CONFEDERATION OF INDIAN INDUSTRY

Eigenvectors of net-zero energy transition: Pathways to Viksit Bharat 2047

Prepared for 6th International Energy Conference and Exhibition

September 2025

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FOREWORD

CII

India stands at a defining moment in its energy transition journey. The nation has achieved a remarkable milestone of crossing 50% non-fossil capacity, five years ahead of its Nationally Determined Contributions (NDCs). This progress is not only a testament to India's ambition but also its ability to balance sustainability with economic growth.

The analysis in this report, Eigenvectors of net-zero energy transitions: Pathways to Viksit Bharat 2047, highlights that India's pathway to becoming a developed economy will demand three times more primary energy supply by 2047 and a forty-fold scale-up of non-fossil sources. These numbers underscore both the opportunities and the challenges that lie ahead.

What makes this study distinct is its human-centric lens. By treating the net-zero transition as a multidimensional optimization challenge—balancing energy security, affordability, competitiveness, and environmental sustainability—it provides actionable guidance for policymakers, businesses, and investors.

CII is proud to convene stakeholders through the 6th International Energy Conference and Exhibition, advancing dialogue on renewable energy, nuclear power, storage, and carbon markets. With EY as our knowledge partner, we are confident this report will strengthen the foundation for India's collective march toward a resilient and prosperous Viksit Bharat 2047.

Chandrajit Banerjee

Director General
Confederation of Indian Industry

EY

India's aspiration to reach net-zero by 2070 requires radical shifts that move far beyond incremental change. By 2047, with a projected $30 trillion GDP and 1.5 billion people, the country's energy demand will triple. Meeting this will require bold advances in renewable integration, nuclear energy deployment, storage innovation, and credible carbon markets.

This report, developed jointly with CII, introduces an "eigenvectors" approach—using advanced data analysis to distill the complexity of India's energy transition into underlying patterns and trade-offs. The findings are clear: energy costs must remain competitive, imports of critical technologies must be secured, and environmental health must not be compromised if India is to achieve a human-centric energy transition.

At EY, we see this transition as an opportunity to combine global expertise with India's unique development context. We remain committed to helping industry leaders, policymakers, and investors navigate the disruptions of technology, markets, and geopolitics to unlock sustainable growth.

The insights from the report will not only inform strategies for India but also contribute to the global discourse on energy transitions in the Global South. Together with CII and our partners, we aim to translate ambition into action and ensure that India's pathway to Viksit Bharat 2047 is both inclusive and resilient.

Somesh Kumar

Partner & Leader, Power & Utilities (GPS), EY India

CONTENTS

ACRONYMS

ACVAs	Accredited Carbon Verification Agencies
AERB	Atomic Energy Regulatory Board
AHWR	Advanced Heavy Water Reactor
ALMM	Approved List of Models and Manufacturers
AMD	Atomic Minerals Directorate for Exploration and Research
AMR	Advanced Modular Reactor
BESS	Battery Energy Storage Systems
BOO	Build Own Operate
BOOT	Build Own Operate Transfer
BSRs	Bharat Small Reactors
CCCs	Carbon Credit Certificate
CCTS	Carbon Credit Trading Scheme
CDM	Clean Development Mechanism
CERC	Central Electricity Regulatory Commission
CLND	Civil Liability for Nuclear Damage Act
CPCB	Central Pollution Control Board
CTU	Central Transmission Utility
DAE	Department of Atomic Energy
ECS	Energy Cost Share
EEE	Electrical and Electronic Equipment
EoL	End of Life
EPR	Extended Producer Responsibility
ETS	Emission Trading Schemes
FBR	Fast Breeder Reactor
FDRE	Firm Dispatchable Renewable Energy
FEC	Final Energy Consumption
FGD	Flue Gas Desulphurisation
FY	Fiscal Year
GEC	Green Energy Corridor
GHG	Greenhouse Gas
GNA	General Network Access
GWP	Global Warming Potential over 100 years (as per IPCC AR5)
ICM	Indian Carbon Market
IGBTs	Insulated Gate Bipolar Transistors
InSTS	Intra-State Transmission System
IPCC	Intergovernmental Panel on Climate Change
IPPs	Independent Power Producers
ISTS	Inter-State Transmission Systems
Kgoe	Kilogram of Oil Equivalent
LCOE	Levelised Cost Of Electricity
LFP	Lithium Iron Phosphate
LMFP	Lithium Manganese Iron Phosphate
LW	Light Water (reactors)
MoEFCC	Ministry of Environment, Forest and Climate Change
MoP	Ministry of Power
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MOX	Mixed Oxide Fuel
Mtoe	Million Tonnes of Oil Equivalent
NCT	National Committee on Transmission
NCV	Net Calorific Value
NDCs	Nationally Determined Contributions
NEA	Nuclear Energy Agency (OECD)
NGCC	Natural Gas Combined Cycle
NPCIL	Nuclear Power Corporation of India Limited
NPPs	Nuclear Power Plants
OEMs	Original Equipment Manufacturers
OPEX	Operating Expenditure
PAT	Perform Achieve Trade
PCA	Principal Component Analysis
PEC	Primary Energy Consumption
PFBR	Prototype Fast Breeder Reactor
PHWR	Pressurized Heavy Water Reactor
PLI	Production Linked Incentive
PM2.5	Particulate Matter $\leq$ 2.5 micrometers
POSOCO	Power System Operation Corporation (now Grid Controller of India Ltd.)
PPA	Power Purchase Agreement
PRO	Producer Responsibility Organisation
PROs	Producer Responsibility Organisations
PRTRF	Power Reactor Thorium Reprocessing Facility
PSDF	Power System Development Fund
PWR	Pressurized Water Reactor
RCC	Reinforced Cement Concrete
RDSS	Revamped Distribution Sector Scheme
RECs	Renewable Energy Certificates
RETV	Residential Envelope Transmittance Value
RoW	Right of Way
RPCs	Regional Power Committees
RTC	Round-The-Clock
RTM	Regulated Tariff Mechanism
SBs	Standardised Baselines
SLAs	Service Level Agreements
SLDCs	State Load Dispatch Centers
SMR(s)	Small Modular Reactor(s)
SoH	State of Health
STU	State Transmission Utility
TBCB	Tariff Based Competitive Bidding
TTC	Total Transfer Capability
USERs	Uniform System of E-Reporting (MoP initiative)
UTSF	Uranium Thorium Separation Facility
VCM	Voluntary Carbon Market

01 Executive summary

What is disrupting the energy industry?

As the sector completes 25 years in this decade, it must navigate geopolitical instability, AI-led demand surge and the accelerating energy transitions. To remain resilient, utilities need to modernize grids, integrate renewables and drive digital transformation. Key technologies such as AI, smart grids, and energy storage will be critical to boosting operational efficiency and flexibility. Managing supply chain disruptions and strengthening cybersecurity will be strategically imperative, while financial planning and strategic investments in renewable energy and technology will ensure long-term sustainability. CEOs are focusing on leveraging technology, strategic transactions, and AI to drive efficiency, navigate volatility, and ensure long-term growth in a rapidly evolving market.

Navigating net-zero energy pathways

India's energy transitions stand at a pivotal juncture, navigating geopolitical volatility, economic imperatives, and the urgent drive toward net-zero emissions by 2070. This report employs an "eigenvectors" framework, drawing from multidimensional optimization and machine learning to distil the complex dynamics of this transformation into foundational patterns and trends. By analyzing human-centric indicators, we uncover transient trade-offs shaping the net-zero energy pathways. The report frames 'net-zero energy transition' as a multidimensional optimization problem, where countries in the Global South, including India, traverse a 'transition space' defined by human-centric development imperatives for driving economic development goals. Employing data-driven techniques, we reduce complexity to uncover underlying trends. These are not merely technological shifts such as renewables, nuclear, bio-energy. etc., rather more foundational, human-centric changes improving security, reliability, and affordability of energy as a commodity for economic development, aligning with Viksit Bharat goals for 2047. We analyze primary energy intensity, energy cost share relative to GDP, energy imports, GHG emission intensity and identify other indicators, all of which are foundational to understand the long-term trends and transient trade-offs governing the speed and scale of net-zero energy transition.

Key findings reveal that **Viksit Bharat by 2047** **with a projected** **US$30 trillion** **GDP and** **1.5 billion population,** will demand ~3x current primary energy supply (~35,000 TWh), necessitating a 40x surge in non-fossil sources to meet two-thirds of this demand.

Historical trends (2000-2021) show declining energy and GHG intensity, but future ambitions require radical shifts, as projections highlight non-linear pathways diverging from past trajectories.

The share of energy costs relative to economic output (ECS) shows a remarkable long-term stability across large industrialized economies. This stability suggests that over time, the long-run elasticity of energy intensity to energy price is approximately -1. This means that when energy prices increase, the economy adjusts by improving energy efficiency, preventing a long-term rise in energy expenditure as a percentage of GDP. When ECS exceeds 10%–11% of GDP, economic growth rates tend to decline.

For India, policy-driven pathways for net-zero energy transitions must be adequately informed through tracking ECS, a vital feature to balance net-zero emission goals with affordability and cost competitiveness.

Security analysis highlights rising low-carbon energy technology imports at 0.211% of GDP in FY25. Environmental concerns persist as India and China are among the worst performing large economies on PM2.5 exposure levels – a vital feature that impacts our collective experience of achieving Viksit Bharat 2047 goals.

Sectoral deep dives underscore momentum and challenges

Renewable energy-powered electrification has achieved critical momentum. India hit ~50% non-fossil capacity five years ahead of NDCs for 2030, driven by solar and wind capacity additions in the last decade. Procurement of utility scale renewable electricity has diversified into hybrid configurations with ~22 GW FDRE and 35 GWh BESS auctions either completed or under progress. However, India's rapid buildout of renewable energy has outpaced the development of transmission infrastructure, with low TTC/Peak Demand ratios risking curtailment. Implementation of green energy corridors must be accelerated and synchronised with the trajectory of renewable energy procurement plans. This dedicated infrastructure for solar/wind evacuation directly tackles low TTC/Peak ratios by reducing congestion and enabling efficient transfer from renewable energy-rich to demand-heavy areas.

Civil nuclear energy is finally moving from promises to real value proposition. It is gaining traction via the Nuclear Energy Mission, targeting 100 GW by 2047 from 8.8 GW today. Small modular reactors offer baseload complementarity to renewables, leveraging India's thorium reserves for security and optimize levelized cost of energy services from modularity. Amendments under progress in the Atomic Energy Act, Civil Liability for Nuclear Damage Act and public-private deployment models like Bharat Small Reactors from NPCIL are welcome initiatives to de-risk investments. More importantly, civil nuclear energy helps balance emission reduction goals with security, reliability and affordability of energy.

Waste from solar PV systems deployed across India could reach 594 kt by 2030. Producer Responsibility Organizations (PROs) and advanced recycling techniques can transform waste into valuable resources, reducing import reliance of critical raw materials such as crystalline silicon ingots and copper.

The Carbon Credit Trading Scheme (CCTS) sets intensity targets for 743 entities across eight sectors, fostering compliance and voluntary offsets. Building integrity of carbon credits registered under CCTS is vital for international transfers, unlocking finance for net-zero.

By prioritizing these, India can unlock resilient growth, creating jobs, enhancing energy security, and contributing to global climate goals. EY and CII call for collaborative action to realize this human-centric vision, turning disruptions into opportunities for a sustainable Viksit Bharat.

Policy enablers for India's net-zero energy transition

Renewable energy and grid integration

- Standardize and automate data submissions for transmission planning
- Synchronize transmission build-out with 50 GW annual renewable energy procurement trajectory
- Streamline Right of Way (RoW) approvals via centralized single-window clearances
- Enforce legally binding timelines for transmission projects
- Repower old wind sites with state-specific guidelines and incentives
- Scale private investment in intra-state transmission through TBCB adoption
- Bring in independence and autonomy of State Load Dispatch Centres (SLDCs)

Civil nuclear energy

- Operationalize SMR roadmap
- Implement the proposed legislative reforms on Atomic Energy Act and Civil Liability for Nuclear Damage Act
- Secure nuclear fuel supply chain - Scale up investments in AHWRs and Fast Breeder Reactors for thorium utilization
- Streamline regulatory framework - Create a dedicated SMR regulatory framework within AERB with risk-informed, tech-neutral guidelines
- Enable regulatory pathways for repurposing retired coal plant sites with SMRs

Circular economy

- Establish a government-backed spot exchange for critical minerals to enable transparent price discovery
- Set up bonded warehouses under MCX for hedging, stockpiling, and supply security
- Implement a Battery Aadhaar system to track battery lifecycle and enforce safe scrap handling
- Harmonize GST on battery scrap to curb informal channels and reduce disposal costs
- Launch a national digital scrap-exchange platform to aggregate supply and stabilize prices

Carbon markets

- Monitor the real-time status and progress of project applications through a project tracking system
- Enforce annual performance review of accredited carbon validation and verification bodies (ACVAs/VVBs)
- Integrate standardized baselines to streamline project development within the CCTS offset mechanism
- Adopt credit issuance methodologies aligned with global benchmarks to enable seamless transferability of Indian credits across international markets

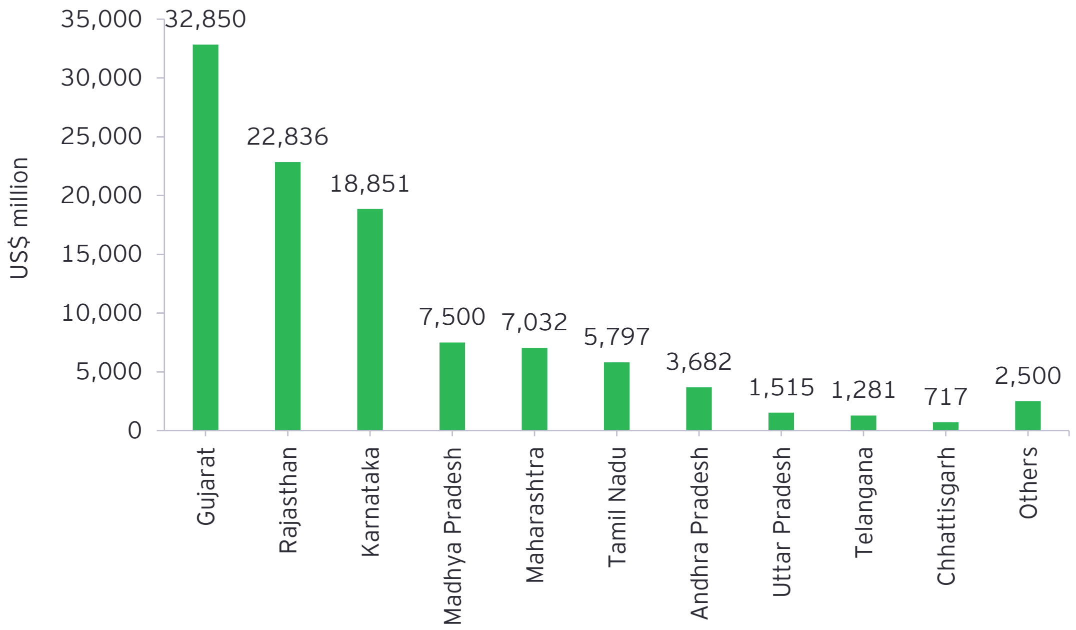
Energy transition investment monitor (ETIM)

https://etim-india.com

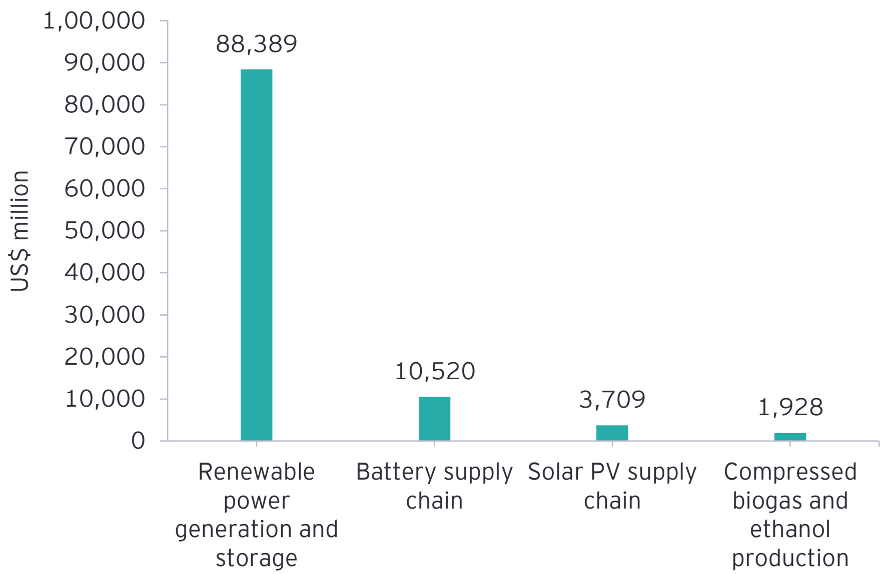
Ernst & Young LLP (EY India) in collaboration with the Confederation of Indian Industry (CII) is facilitating the development of 'Energy Transition Investment Monitor' (ETIM), a platform that enables global investors to identify and track investment opportunities across their full development cycle. The platform enables project developers to register / verify project level information of India's expanding pipeline of renewable energy investments.

ETIM also functions as a matchmaking platform for project developers and investors to establish first point of contact. Developers can add or edit projects on the platform, highlight specific requirements for capital, and in doing so receive a "verified by developer" mark that enhances the authenticity and reliability of the information. Investors registered on the platform gain access to a credible pipeline across the value chain of low carbon energy services and technology supply chains. This interactive functionality bridges the gap between India's active renewable energy project pipeline and the capital required to realize those projects, unlocking new avenues for financing the energy transition.

Top states advancing energy transition investment pipeline*



Markets and applications driving energy transition investment pipeline*



*Projects under construction; Source: EY Analysis

Total value of projects under construction

~ US$105 billion

02 Introduction to eigenvectors to analyze the state of energy transitions

Multiple energy transitions are progressing at speed and scale: Analyzing past and future trends from the lens of human-centric development imperatives in Global South

Multiple transitions reshaping energy systems are progressing at speed. Most often people perceive these transitions as renewables, nuclear reactors, bio-energy, hydro and other non-fossil energy technologies deployed at scale, rising in share to replace fossil fuel dominance in the primary energy mix. However, the true underlying transitions unfolding in the Global South, including India, are much more foundational and human-centric in nature. Countries of Global South are constantly working to balance net-zero emission goals with improving security, reliability and affordability of 'energy as a commodity / service' for meeting economic development objectives. NDCs under the Paris Agreement reflect how different countries are advancing energy transition policies to accelerate net-zero emissions between 2040 and 2070. However, the speed and scale required for this transition is often entangled with balancing other development imperatives beyond net-zero emissions. Global South, including India, is increasingly facing trade-offs between emission reduction goals and the following: 1. Security of low carbon energy production, transformation and end-use technologies and raw material supply chains; 2. Cost competitiveness, affordability and reliability of low carbon energy services for meeting economic development objectives; 3. Environmental degradation, e.g., land, groundwater, minerals and other resources for self-reliance of low carbon energy services.

These underlying or foundational transitions can be broadly mapped as development imperatives related to: energy access and efficiency, competitiveness and affordability, security and resilience, sustainability and circularity. The trade-offs are often exacerbated during the course of transition by geopolitical risks, conflicts and disruptive technologies such as AI. Some useful examples of these trade-offs include: affordability vs GHG emissions for green hydrogen offtake, affordability vs import dependency of solar PV modules / cells and manufacturers (ALMM/ALCM), import dependency vs GHG emissions of battery energy storage and electric vehicles, affordability vs PM2.5 exposure of baseload coal power generation etc.. In July 2025, the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India granted exemption for coal-fired power plants outside a 10-km radius of populated cities from installing Flue Gas Desulphurisation (FGD) systems. This is an example of balancing act for managing the trade-offs between affordability and PM2.5 exposure impacts arising from coal power generation.

This report maps energy market features with development imperatives shaping the global energy transitions and relevant human-centric indicators to encapsulate the information for best description of the state of energy transition. The historical evolution and future convergence of these indicators, for example, primary energy intensity, GHG emission intensity, import dependency of primary energy and critical low carbon technologies / raw materials, energy cost share, air pollution intensity etc. are foundational for human-centric understanding and description of the state of net-zero energy transition for the policymakers. Balancing the transient trade-offs will need a robust understanding of the correlations between multiple development imperatives and net-zero emission goals thereby making a strong case for dimensionality reduction, a useful and essential machine learning tool to analyze underlying trends and patterns ("eigenvectors") in a lower dimensional space.

The approach involves treating 'net-zero energy transition' as a multidimensional optimization problem, where countries navigate a "transition space" defined by human-centric indicators that encapsulate trade-offs between multiple development imperatives. It employs data-driven techniques to reduce complexity and uncover underlying trends and patterns. The analysis treats time-series historical evolution and future convergence (ambition) of indicators as vectors and performs statistical analysis to distil the complex transformation into 'eigenvectors' (underlying patterns and trends) which represent primary directions of variance in a high dimensional transition matrix.

Source: EY Analysis. The features analyzed in this report are limited and selected based on availability of harmonised time series data for each country in the public domain. The feature list is not exhaustive and one can add more features to comprehensively encapsulate the multiple policy driven transition goals to adequately capture all the critical development imperatives of the Global South. Historical data for 2000–2021 is compiled from sources like the Emissions Database for Global Atmospheric Research (EDGAR), International Energy Agency (IEA), World Bank, etc. and analyzed for trends, correlations, and convergence implications.

Analytical methodology for understanding the principal directions of energy transitions

STEP 01

Feature selection and vector construction

Identify key energy market features that encapsulate the high dimensional multifaceted nature of energy transitions, aligned with NDC goals and other critical development imperatives for Global South. These features include: GHG emissions per GDP (carbon intensity), primary energy intensity per GDP (efficiency), energy import share (security), PM2.5 exposure (health/environmental degradation), primary energy use per capita (access), and GHG per capita (sustainability). These are chosen for their relevance to Paris Agreement pillars (mitigation, adaptation, finance) and Global South priorities (e.g., growth, jobs, health, security, resilience, etc.). Construct feature vectors as time-series datasets (annual data from 2000–2025 or latest available).

STEP 02

Data preparation and handling multidimensionality

Construct the feature vectors into a high dimensional transition matrix (years as rows, features as columns). Normalize/standardize data (e.g., z-scores) to handle varying units (e.g., tons vs. percentages) and ensure comparability. Features are correlated often creating redundancy in analyzing the transition pathways. This justifies dimensionality reduction to reveal underlying patterns.

STEP 03

Dimensionality reduction

Analyze long-term convergence of features to distinguish historical transition from future ambition driven by policy goals. Apply principal component analysis (PCA) to transform the high-dimensional feature matrix into lower dimensions (e.g., 2–3 principal components as "eigenvectors") that capture >95% variance. PCA computes eigenvectors of the covariance matrix, projecting data onto axes of maximum variance (e.g., PC1 might represent "access, efficiency and sustainability goals" loading heavily on primary energy intensity, emission intensity; PC2 on "sustainability and security" loading on emissions, pollution and imports).

STEP 04

Plotting the high dimensional transition pathway in 2D space (historical vs. future)

Project the historical and future energy transition onto principal eigenvectors in the reduced 2D space (PC1 vs. PC2) for linear separation.

Mapping of energy transition market features with development imperatives and human-centric indicators

Energy market features

Energy supply and demand

- Primary energy production, imports and exports
- Primary energy supply and transformation
- Final energy consumption, imports and exports

Cost of energy services for economic development

- Retail energy prices, taxes and subsidies
- Total energy cost / expenditure for end-users

Imports and exports of primary energy, production / transformation technology, components and raw materials

- Imports of polysilicon, ingots, wafers, critical minerals and raw materials, rare-earth magnets, MOSFET/IGBTs, PV cell/module, Li-ion battery cell/module/pack, electrolyzer / fuel cell, etc.

