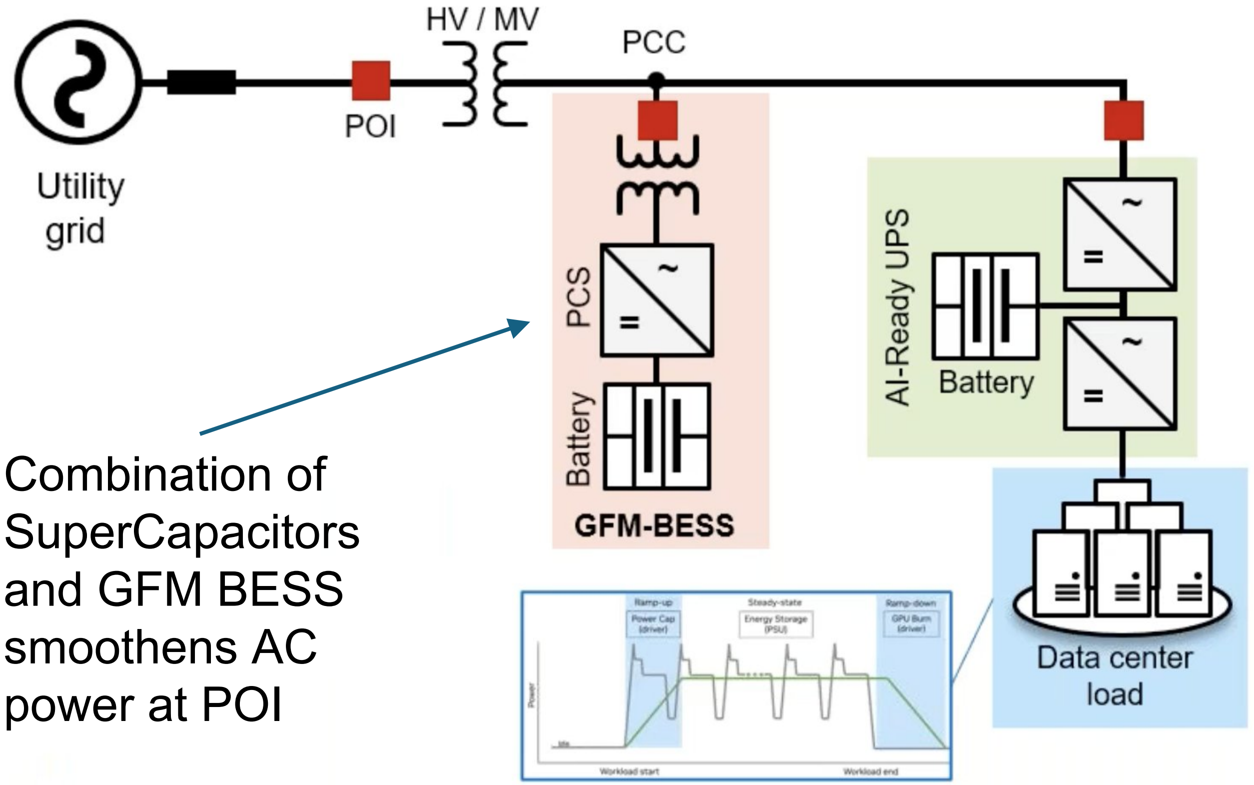


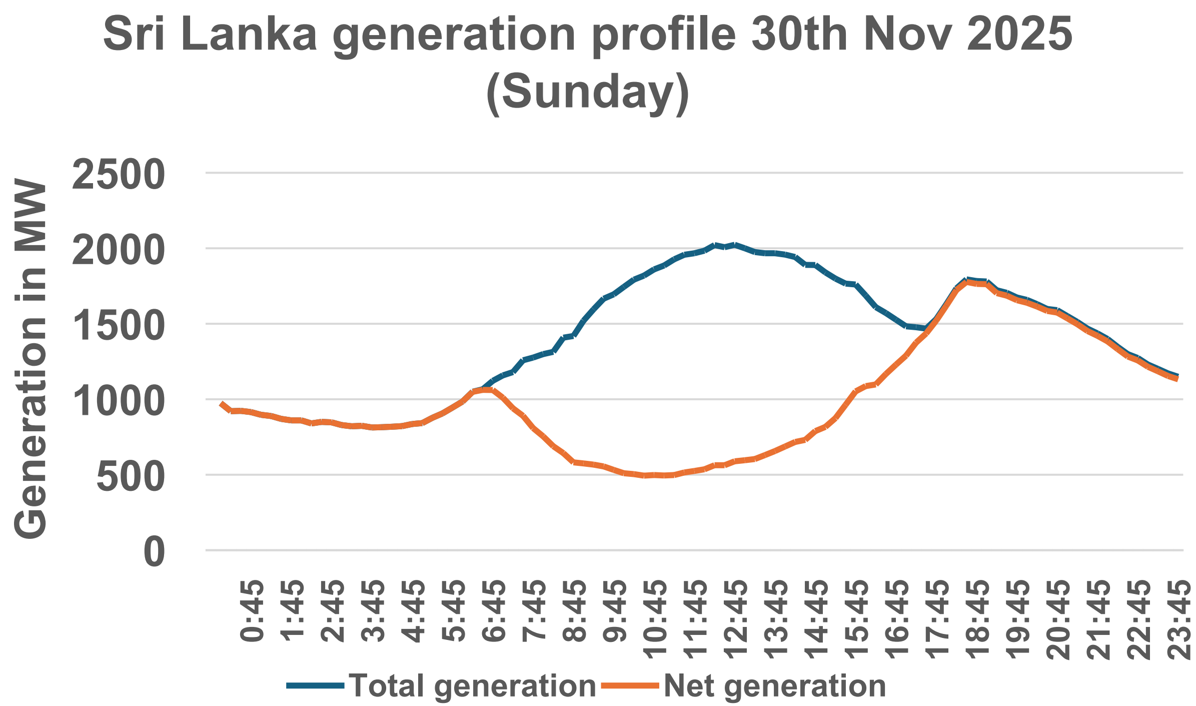
*Image taken from P. Patel et al. "Characterizing Power Management Opportunities for LLMs in the Cloud", Association for Computing Machinery, April 2024.

Combination of SuperCapacitors and GFM BESS smoothens AC power at POI

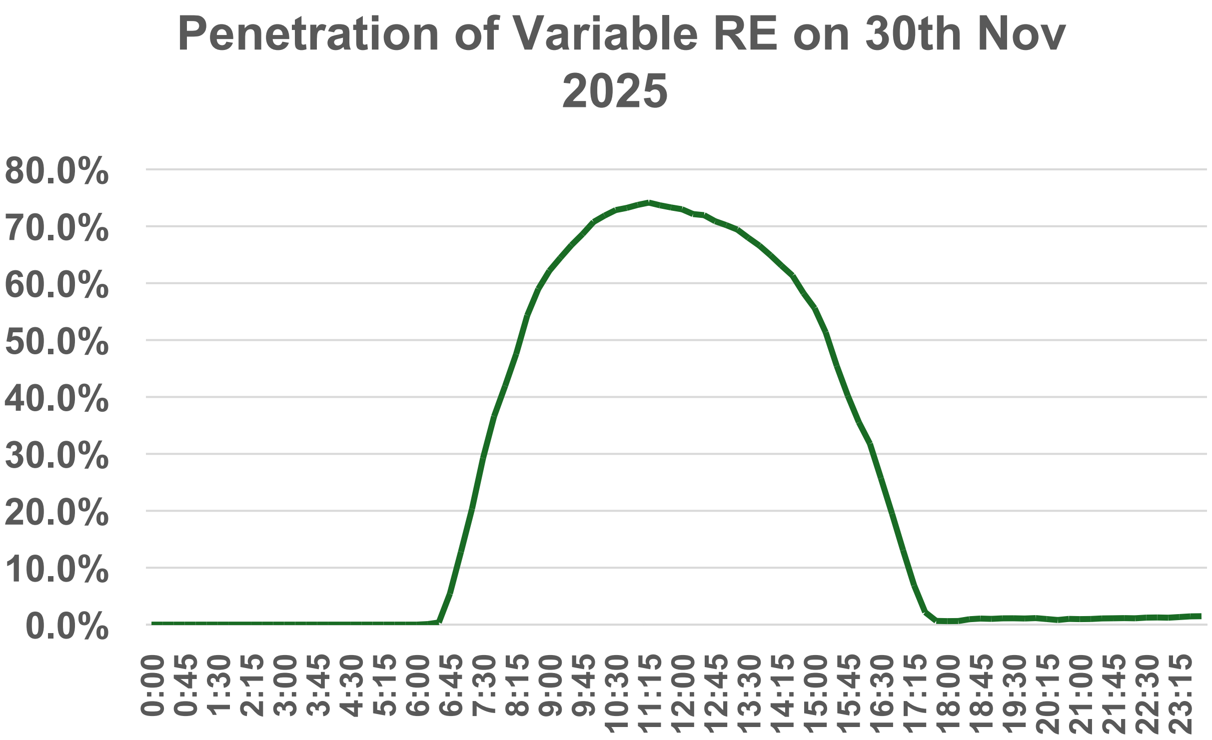


Source: Quanta Technologies webinar

Sunny Sunday on an island



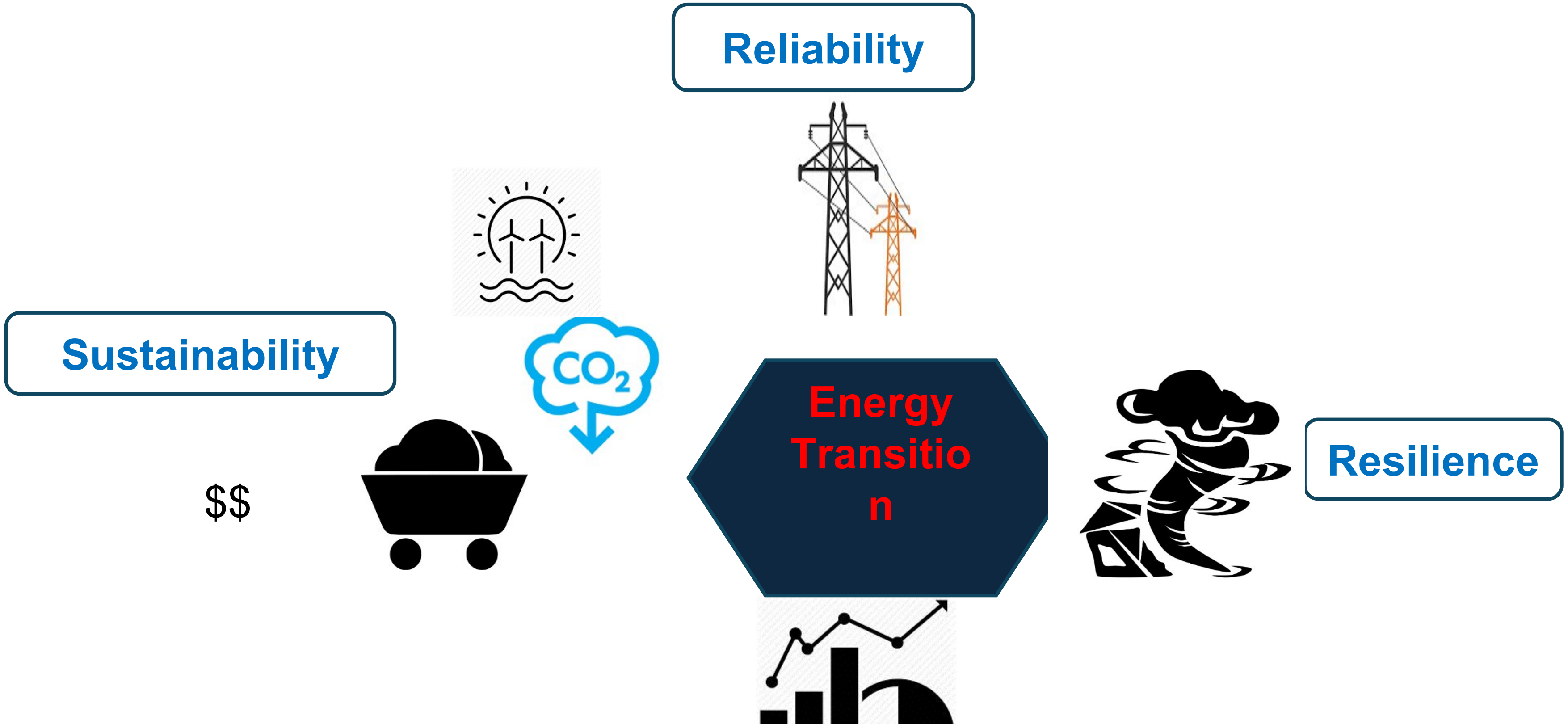
Total generation includes estimated rooftop solar
Net Generation is Total generation less wind and solar
Source: Public Utilities Commission of Sri Lanka