Negative externalities

- GHG emissions
- PM 2.5 exposure
- Waste generation (recycling efficiency)

Development imperatives governing the speed and scale of energy transition

- Access and efficiency
- Cost competitiveness and affordability
- Security and resilience
- Sustainability and circularity

Human-centric indicators for describing the state of energy transition

Normalization factors: GDP and Population

- Primary energy intensity (per GDP)
- GHG emission intensity (per GDP)
- Energy cost/expenditure share of GDP
- Energy imports share of GDP
- Energy production/transformation technology and raw material imports share of GDP
- Primary energy intensity per capita
- GHG intensity per capita
- Energy cost/expenditure per capita
- Energy imports per capita
- Energy production/transformation technology and raw material imports per capita
- PM 2.5 exposure per cubic meter

Viksit Bharat's (~1.5 billion population and US$30 trillion GDP) **primary energy needs will be ~3x more than the current levels**

Primary energy per capita (kg of oil eq./capita/year)

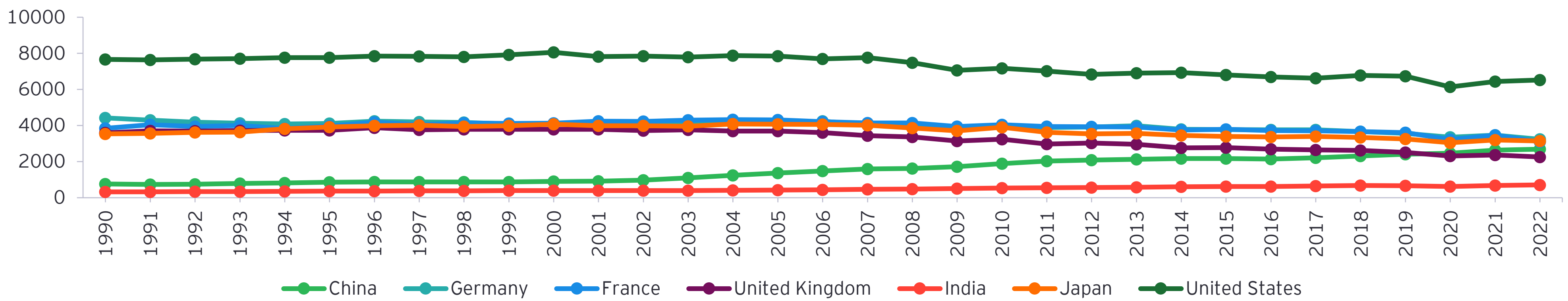
- Developed regions show a downward trend in primary energy per capita. This decline reflects efficiency gains - renewable energy adoption, transformation and end-use efficiency improvements.
- China's rise aligns with heavy industrialization, AI diffusion and urbanization.
- In the long term, as energy access becomes universal, sustainable and efficient, per capita energy use may converge. However, the direction of this convergence will rely on the energy intensity of AI diffusion and structural shifts of economic development from services to heavy industry / manufacturing.
- Renewables and nuclear energy adoption, electrification of end-use (e.g., electric vehicles) will moderate PEC per capita growth in developing nations such as India while reducing usage in developed ones.
- For India, previous studies analyzing final energy consumption (FEC) per capita vs human development index (HDI) indicate convergence between 1,300-1,400 kgoe per capita for achieving 0.9 HDI.
- Taking this into account, primary energy per capita may converge to ~2,000 kgoe per capita from current levels of ~700 kgoe per capita

Implications

- Total primary energy supply for Viksit Bharat's 1.5 billion population: ~35,000 TWh (~3,000 Mtoe)
- ~3x more than current levels of total primary energy (~10,500 TWh or ~903 Mtoe); Current levels of renewables and nuclear energy mix in total primary energy is ~0.05x (0.035x and 0.014x)
- Non-fossil energy sources must increase by ~40 times current levels to contribute at least two-third of total primary energy supply required for Viksit Bharat
- Negative elasticity of primary energy intensity per capita to per GDP is the principal challenge and a unique opportunity for unlocking value in net-zero energy transitions

Source: Garg A., Patange, O., Vishwanathan S.S., Nag, T., Singh, U., and Avashia V., (2024). Synchronizing energy transitions toward possible Net Zero for India: Affordable and clean energy for all.

Primary energy intensity* (kgoe per capita)



Source: EY Analysis; https://databank.worldbank.org/source/world-development-indicators/; *Primary energy refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.

Non-fossil energy supply must increase ~40x of current levels to contribute at least two-third of total primary energy needs of Viksit Bharat

Primary energy per GDP (kgoe/$ 2017 PPP GDP)

- All regions show a downward trend in energy use per GDP from 2000 to 2020. However, the rate of decline appears to slow over time, indicating a potential lower bound at ~0.05 kgoe/$ GDP for service based economies and ~0.10 kgoe/$ GDP for economies based on heavy industry.
- This decline indicates improving energy efficiency as less energy is required to produce a unit of economic output (GDP). Technological advancements improving energy efficiency across the value chain from extraction, production, transformation and end-use, and shifts to renewable energy sources have likely contributed to this decline. For example, China's steep decline reflects rapid renewable energy deployment and efficiency improvements, though its levels remain higher than others because of its large industrial base,
- Historically, energy efficiency improvements follow a diminishing returns pattern as technology matures. Over the long term, as India adopts best technologies in energy efficiency and renewable energy, this metric may converge in the range of ~0.05-0.10 kgoe/$ GDP from the current levels of ~0.10 kgoe/$ GDP. This reflects a practical limit where further efficiency gains become marginal without radical technological shifts.

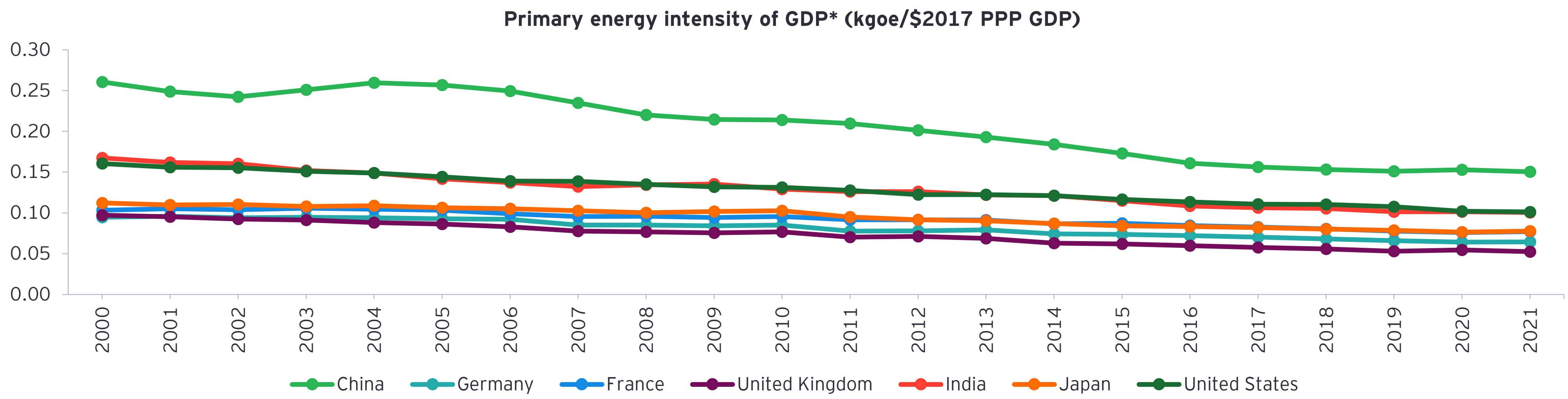
Implications

- Total primary energy supply for Viksit Bharat's ~US$30 trillion GDP (PPP): ~35,000 TWh (~3,000 Mtoe)
- ~3x more than current levels of total primary energy (~10,500 TWh or 903 Mtoe); Current levels of renewables and nuclear energy mix in total primary energy: ~0.05x (0.035x and 0.014x)
- Non-fossil energy sources must increase ~40x current levels to contribute at least two-third of total primary energy required for Viksit Bharat

India's total primary energy supply mix (%)

Source	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21	2021-22	2022-23	2023-24
Crude Oil	36.08	36.38	37.32	36.44	34.99	34.75	32.67	31.79	31.95	29.83
Natural Gas	7.48	7.32	7.63	7.7	7.44	7.85	8.04	7.73	6.71	6.99
Coal	59.27	57.56	55.97	56.7	57.31	55.79	56.3	58.57	58.4	60.21
Nuclear	1.46	1.45	1.44	1.39	1.29	1.59	1.58	1.58	1.43	1.38
RE	2.75	2.42	2.59	2.76	3.00	3.39	3.69	3.64	3.85	3.53

Source: EY Analysis; https://databank.worldbank.org/source/world-development-indicators/; https://data.worldbank.org/indicator/PA.NUS.PPP; MOSPI Energy Statistics 2025



*Energy intensity level of primary energy is the ratio between energy supply and gross domestic product (GDP) measured at purchasing power parity (PPP). Energy intensity is an indication of how much energy is used to produce one unit of economic output. Lower ratio indicates that less energy is used to produce one unit of output.

GHG intensity of primary energy supply for Viksit Bharat should converge to ~1.0 kg CO2eq per kgoe from current levels

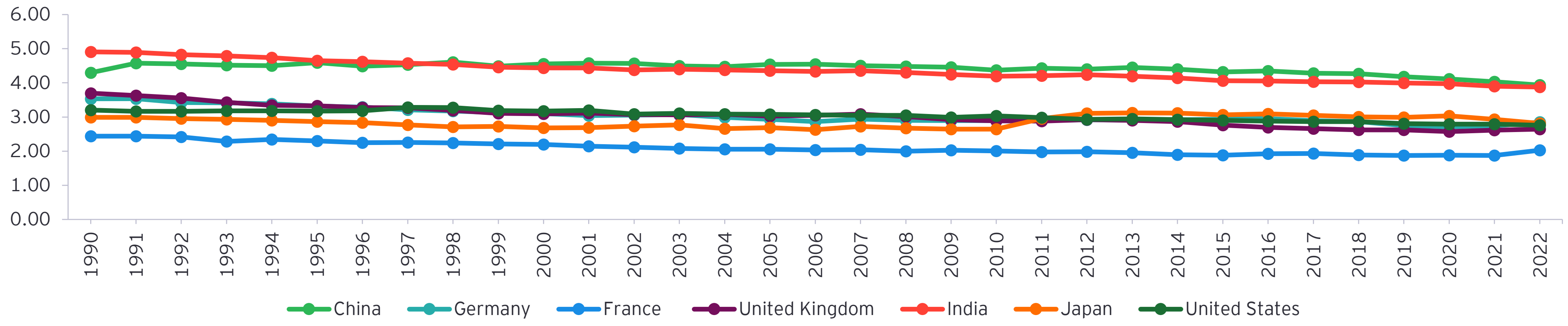
GHG per capita (tons CO2eq/cap/year)

- China's rapid rise aligns with industrial growth powered by AI and fossil fuels, posing a significant challenge to reverse the trend, while developed nations' decline indicates successful climate policies and initiatives.
- Developing nations including India will likely peak from current levels of ~3 tons CO2eq/cap/year to reach an inflection point and then decline along with developed nations as low-carbon, sustainable and cleaner energy technologies become more competitive and secure.
- A long-term convergence of ~2 tons CO2eq per capita is consistent with global net-zero ambitions.

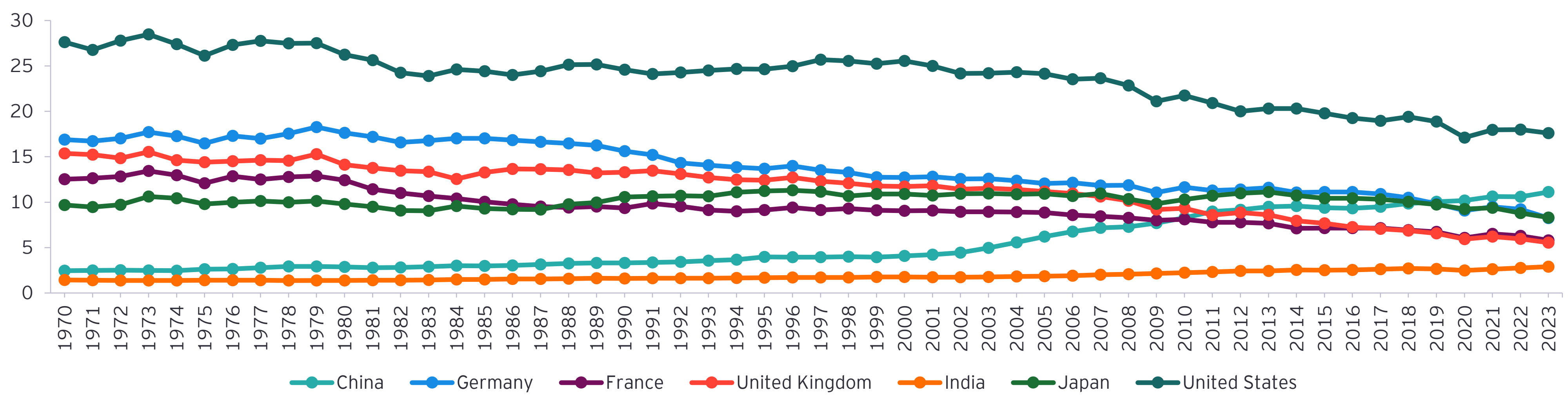
Implications

- GHG intensity of primary energy supply for Viksit Bharat (1.5 billion population) may converge to ~1 kg CO2eq per kgoe from current levels
- Total annual GHG emissions for Viksit Bharat may converge to ~3 billion tons CO2eq
- India's current levels of GHG intensity of primary energy must

GHG intensity of primary energy (kgCO2eq / kgoe) derived from per capita trends



GHG intensity per capita (tons CO2eq/cap/year)



Source: EY Analysis; EDGAR - Emissions Database for Global Atmospheric Research GHG Booklet 2024; https://edgar.jrc.ec.europa.eu/report_2024#data_download

* GHG emissions include CO2 (fossil only), CH4, N2O and F-gases. They are aggregated using Global Warming Potential values from IPCC AR5 (GWP-100 AR5).

Total annual GHG emissions of Viksit Bharat should peak and then converge to ~3 billion tons CO2eq

GHG per GDP (tons CO2eq/kUSD/year)

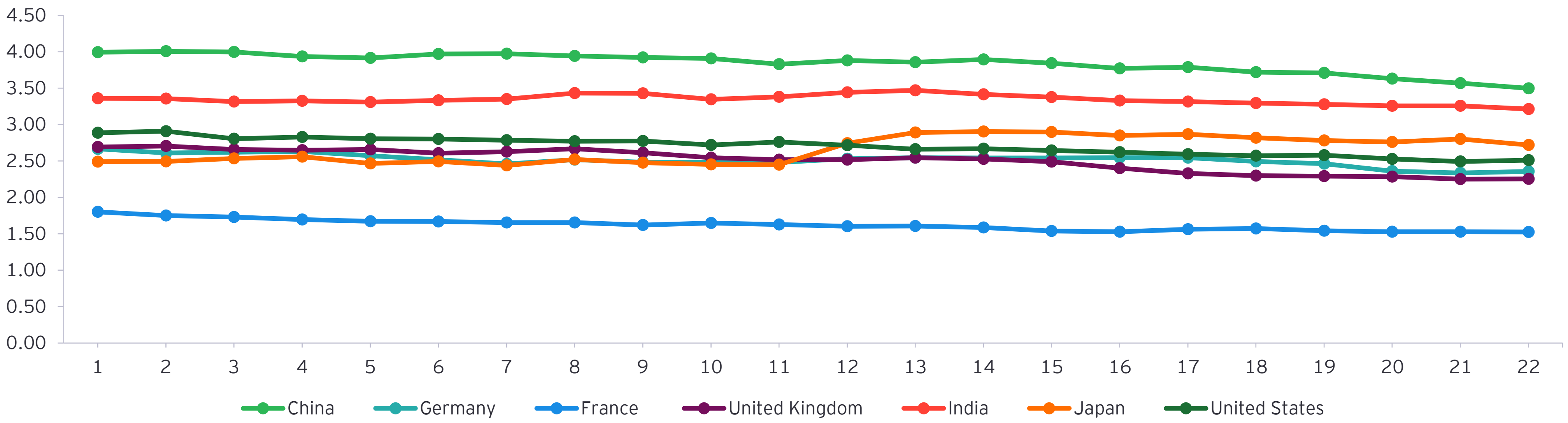
- China's sharp decline is likely due to rapid increase in renewable energy adoption.
- Other regions' downward trajectory suggests continued gradual decoupling of global emissions from economic growth.
- Many regions with high nuclear, offshore wind and hydro energy shares coupled with lower industrial base are already near ~0.1 tons CO2eq/kUSD. This metric is highly sensitive to primary energy mix and efficiency.

Less than ~0.05 tons CO2eq/kUSD aligns with net-zero scenarios where residual emissions are minimal and can be offset by carbon removal technologies.

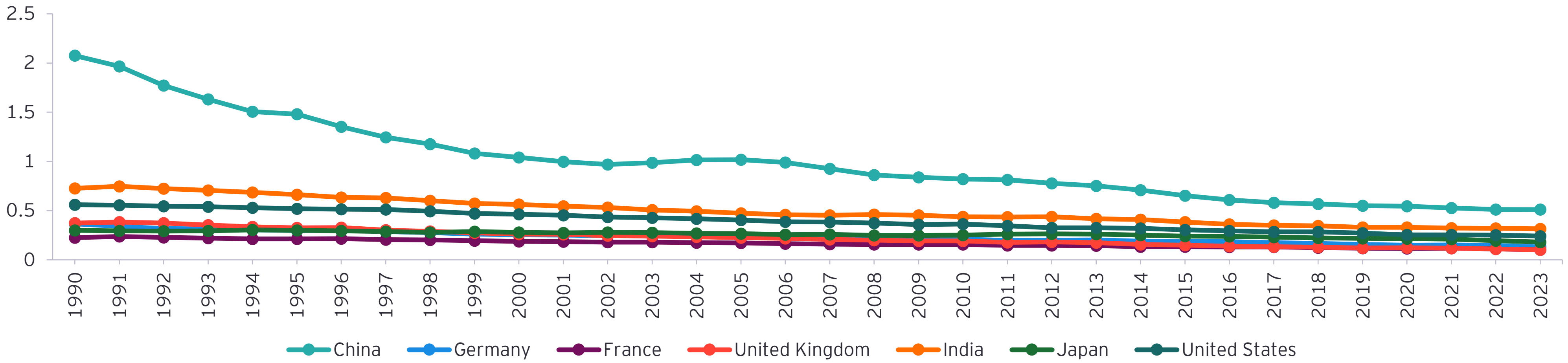
Implications

- GHG intensity of primary energy supply for Viksit Bharat (1.5 billion population) may converge to ~1 kg CO2eq / kgoe from current levels.
- Total annual GHG emissions for Viksit Bharat may converge at ~3 billion tons CO2eq.

GHG intensity of primary energy (kgCO2eq / kgoe) derived from per GDP trends



GHG intensity per GDP (tons CO2eq/kUSD/year)



Source: EY Analysis; EDGAR GHG Booklet 2024; https://edgar.jrc.ec.europa.eu/report_2024#data_download

* GHG emissions include CO2 (fossil only), CH4, N2O and F-gases. They are aggregated using Global Warming Potential values from IPCC AR5 (GWP-100 AR5).

The share of energy costs relative to economic output (ECS) shows a remarkable long-term stability across large industrialized economies

Energy cost share (ECS) is defined as ratio of Total Energy Expenditure to GDP.

Total energy expenditure refers to the aggregate cost of all final energy consumption (FEC), usually retail prices, and then expressed as a share of GDP: Total Energy Expenditure = $\sum i(Qi \times Pi)$

- Where:Qi: Quantity of final energy consumed by fuel type i (e.g., electricity, gasoline, coal)
- Pi: Retail price of energy including all taxes and subsidies per unit for fuel type i (in national currency)
- The sum is taken over all final energy sources consumed in the economy

The time series exhibit stable averages, with fluctuations driven by external energy price shocks (e.g., 1980, 2008 peaks). The energy cost share (% of GDP) is stable, with means ranging from 6.2% (Norway) to 9.17% (Canada) and standard deviations of 0.01-0.02, indicating low to moderate variability. Spikes (e.g., ~1980, ~2008) align with global energy price shocks (oil crises, commodity booms).

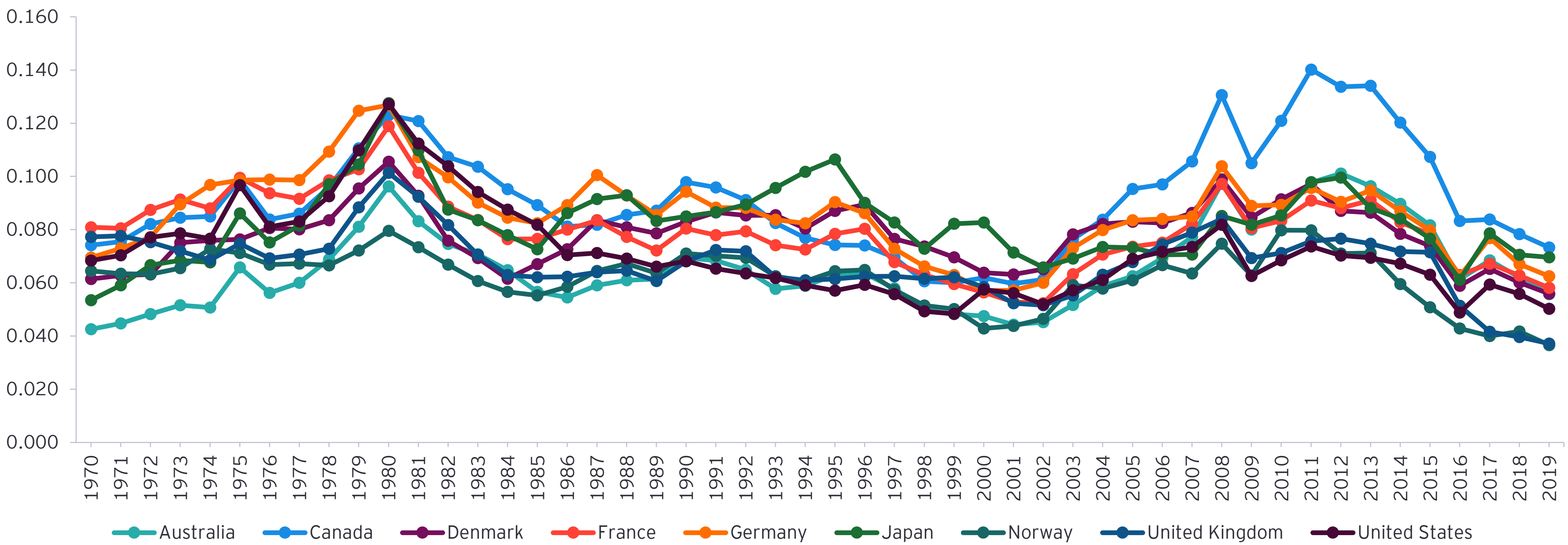
This stability suggests that over time, the long-run elasticity of energy intensity to energy price is approximately -1. This means that when energy prices increase, the economy adjusts by improving energy efficiency, preventing a long-term rise in energy expenditure as a percentage of GDP.

When ECS exceeds 10%-11% of GDP, economic growth rates tend to decline. Historical analysis shows that high ECS periods coincide with economic slowdowns and recessions. For instance, during the 1970s oil crises, ECS in the US and Europe exceeded 10%-12%, leading to growth reductions. This suggests an upper affordability threshold, beyond which economies struggle to maintain growth.

A stable, low ECS suggests energy costs will no longer be a significant economic constraint, freeing resources for other priorities (health, climate resilient infrastructure, education, etc).

For India, policy-driven pathways for net-zero energy transitions must be adequately informed from analysis of its impact on ECS in order to avoid economic shocks and ensure affordability, cost competitiveness.