Includes rooftop solar

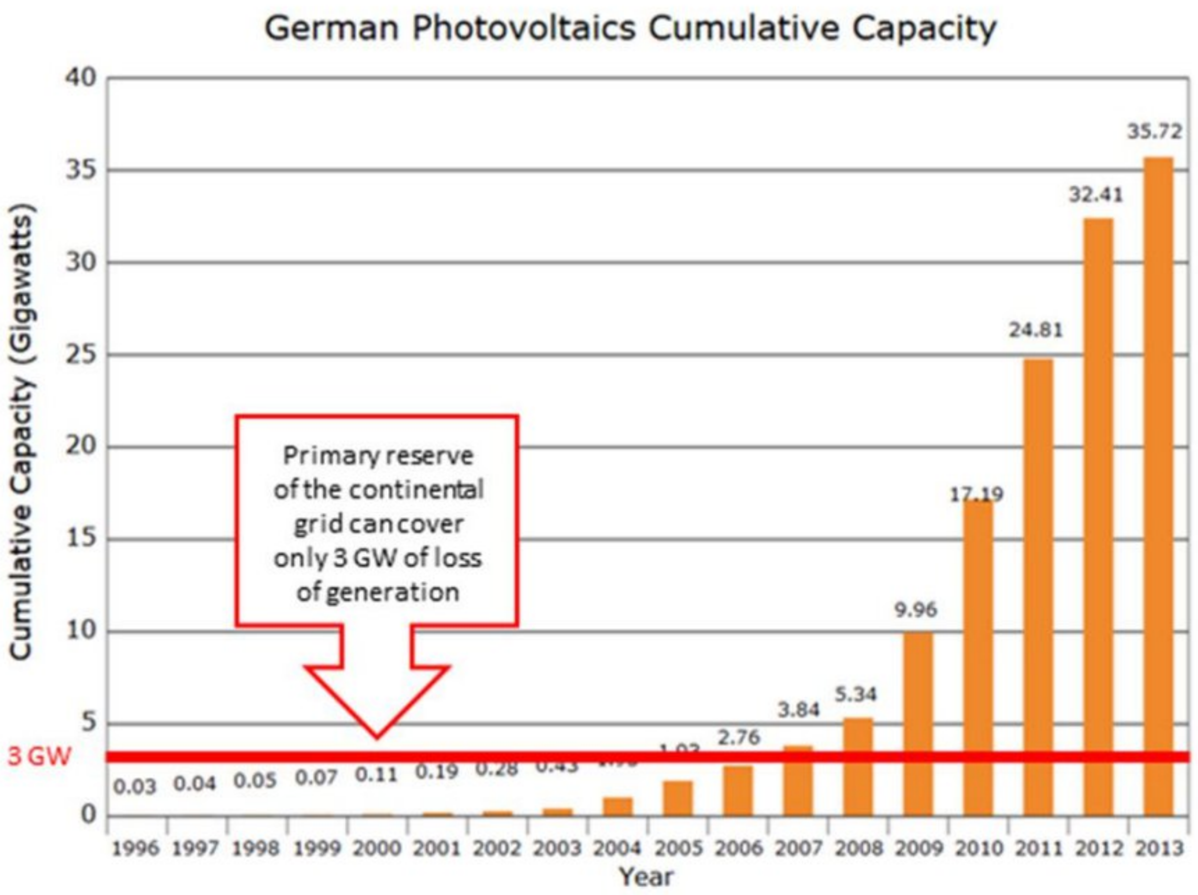
- System becomes vulnerable in case of any contingency
- System strength, Inertia, Frequency Control, Voltage control the key
- Adoption of relevant standards like IEEE 1547:2018

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



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

ENTSOE April 2012 report red flagged this issue

Extensive retrofits in Germany solar PV

Source: 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 28th April 2025

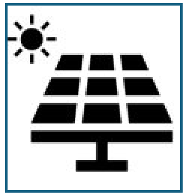
- Oscillations in the system and low voltages in Spain
  - Transmission Lines were reconnected
  - Solar curtailed in Spain to reduce export to France
  - Spain to France HVDC mode changed to fixed power
- Oscillation mitigation steps led to high voltages in Spain
- Further tripping of solar generation 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

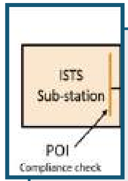


Sustainable ecosystem for equipment testing - development of lab / field testing facilities, technical consulting, logistics etc.

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

Big Data Analytics, AI/ML deployment and cybersecurity

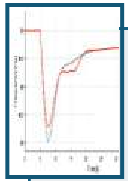
Regulations and Standards



Interconnection Point / Point of Interconnection

Reactive Capability test

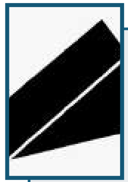
Voltage Ride Through Requirement (Low/High)



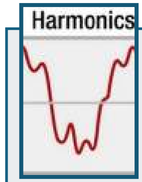
Frequency Response

Active and Reactive Power - Set Point Control

Design Requirement – Weather, Temperature Extremes etc.