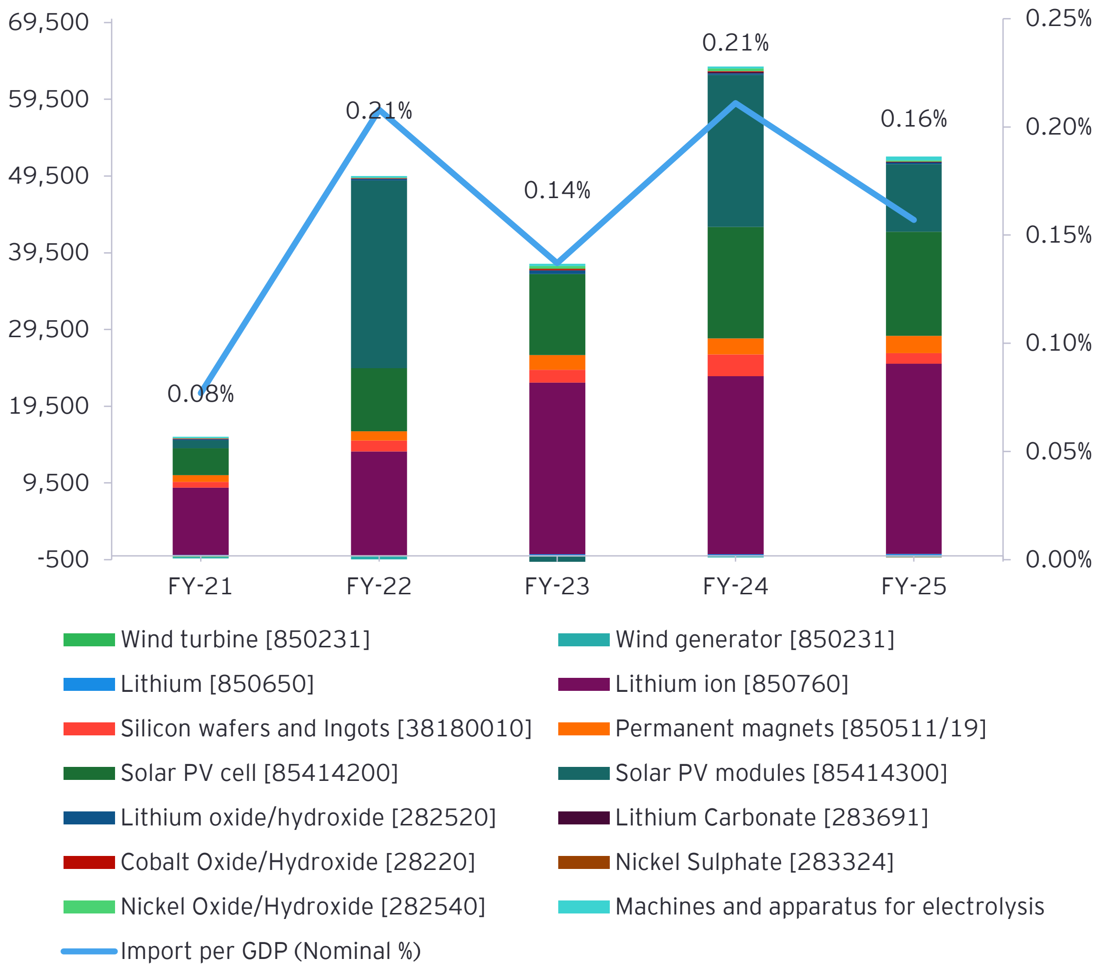
Energy cost share (ECS) relative to GDP (%)



Source: Igor Bashmakov, Michael Grubb, Paul Drummond, Robert Lowe, Anna Myshak, Ben Hinder, "Minus 1" and energy costs constants: Empirical evidence, theory and policy implications, Structural Change and Economic Dynamics, 2024, ISSN 0954-349X, https://doi.org/10.1016/j.strueco.2024.06.010.

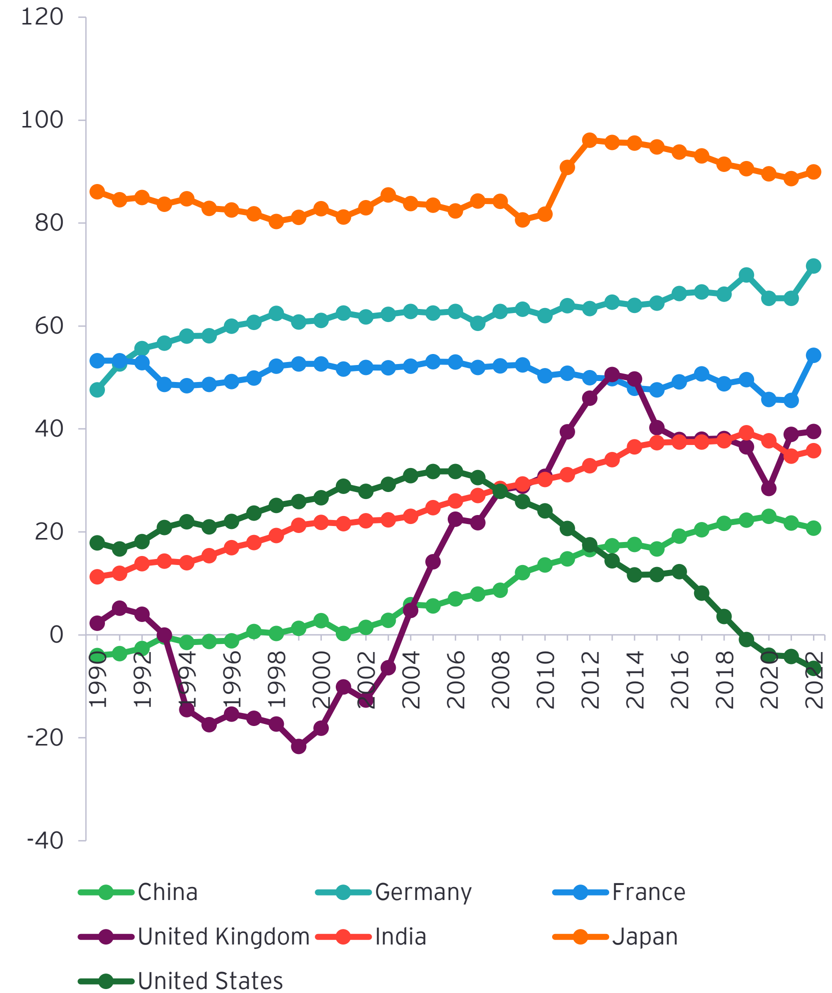
Security of net-zero energy transitions can be analyzed from the import dependence of primary energy supply, critical low carbon energy production / transformation technologies and raw materials

All India net imports of low carbon energy technologies and raw materials in INR crore (import – export)



Source: EY Analysis; https://www.dgft.gov.in/CP/?opt=trade-statistics

Energy imports, net (% of energy use)

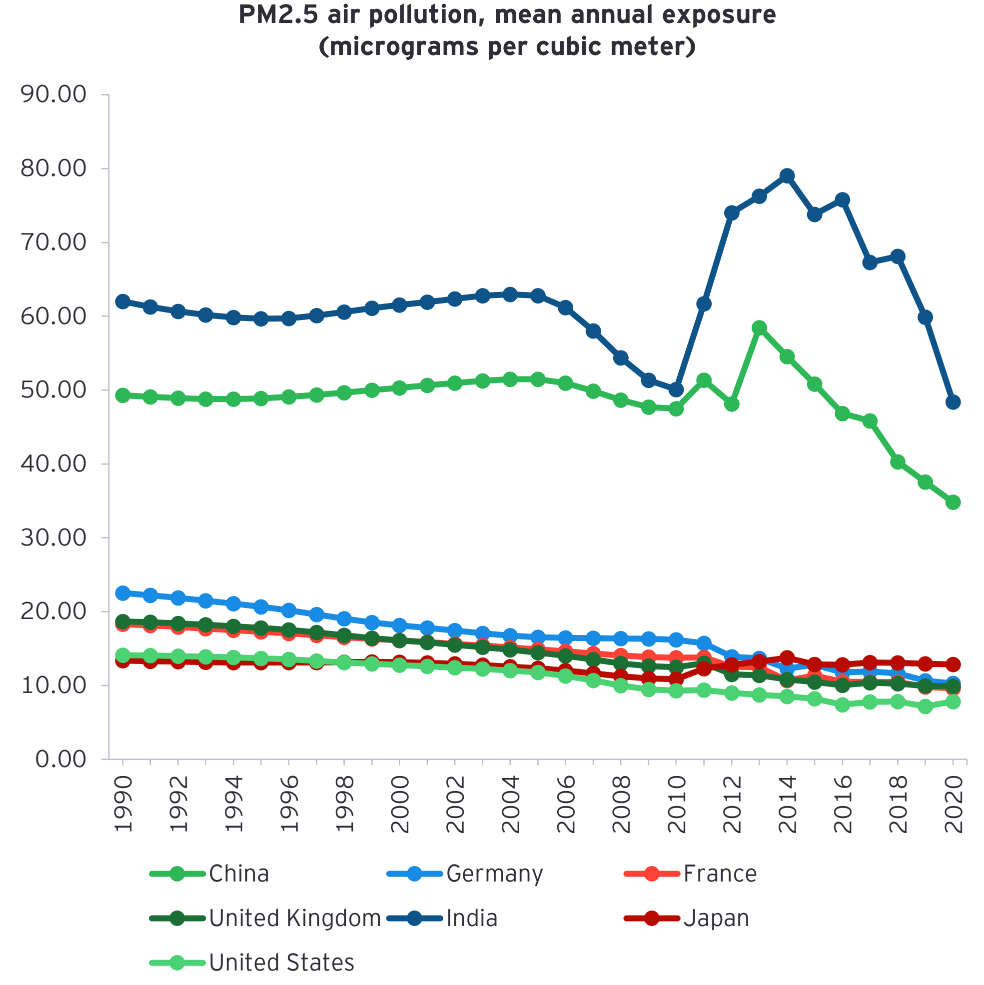


Source: EY Analysis; https://data.worldbank.org/indicator/EG.IMP.CONS.ZS

India and China are among the worst performing large economies on PM2.5 exposure levels – a vital feature that impacts our collective experience of achieving Viksit Bharat 2047 goals

PM2.5 air pollution, mean annual exposure (micrograms per cubic meter)

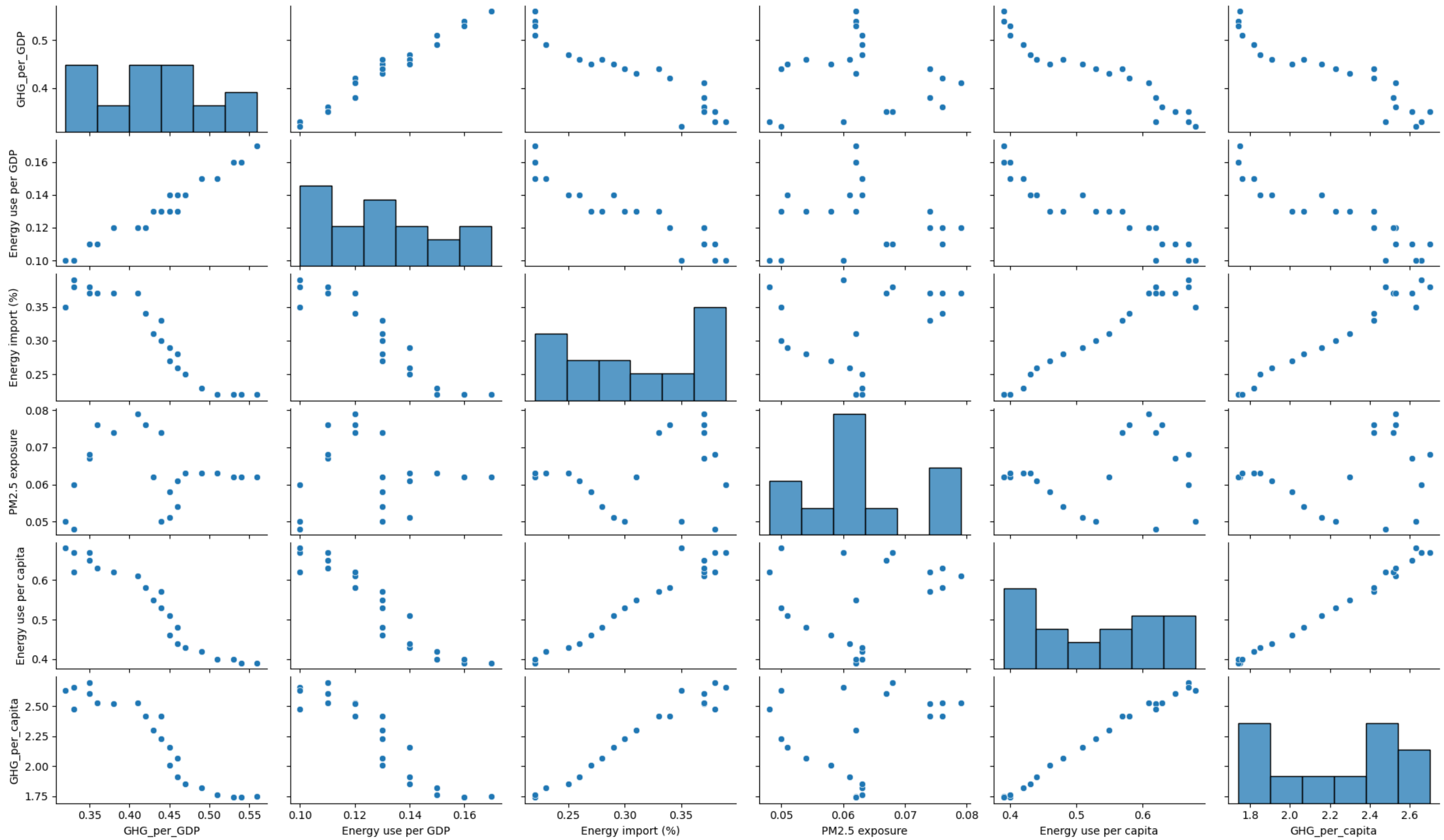
- China and India exhibit higher PM2.5 levels compared to Western nations (Germany, France, the UK, the US), reflecting differences in industrialization, energy use, and regulatory frameworks. China's peak in the early 2000s aligns with its economic boom, while India's slower rise suggests ongoing industrial growth.
- All regions show a consistent decline from 2000 to 2020, with China's drop being the most dramatic (from 75 to 35 µg/m³) and Western nations stabilizing at 10–15 µg/m³. This indicates global efforts to reduce air pollution, likely driven by stricter environmental regulations, industrial emission controls, and the adoption of cleaner energy sources.
- PM2.5 levels above 25 µg/m³ are considered hazardous by the World Health Organization (WHO), with levels above 10 µg/m³ still posing risks. In 2020, China and India remained above this threshold (35 and 30 µg/m³), suggesting ongoing health risks (e.g., respiratory issues, cardiovascular diseases), while Western nations were closer to or below the safe limit, indicating better public health outcomes.
- The sharp decline in China post-2010 reflects aggressive air quality policies (e.g., the Air Pollution Prevention and Control Action Plan since 2013), including coal plant closures and introduction of emission standards. The steady decline in Western nations suggests decades of environmental policy success, such as the Clean Air Act in the US.
- The initial rise in China and India correlates with rapid economic growth and industrialization, increasing emissions from manufacturing and energy production. The subsequent decline suggests a shift toward cleaner technologies and services, aligning with global trends toward sustainability.
- Long term, if current trends continue, PM2.5 levels may converge to < 10 µg/m³ globally, especially as developing nations adopt advanced pollution controls and non-fossil energy sources. However, this will depend on sustained policy efforts and economic development balancing growth with environmental health.



Source: https://databank.worldbank.org/source/world-development-indicators/

*Population-weighted exposure to ambient PM2.5 pollution is defined as the average level of exposure of a nation's population to concentrations of suspended particles measuring less than 2.5 microns in aerodynamic diameter, which are capable of penetrating deep into the respiratory tract and causing severe health damage. Exposure is calculated by weighting mean annual concentrations of PM2.5 by population in both urban and rural areas.

Covariance matrix of India's energy transition features for the period 2000-21



- Strong correlations observed between primary energy intensity, GHG intensity and energy imports.
- The 22-year historical transition can be explained with two principal eigenvectors-enabling dimensionality reduction.

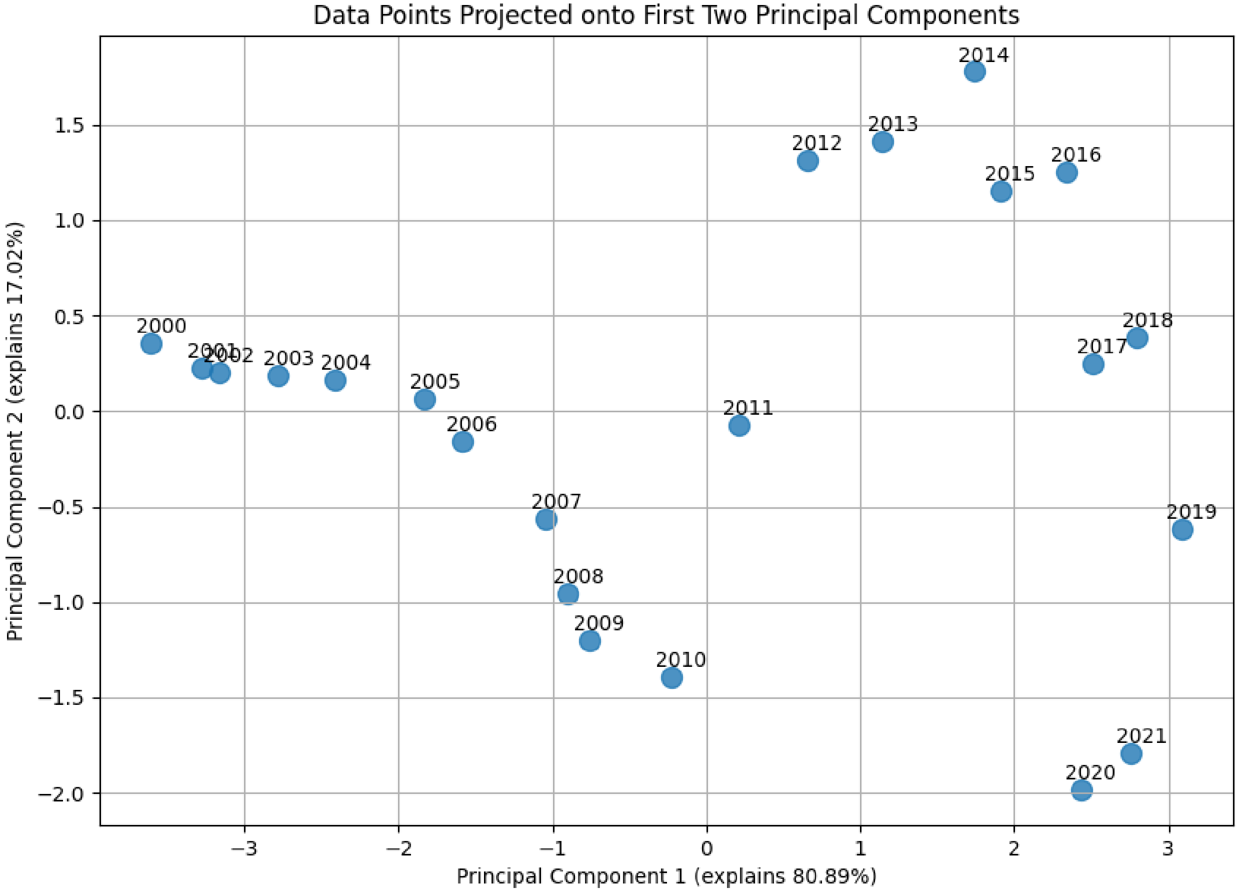
Source: EY Analysis

Projecting the historical (2000-21) energy transition features onto principal eigenvectors for linear separation and lower dimensional visualisation

Year	GHG per GDP (tonsCO2eq/kUSD/yr)	Primary energy intensity (toe/kUSD 2017 PPP GDP)	Energy import share (ratio)	PM2.5 mean annual exposure (nanograms per m3)	Primary energy (toe per capita)	GHG per capita (tonsCO2eq/cap/year)
2000	0.56	0.17	0.22	0.062	0.39	1.75
2001	0.54	0.16	0.22	0.062	0.39	1.74
2002	0.53	0.16	0.22	0.062	0.40	1.74
2003	0.51	0.15	0.22	0.063	0.40	1.76
2004	0.49	0.15	0.23	0.063	0.42	1.82
2005	0.47	0.14	0.25	0.063	0.43	1.85
2006	0.46	0.14	0.26	0.061	0.44	1.91
2007	0.45	0.13	0.27	0.058	0.46	2.01
2008	0.46	0.13	0.28	0.054	0.48	2.07
2009	0.45	0.14	0.29	0.051	0.51	2.16
2010	0.44	0.13	0.30	0.050	0.53	2.23
2011	0.43	0.13	0.31	0.062	0.55	2.30
2012	0.44	0.13	0.33	0.074	0.57	2.42
2013	0.42	0.12	0.34	0.076	0.58	2.42
2014	0.41	0.12	0.37	0.079	0.61	2.53
2015	0.38	0.12	0.37	0.074	0.62	2.52
2016	0.36	0.11	0.37	0.076	0.63	2.53
2017	0.35	0.11	0.37	0.067	0.65	2.61
2018	0.35	0.11	0.38	0.068	0.67	2.70
2019	0.33	0.10	0.39	0.060	0.67	2.66
2020	0.33	0.10	0.38	0.048	0.62	2.48
2021	0.32	0.10	0.35	0.050	0.68	2.63

- Principal component 1 = α1*feature1 + α2*feature2 + α3*feature3 + α4*feature4 + α5*feature5 + α6*feature6
- Principal component 2 = β1*feature1 + β2*feature2 + β3*feature3 + β4*fetaure4 + β5*feature5 + β6*feature6

Where, feature1-6 represents time series data scaled from 2000-21 (see table); α1-6 and β1-6 represent loadings / weights that reflect the importance of that feature computed using machine learning algorithm for dimensionality reduction



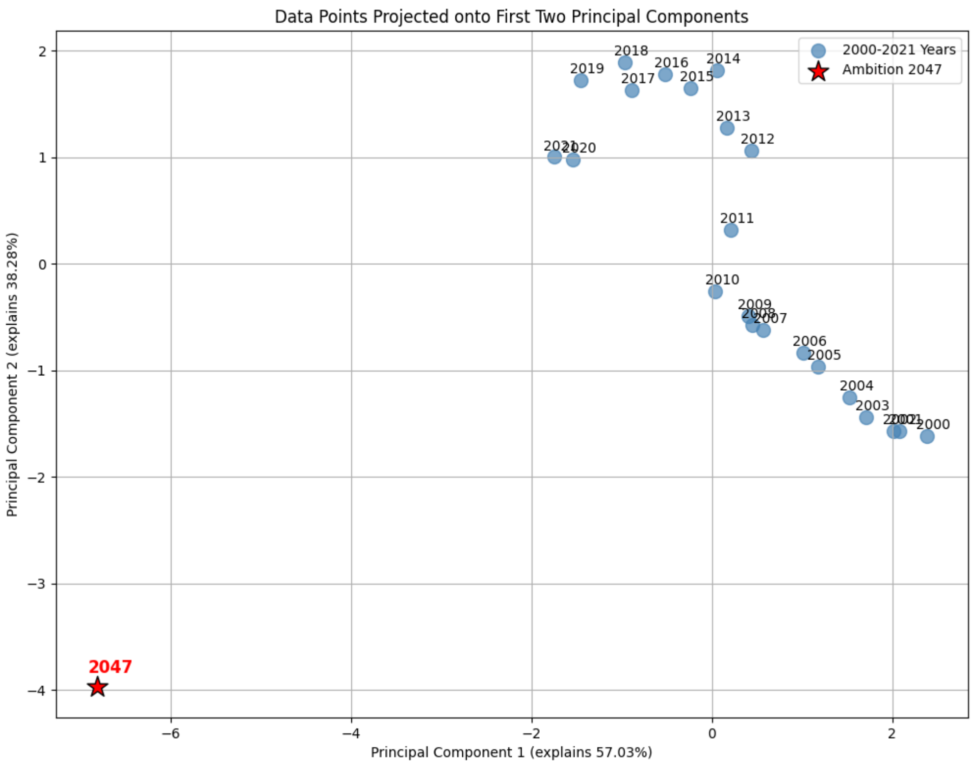
Source: EY Analysis

Projecting the future energy transition (2000-21 + 2047 ambition) onto principal eigenvectors for linear separation and lower dimensional visualisation

Energy transition features	Net-zero ambition for 2047*
GHG per GDP (tons CO2eq/kUSD/yr)	0.050
Primary energy intensity (toe/kUSD 2017 PPP GDP)	0.050
Energy import share (ratio)	0.100
PM2.5 mean annual exposure (nanograms per cubic meter)	0.010
Primary energy (toe per capita)	2.000
GHG per capita (tonsCO2eq/cap/year)	2.000

- When the 2047 ambition is considered, the principal components (PC1 and PC2) drastically re-orient themselves with different loadings (importance / significance) among features.
- For the historical transition (2000-21), PC1 had high loadings for primary energy, GHG and imports and PC2 had high loadings for PM2.5 exposure as per the correlation matrix.
- Whereas, for the future energy transition, the 2047 point is incredibly far from the historical cluster. Its relative position to the historical cluster means it represents a state of radically lower emissions, import reliance, pollution, energy / GHG intensity of GDP.
- More importantly, this dramatic separation mathematically confirms that the net-zero energy transition is not a simple linear extension of the historical 2000-2021 trends.

- Limitations: As we incorporate more features (e.g., energy cost share, waste generation and recycling efficiency, technology and raw material imports, etc.) to analyze India's net-zero energy transition, the number of principal components (eigenvectors capturing >95% variance) for low dimensional mapping of transition may also increase depending on how all the features correlate with each other. In the future iterations of this report, we will compare India's eigenvectors (~PC loadings) with that of other countries, for example, China, the US, and EU to draw useful insights for policy actions.