Ramping Capability

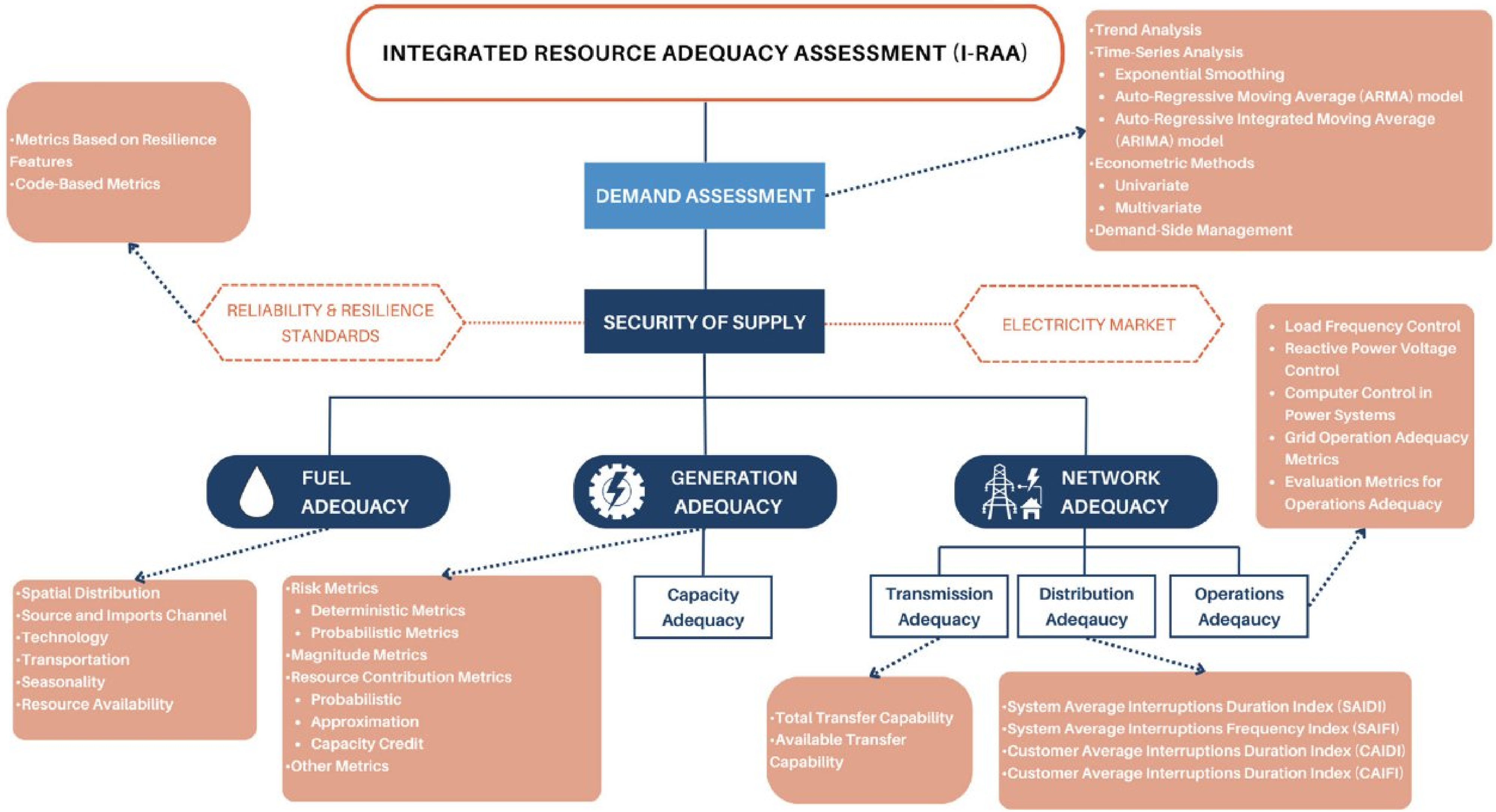


Power Quality Requirements

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

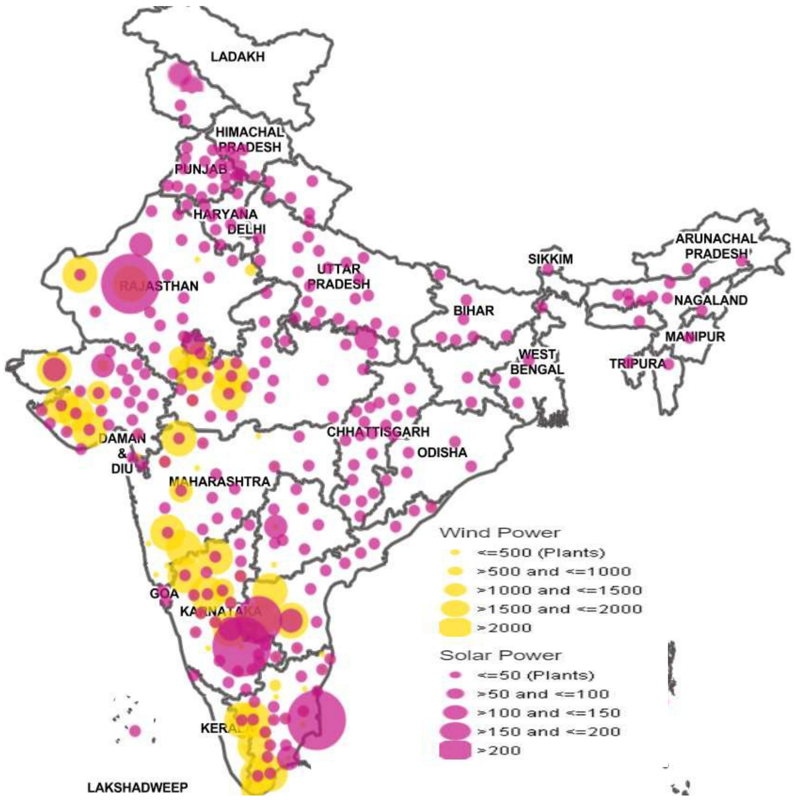
Resource Adequacy



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

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

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

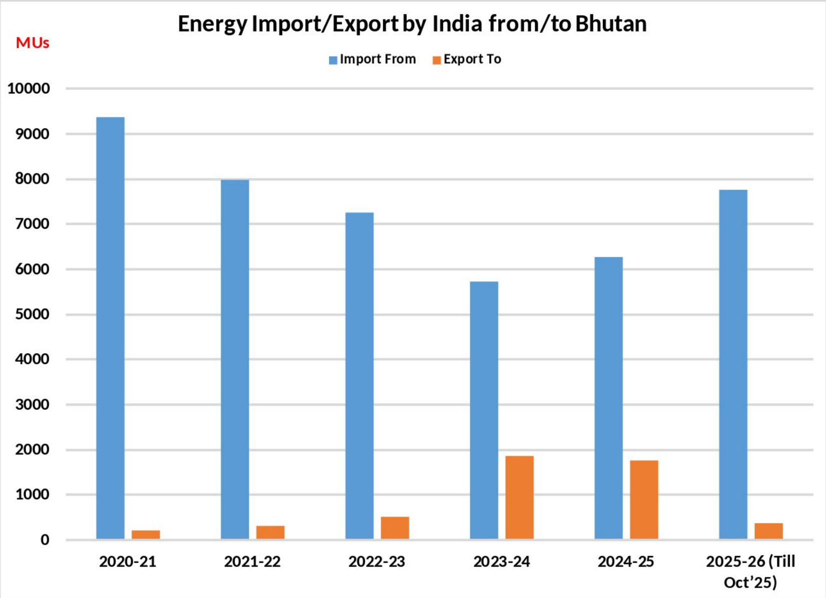
Disaster Management and Resilience