Source: EY analysis; *derived from long term convergence trends analysed in previous slides

Conclusion: Toward a human-centric energy transition

India's path to Viksit Bharat 2047 requires more than just achieving gigawatt or emissions targets. A **human-centric transition** demands:

- **Universal access to affordable, reliable, and clean energy,**
- **Secure and self-reliant technology supply chains,**
- **Circular economy principles to manage environmental externalities,**
- **Integrated planning using multidimensional metrics rather than siloed targets.**

India's energy transition is defined by a set of **ambitious yet fragmented goals** announced under various national frameworks and international commitments. These include:

- **500 GW of non-fossil energy capacity by 2030**
- **50% of energy requirement from renewable sources by 2030**
- **One billion tons of projected carbon emissions reduction by 2030**
- **45% reduction in carbon intensity of the economy by 2030**
- **Net zero emissions by 2070**

Individually, these targets reflect an impressive aspiration for decarbonization. However, they largely focus on **supply-side expansion** and **emission reductions**, without adequately capturing the **interlinkages, trade-offs, and human development dimensions** shaping India's energy future. **While useful, these single-variable metrics overlook the systems-level interactions shaping the energy transition. The report argues that linear metrics cannot capture multidimensional trade-offs.** They do not explain whether:

Energy is **affordable** for households and industries,

Supply chains for critical technologies and minerals are **secure,**

Energy use is **efficient** and supports **economic competitiveness,** or

Environmental externalities like **air pollution** and **waste generation** are managed sustainably.

We suggest an integrated approach that goes beyond how much energy we produce, we must also ask deeper questions:

How energy is consumed: Access and efficiency of energy use are fundamental for inclusive growth.

At what cost: Energy affordability and cost-competitiveness shape economic productivity and household welfare.

Trading energy as a service / commodity: Security of supply chains, trade dependencies, and system resilience determine long-term stability.

Managing externalities: Pollution, carbon emissions, and waste impacts need to be addressed alongside energy security and growth.

The shift from **fragmented supply-centric targets** to **human-centric development indicators** provides a fuller picture of the energy transition's implications for people, the economy, and the environment.

India's energy transition will benefit by shifting from fragmented, target driven planning to integrated, risk-informed policymaking. Unintended consequences (e.g., curtailment risks and import dependencies) can be anticipated early through multidimensional analysis.

Trade-offs between affordability, security, and sustainability become explicit, enabling better prioritization.

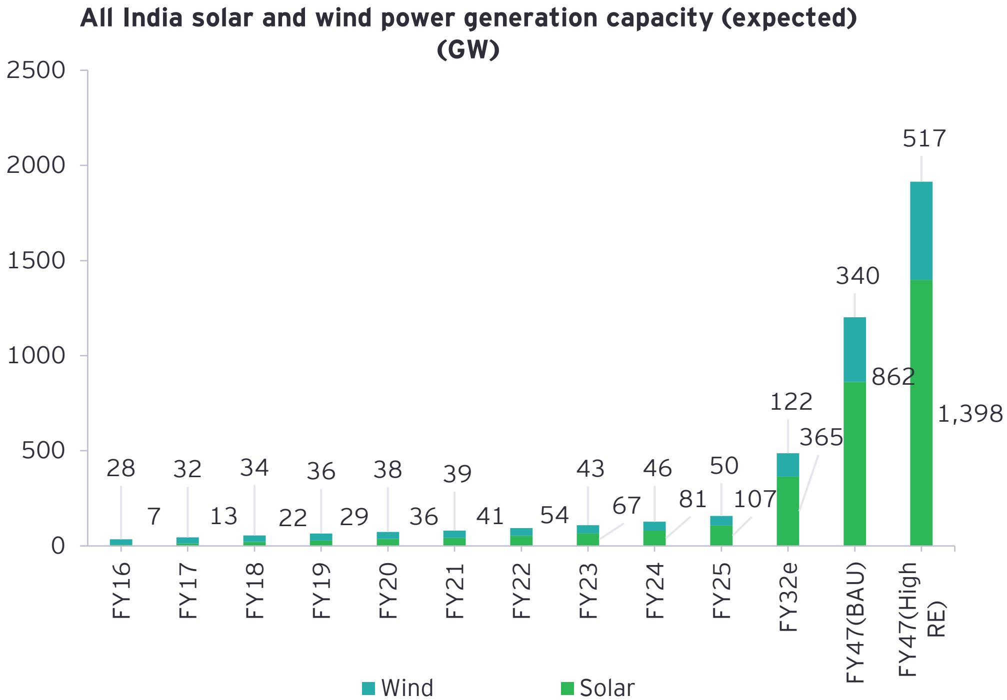
Resilience to geopolitical shocks, technology disruptions, and climate risks can be built systematically.

This approach thus transforms policymaking from reacting to isolated problems into optimizing across multiple objectives simultaneously—economic growth, social well-being, environmental protection, and global competitiveness.

Source: EY analysis; *derived from long term convergence trends analysed in previous slides

03 Renewable energy: Achieving critical momentum

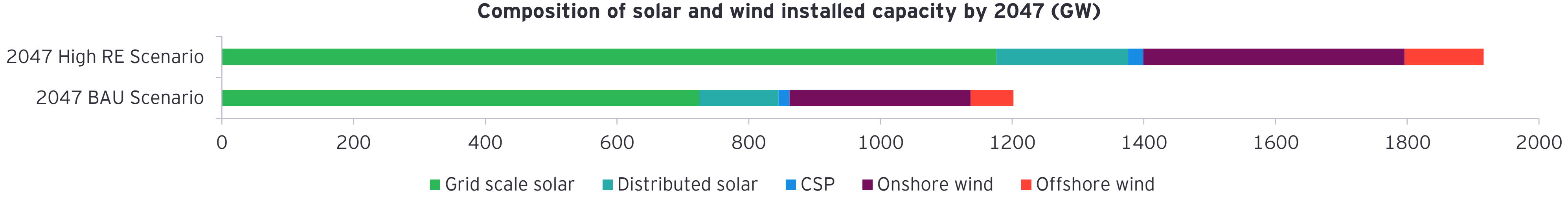
India has achieved ~50% share of power generation capacity from non-fossil energy sources five years ahead of the target set under Nationally Determined Contributions (NDCs) under the Paris Agreement



India's renewable energy sector has reached critical momentum in capacity additions achieving ~188 GW as on 30 July 2025. Non-fossil sources contributed ~243 GW of installed capacity (including large hydro ~49.6 GW and nuclear ~8.8 GW) which is >50% of all India installed capacity (~490 GW as on 30 July 2025), five years ahead of the target set under its NDCs under the Paris Agreement. Despite making up over ~40% of total installed power generation capacity (~490 GW as on 30 July 2025), renewable energy sources contribute less than 15% of all India electricity generation in kWh.

Solar power has been the key driver, contributing over 120 GW, while wind energy lags at around 50 GW. This expansion is a result of enhanced institutional capacity for periodic demand aggregation and streamlined bulk procurement, derisked power purchase agreements, enforced payment security systems, harmonized regulations governing green energy open access markets, etc.

The market, largely driven by plain vanilla wind and solar power auctions, has progressed towards hybrid projects blending solar-wind-storage technologies and merchant power markets. The market has evolved into Round-the-Clock (RTC), Firm and Dispatchable Renewable Energy (FDRE) models. This transition is aligned to provide greater flexibility for integrating large shares of intermittent renewable energy with the grid. Multiple variants of generation profiles – load following, peak hour supply, round the clock, etc., are being adopted to suit power procurement needs of discoms.

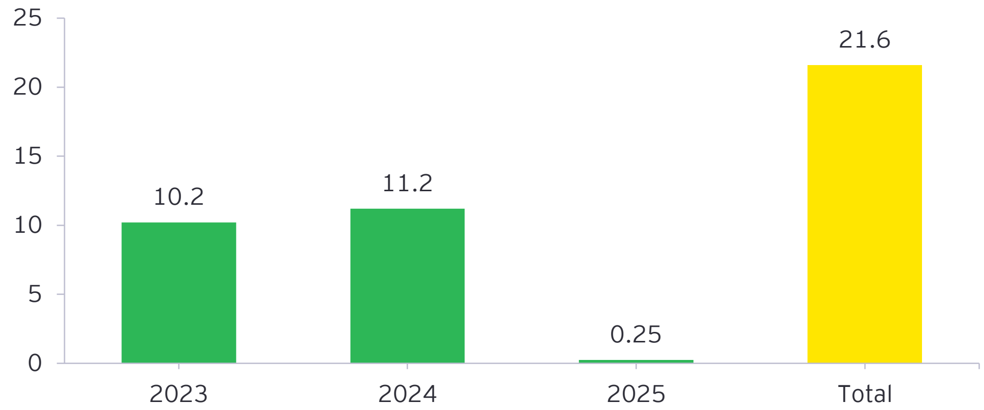


Source: MNRE, MoP, CEA, EY Analysis; https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2064702 , https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=2064702; https://www.pib.gov.in/PressReleasePage.aspx?PRID=2144627 , IESS 2047, https://mnre.gov.in/en/energy-storage-systemsess-overview/

- Business-As-Usual (BAU) Scenario: This describes the level of effort which is deemed practically achievable based on historical trends as well as recent progress.
- High RE: This considers extremely aggressive and ambitious options depending on technical limits and capabilities.

Utility scale renewable energy procurement has diversified into hybrid configurations blending solar - wind - storage and merchant power sales for enabling firm, dispatchable, round the clock supply at competitive prices

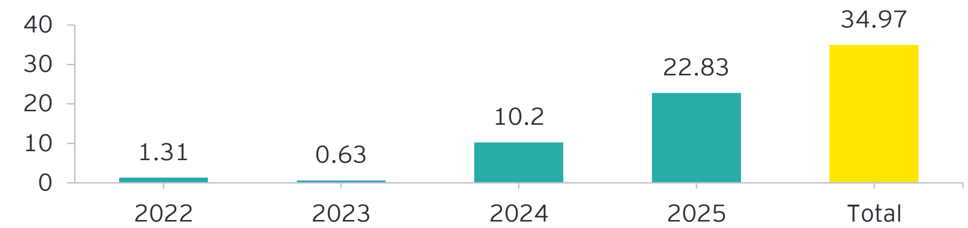
FDRE tenders - Status quo (2023 - 2025)



Parameter	Capacity (GW)	Quantity (No.s)
Total	21.6	20
RFP Stage	5.1	5
Bidding Closed	-	-
Awarded	5.8	6
Under Construction	6.3	4
Cancelled	6.7	5

Note: Cancelled capacity includes capacity not awarded

Standalone BESS tenders - status quo (2022 - 2025)



Project stage	Capacity (GWh)	Quantity (No.s)
Total	34.8	39
Operational	0.04	1
Under Construction	5.50	7
Awarded	6.90	10
Cancelled/ On Hold	4.70	9
Bidding Closed	0.50	1
Tender Open	5.50	7
Notice for Tender	10.02	2

Tender type	Capacity (GWh)	Quantity (No.s)
EPC	13.1	12
BOOT	2.9	5
BOO	18.7	22

Capacity under VGF	No. of tenders	VGF (%)
12.1 GWh	15	30% of Capex

Source: EY Analysis based on information compiled by Debmalya Sen - India Energy Storage Alliance (IESA), https://www.linkedin.com/posts/debmalya-sen_standalone-bess-tariff-update-activity-7343599816930668544-tQP0?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A, https://www.linkedin.com/posts/debmalya-sen_india-ess-market-update-june-2025-1st-anniversary-activity-7345349000843161600-RXVR?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A, https://www.linkedin.com/posts/debmalya-sen_fdre-2023-2025-activity-7350797945534902272-8LtF?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A

Utility scale renewable energy procurement strategies have diversified to include advanced tendering mechanisms designed to ensure firm, reliable, and dispatchable renewable power. A key development has been the rise of FDRE tenders, which have seen over 21.6 GW of capacity tendered between 2023 and 2025. These tenders are structured to provide peak power or RTC supply, often through hybrid configurations backed by storage. While a substantial portion of this capacity has been awarded or is under construction, a significant fraction remains at the request-for-proposal or cancelled stage—indicating both the high ambition and ongoing market adjustment to new commercial models.

FDRE procurement is a shift from plain renewables to "firm" power, aligning with India's net-zero goals and grid integration needs.

Simultaneously, standalone BESS tenders have gained momentum as a critical enabler of grid stability and renewable energy integration. Between 2022 and 2025, nearly 35 GWh of BESS capacity has been tendered across 39 projects, supported through multiple contracting structures including EPC, BOOT, and BOO. To accelerate cost competitiveness, the government has introduced Viability Gap Funding (VGF) covering up to 30% of capital expenditure, with 12.1 GWh of capacity already covered under VGF-supported tenders.

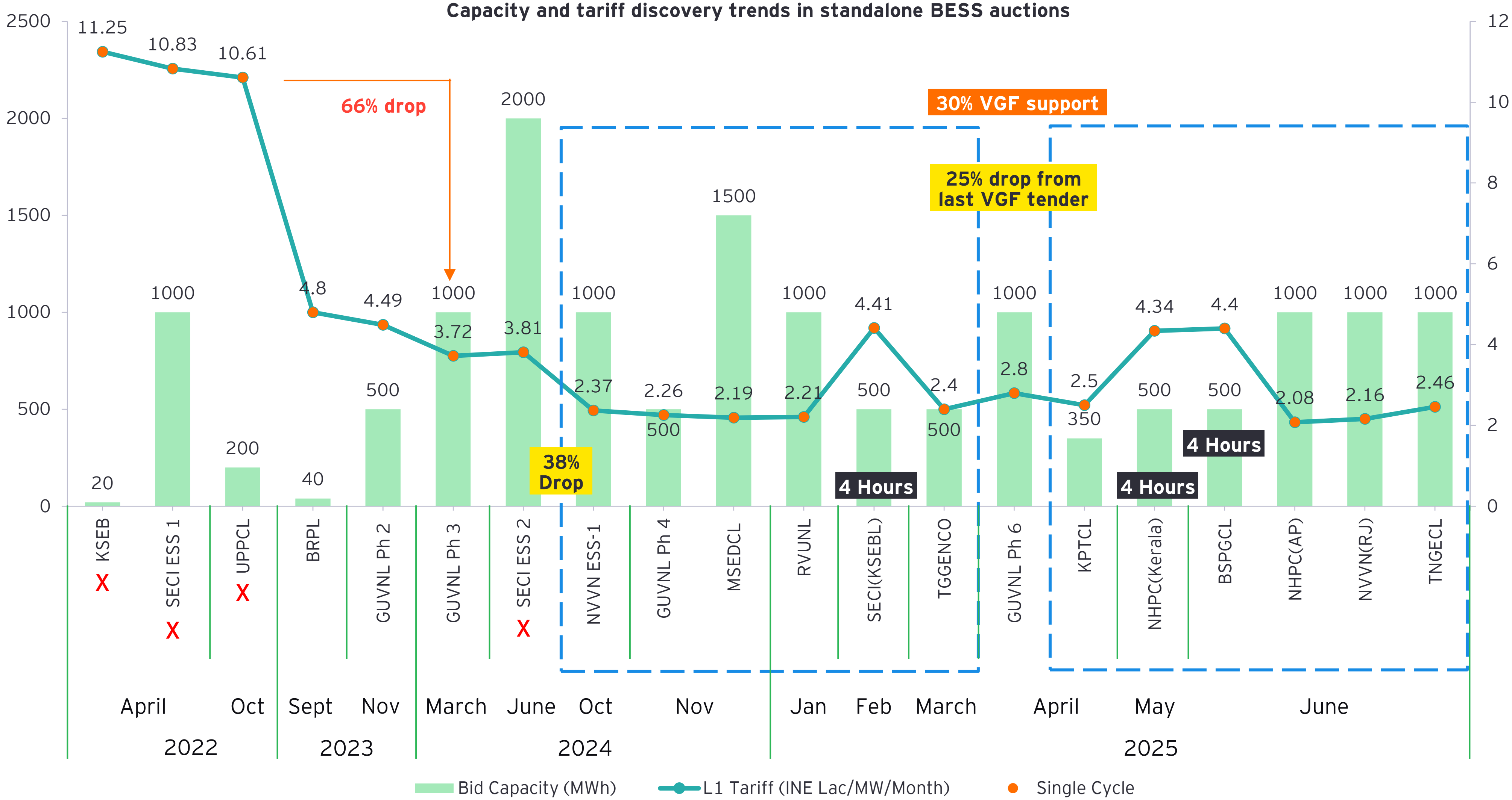
Standalone BESS auctions underscore increasing participation and learning for competitive tariff discovery

Tariffs for BESS as a service have shown steep decline—by as much as 66% in some periods —and stabilized in the last two years due to falling prices of batteries, VGF intervention and enhanced industry confidence.

Recent BESS tenders have increasingly mandated longer storage durations (up to 4 hours), reflecting India's ambition to move beyond peak shaving toward deeper energy shifting and grid support.

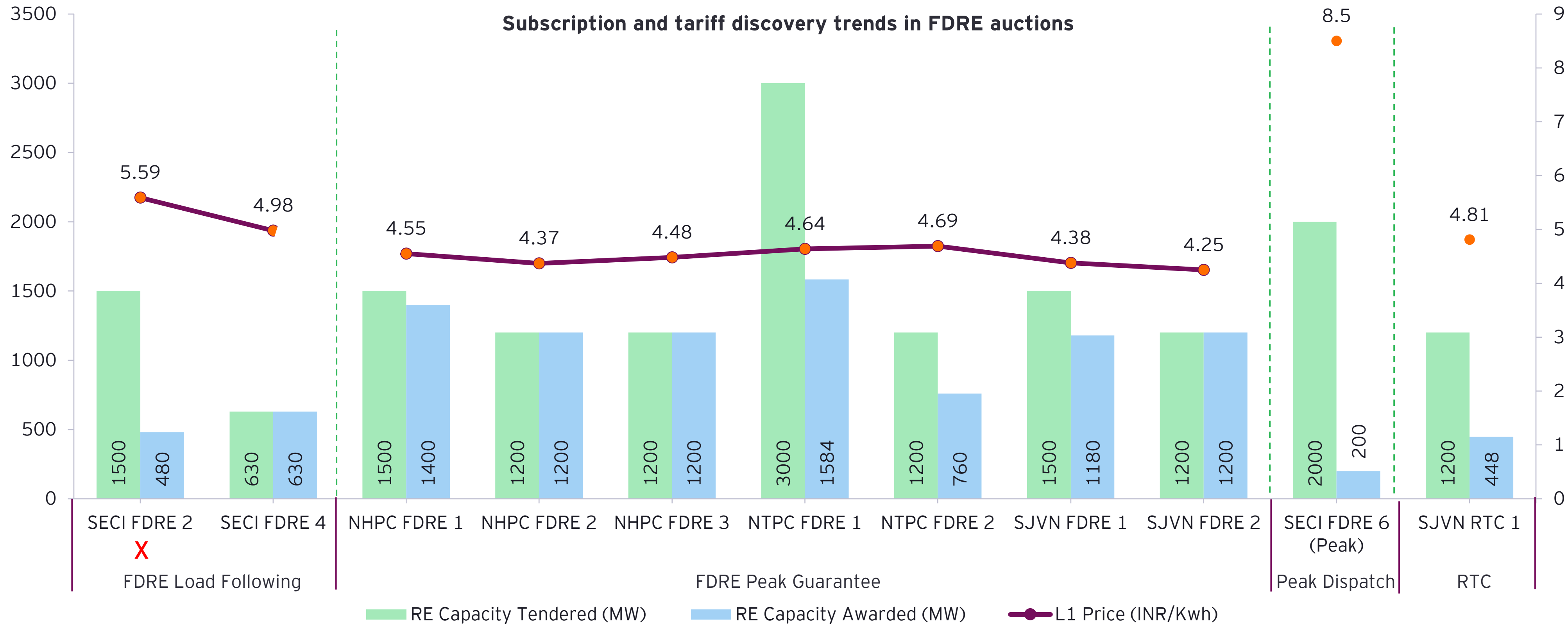
Auctions for peak supply and load-following products have resulted in tariffs in the range of INR4.25 to INR4.69/kWh, with RTC tenders commanding a slightly higher premium around INR4.81/kWh, given the guaranteed dispatch requirement. While capacity awarded has varied across tendering rounds, with some auctions falling short of full award, the trend underscores increasing participation and a learning curve among both procurers and developers.

Capacity and tariff discovery trends in standalone BESS auctions



Source: EY Analysis based on information compiled by Debmalya Sen - India Energy Storage Alliance (IESA), https://www.linkedin.com/posts/debmalya-sen_standalone-bess-tariff-update-activity-7343599816930668544-tQP0?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A, https://www.linkedin.com/posts/debmalya-sen_india-ess-market-update-june-2025-1st-anniversary-activity-7345349000843161600-RXVR?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A, https://www.linkedin.com/posts/debmalya-sen_fdre-2023-2025-activity-7350797945534902272-8LtF?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A

FDRE procurement needs targeted interventions to boost subscription and innovation



The downward trend signals improving affordability of dispatchable renewables, making them competitive with fossil fuels. However, specialized models like peak dispatch remain costlier, indicating that storage tech needs further innovation to reduce premiums.

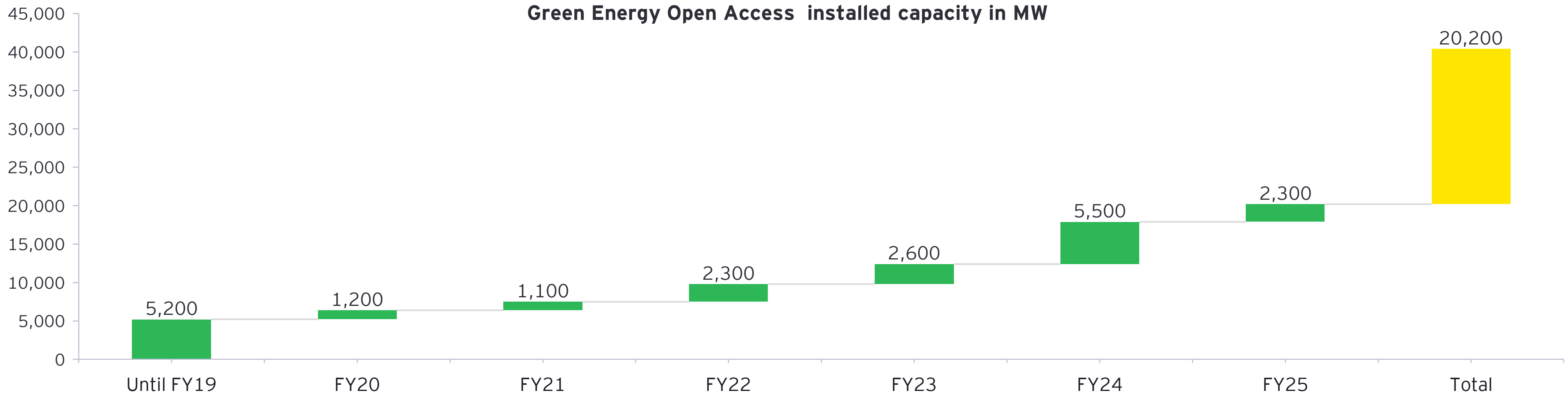
Undersubscription in ambitious tenders points to market gaps, such as limited domestic storage manufacturing or financing challenges.

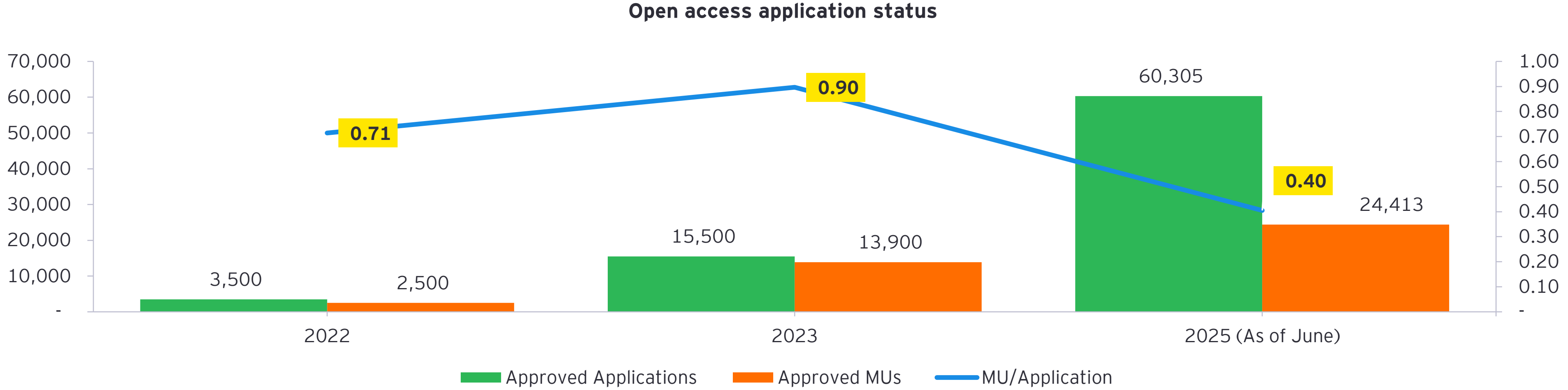
This calls for targeted interventions to boost subscription and innovation.

Note: NTPC 1: 1,584 MW awarded out of 3,000 MW, NHPC 1: 1.4 GW awarded out of 1.5 GW, NTPC 2: 760 MW awarded out of 1,200 MW, SECI FDRE 6: 200 MW awarded out of 2 GW, SJVN RTC 1: 448 MW awarded out of 1.2 GW

Source: EY Analysis based on information compiled by Debmalya Sen - India Energy Storage Alliance (IESA), https://www.linkedin.com/posts/debmalya-sen_standalone-bess-tariff-update-activity-7343599816930668544-tQP0?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A, https://www.linkedin.com/posts/debmalya-sen_india-ess-market-update-june-2025-1st-anniversary-activity-7345349000843161600-RXVR?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A, https://www.linkedin.com/posts/debmalya-sen_fdre-2023-2025-activity-7350797945534902272-8LtF?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A

Independence and autonomy of state level authorities designated for permitting grid connectivity and green energy open access can help balance emerging trade-offs





Source: IEEFA, JMK Research and Mercom India Research

Stakeholder perspectives of emerging challenges

- Grid operators are wary of excess banking that renders the grid more vulnerable to load-generation imbalance, frequency deviations, blackouts in the worst-case scenario including additional costs for inertia and frequency response services.
- Discom's power purchase cost becomes more vulnerable to diurnal price arbitrage in the power markets from excess banking that allows captive consumers to inject renewable energy during low-demand periods and withdraw during peak hours.
- IPPs and captive consumers are exposed to unpredictable outcomes from frequent revisions to regulatory charges under open access regulations.
- Several states cap or disallow banking and introduce conditions for withdrawal thereby denying the benefits allowed under National Green Energy Open Access Rules for captive consumers.
- Limited capacity in existing transmission corridors and slower than anticipated expansion is delaying connectivity for planned projects.

India's rapid buildout of renewable energy has outpaced the development of transmission infrastructure

India's rapid buildout of renewable energy has outpaced the development of its transmission infrastructure, creating a growing risk of curtailment for even the most technically and financially sound projects. This challenge is especially acute for solar, wind, and hybrid projects under RTC and FDRE tenders, as well as storage-backed projects that depend on uncongested corridors during peak hours to deliver flexibility. Without sufficient transmission availability, these projects face delays, reduced bankability, and underutilization—undermining the very goals of India's clean energy transition.

This misalignment between generation growth and transmission readiness can be better understood through three transmission adequacy ratios (see next page) that have become central to planning and operations: GNA/TTC, GNA/Peak Demand, and TTC/Peak Demand. These are not just technical indicators—they are strategic metrics that provide forward-looking insight into grid sufficiency, investment viability, and system resilience.

The March 2025 data reveals emerging areas of concern:

Low TTC/Peak Demand ratios in states like Karnataka, Maharashtra, and Rajasthan highlight limited physical transmission headroom—raising red flags about reliability during peak hours.

High GNA/TTC ratios, exceeding 150% in Karnataka and Gujarat, point to oversubscription, leaving little flexibility for new capacity, cross-border trades, or ancillary services.

Low GNA/Peak Demand ratios in key states such as Karnataka, Punjab, Rajasthan, Uttar Pradesh, Maharashtra, West Bengal and Andhra Pradesh suggest that peak loads may not be adequately backed by firm transmission rights—potentially straining the system during high-demand periods.

Each ratio offers unique insights:

GNA/TTC reflects the extent to which available transfer capability is already reserved. A ratio above 1.0 signals grid saturation, where new access becomes increasingly difficult and congestion risks rise.

GNA/Peak Demand indicates whether a state has secured enough contractual access to meet its maximum load. Low values here suggest under-preparedness and raise the specter of load shedding or procurement shortfalls.

TTC/Peak Demand measures the physical grid's ability to handle peak demand, even under contingency scenarios. A healthy ratio (ideally above 1.3) ensures resilience and headroom to absorb fluctuations and outages.

Collectively, these metrics offer a powerful lens to guide planning and decision-making:

Grid reliability: Operators can proactively manage congestion and maintain stable supply.

Renewable integration: Transmission bottlenecks can be identified early to prevent curtailment.

Project bankability: Developers and financiers gain visibility into transmission readiness and associated risks.

Policy and investment planning: Regulators and planners can prioritize corridor upgrades and align transmission expansion with energy transition goals.

As India races toward its renewable energy targets, embedding these ratios into regular system planning—at state levels—will be critical to ensure that clean power not only gets generated, but reliably reaches the consumers who need it.

Regional disparities and bottlenecks: RE-potential states like Rajasthan (high solar), Karnataka, and Maharashtra face low TTC/Peak Demand ratios, indicating physical infrastructure limitations that could lead to curtailment of variable renewables (e.g., excess solar during the day). This misalignment risks underutilizing new renewable projects, as seen in broader trends where India loses gigawatts of renewable energy due to transmission congestion.

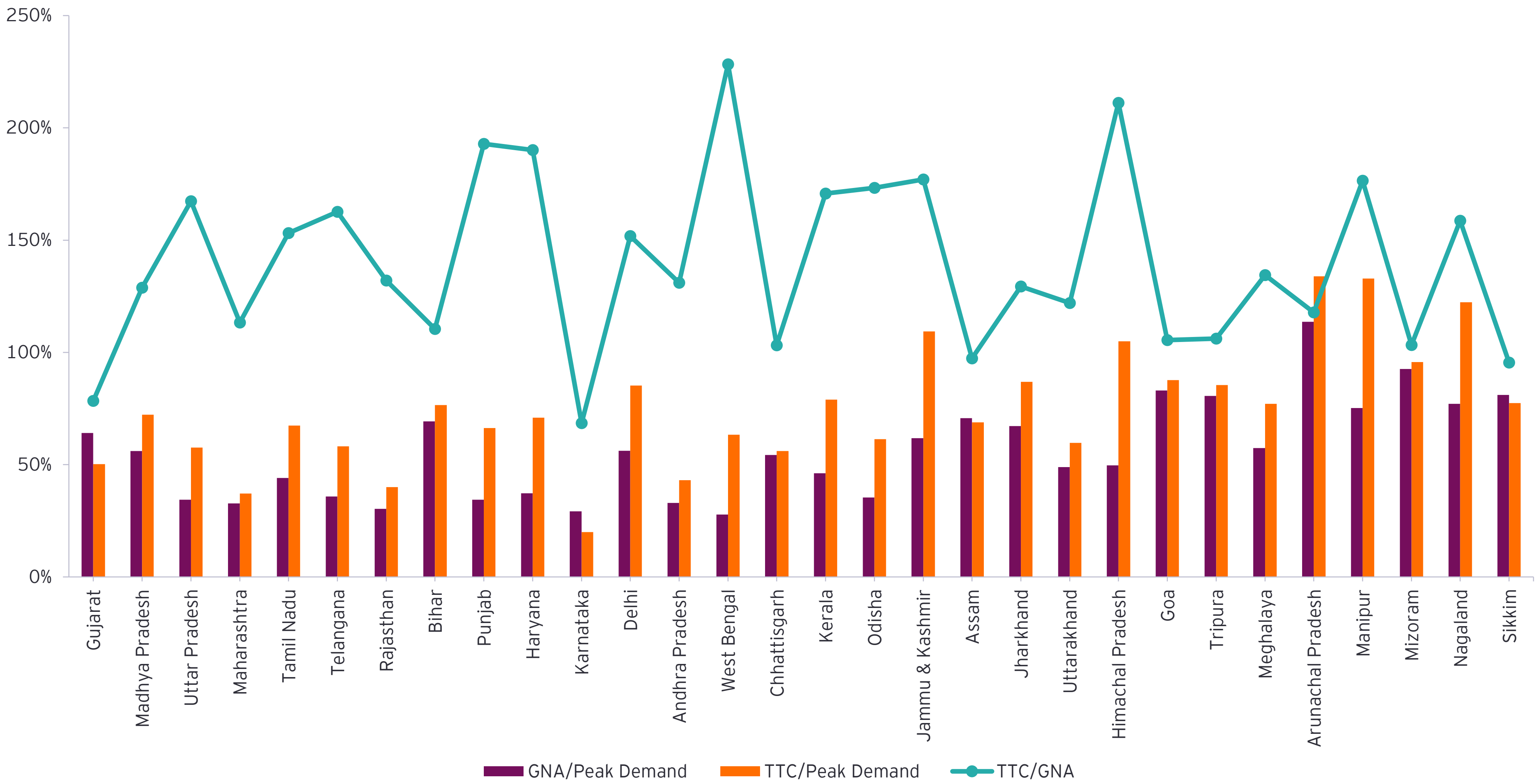
Impact on renewables pipeline: High GNA/TTC and low GNA/Peak ratios exacerbate delays in project execution, as developers face grid saturation and insecure access. This is critical amid India's rapid renewable energy addition (~30-50 GW annually), where geographic mismatches with renewable energy generation in remote areas far from demand centers amplify issues.

System-wide resilience: Low ratios overall suggest vulnerability to variability, with inadequate storage compounding issues.

These insights reveal that without targeted interventions, transmission inadequacies could slow renewables expansion.

High GNA/TTC and low GNA/Peak ratios exacerbate delays in project execution as developers face grid saturation and insecure access

Transmission infrastructure adequacy across India for renewables integration



Source: EY Analysis based on data from https://indiatransmission.org/ and https://www.researchgate.net/publication/385109162

Green energy corridor is not only pivotal for India's renewable energy expansion goals but also a cornerstone of its strategy to realise Viksit Bharat development imperatives for 2047

India's Green Energy Corridor (GEC) initiative is a strategic program designed to connect renewable energy generation centers with demand hubs, ensuring smooth grid integration of variable sources like wind and solar. The program operates through two main components — the Inter-State Transmission System (ISTS) and Intra-State Transmission System (InSTS) — supported by advanced control centers, reactive power compensation, and storage infrastructure.

Implementation progress
The GEC is being rolled out in multiple phases:

Phase I (InSTS-I) began in 2015–16 with the aim of integrating around 24 GW of renewable capacity across eight states, including Tamil Nadu, Karnataka, Rajasthan, Andhra Pradesh, Maharashtra, Gujarat, Himachal Pradesh, and Madhya Pradesh. While completion was initially set for 2022, deadlines have shifted to 2024–25 due to issues such as land acquisition and forest clearances. This phase, budgeted at about INR10,141 crore, is co-financed through central grants, loans from Germany's KfW, and state equity.

Phase II covers both InSTS-II and ISTS projects, including grid links to Ladakh. It targets integration of roughly 20 GW in states such as Gujarat, Himachal Pradesh, and Kerala, supported by 10,750 circuit kilometers of lines and 27,500 MVA of substations, with completion expected by 2026–27.

Phase III has been announced to strengthen intra-state networks, with an estimated cost of INR56,000 crore. The Union Government will fund about 40%, with the remainder from state budgets. Major investment is planned in Gujarat, Rajasthan, Maharashtra, Karnataka, and Andhra Pradesh.

Expected outcomes
Phases II and III together aim to integrate an additional 44 GW of renewable capacity, add over 20,000 km of transmission lines, and build more than 50,000 MVA of substation capacity. These upgrades will help move power from resource-rich but low-consumption states to high-demand centres, addressing regional imbalances and easing congestion.

Key challenges
GEC implementation faces persistent bottlenecks. Land acquisition and Right-of-Way disputes can delay projects for months or years. Coordination between central and state agencies is complex, as states have differing priorities and resource constraints. Even when central funding is assured, some states struggle to mobilise their share, leading to missed timelines. Technical hurdles also remain, particularly in integrating intermittent renewables through improved forecasting, grid-balancing technologies, and storage — areas where deployment is still limited.

By aligning generation growth with transmission readiness, and by resolving institutional and technical hurdles, the GEC can play a central role in meeting India's renewable energy expansion goals and supporting broader economic development objectives.

Source: EY analysis; Yash Kumar, https://www.impriindia.com/insights/green-energy-corridor/

Enablers for sustained momentum

Standardize and automate stakeholder data submissions

Transmission planning in India relies on timely, accurate, and comprehensive data from various entities, including STUs, POSOCO, RPCs, and renewable energy developers. In practice, these inputs are often delayed, inconsistent, or submitted in incompatible formats, which undermines the integrity of power flow studies and generation forecasts. Manual data handling increases the risk of errors, and there is no real-time system to monitor compliance. These shortcomings result in suboptimal planning decisions and missed opportunities for proactive infrastructure development. Moreover, these delays in data submission schedules affects coordination across the planning ecosystem, contributing to execution delays and network constraints. India should implement a centralized digital portal for all planning-related data submissions, standardized across states and entities. The system must support automated reminders, validation checks, and status dashboards accessible to CTU and other stakeholders. Timelines for data provision should be mandated by regulation, with non-compliance triggering penalties or exclusion from planning considerations. The portal should interface directly with CTU's power system modeling tools, enabling real-time scenario analysis. In addition, a biannual public compliance report published by CTU could help benchmark data quality and timeliness, ensuring greater accountability and coordination among all actors involved.

Synchronise transmission infrastructure development with 50 GW per annum renewable energy procurement trajectory

Despite India's ambitious renewable energy targets, transmission infrastructure frequently lags behind generation projects commissioning timelines. Many renewable energy projects face delays in evacuation due to unfinished transmission lines or pending approvals. This mismatch not only leads to curtailment but also disincentivizes developer participation in future bids due to heightened operational risks. Inadequate coordination between renewable energy procurement trajectory, project pipeline (awarded and PPA signed) and CTU's transmission planning framework further compounds the issue. The disconnect delays financial closure, hinders renewable energy integration, and puts stress on the grid by forcing renewable energy to rely on overburdened corridors.

To address this, institutionalise lock-step planning of transmission infrastructure synchronized with renewable energy auctions and project timelines, mandating pre-auction corridor assessments and feasibility studies for the 50 GW annual renewable energy procurement trajectory, with quarterly reviews to reduce curtailment risks and enhance investor confidence. Transmission project planning and approvals must precede or closely follow renewable energy auctions. Corridor-level trace studies, RoW feasibility, and environmental assessments should be completed in advance to inform renewable energy auctions. Tie renewable energy auction calendars to CTU/ STU "transmission-by-design" milestones (RoW cleared, tower schedules, bays ready) with public quarterly dashboards. Implementing agencies must establish a joint working group to share project pipeline data and align timelines. These reforms will reduce curtailment risk, improve investor confidence, and enable faster renewable energy integration into the grid.

Streamline Right of Way (RoW) approvals through centralized single window clearances

Telecom sector's Gati Shakti Sanchar portal is a model worth replicating for automated RoW approvals. RoW challenges remain in the timely execution of transmission projects. Varying compensation policies across states, lack of clarity in forest clearance procedures, and prolonged legal disputes often delay projects by months or even years. These delays result in cost overruns, hinder power evacuation, and disrupt synchronized commissioning of infrastructure. Moreover, project developers have limited recourse to resolve disputes efficiently, particularly in forested or tribal regions. The absence of a single-window system and the multiplicity of authority layers further slow down project execution. To improve execution timelines, a uniform national RoW compensation and clearance framework should be adopted across all states, based on MoP's latest guidelines. The planning phase should include digital route validation using PM Gati Shakti and geospatial tools to pre-identify conflict zones. A single-window portal for RoW, forest, and environmental clearances—with integrated timelines and automatic escalation mechanisms—should be launched to streamline approvals. States must establish dedicated RoW facilitation cells to resolve land-related issues proactively. Empowering local administrations and incentivizing early resolution through policy mandates will reduce litigation and accelerate corridor readiness.

Institutionalize joint ISTS-InSTS planning and execution tracking

A significant weakness in India's transmission ecosystem lies in the disjointed planning and implementation of Inter-State Transmission Systems (ISTS) and intra-state networks (InSTS). While CTU may plan and build ISTS infrastructure on time, the corresponding InSTS projects are often delayed by State Transmission Utilities (STUs), especially in RE-rich states. This leads to congestion, stranded ISTS assets, and delays in renewable power evacuation. The absence of synchronized execution timelines, shared tracking platforms, and joint accountability results in underutilization of investments and weakens the reliability of the overall grid. To bridge this gap, coordinated ISTS-InSTS planning must be institutionalized through regional planning forums involving CTU, STUs, and regulatory agencies. Each transmission project should include an associated downstream readiness assessment, and implementation schedules must be jointly committed and reviewed. A joint execution dashboard—updated quarterly—should be introduced to track milestones, flag bottlenecks, and build transparency. Regulatory oversight by CERC or forum of regulators may further strengthen cross-agency coordination and performance accountability

Delegate project approval powers and enforce decision timelines

Large transmission projects in India—particularly those exceeding INR500 crore—require approval from multiple bodies including CTU, the National Committee on Transmission (NCT), and the Ministry of Power (MoP). This multi-tiered process often leads to delays of several months, particularly when several proposals are pending simultaneously or when there is ambiguity on priority. The absence of statutory deadlines for approvals adds further uncertainty, impacting the ability of developers to mobilize resources and meet commissioning targets. This procedural inertia slows down capacity addition and creates bottlenecks in transmission infrastructure rollout.

Empowering CTU to independently approve projects below a pre-defined financial threshold would streamline decision-making and reduce procedural congestion. For higher-value projects, fixed review timelines should be enforced—preferably within 60 days—for both NCT and MoP, supported by a digital documentation and workflow system. Projects of strategic importance or linked to time-sensitive renewable energy zones should be categorized under a fast-track approval window. Transparency can be enhanced through periodic publication of project approval timelines and status updates. These reforms would provide predictability to developers and enable more efficient capital allocation and execution.

Legally enforce planning and execution timelines

Despite the national transmission planning process undertaking semi-annual updates and coordination meetings, absence of statutory enforcement mechanisms undermines its effectiveness. Key deadlines related to data submission, project clearance, site readiness, and commissioning are often missed without consequence. This results in inconsistent buildout of infrastructure, missed renewable energy integration targets, and lower transmission utilization efficiency. Stakeholders lack performance-linked obligations, and there is limited public reporting on delays or accountability for missed milestones. To improve discipline in the planning and execution cycle, legally binding timelines should be embedded within the Electricity Rules or enforced through CERC regulations. Penalties for delay and incentives for timely completion can be linked to performance-based budgets and tariff approvals. Planning, execution, and compliance milestones should be monitored via an integrated digital platform that is publicly accessible. Regulatory oversight and quarterly reporting should become standard practice for all ISTS and InSTS projects. These measures can help institutionalize time-bound delivery and restore confidence among developers, utilities, and investors.

Maximize generation from high-potential wind sites through repowering

Several high-wind resource sites in India, particularly in Tamil Nadu and Gujarat, are currently occupied by aging wind turbines with capacities as low as 225–500 kW. These older machines occupy prime wind locations but contribute marginally to the overall generation output due to outdated technology and poor capacity factors. Despite the launch of the National Wind Repowering Policy in 2016, its implementation remains negligible at the state level. Fragmented land ownership—often in plots as small as 0.5 acres—and the absence of streamlined repowering procedures have hindered adoption. Furthermore, lack of alignment between industry stakeholders, transmission utilities, and state governments has slowed down evacuation planning for potential repowering clusters.

States must urgently adopt and adapt the national repowering policy by developing state-specific guidelines with a clear focus on land aggregation, regulatory fast-tracking, and developer incentives. Public-private partnerships can be promoted to structure land use under real estate-inspired models, where landowners retain ownership and receive annuity or profit-sharing post-repowering. Transmission utilities at both the state and central levels must proactively assess evacuation requirements and fast-track augmentation in key wind corridors. A centralized portal to map aging turbines and streamline clearances, combined with industry-state taskforces, can unlock several GW of high-quality wind capacity from existing sites—without requiring new land or extensive infrastructure development.

Scale private investment in intra-state transmission through TBCB adoption

With the phasing out of ISTS transmission charge waivers for renewable energy projects, developers are increasingly looking to connect to intra-state networks. However, many STUs continue to rely on the regulated tariff mechanism (RTM) model, under which projects are developed in-house or by state-owned companies. This limits competition, delays project timelines due to limited execution capacity, and constrains innovation and cost efficiency.

At the same time, the shift of large renewable energy pipelines to intra-state networks places significant stress on the planning and financial capacity of STUs. Only a few progressive states have adopted the TBCB route at the intra-state level, missing an opportunity to attract private capital and technical expertise. To improve capacity rollout, states should proactively transition to the TBCB model for intra-state transmission development. This will introduce greater competition, reduce tariffs, and bring in private-sector efficiency. The Ministry of Power and CEA can support this shift by developing a model bidding framework tailored for state use, with technical assistance for bid design and project structuring. STUs can take the role of planners and regulators while transmission service providers execute and operate the assets under well-defined contracts. Early-mover states should be showcased as case studies to encourage wider adoption, and performance-linked incentives from central schemes (such as RDSS or PSDF) can be tied to the use of TBCB. A coordinated push will enable faster and cost-effective grid buildout critical for integrating upcoming renewable capacity.

Independent and autonomous state load dispatch centers

At the state level, nodal agencies responsible for handling grid connectivity approvals are the SLDCs, which operate under the administrative control of their respective STUs hampering independence and timely decision making.

To strengthen their autonomy, SLDCs should be carved out as independent entities with ring-fenced budgets, empowered CEO selection committees, and clearly defined multi-year performance targets—such as improving forecasting accuracy and adhering to service-level agreements (SLAs) for open access decisions. This would enhance accountability, transparency, and operational efficiency, while reducing conflicts

Source: EY analysis

04 Civil nuclear energy: From promises to real value proposition

India's civil nuclear energy market is moving from promises to real value proposition

Current status and targets

At present, nuclear energy contributes ~3% to the total electricity generation in the country. In 2024-25, nuclear power plants generated ~56.7 billion units (BUs) of electricity. The government is making efforts to increase the nuclear fuel sources both by augmenting domestic production and imports from diverse sources. The government has announced the Nuclear Energy Mission with a target of reaching ~100 GW installed nuclear power generation capacity by 2047. The government has also announced measures for enabling R&D in SMRs and new advanced technologies. At present, the installed nuclear power capacity comprises 24 reactors with a total capacity of ~8,780 MW. In addition, a total capacity of 13,600 MW (including 500 MW PFBR being implemented by BHAVINI) is under different stages of implementation. On its progressive completion, the installed nuclear power capacity is expected to reach 22,380 MW by 2031-32.

SMRs complement intermittent renewables to achieve net-zero emissions

India's power generation mix continues to rely heavily on fossil fuels, particularly coal, which has consistently contributed ~75% of total electricity generation from FY16 to FY25. This sustained dominance highlights coal power generation's critical role as the baseload generator, ensuring uninterrupted, round-the-clock electricity supply across the country.

The emergence of Small Modular Reactors (SMRs) has strengthened the business case for civil nuclear energy in India's energy transition, particularly as a promising low carbon baseload alternative to coal power generation without compromising reliability, security and grid stability imperatives. SMRs are compact nuclear reactors that have a power capacity of up to 300 MWe per unit, which is about one-third of the generating capacity of conventional GW scale PHWR nuclear power reactors operating in the country. SMRs are: Small – with a power from 2–300 Mwe and Modular – making it possible for systems and components to be factory-assembled and transported as a unit to a location for installation. SMRs are compact, scalable, and can be deployed on or near existing coal plant sites, allowing for the reuse of grid infrastructure and minimizing land acquisition challenges. They are designed with passive safety features and require significantly less water, making them suitable for deployment in arid or water-stressed regions. Moreover, SMRs can operate flexibly, adjusting output to complement variable renewable sources and thereby playing a crucial role in balancing the grid.

- SMRs can be co-located with retiring coal plants, easing transition logistics.
- Passive safety systems and lower water use improve siting flexibility.
- SMRs support flexible, grid-responsive operation alongside renewables.
- SMRs reduce LCoE by 20%-30% vs. large reactors via modularity

Nuclear Energy Mission

- Target: 22GW by 2032 and 100GW by 2047
- INR20,000 crore allocated for R&D of five indigenously developed SMRs by 2033
- BARC is developing high temperature gas-cooled reactors for hydrogen co-generation
- Molten salt reactors envisaged for utilizing thorium and other SMRs targeted for retiring coal plants
- Legal framework reforms initiated to de-risk public private partnerships through selective amendments in the Atomic Energy Act and the Civil Liability for Nuclear Damage Act

Nuclear energy as a service

- NPCIL invited proposals from industrial energy consumers and energy service providers to set up 220 MWe Pressurized Heavy Water Reactor (PHWR) Bharat Small Reactors (BSRs) on brownfield or greenfield sites.
- Energy intensive industries can secure access to low carbon baseload electricity from these reactors for their own use, aligning with India's decarbonization goals.
- NPCIL acts as the authority, while participants (USERs) provide land and finance construction. However, NPCIL retains legal ownership (post, operation, maintenance, and decommissioning responsibilities under the Atomic Energy Act, 1962).
- USERs bear upfront costs but receive electricity at a tariff determined by the Department of Atomic Energy (DAE). The project is structured in phases: pre-project (site evaluation), construction, and operation.