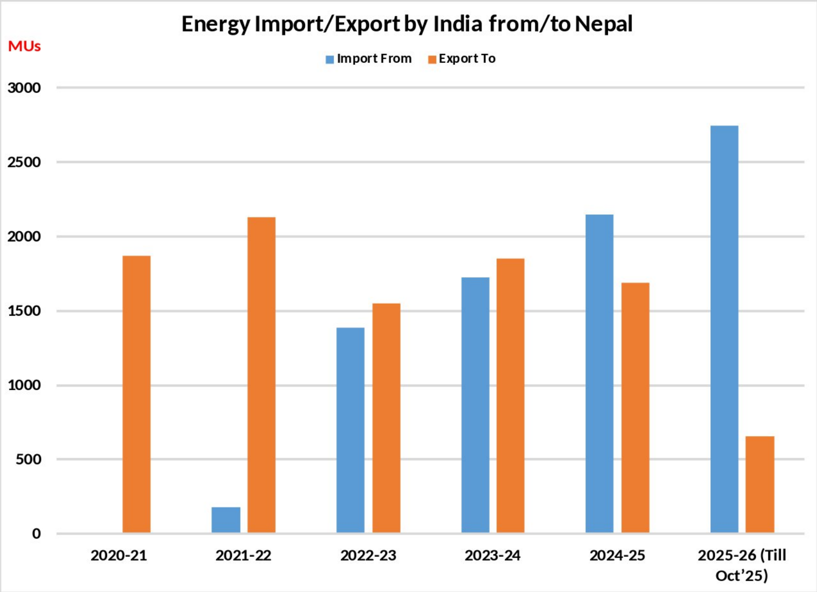
System Integrity Protection Scheme

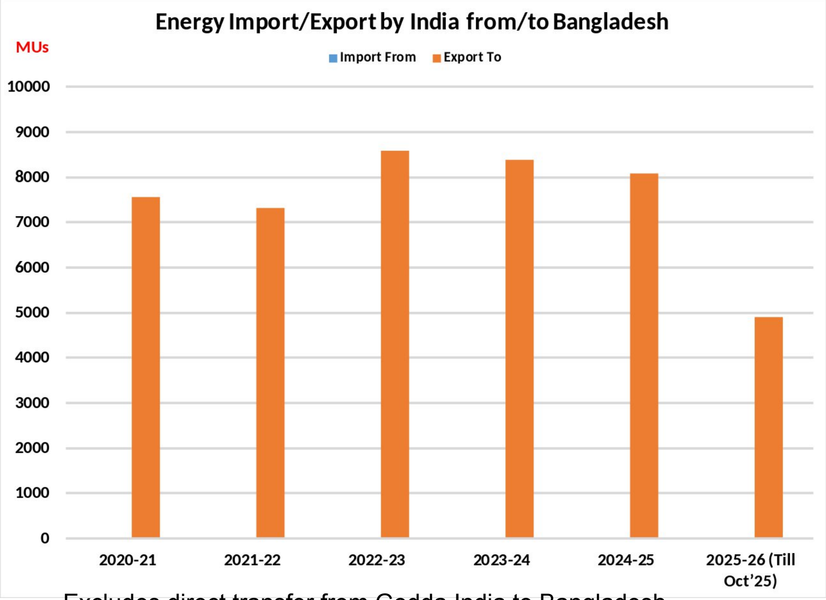
Communication, cyber security etc.

- ✓ 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

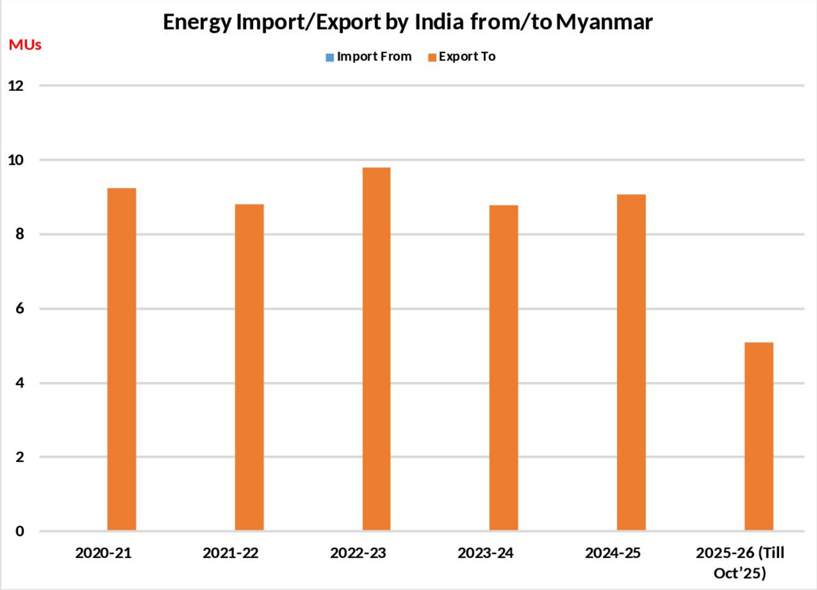
Cross Border exchanges







Excludes direct transfer from Godda India to Bangladesh



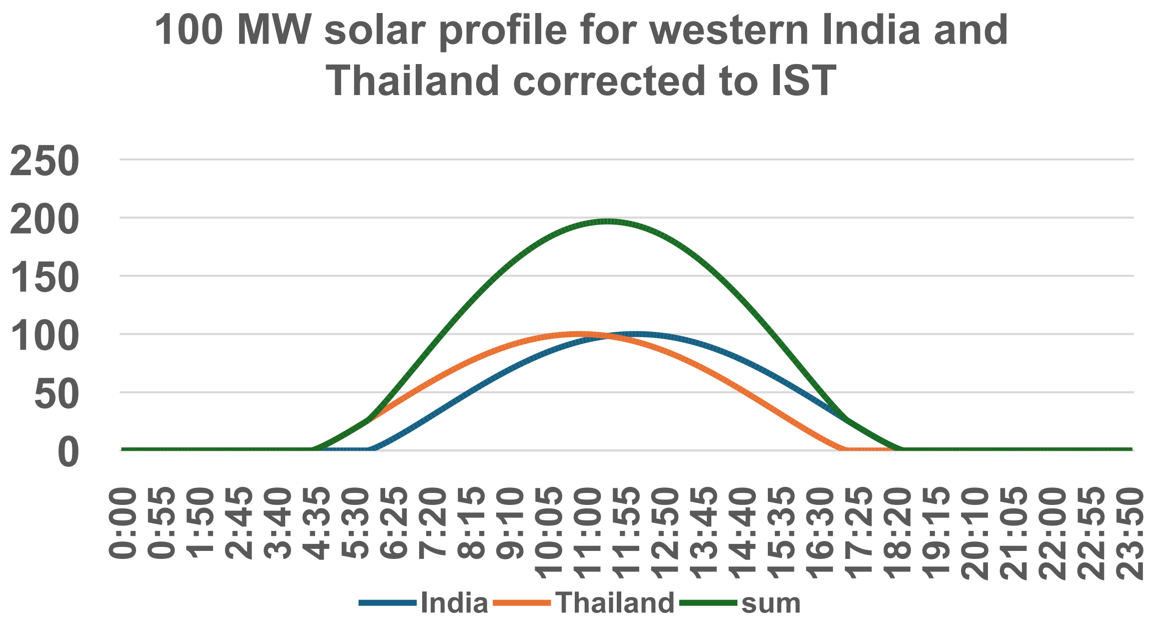
Participation in Indian energy markets –including power exchanges