NPCIL-NTPC JV "ASHVINI"

- Tasked with building and operating new nuclear power generation projects
- First project: 4x700 MWe PHWR in Rajasthan

Source: https://www.pib.gov.in/PressReleseDetailm.aspx?PRID=214728, NITI Aayog-India Energy Dashboard, CEA, IAEA Power Reactor Information System (PRIS), https://www.npcil.nic.in; https://www.pib.gov.in/PressReleasePage.aspx?PRID=2100108

SMR applications, complementary advantages over renewables, emerging designs and business models

Small modular reactors add value when applied to complement renewables for heat and baseload electricity generation services, accelerating decarbonization of the economy-wide GHG emissions. Where 'large' nuclear reactors are generally only dedicated to the production of very large quantities of electricity for the national network, SMRs can aim to meet specific and local needs for heat and /or electricity. Thanks to their low power, they are easier to integrate into small electrical or heat networks, close to industries and isolated sites.

More than 80 commercial SMR designs are being developed around the world and some SMRs are operational in Russia, China and Argentina. Globally, SMRs are expected to be deployed from 2030, while AMRs are anticipated to arrive from 2040. Two types of water reactors exist: Gen. III: traditional water reactors; Gen. III+: traditional water reactors with enhanced safety features. SMRs can be traditional water reactors, with lower power ranges compared to large Nuclear Power Plants (NPPs). Advanced Modular Reactors (Gen. IV) bring together various technologies that aim to improve the fuel cycle and the safety.

SMR design intends to bypass some of the financial, timing, centralization, safety and waste management issues that hinder the widespread adoption of conventional reactors. For instance, several Gen. IV and Gen. III+ technologies will include passive safety features and will use nuclear waste from large NPPs to close the fuel cycle. While SMRs include both Gen. III/III+ and Gen. IV, it is vital to distinguish between Gen. III/III+, which are miniaturized versions of existing power plants and are already mature, and Gen. IV (AMRs), which hold significant technological promises. Gen. IV reactor types offer various value propositions, including higher heat applications, enhanced safety, fuel cycle closing but they are at a lower level of technological maturity. One of the key strengths of SMRs is their versatility, encompassing both on-grid and off-grid applications. With cogeneration, power flexibility and high temperatures, SMRs can provide power to the grid, district heating, industries and remote areas.

Two main business models will likely emerge from the applications and client needs. First, a manufacturer model mainly based on design and licensing (which can also include component manufacturing and NPP construction), similar to a large NPP, and adapted to grid application. Second, an "energy-as-a-service" model, providing turnkey solutions to final client and more adapted for off-grid applications. Finally, SMRs are gaining momentum, with over 80 projects underway worldwide. However, it is important to acknowledge that despite the excitement surrounding SMRs, only a few projects are at advanced stage and yet to demonstrate commercial viability.

01 Baseload capacity

SMRs offer a high amount of reliable, carbon-free baseload power as a substitution of phasing out fossil sources in a context of electrifying uses.

02 Grid stabilization

Variable renewable sources need to be backed by enhanced stability of electricity grids through flexible operation or load following.

03 Cogeneration

SMRs allow for cogeneration of heat and electricity and address growing electricity demand for off-grid applications.

04 Land use

Nuclear has the lowest median land-use intensity at 7.1 ha/TWh/year. In comparison, solar PV has a 2,000 ha/TWh/year land-use intensity.

05 Decentralization

SMRs are an affordable option to 2-300 MWe or even less users and are available for more diverse applications than historical NPPs, including remote locations.

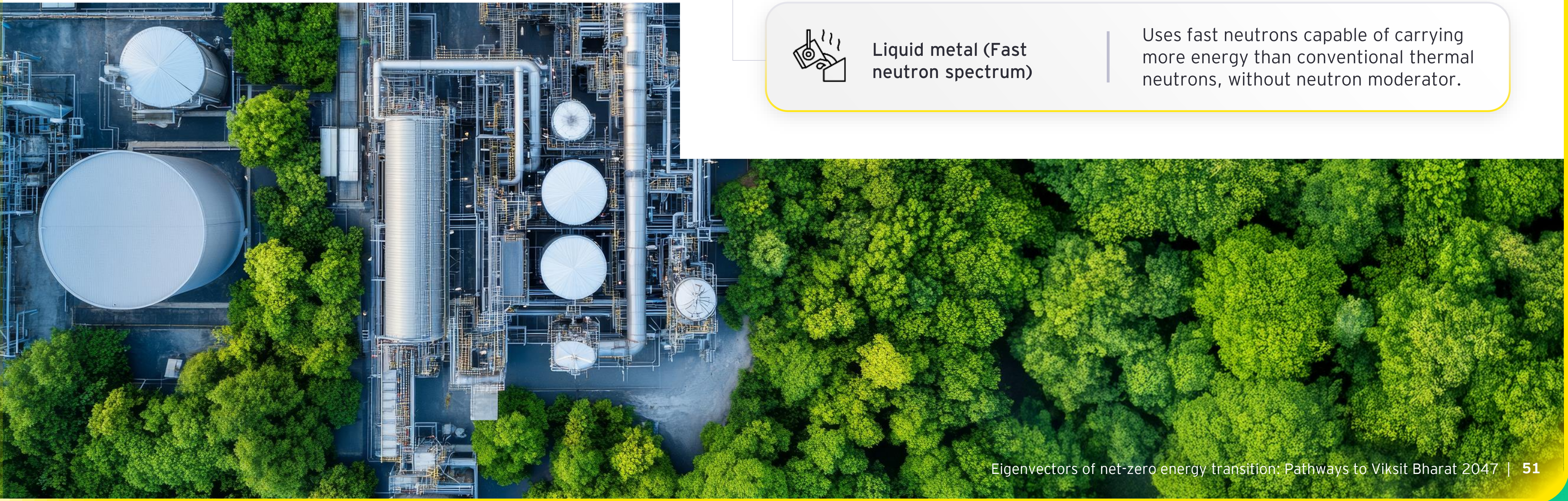
Gen. II/III + SMR

Water Cooled

Historical design of nuclear power plants, using uranium to produce steam for the turbine in separate steam generators

Gen. IV Advanced Reactors AMR

High Temperature Gas Cooled Reactor (HTGR)	Uses helium or alternative gas like nitrogen as coolant with fissile material surrounded by three ceramic layers.
Molten Salt	A self-regulating critical geometry uses an enriched molten salt mixture as coolant and fuel to generate hear
Liquid metal (Fast neutron spectrum)	Uses fast neutrons capable of carrying more energy than conventional thermal neutrons, without neutron moderator.



Power range and design status of various SMRs - 1/3

Power range (Mwe)	SMR design	Country(ies) of origin	Design status
Water cooled SMRs - Land based			
301 - 500	Integrated Modular Water Reactor (IMR)	Japan	CD
	United Kingdom Small Modular Reactor (UK SMR)	UK	CD
	International Reactor Innovative and Secure (IRIS)	International Consortium	BD
	Indian Pressurized Heavy Water Reactor – 700 MWe (IPHWR-700)	India	UC
	Advanced Heavy Water Reactor – 300 MWe (AHWR-300)	India	CD
201 - 300	Westinghouse Small Modular Reactor (W-SMR)	US	CD
	Water-Water Channel Reactor – 300 MWe (VK-300)	Russia	DD
	Boiling Water Reactor – X (300 MWe) (BWRX-300)	US and Japan	PL
	Canada Deuterium Uranium – Small Modular Reactor (CANDU-SMR)	Canada	CD
	Advanced Heavy Water Reactor – 300 MWe (Low Enriched Uranium) (AHWR-300 LEU)	India	BD
151 - 200	Small Modular Reactor – 160 MWe (SMR-160)	US	PD
	Nuclear Unified Western Advanced Reactor Design (NUWARD)	France	CD
	Modular Power Reactor (mPower)	US	CD
	China Advanced Passive 200 (CAP200)	China	CD
100 - 150	Compact Modular Reactor – 100 MWe (KARAT-100)	Russia	CD
	System-integrated Modular Advanced Reactor (SMART)	Republic of Korea and Saudi Arabia	CeD
	District Heating Reactor – 400 MWt (DHR400)	China	BD
	Advanced Compact Pressurized Water Reactor – 100 MWe (ACP100)	China	DD

Legend
CD – Conceptual Design
BD – Basic Design
DD- Detailed Design
PL- Pre-licensing
CeD- Certified Design
LS- Licensing Stage
UC- Under Construction
PD- Preliminary Design
EP- Experimental Phase
PCD- Pre-Conceptual Design

Source: IAEA-SMR Book 2012, 2012, 2016 and 2020 available at https://aris.iaea.org/Publications

Power range and design status of various SMRs - 2/3

Power range (Mwe)	SMR design	Country(ies) of origin	Design status
Water cooled SMRs - Land based			
100 - 400	Pressurized Water Reactor (VBER-300)	Russia	LS
High temperature gas cooled SMRs			
201 - 300	High Temperature Reactor – Pebble-bed Modular (HTR-PM)	China	UC
	Gas Turbine High Temperature Reactor – 300 (GTHTR-300)	Japan	PL
	Gas Turbine – Modular Helium Reactor (GT-MHR)	Russia	PD
	Modular Helium Reactor – Thermal (MHR-T)	Russia	CD
	Steam Cycle – High Temperature Gas-cooled Reactor (SC-HTGR)	US	CD
151 - 200	Pebble Bed Modular Reactor – 400 MWe (PBMR-400)	South Africa	PD
Fast neutron spectrum SMRs			
401 - 500	Westinghouse Lead-cooled Fast Reactor (Westinghouse LFR)	US	CD
	Prototype Fast Breeder Reactor – 500 MWe (PFBR-500)	India	OP
	Fast Breeder Reactor – Units 1 & 2 (FBR-1 & 2)	India	BD
201 - 300	Fast Reactor with Lead Coolant – Experimental Demonstration, 300 MWe (BREST-OD-300)	Russia	DD
	Energy Multiplier Module 2 (EM2)	US	CD
100 - 200	Advanced Reactor Concept – 100 MWe (ARC-100)	Canada	CD
	Lead-Bismuth Fast Reactor (SVBR)	Russia	DD
	Super Safe, Small & Transportable Advanced Reactor (SUPERSTAR)	US	CD
	Lead-cooled Fast Reactor – Advanced Small 200 (LFR-AS-200)	Luxembourg	PD

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Source: IAEA-SMR Book 2012, 2012, 2016 and 2020 available at https://aris.iaea.org/Publications

Power range and design status of various SMRs – 3/3

Power range (Mwe)	SMR design	Country(ies) of origin	Design status
Molten Salt SMRs			
> 301	Molten Chloride Salt Fast Reactor (MCSFR)	US and Canada	CD
201 - 300	Thorium Converter Reactor (ThorCon)	International Consortium	BD
	Stable Salt Reactor – Wasteburner (SSR-Wasteburner)	UK and Canada	CD
	Liquid Fluoride Thorium Reactor (LFTR)	US	CD
151 - 200	Integral Molten Salt Reactor (Integral MSR)	Canada	CD
	Small Thorium Molten Salt Reactor – 400 (smTMSR-400)	China	PCD
	FUJI Molten Salt Reactor (FUJI)	Japan	EP
100 - 150	Kairos Power – Fluoride Salt-cooled High Temperature Reactor (KP-FHR)	US	CD
	Mark 1 Pebble-Bed Fluoride Salt-cooled High Temperature Reactor (MK1 PB-FHR)	US	PCD

Legend
CD – Conceptual Design
BD – Basic Design
DD- Detailed Design
PL- Pre-licensing
CeD- Certified Design
LS- Licensing Stage
UC- Under Construction
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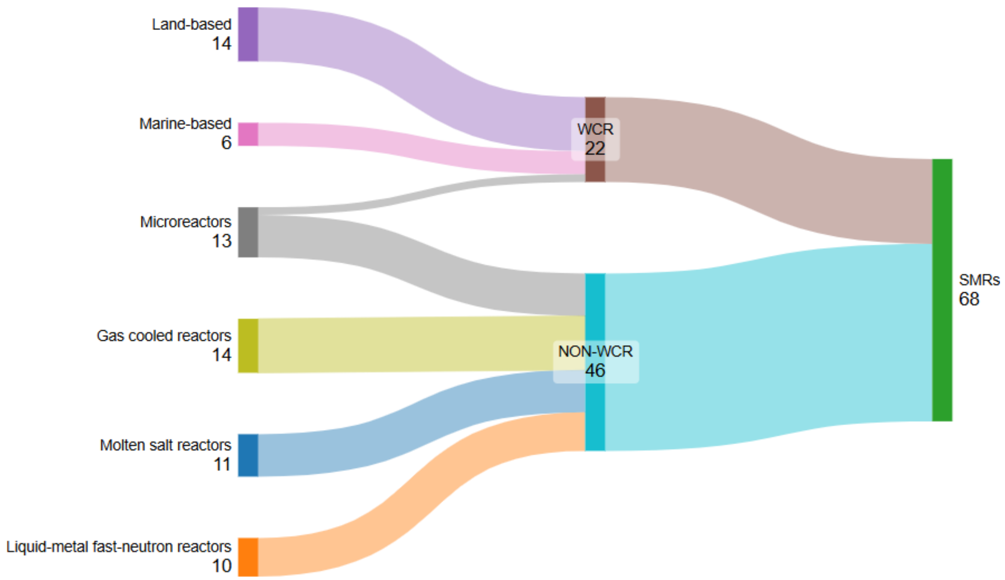
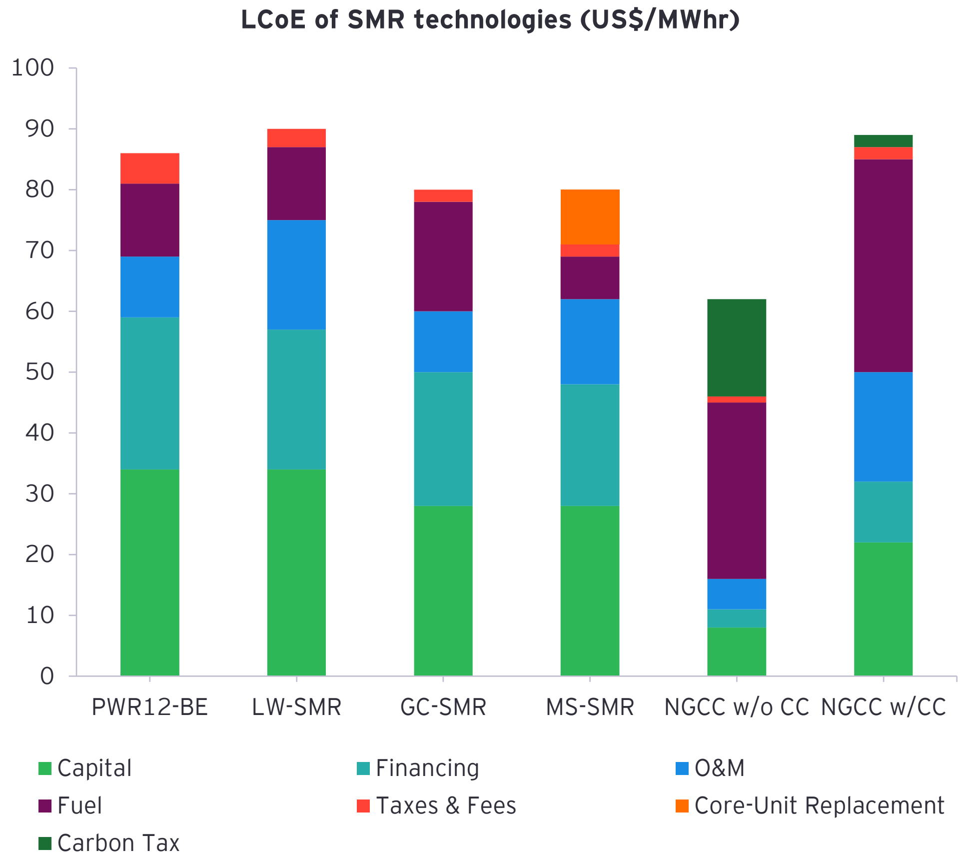
PCD- Pre-Conceptual Design

Source: IAEA-SMR Book 2012, 2012, 2016 and 2020 available at https://aris.iaea.org/Publications





SMRs are categorized by their coolant and neutron technology, each serving specific applications. Land-based, water-cooled SMRs use mature light and heavy water designs, with projects in Argentina, China, Russia, the US, the UK, and France. Marine-based SMRs are floating, barge-mounted units, like Russia's Akademik Lomonosov, with designs also in China, Korea, and the US. High-temperature gas-cooled SMRs provide heat above 750°C for power generation and industrial use. Fast-neutron, liquid metal-cooled SMRs use sodium, lead, or lead-bismuth for efficient fast-spectrum reactors. Molten salt SMRs offer low-pressure, high-efficiency operation and flexible fuel cycles. Microreactors, under 30 MW(th), target microgrids, remote sites, and disaster recovery, with active development in Canada and the US.

Legend
PWR12-BE - Pressurized Water Reactor, 12 MWe, Better Experience
LW-SMR - Light-Water Small Modular Reactor
GC-SMR - Gas-Cooled Small Modular Reactor
MS-SMR - Molten Salt Small Modular Reactor
NGCC w/CC - Natural Gas Combined Cycle with Carbon Capture (90%)
NGCC w/o CC - Natural Gas Combined Cycle without Carbon Capture

Source: https://www.pib.gov.in/newsite/PrintRelease.aspx?relid=112034, https://www.barc.gov.in/randd/tfc.html, https://aris.iaea.org/publications/smr_book_2020.pdf,NITI Aayog, SMR Book -2024 - IAEA https://www.pib.gov.in/PressReleasePage.aspx?PRID=2099244; https://www.pib.gov.in/newsite/PrintRelease.aspx?relid=112034, https://www.barc.gov.in/randd/tfc.html, https://aris.iaea.org/publications/smr_book_2020.pdf,NITI Aayog, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2099244, Techno-economic analysis of Advanced SMRs by Anthony Asuegaa, Braden J. Limba and Jason C. Quinn- Science Direct

Leveraging India's thorium advantage for security and resilience of SMR adoption

India holds one of the world's largest reserves of thorium, primarily in the form of monazite sands found along the coasts of states like Andhra Pradesh, Odisha, Tamil Nadu, Kerala, and West Bengal. The Atomic Minerals Directorate for Exploration and Research (AMD), under the Department of Atomic Energy (DAE), has established 11.93 million tonnes of in-situ monazite, containing approximately 1.07 million tonnes of thorium.

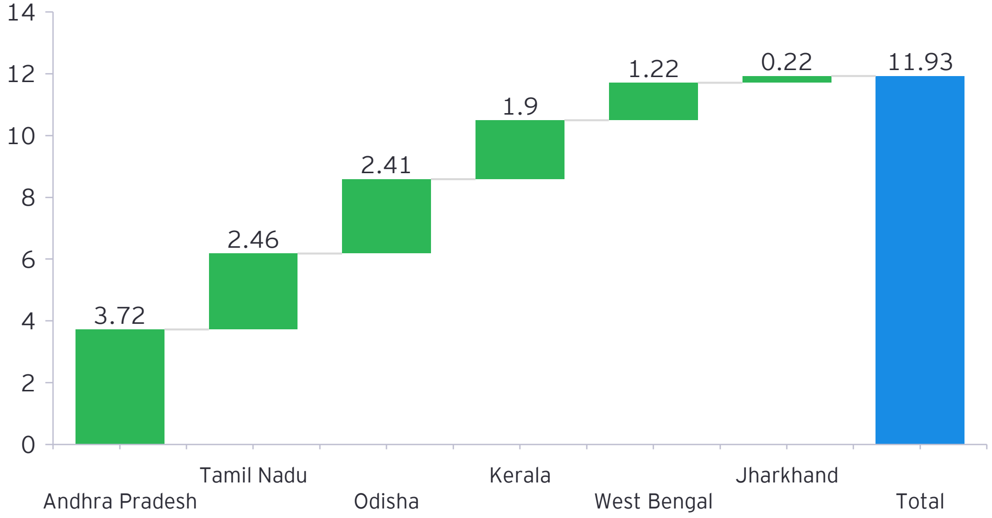
Recognizing the potential of thorium as a long-term energy source, India adopted a Three-Stage Nuclear Power Programme, focused on the sustainable use of its limited uranium and abundant thorium resources. The stages are:

- Stage I – Pressurised Heavy Water Reactors (PHWRs)
  Utilizing natural uranium as fuel, PHWRs generate plutonium as a by-product for use in fast breeder reactors.
- Stage II – Fast Breeder Reactors (FBRs)
  These reactors breed plutonium and simultaneously convert thorium into uranium-233 (a fissile material) for the next stage.
- Stage III – Advanced Heavy Water Reactors (AHWRs)
  Designed for direct use of thorium-232 and uranium-233, these reactors will enable large-scale thorium utilization, offering sustainable and low-waste energy production.

Significant progress has been made in thorium fuel cycle development, from mining and extraction to fabrication, irradiation, and reprocessing:

- Thoria fuel fabrication methods are well-established, and multiple tonnes have been prepared by BARC and NFC.
- Irradiation experiments have been conducted in research and power reactors such as CIRUS, Dhruva, PHWRs, and FBTR.
- Reprocessing facilities, including the Uranium Thorium Separation Facility (UTSF) at BARC and Power Reactor Thorium Reprocessing Facility (PRTRF), have successfully recovered uranium-233 from spent thoria fuel.
- The KAMINI reactor, a unique facility operating on U-233, stands as a proof of concept for the third-stage cycle.

Monazite reserves in India (In million tons)



Two Advanced Heavy Water Reactor (AHWR) design variants have been developed:

- AHWR (300 MWe): Uses (Th-Pu) MOX and (Th-U233) MOX fuel, operates on a closed fuel cycle, and includes an integrated fuel fabrication and reprocessing facility.
- AHWR-LEU (300 MWe): Utilizes (Th-LEU) MOX fuel with low-enriched uranium (19.75% U-235) and is based on a once-through fuel cycle with long-term spent fuel storage.

These reactors incorporate advanced safety features and aim to demonstrate the full thorium fuel cycle for eventual commercial-scale deployment.

Source: https://www.pib.gov.in/newsite/PrintRelease.aspx?relid=112034, https://www.barc.gov.in/randd/tfc.html, https://aris.iaea.org/publications/smr_book_2020.pdf,NITI Aayog, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2099244

Action plan and recommendations

Operationalise SMR roadmap

India's nuclear sector, though mature in PHWRs, is still in the early stages of readiness for next-generation technologies like SMRs. Key challenges include limited industrial precision, early-stage R&D in advanced designs, and underdeveloped nuclear-grade supply chains. With the recent launch of the INR20,000 crore Nuclear Energy Mission, the focus must now shift to execution and ecosystem development.

Key priorities:

- Finalize an SMR roadmap with clear technology choices and deployment milestones
- Release a policy framework detailing regulatory support, siting norms, and grid integration
- Launch a PLI-style incentive scheme for domestic manufacturing of SMR components
- Strengthen nuclear-grade supply chains through quality assurance and vendor development
- Foster public-private collaboration for accelerated R&D and commercialization

Implement legislative reforms

India has signaled intent to amend restrictive nuclear laws, but the private sector remains cautious in the absence of legal clarity and risk mitigation. The Atomic Energy Act and Civil Liability for Nuclear Damage Act (CLND) continue to limit participation, especially from foreign OEMs wary of supplier liability. To unlock private investment, legal reforms must now move from intent to implementation.

Key priorities:

- Expedite passage of amendments to the Atomic Energy Act and CLND Act
- Establish clear, transparent liability-sharing frameworks to reassure investors and OEMs
- Define private sector roles under the Bharat Small Reactors
- Provide legal clarity on permissible private activities in nuclear power and fuel cycle

Secure nuclear fuel supply

India must complement uranium import diversification with accelerated thorium technology development and strategic stockpiling.

- Fast-track bilateral uranium supply agreements and enhance stockpiles
- Scale up investments in AHWRs and Fast Breeder Reactors for thorium utilization
- Promote international collaboration on advanced fuel cycles, including molten salt and HTGR technologies

Streamline regulatory framework

India's nuclear regulatory framework, built around large reactors, is not yet equipped to support the distinct characteristics of SMRs and their emerging non-electric applications. Gaps in licensing pathways, modular design approval, and oversight for uses like hydrogen production hinder innovation and timely deployment.