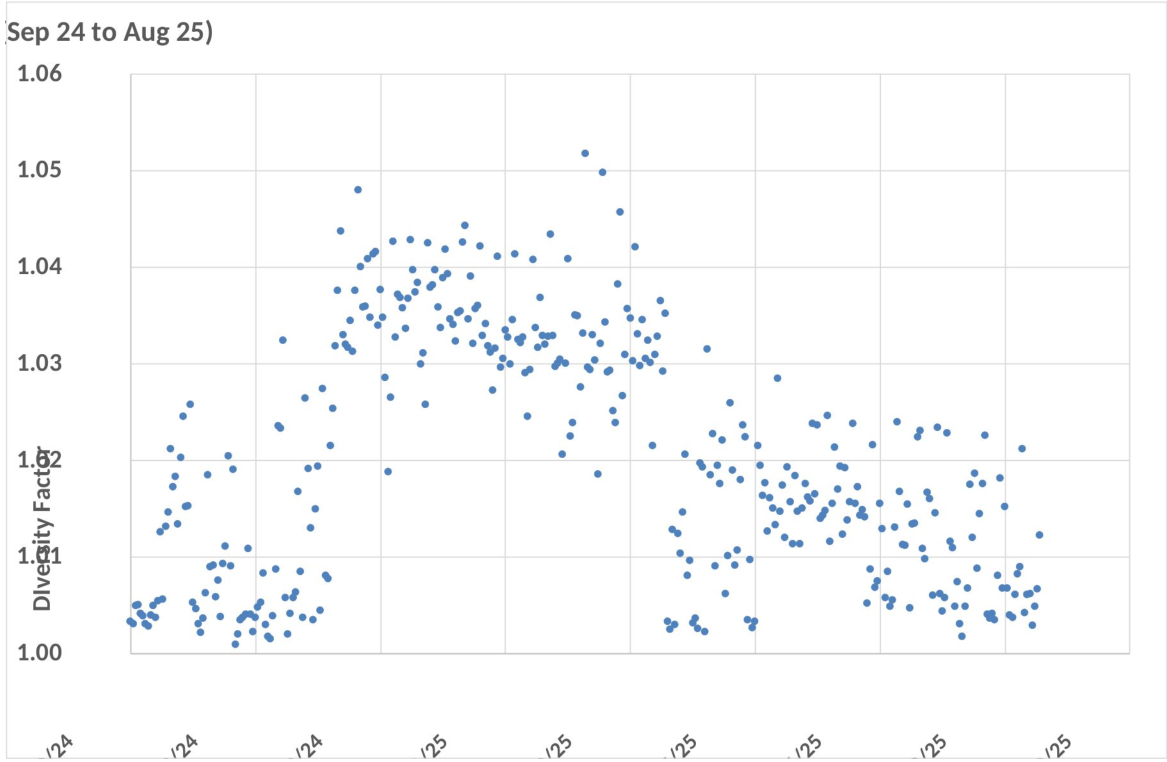
Harnessing diversity in load and generation patterns

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 smoothening if interconnected

OSOWOG: Proposed Electricity Grids Interconnection

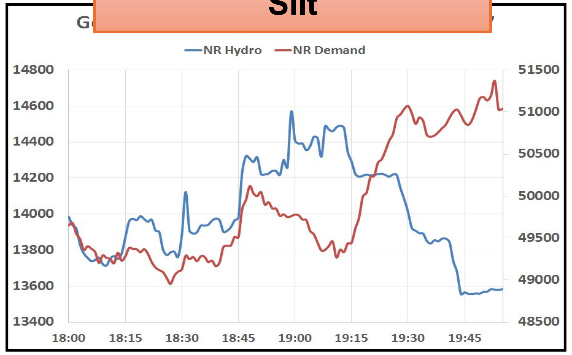
Grid Resilience

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

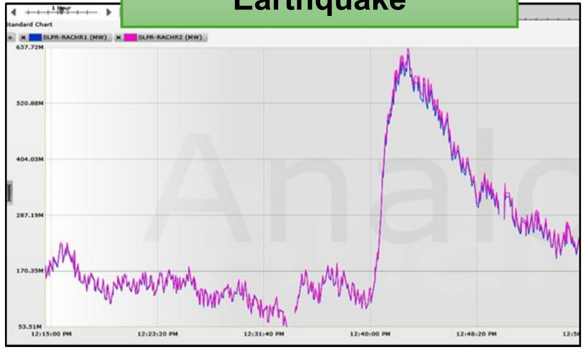
Cyclones
- Phailin **(2013)**
- Hud-Hud **(2014)**
- Vardah **(2016)**
- Titli **(2018)**
- Bulbul **(2019)**
- Amphan **(2020)**
- Nivar **(2020)**
- Biparjoy **(2023)**
- **Dana (2024)**
- **Montha (2025)**

Natural Disasters in Recent History which impacted Electricity Grid in India

Silt

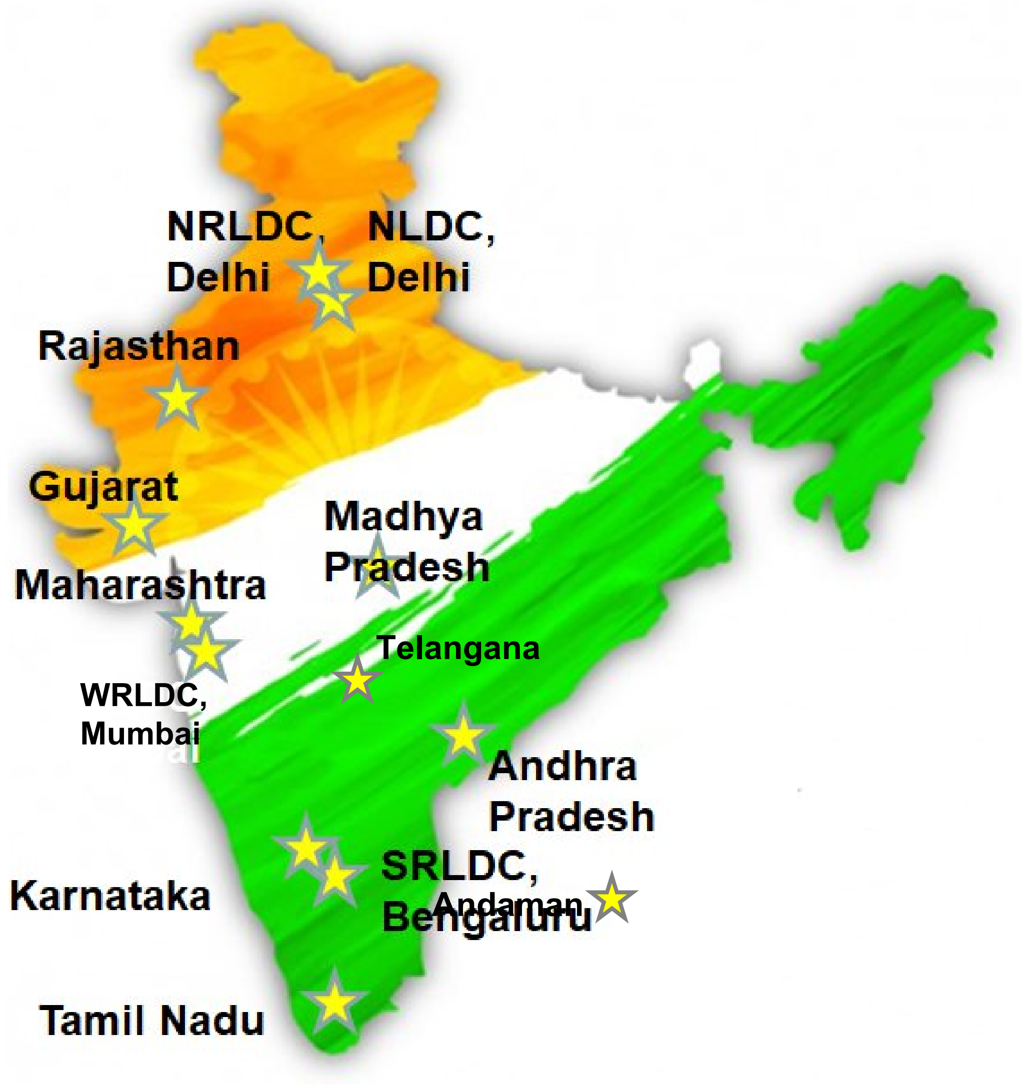


Earthquake



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

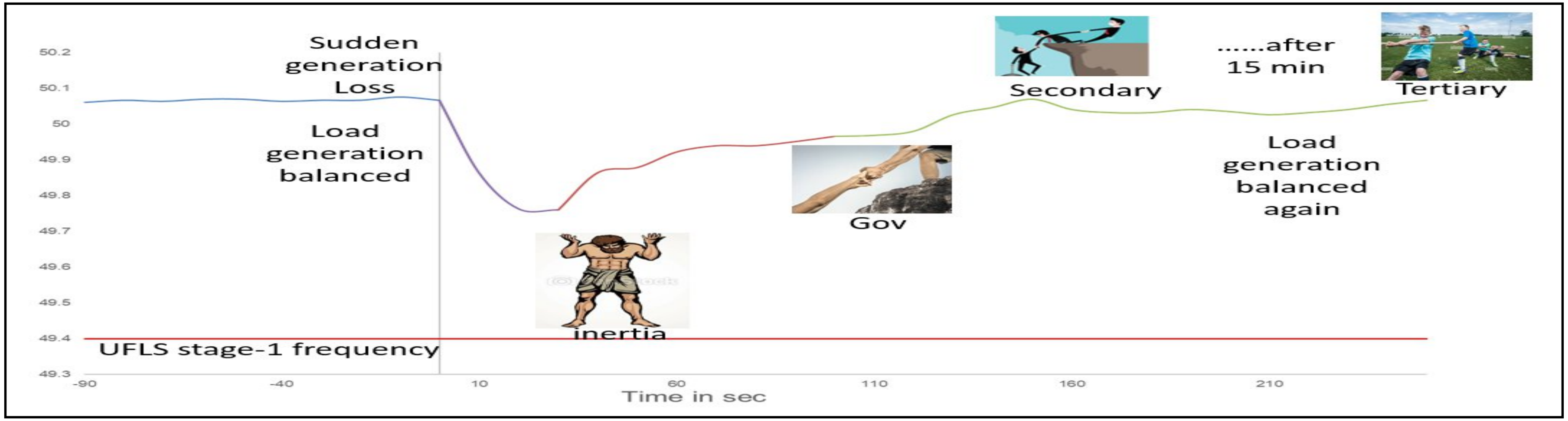
VRE forecasting through Renewable Energy Management Centres (REMCs)



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 (NWPs) 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
Primary Response (Automatic)	Instantaneous after frequency crosses dead band	Within 45 sec	5 min	All generators, Energy Storage
Secondary Reserve Ancillary Service (Automatic)	Within 30 sec	Within 15 Min	30 min or till replaced by Tertiary Reserves	All generators, Energy Storage, DR
Tertiary Reserve Ancillary Service (Manual)	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?