Key priorities:

- Create a dedicated SMR regulatory framework within AERB with risk-informed, tech-neutral guidelines
- Launch pilot regulatory sandboxes for efficient licensing of first-of-a-kind reactors
- Adapt regulations to cover non-electric applications like hydrogen generation and desalination
- Enable regulatory pathways for repurposing retired coal plant sites with SMRs
- Build regulatory capacity to assess advanced and hybrid nuclear systems

05 Circular economy and extended producer responsibility (EPR) of solar PV and battery supply chains

Producer responsibility organizations transform fragmented, inefficient solar PV panel waste handling into a coordinated system, reducing costs and managing compliance

- CEEW research suggests that by 2030, India could generate between 106 kt and 722 kt of solar module waste, depending on degradation rates and waste management scenarios. The cumulative figure leans toward a base case projection of 594 kt by 2030 (using a 1.4% degradation rate), but this varies with different models and assumptions. Around 44% of this will be generated from new capacities. The 334 kt of waste generated from the existing capacity by 2030 translates to about 5.1 GW in solar capacity (using the 65 tons/MW conversion factor). It is expected that 67% of the waste (approximately 227 kt) would be be generated in just five states: Rajasthan, Gujarat, Karnataka, Andhra Pradesh and Tamil Nadu

- A Producer Responsibility Organisation (PRO) is authorized by several producers (e.g., solar PV module or electronics manufacturers) to handle collective responsibilities. It operates as a single point of coordination, managing a nationwide (pan-India) network of collection centers, storage facilities, and logistics partners. The PRO aggregates EoL waste from various sources, ensures safe transportation, channels the materials to authorized recyclers, and handles compliance reporting to regulatory bodies like the Central and State Pollution Control Boards.

Key functions:

- **Collection:** Establishes drop-off points, reverse logistics, and partnerships for gathering waste from consumers, installers, or project sites.

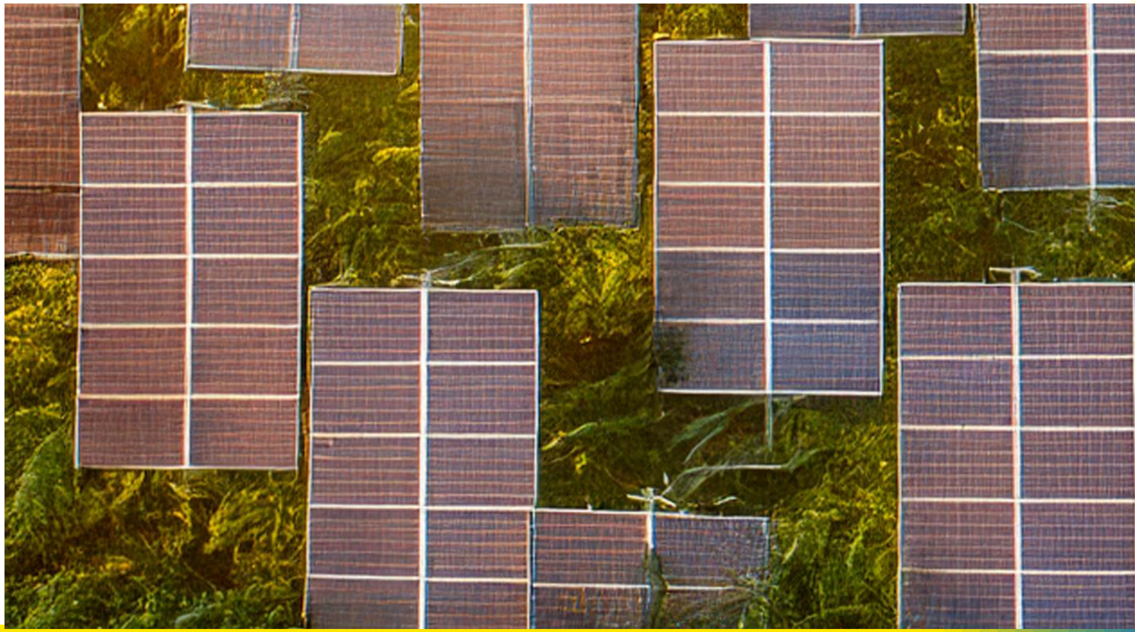
- **Transport:** Organizes efficient, environmentally safe movement of waste to prevent damage or leakage of hazardous materials (e.g., heavy metals in solar panels).

- **Recycling:** Directs waste to certified recyclers for material recovery, such as glass, aluminum, silicon, and precious metals from solar PV modules.

- **Compliance and reporting:** Tracks waste volumes, recovery rates, and environmental impacts, submitting reports to ensure producers meet EPR targets without individual effort.

- Under the E-Waste Rules (amended in 2022 to include solar PV waste), producers must ensure a certain percentage of their sold products are collected and recycled. PROs allow smaller or multiple producers to pool resources, making compliance feasible. This model shifts from individual producer efforts to a collaborative, outsourced system, similar to PROs in Europe (e.g., under WEEE directives) but adapted to India's context.

- **Economies of scale:** By aggregating waste from multiple producers, PROs can handle larger volumes, reducing per-unit costs for collection, transport, and recycling. For instance, a single pan-India network avoids redundant infrastructure (e.g., multiple small collection centers), potentially lowering logistics costs by 20%-30% through optimized routes and bulk shipping.
- **Standardized processes:** PROs implement uniform protocols for handling, sorting, and processing waste, minimizing errors and delays. This streamlines operations, such as using specialized equipment for dismantling solar panels, leading to faster throughput and reduced operational downtime.
- **Resource optimization:** Central management allows better forecasting of waste volumes (using data from producers), enabling proactive planning for storage and recycling capacity. This avoids bottlenecks, like overflow at collection points, and integrates with digital tools for tracking (e.g., EPR portals).
- **Cost sharing:** Producers share expenses, making it viable for smaller manufacturers who might otherwise struggle with EPR compliance, thus broadening participation and increasing overall system efficiency.
- **Higher collection and recovery rates:** A nationwide network improves accessibility, especially in remote areas where solar installations are common (e.g., rural Rajasthan or Gujarat). This reduces waste leakage into landfills or informal sectors, potentially boosting collection rates from the current low levels (often <20% for e-waste) to 70%-80% as seen in mature PRO systems.
- **Environmental and health benefits:** By channeling waste to authorized recyclers, PROs enable proper treatment of hazardous components (e.g., cadmium in thin-film solar panels), minimizing pollution and health risks. This promotes circular economy principles, recovering valuable materials like silver and silicon for reuse, reducing virgin resource extraction.
- **Reduced informal sector dominance:** Informal recycling often leads to low recovery (e.g., only aluminum frames) and hazards like open burning. PROs formalize the chain, enforcing standards and integrating informal workers safely, improving overall effectiveness in waste diversion from harmful practices.
- **Regulatory compliance and transparency:** Centralized reporting allows accurate data on waste flows, helping regulators monitor progress toward national targets. This builds trust and enables policy refinements, such as incentives for high-recovery technologies.
- **Challenges addressed:** While not eliminating issues like high upfront costs or logistics, PROs mitigate them through collective funding and partnerships, making waste management more resilient.
- Overall, PROs transform fragmented, inefficient waste handling into a coordinated ecosystem, potentially increasing recycling effectiveness by enabling 80%-90% material recovery (vs. 10%-20% in informal setups) and supporting India's circular economy goals for solar waste, projected to reach 19,000 kt by 2050.



Source: EY analysis; https://www.ceew.in/sites/default/files/how-can-india-enable-circular-economy-with-solar-waste-management.pdf

Solar PV panel waste is currently exempt from specific EPR recycling targets but must be stored by manufacturers and producers until 2034-35

Compliance mandate under E-Waste Management Rules, 2022

Solar PV modules, panels, and cells are now classified as electrical and electronic equipment (EEE) waste under Chapter V of the E-Waste Management Rules, 2022, which came into effect on 1 April 2023. Unlike other e-waste categories, solar PV waste is currently exempt from specific EPR recycling targets but must be stored by manufacturers and producers until 2034-35.

- Manufacturer and producer shall register on the CPCB Portal.
- Store PV modules/panels/cells waste through FY 2034–35 per CPCB guidelines.
- File annual returns by 31 March each year until FY 2034–35.
- Manage other solar waste (inverters, batteries) under existing hazardous-waste rules.
- Maintain a distinct "Solar PV Waste" inventory on the portal.
- Follow all CPCB SOPs and technical guidelines.

CPCB guidelines (draft) for Safe Handling and Disposal of Solar Photovoltaic Modules / Panels

- Producers must establish and publicize take-back collection mechanisms and collection points
- Transportation must occur in covered vehicles, preferably those authorized for hazardous waste
- Solar waste must never be dumped in open areas or sold to unauthorized entities
- Storage facilities must be covered, dry, and well-ventilated with impervious, non-leachable flooring
- Minimum space requirement of 19.5 cubic meters per tonne of stored waste
- Maximum stacking height of 2 meters or 20 layers
- Mandatory fire protection systems and emergency response plans

Solar panel recycling technologies

Thermal Delamination

Using high temperatures (300-650°C) to separate components - most cost-effective but energy-intensive

Chemical Delamination

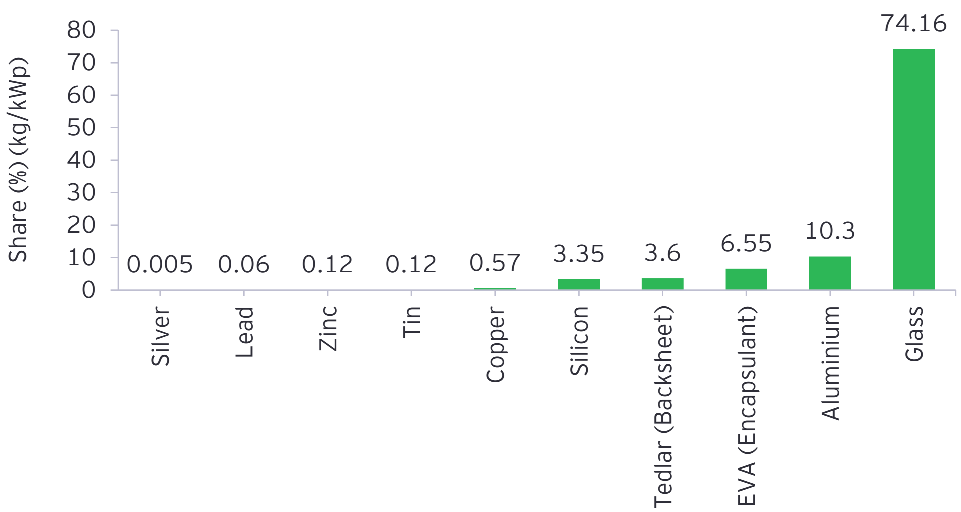
Using solvents and acids for separation - effective but time-consuming (up to 10 days) and requires hazardous chemical handling

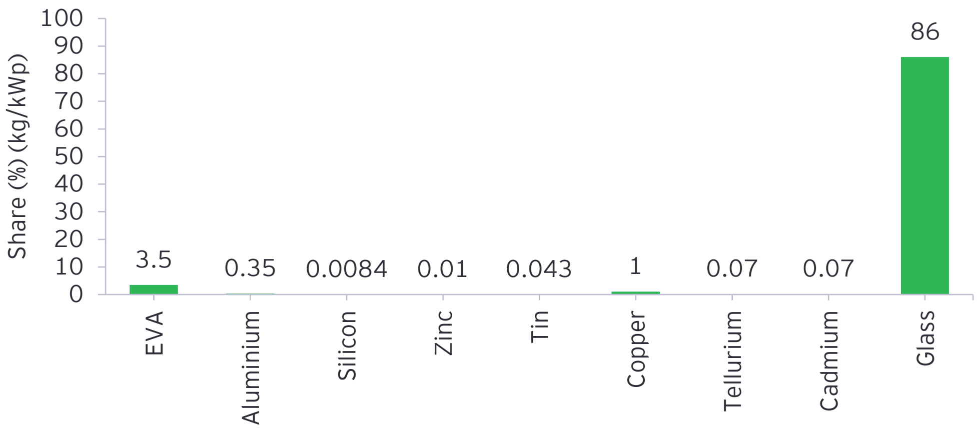
Mechanical Delamination

Physical shredding and separation - simplest method but less efficient for polymer removal

Source: EY analysis; CPCB E-waste management rules

High recovery rates of valuable materials from solar PV panel waste recycling is both costly and challenging at scale





Recycling method / technology	Pros	Cons
Mechanical Delamination	▪ Low capital expenditure: less investment in equipment/infrastructure ▪ Proven at commercial scale: widely used due to simplicity and cost-effectiveness	▪ Lower recovery rate: recovers about 75%-80% (mainly glass, aluminum) ▪ Limited high-value material recovery: struggles to efficiently recover silicon and silver
Thermal Delamination	▪ Higher recovery rate: more effective than mechanical ▪ Lab-validated: demonstrated in lab and pilot-scale settings	▪ Higher capital expenditure: requires specialized furnaces and emission controls ▪ Exhaust gas management is needed to avoid pollution
Chemical Delamination	▪ Highest recovery rate among methods ▪ High purity materials: especially silicon and silver ▪ Lab-validated effectiveness	▪ Chemical disposal: challenging and costly at scale ▪ Higher costs: capital/operating costs are greater due to chemical handling and safety

Source: EY Analysis; https://www.ceew.in/sites/default/files/how-can-india-enable-circular-economy-with-solar-waste-management.pdf

Action plan for advancing circular economy of solar PV panels

Enhanced regulatory framework

- Effective categorization of solar waste. Develop clearer guidelines for stakeholders involved in the circular economy value chain.
- Mandatory extended producer responsibility implementation.

Infrastructure development

- Incremental technology adoption- Phased approach to recycling technology development, starting with bulk recycling in 2025, transitioning to a mixed approach by 2030, and achieving full high-value recycling by 2040.

Informal sector integration

- Strategic integration of informal sector capabilities into formal waste management systems can leverage existing networks while improving working conditions and environmental practices.

Financial incentive mechanisms

- Development of financial incentive structures should support the establishment of recycling infrastructure while ensuring economic viability.

Recycling and collection targets

- Development of certification standards and labeling mechanisms for solar recycling and environmentally responsible processes.
- Quality standards development for collection, processing, and material recovery.

Landfill restrictions and product stewardship

- Coupling landfill restrictions with product stewardship schemes as an effective intervention to promote collection and recycling activities.

Downstream material management

- Need for robust downstream management of recovered materials.
- Effective integration of the recycling value chain requires coordination between collection, processing, and market development activities.

Certification and standards

- Development of certification standards and labeling mechanisms for solar recycling and environmentally responsible processes.
- Quality Standards Development for collection, processing, and material recovery.

Li-ion battery recyclers are adapting to withstand long-term structural challenges and commodity price volatility

'Buy-and-Sell' (Open market): In this model, recyclers purchase end-of-life (EOL) or process scrap batteries directly from OEMs, dismantlers, or collectors, extract valuable materials (e.g., nickel, cobalt, lithium) from the black mass and sell these recovered materials on the open market to battery manufacturers or commodity traders. It operates like a commodity trading model; revenues depend on raw material spot prices. Exposure to market volatility is high—when cobalt/lithium prices drop, profit margins shrink. This is more common in North America and Europe at present.

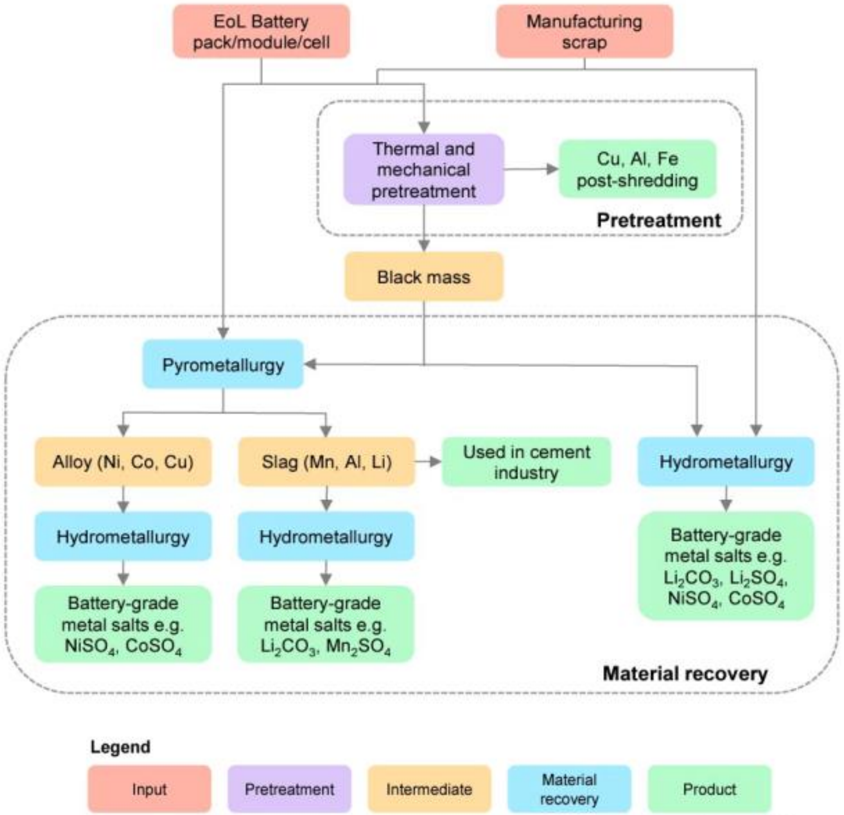
Closed-loop / Tolling: In this model, recyclers form long-term partnerships with OEMs or battery manufacturers. Batteries are recycled and materials returned to the same entity under a pre-agreed fee or "tolling" arrangement (not sold on the open market). It often involves take-back schemes embedded in OEM supply chains. Revenue is service-based (processing fees) rather than commodity trading. OEMs retain ownership of recycled materials - recycler earns a stable fee for processing. China leads with this model due to vertically integrated supply chains between cell makers and recyclers.

In the short term, the profit margins of pure-play recyclers are under pressure from low raw material prices. Those that operate in a closed loop/tolling arrangement are more protected from current market dynamics. In the long-term, as end-of-life batteries become more abundant than manufacturing scrap, companies will want to seize the opportunities of the 'open buy and sell' model. To increase value add and improve margins, black mass refiners are vertically integrating in both directions - into collection, shredding/black mass production, and precursor cathode production (pCAM).

Chinese scrap accounts for more than ~80% of global recycling scrap in 2024 and the large majority of this is process (manufacturing) scrap. China has scaled its battery manufacturing capacity to keep pace with global battery demand, resulting in process scrap being the dominant contributor to its regional scrap pool.

Approximately 95% of global recycling capacity uses Hydrometallurgy or variants thereof and recycling processes are evolving to improve recovery rates and minimize costs.

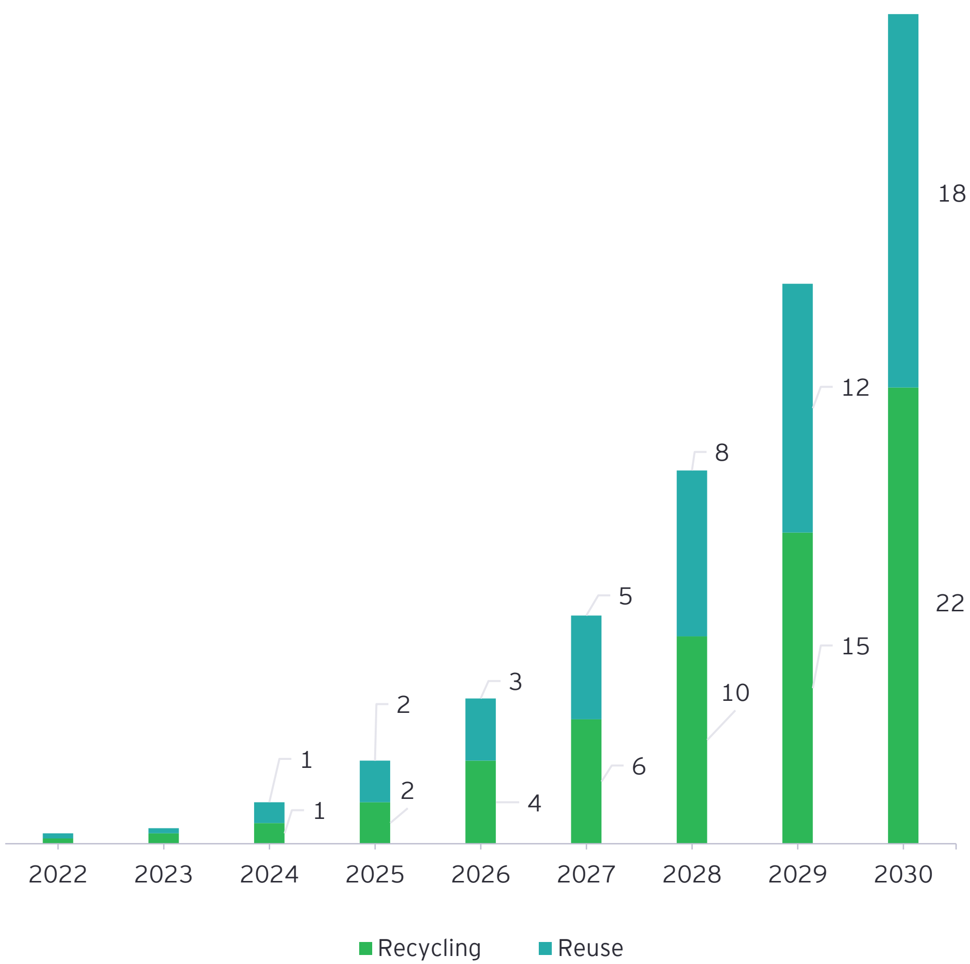
Second-life batteries consist of cells, modules, and packs that are repurposed into less power-intensive applications when they approach their end of life. The EoL of a battery is typically taken at 70%-80% state of health (SoH). Beyond this value, performance degradation is accelerated and such batteries can only be used effectively at a lower C-rate, for instance in residential storage systems. Some second-life batteries make their way back into EVs, if a similarly aged battery pack needs one of their cells/modules being replaced.



Note: EoL = end of life; Cu = copper; Al = aluminium; Fe = iron; Ni = nickel; Co = cobalt; Mn = manganese; Li = lithium; $NiSO_4$ = nickel sulphate; $CoSO_4$ = cobalt sulphate; Li_2CO_3 = lithium carbonate; Mn_2SO_4 = manganese sulphate; Li_2SO_4 = lithium sulphate.

Annual Li-ion battery recycling and reuse volumes will likely cross ~40 GWh by 2030

Annual LiB recycle and reuse volume in GWh



49 GWh Reuse

(Cumulative from 2022-30)

- Reuse

(Cumulative from 2022-30)

- Reuse

(Cumulative from 2022-30)

59 GWh Recycle

(Cumulative from 2022-30)

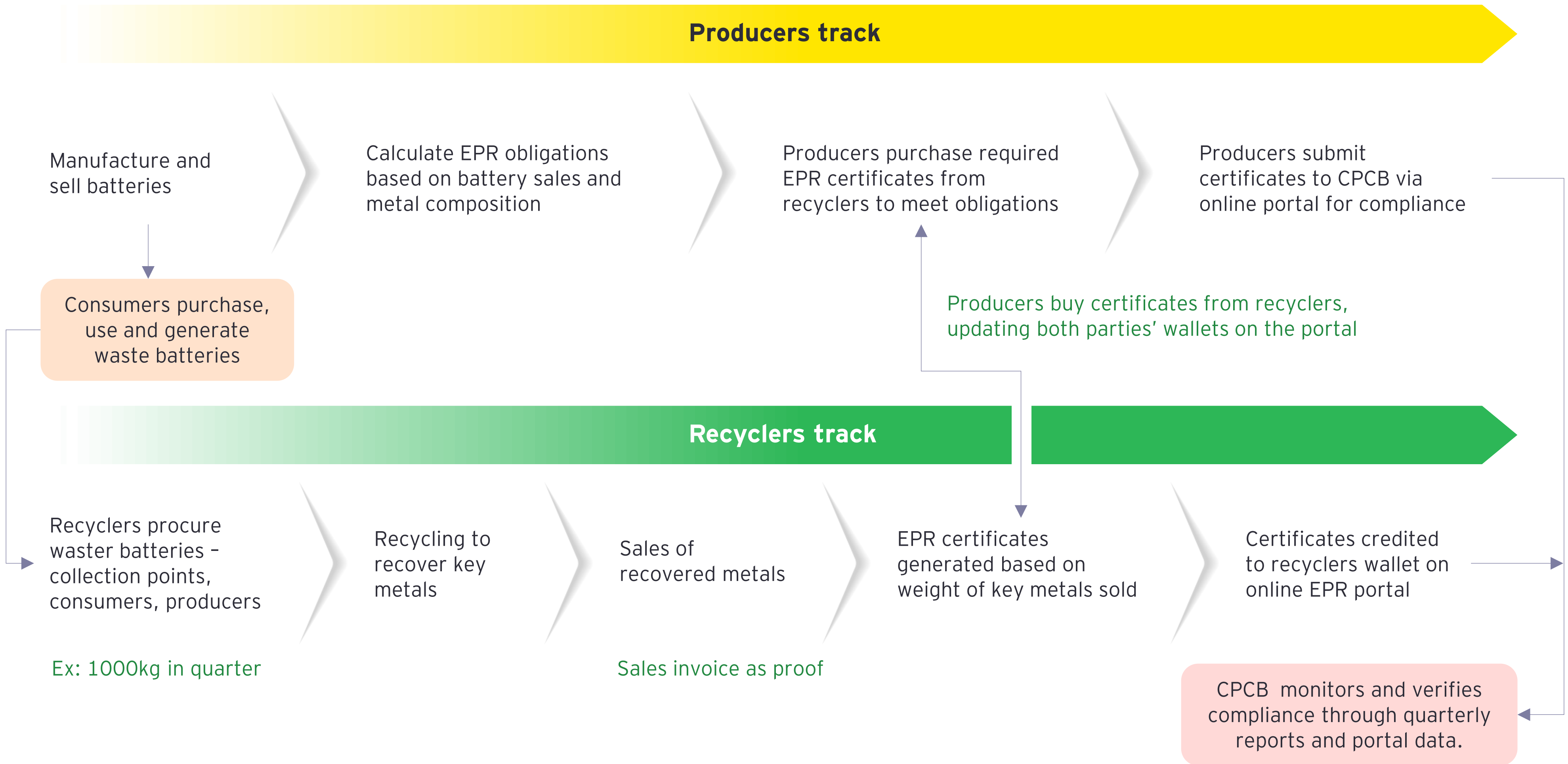
53 GWh Recycle

(Cumulative from 2022-30)

15 GWh Recycle

(Cumulative from 2022-30)

Battery recycling and reuse is transitioning from early-stage to strategic scaling



- Battery recycling and reuse is transitioning from early-stage to strategic scaling.
- The industry faces cost pressures, regulatory drivers, and technological bottlenecks but offers huge environmental and cost-saving opportunities if vertical integration, process innovation, and policy alignment continue.