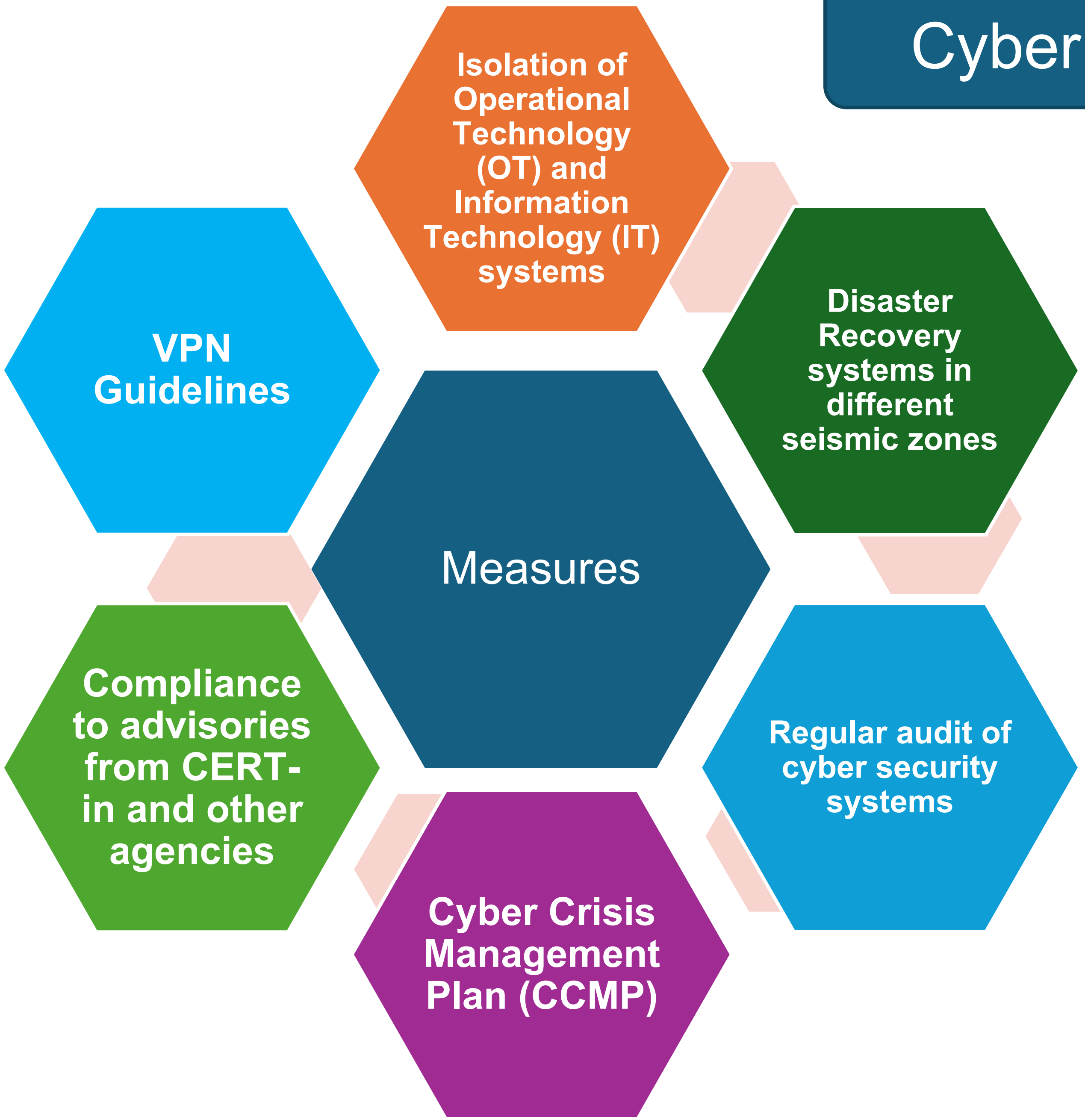
Visualization and Situational Awareness in Control Centres

- 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)

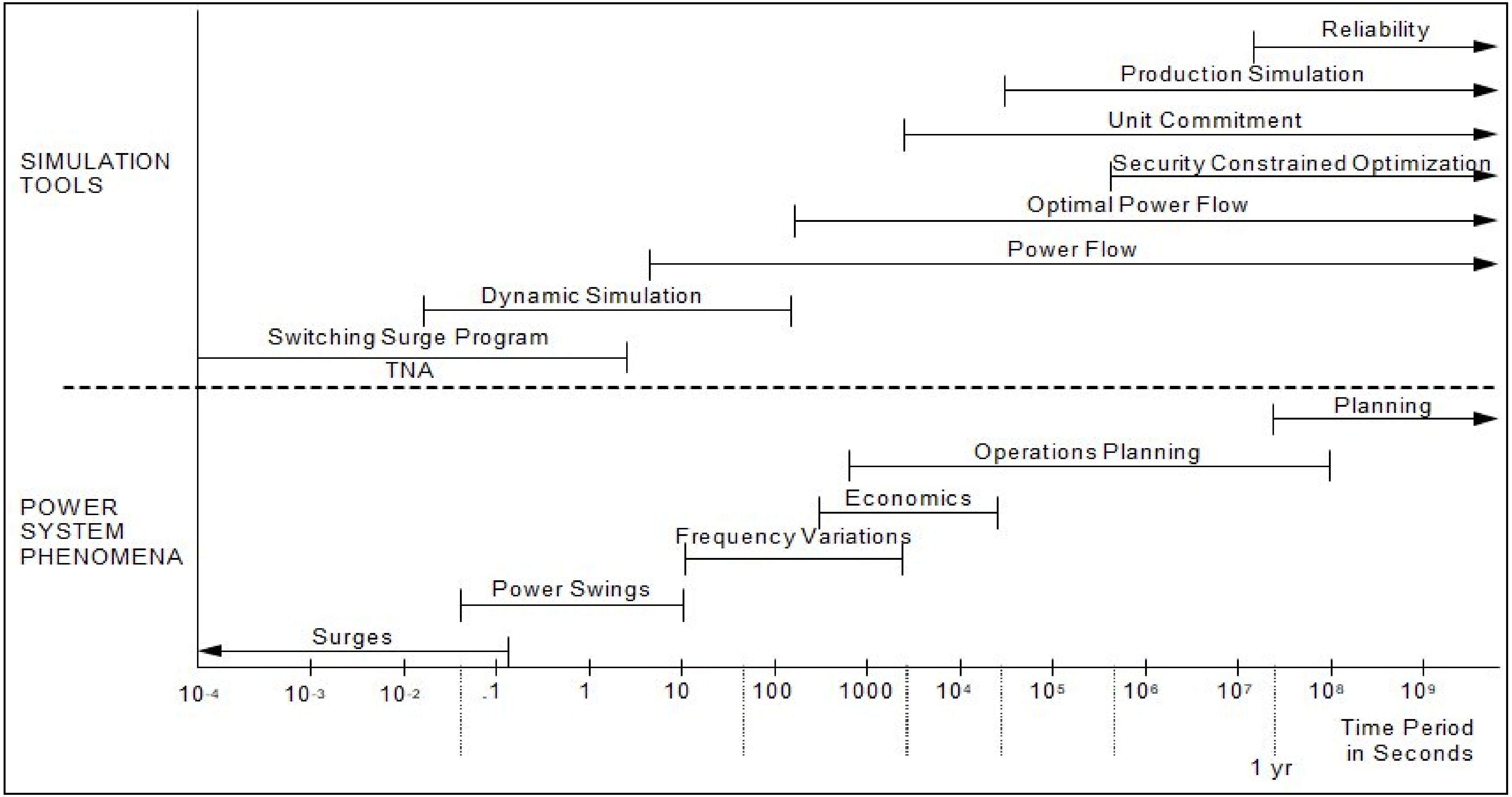
***NERC White Paper on AI and ML in Real Time System Operation; Nov 2024**

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!

For any further queries, please mail to
srnarasimhan@gmail.com