Challenges and enablers

Challenges

- Informal supply chain of battery scrap: Lack of registration for entities/individuals (kabadiwalas, scrap dealers) involved in waste collection from end-users, segregation, storage and transportation is rendering the waste supply chain to be perceived as informal and inefficient. This is resulting in wildly fluctuating prices for battery scrap segregated from e-waste (dominant source for recyclers in the current scenario) and is driven by the supply chain dominance from few informal / unregistered bulk aggregators/suppliers.
- High GST Burden: The GST rate (18%) on battery scrap and waste, potentially leading to market distortion, non-compliance etc.
- Diminished value of recycled materials from LFP or LMFP battery waste
- Lack of consumer awareness and participation, skilled labor in the battery recycling industry is hindering further investment and expansion.
- Lack of labelling / data with respect to operational history of batteries, battery chemistry, etc., is a challenge for quick and easy determination of state of charge/state of health for waste batteries of different chemistries which make reuse difficult and recycling processes complex and inefficient.

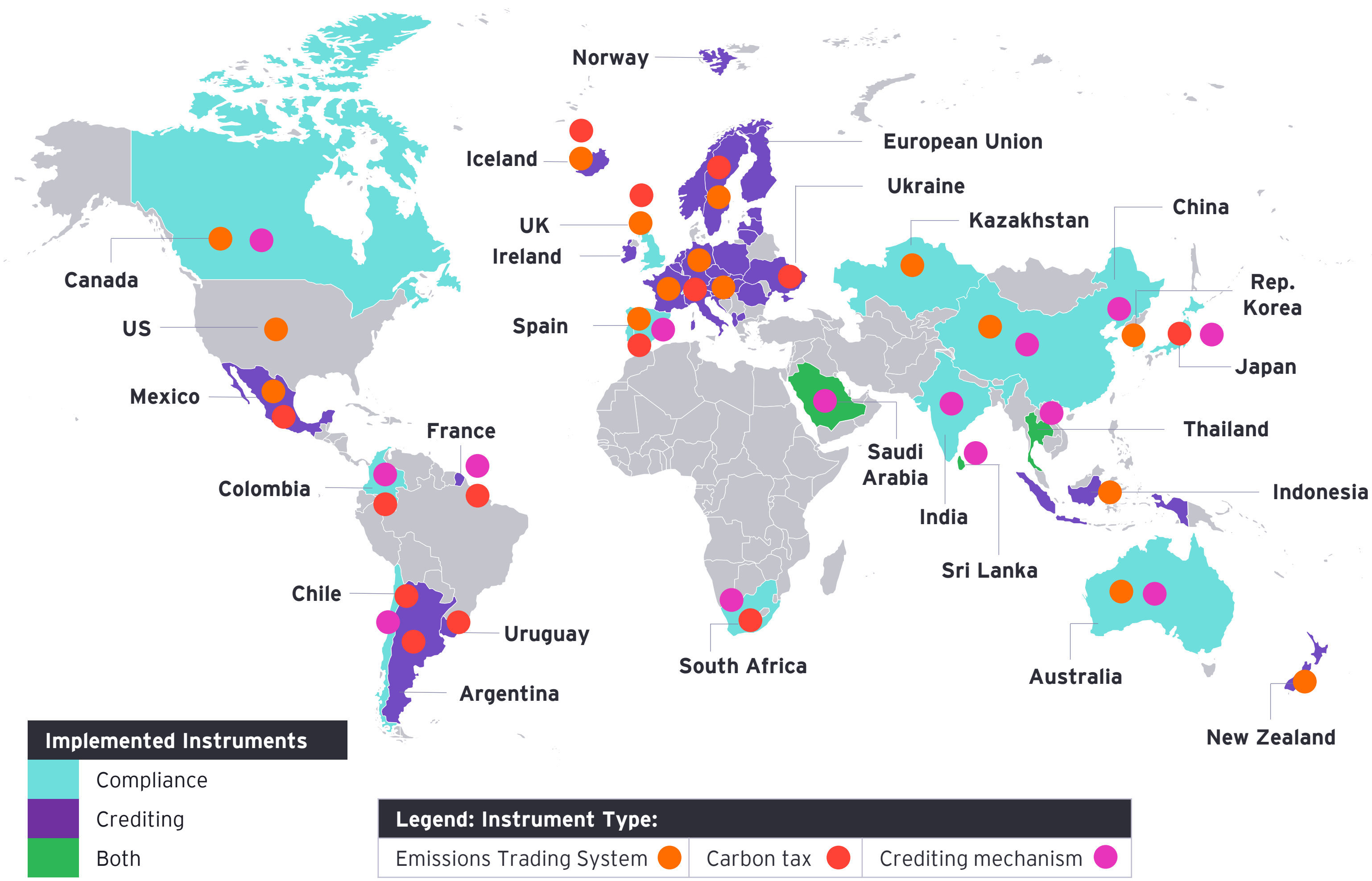
Enablers

- Establish a robust spot exchange market for critical minerals via government-backed platforms to help trade and benchmark real time prices of battery minerals and intermediate products (e.g. black mass) including refurbished batteries and its components.
- Create bonded warehouses for critical minerals under MCX, offering price-risk hedging and national stockpiles which shall be funded by the Critical Minerals Mission
- Develop and implement battery Aadhaar system to capture and share battery operational data (manufacturer, chemistry, cycles, state of health) across stakeholders
- Introduce mandatory registration for entities and individuals involved in collection, transportation, segregation and storage of battery scrap/waste from end-users. Enforce through transport permits and penalties for unregistered entities.
- Restrict inter-state transportation of bulk e-waste or battery scrap/waste by unregistered producers, recyclers to ensure availability of such scrap for local recyclers.
- Harmonize GST on battery scrap to reduce incentives for informal channels and lower end-of-life costs.
- Create a uniform, digital scrap-exchange platform to aggregate supply and stabilize prices.
- Strengthen take-back initiatives like a digital D2C marketplace that collects from retail outlets, service centers, and public spaces EPR programs.

06 Carbon markets: Building integrity for international exchange and transferability

Carbon market mechanisms around the world

Carbon markets around the world[1]

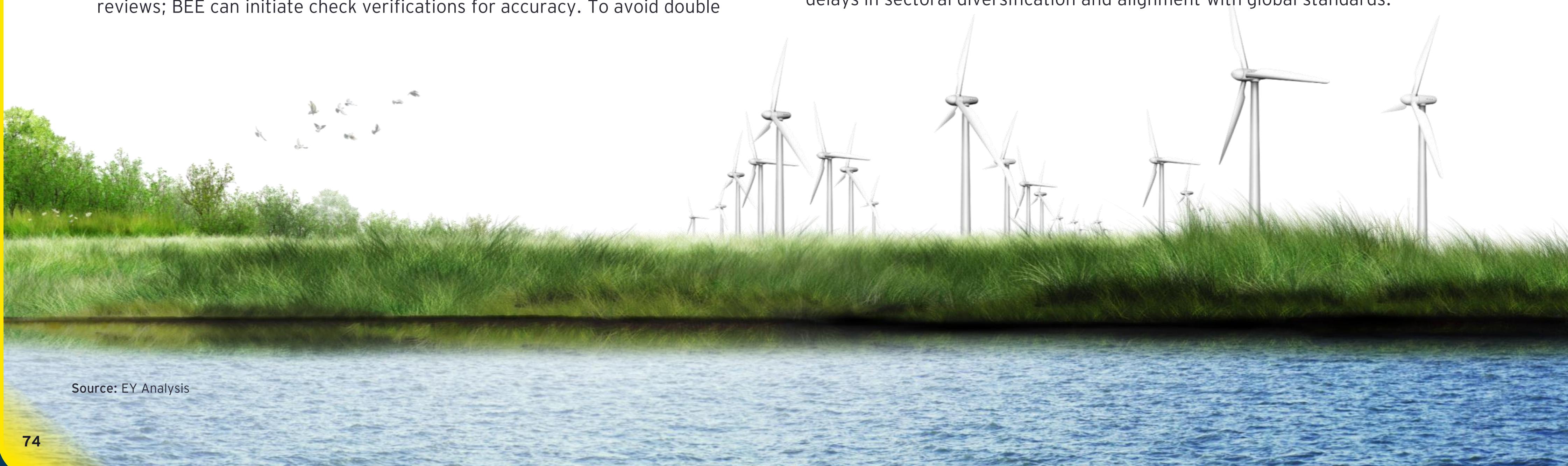


Currently, carbon markets operate in two main forms. The first is through emission trading schemes (ETS), whereby companies are expected to meet intensity-based or absolute targets for emission reductions. To do so, they can buy and sell allowances/carbon credits. For example, the Government of India's CCTS includes a compliance mechanism based on a baseline and credit system: companies that emit less than the assigned baseline earns carbon credits, which can then be sold to companies that exceed their limits. Similarly, EU's ETS follows a cap-and-trade model, where in the total amount of emissions permitted is set, and companies must hold enough allowances to cover their emissions, trading these as needed. The second is project-based carbon offset markets, which include mechanisms that enable emission reduction projects to generate tradable carbon credits. These include the compliance offset markets under Article 6 of the Paris Agreement; the erstwhile CDM under the Kyoto Protocol (Broekhoff et al., 2025); privately operated voluntary carbon markets (VCMs)- such as Verra and Gold Standard; and government-run voluntary schemes, such as India's CCTS - offset, which was launched in December 2023.

Note: 1Regional carbon taxes/ETS have been considered where under consideration (e.g., Spain - Catalonia Carbon Tax and US - North Carolina ETS) in the absence of a single country-wide carbon tax or ETS; 2In the US, regional Pennsylvania and North Carolina). Source(s): EY Insights analysis of The World Bank Carbon Pricing Dashboard, accessed on 8 September 2025, International Carbon Action Partnership (ICAP) ETS map and regulatory websites; https://www.ceew.in/sites/default/files/voluntary-carbon-offset-mechanism-and-challenges-in-carbon-credit-trading-scheme-market-for-india.pdf

Government of India's Carbon Credit Trading Scheme (CCTS): GHG emission intensity targets are notified for ~743 entities across 8 sectors under first trajectory of compliance mechanism

- In December 2022, the Government of India through Ministry of Power amended the Energy Conservation Act, 2001, establishing a framework for the Indian carbon market (ICM). Subsequently, The Ministry of Environment, Forest and Climate Change (MoEFCC) notified the Carbon Credit Trading Scheme (CCTS) in June 2023, with amendments in 2024 and further notifications in June 2025, establishing India's compliance and offset markets. CCTS builds on the Perform, Achieve, and Trade (PAT) scheme, transitioning from energy savings certificates to carbon credits, aiming to cover obligated sectors like power and industry by 2026.
- Compliance mechanism (for obligated entities): The Bureau of Energy Efficiency (BEE) sets GHG intensity targets, requiring entities to submit monitoring plans within three months of trajectory periods, detailing emission sources, data flows, and methodologies (e.g., IPCC defaults or site-specific factors). Monitoring involves continual activity data measurement, lab-accredited NCV calculations, and quarterly/annual reporting via standardized forms. Verification by accredited agencies ensures reasonable assurance, with materiality thresholds at 2% of emissions, site visits, and independent reviews; BEE can initiate check verifications for accuracy. To avoid double counting, renewable energy claims require documentation excluding Renewable Energy Certificates, and captured emissions (e.g., CCUS) are adjusted only if permanently stored. The ICM Registry tracks Carbon Credit Certificates (CCCs), enabling trading on power exchanges.
- Offset mechanism (for non-obligated entities): Allows voluntary projects to generate credits using government-approved methodologies (bottom-up or top-down, aligned with ISO 14064). Project registration involves submitting a Project Design Document (PDD) for public comments (30 days), followed by validation by Accredited Carbon Verification Agencies (ACVAs), including on-site inspections for high-emission projects (>100,000 tCO_2e/year). Methodologies emphasize conservativeness, additionality, and baselines below business-as-usual. Verification assesses monitoring reports with materiality thresholds (0.5%-2%), resolving issues via corrective actions before credit issuance.
- These mechanisms prioritize monitoring, reporting and verification, third-party accreditation, and transparency but face implementation gaps, such as delays in sectoral diversification and alignment with global standards.



Source: EY Analysis

Compliance market

- Aluminium
- Chlor Alkali
- Cement
- Fertiliser
- Iron & Steel
- Pulp & paper
- Petrochemicals
- Petroleum Refinery
- Textile

Offset market

- Energy
- Industries
- Waste handling, disposal
- Agriculture
- Forestry
- Transport
- Construction
- Fugitive emissions
- CCUS
- Solvents use

GHG emission intensity targets notified for ~743 entities across 8 sectors under first trajectory of compliance mechanism

India's carbon offset market: Barriers to quality, integrity, and global linkages

CEEW analysis shows India has emerged as a significant supplier of carbon credits to voluntary carbon markets (VCMs), issuing over 278 million credits between 2010 and 2022, representing roughly 17% of global supply. While projections suggest the sector could generate US$20–40 billion in revenue by 2030, persistent integrity and quality issues limit its potential for integration with compliance systems such as the EU Emissions Trading System (EU ETS).

Performance and delays

Independent assessments of Indian-origin projects on the Verra verified carbon standard registry reveal widespread delays, particularly among unregistered energy-sector projects. Over 70% of such projects exceed established reference timelines for registration, with energy industries showing the most pronounced delays. The energy demand segment also experiences bottlenecks—66% of unregistered projects surpass the benchmark duration for approval. These delays slow the monetisation of carbon assets and erode investor confidence.

Sectoral profile

Participation in VCMs is heavily skewed towards energy industries (46% of projects) and energy demand (23%), with agriculture, forestry, and other land use (AFOLU) representing about one-fifth of activity. Sectors such as transport, waste management, CCS, and industrial processes have a presence but remain underrepresented despite notable mitigation potential.

Quality alignment challenges

Many Indian credits fall short of the stringent requirements under leading compliance regimes, particularly around robust financial additionality testing and the use of conservative baselines. Large-scale renewable energy projects—which dominate India's carbon credit portfolio—often struggle to demonstrate that they rely on carbon finance to proceed, especially in markets where such projects are already competitive with fossil fuel alternatives. The geographic context further complicates additionality claims; in emerging economies with high renewable energy penetration, it is harder to prove emission reductions beyond business as usual.

Market saturation and shifting standards

The VCM landscape is becoming more competitive. Major registries have tightened eligibility, prioritising projects in least developed countries, underserved regions, and small island developing states. This shift has slowed certification for some Indian projects as methodologies are re-examined. In parallel, many large renewable energy developers are pivoting towards instruments such as renewable energy certificates (RECs) and international RECs (I-RECs), which generally do not require proof of additionality, making them more attractive for already profitable ventures.

Implications

Unless India addresses delays, diversifies sectoral participation, and improves methodological alignment with top-tier international standards, its carbon offsets may remain excluded from high-value compliance markets. Targeted reforms could include streamlining registry processes, developing additionality frameworks suited to mature renewable markets, and incentivising credit generation in underrepresented sectors with high mitigation potential.

Source: https://www.ceew.in/sites/default/files/voluntary-carbon-offset-mechanism-and-challenges-in-carbon-credit-trading-scheme-market-for-india.pdf

Policy recommendations to build integrity of Indian carbon credits for international exchange and transferability

Monitor the real-time status and progress of project applications through a project tracking system
It is essential to incorporate real-time tracking for each stage of the registration cycle, such as project submission, validation, verification, stakeholder consultations, and certification issuance. These thresholds should align with historical timelines and best practices from frameworks such as the CDM, Verra VCS, and Gold Standard. A centralized database should include phase-wise timelines, detect delays, and notify stakeholders via automated alerts. In case of delays, a grace period may be provided, followed by the submission of a mandatory issue report by the particular ACVA outlining the reasons, mitigation measures, and revised timelines. This approach would ensure early identification and resolution of issues in the project development and credit issuance cycle.

Enforce annual performance review of accredited carbon validation and verification bodies (ACVAs/VVBs)

Annual performance review system for accredited carbon validation and verification bodies (ACVAs) should be established to enhance accountability and maintain high operational standards. As independent third parties, these organisations are essential for upholding the market's integrity and ensuring the successful issuance of carbon credits. Since they are deeply involved in validating and verifying projects, their role is crucial. A performance review system should assign performance-based grades to all certified ACVAs, enabling project developers to make informed decisions based on cost-effectiveness and performance metrics.

Project documentation review: Conduct randomized or flagged reviews of submitted projects to check whether ACVAs adhere to compliance standards. Repeated delays, anomalies, or stakeholder feedback should also trigger reviews.

Validation and verification monitoring audits: Conduct randomized remote or onsite audits to observe ACVAs' performance during validation and verification.

Accountability and compliance mechanisms: Address non-conformities through warnings, mandatory corrective actions, or suspensions for severe issues.

Accreditation body feedback: Collaborate with accreditation bodies to improve review systems, share relevant insights, and develop capacity-building resources for ACVAs

Integrate standardized baselines to streamline project development within the CCTS offset mechanism
The CCTS offset mechanism should consider integrating standardized baselines (SBs) to streamline the carbon credit issuance process and overcome barriers to project development projects by small-scale developers, or projects with limited data availability—especially in the energy sectors—could benefit from employing SBs, as they provide an agreed-upon baseline emissions factor, thereby simplifying the baseline identification and additionality demonstration process. Adopting SBs would further reduce the complexity of monitoring as well as calculation requirements for individual projects, thus significantly reducing transaction costs and delays within the credit issuance cycle and streamlining project development and implementation processes.

Source: https://www.ceew.in/sites/default/files/voluntary-carbon-offset-mechanism-and-challenges-in-carbon-credit-trading-scheme-market-for-india.pdf

References

- https://www.sciencedirect.com/science/article/abs/pii/S0306261923000338?fr=RR-2&ref=pdf_download&rr=96def0742c157fb1
- https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors
- https://www.pib.gov.in/PressReleasePage.aspx?PRID=2100108
- https://www.pib.gov.in/PressReleasePage.aspx?PRID=2099244
- https://aris.iaea.org/publications/smr_book_2020.pdf
- https://iced.niti.gov.in/energy/electricity/generation/power-generation
- https://www.pib.gov.in/newsite/PrintRelease.aspx?relid=112034
- https://www.barc.gov.in/randd/tfc.html
- https://world-nuclear.org/information-library/country-profiles/countries-g-n/india
- https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=IN
- https://www-pub.iaea.org/MTCD/Publications/PDF/p15790-PUB9062_web.pdf
- https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/feb/doc202523495401.pdf
- https://smrroadmap.ca/wp-content/uploads/2018/11/SMRroadmap_EN_nov6_Web-1.pdf
- smr-status-sep-2012.pdf
- booklet-fr-2013.pdf
- aris.iaea.org/publications/smr-book_2016.pdf
- https://mnre.gov.in/en/year-wise-achievement/
- https://www.linkedin.com/posts/debmalya-sen_fdre-2023-2025-activity-7350797945534902272-8LtF?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A
- https://www.linkedin.com/posts/debmalya-sen_standalone-bess-tariff-update-activity-7343599816930668544-tQP0?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A
- https://www.linkedin.com/posts/debmalya-sen_india-ess-market-update-june-2025-1st-anniversary-activity-7345349000843161600-RXVR?utm_source=share&utm_medium=member_desktop&rcm=ACoAACcPYXcBpwV7MNVIg7S6rxKsjenvw-OCX4A
- https://ctuil.in/uploads/annual_rolling_plan/168318545197Final%20Procedure%20for%20Electricity%20Rules%20%20Planning%20Regulations%20(1).pdf
- https://indiatransmission.org/inter-regional-corridor
- https://mnre.gov.in/en/energy-storage-systemsess-overview/
- https://powermin.gov.in/sites/default/files/Re_constitution_of_the_National_Committee_on_Transmission_reg.pdf
- https://iced.niti.gov.in/
- https://www.gov.uk/government/publications/national-policy-statement-for-electricity-networks-infrastructure-en-5/national-policy-statement-for-electricity-networks-infrastructure-en-5
- https://www.ceew.in/sites/default/files/how-can-india-enable-circular-economy-with-solar-waste-management.pdf
- https://www.ceew.in/sites/default/files/voluntary-carbon-offset-mechanism-and-challenges-in-carbon-credit-trading-scheme-market-for-india.pdff-life solutions for solar photovoltaics and wind power systems in Viet Nam | United tions Development Programme

- E-Waste Management Rules, 2022
- Safe Handling and Disposal of Solar Photovoltaic Modules, Panels, and Cells (Draft)
- https://www.ceew.in/sites/default/files/how-can-india-enable-circular-economy-with-solar-waste-management.pdf
- https://iea-pvps.org/wp-content/uploads/2020/01/End_of_Life_Management_of_Photovoltaic_Panels_Trends_in_PV_Module_Recycling_Technologies_by_task_12.pdf
- //www.ijesd.org/vol15/IJESD-V15N5-1492.pdf
- WRI India
- Current LIB recycling landscape in India - leading players and commitments ▸ Evreporter
- Battery Waste Management Rules, 2022 and its amendments
- Guidelines for imposition of Environment Compensation (EC) under Battery Waste Management Rules, 2022
- EPR Online portal for Battery Waste Management
- Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 (HWM Rules)
- EU Directive Battery waste
- https://edgar.jrc.ec.europa.eu/report_2024
- IPCC AR6 WGIII Report 2022
- Climate Watch
- The World Bank Carbon Pricing Dashboard, accessed on 25 January 2024, International Carbon Action Partnership (ICAP) ETS map and regulatory websites
- Detailed Procedure for Compliance Mechanism - BEE
- Detailed Procedure for Offset Mechanism under CCTS
- Draft CERC Regulations (Terms and Conditions for Purchase and Sale of Carbon Credit Certificates) 2024
- https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/development-eu-ets-2005-2020_en
- India Energy Security Scenarios 2047 Report by NITI Aayog - https://iess2047.gov.in/_/theme/documents/IESS_v3_one_pagers.pdf
- https://www.pib.gov.in/PressReleasePage.aspx?PRID=1795071

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The Confederation of Indian Industry (CII) works to create and sustain an environment conducive to the development of India, partnering Industry, Government and civil society, through advisory and consultative processes.

CII is a non-government, not-for-profit, industry-led and industry-managed organization, with around 9,000 members from the private as well as public sectors, including SMEs and MNCs, and

an indirect membership of over 365,000 enterprises from 294 national and regional sectoral industry bodies.

For more than 125 years, CII has been engaged in shaping India's development journey and works proactively on transforming Indian Industry's engagement in national development. CII charts change by working closely with Government on policy issues, interfacing with thought leaders, and enhancing efficiency, competitiveness, and business opportunities for industry through a range of specialized services and strategic global linkages. It also provides a platform for consensus-building and networking on key issues.

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For 2024-25, CII has identified "Globally Competitive India: Partnerships for Sustainable and Inclusive Growth" as its Theme, prioritizing 5 key pillars. During the year, it would align its initiatives and activities to facilitate strategic actions for driving India's global competitiveness and growth through a robust and resilient Indian industry.

With 70 offices, including 12 Centres of Excellence, in India, and 8 overseas offices in Australia, Egypt, Germany, Indonesia, Singapore, UAE, UK, and USA, as well as institutional partnerships with about 300 counterpart organizations in almost 100 countries, CII serves as a reference point for Indian industry and the international business community.

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