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Least-Cost Power Sector Transition in India to 2035: Integrating Marginal Abatement Costs, Tariff Dynamics, and Carbon Market Mechanisms

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Abstract: ***The Energy sector in India is undergoing a massive transformation by transitioning to more cleaner resources and technology upgradation to fulfil the commitments of action required to combat the climate change and move forward to the ambitious target of Net Zero by 2070. India's Nationally Determined Contribution (NDC-2035) commits to reducing emissions intensity of GDP by 47% from 2005 levels, achieving 60% cumulative installed capacity from non-fossil sources, and creating a carbon sink of 3.5-4.0 billion tonnes CO_2 equivalent. This paper examines India's least-cost power sector transition under the triple constraint of reliability, carbon reduction, and affordability. Using Marginal Abatement Cost (MAC) curves, Real-Time Market (RTM) signals, and the Carbon Credit Trading Scheme (CCTS), the study demonstrates that India's pathway is not a binary coal-versus-renewables choice or coal exit, but a system optimization balancing efficiency, flexibility, and affordability. Results show that renewables and demand response dominate negative-cost abatement, coal efficiency and flexibility deliver low-cost reductions, while storage and flexibility are indispensable medium-cost enablers. RTM liquidity trends highlight flexibility scarcity, while CCTS introduces carbon costs into dispatch and investment decisions. The integrated framework ensures reliability, decarbonisation, and tariff stability, while enabling a just transition for coal-dependent states.***

Keywords: Marginal Abatement Cost; Power Sector Transition; Carbon Credit Trading Scheme; DISCOM Tariffs; Renewable Energy Integration; Energy Storage; India Energy Policy.

1. Introduction

India's energy sector stands at a critical inflection point, shaped simultaneously by surging demand from rapid economic growth and the imperative of transitioning toward cleaner energy sources. While renewable energy has witnessed remarkable expansion in recent years, coal continues to serve as the backbone of India's electricity supply, resulting in an uneven and complex transition pathway. This duality underscores the "power sector trilemma" of balancing energy security, environmental sustainability, and economic affordability.

In this context, the Government of India has recently approved the country's updated Nationally Determined Contribution (NDC) for the period 2031–2035, to be communicated to the United Nations Framework Convention on Climate Change (UNFCCC). The commitments reflect India's strategic alignment with its long-term vision of *Viksit Bharat @2047* and the national pledge to achieve net-zero emissions by 2070. The key elements of the NDC-2035 include:

- A reduction in the emissions intensity of GDP by 47 percent from 2005 levels by 2035.
- Achieving 60 percent cumulative installed electric power capacity from non-fossil fuel-based energy resources by 2035.
- Establishing a carbon sink of 3.5 to 4.0 billion tonnes of CO_2 equivalent through enhanced forest and tree cover by 2035, relative to 2005 levels.

Together, these commitments highlight India's attempt to reconcile the competing priorities of growth, sustainability, and equity, while navigating the structural challenges of its energy transition. The NDC-2035 thus represents both a milestone in India's climate diplomacy and a domestic policy framework that will shape the trajectory of its power sector transformation over the next decade.

2. Literature Review

- TERI (2023): India's electricity pathways emphasize renewables + storage as least-cost.
- NREL (2020): Solar and wind dominate new-build economics, coal declines post-2030.
- CEA (2024): National Electricity Plan highlights peak demand challenges and flexible coal.
- World Bank (2023): Just transition frameworks stress fiscal and social resilience in coal states.

These studies converge on the insight that renewables are structurally cheaper, but flexibility and carbon pricing determine system viability.

The Triple Constraint

The recent trends in the power scenario in this transient phase is the emergence of **triple constraint** in its power sector. Lets demystify the constraints one by one.

1) Reliability Constraint: Rising Peak Demand vs System adequacy

The Electricity demand growth is now **peak-driven**, not energy-driven. The Summer cooling, urbanisation, EV charging, and data centres are pushing **evening and heat-wave peaks** sharply upward. Peak demand is growing **faster than average energy demand**. The r**ationale for constraint severity depends on various factors.** Power systems must be built for **the highest 1–2% hours**, not averages. The solar solves *daytime energy*, but **evening peaks remain uncovered without firm capacity**. Grid frequency control, ramping, reserves, and inertia cannot yet be fully provided by inverter-based resources alone. **The Implications of the above constraint is that t**he system **must retain adequate firm and flexible capacity** (coal, hydro, storage), even if those assets run fewer hours. This explains why coal capacity persists under NDC-2035 despite declining generation share.

2) Carbon Constraint

Emissions Intensity Reduction under NDC-2035. The NDC requires~**47% reduction in emissions intensity of GDP (2005 baseline) by 2035,60% non-fossil installed capacity in power, and a credible trajectory toward net-zero by 2070**. The resultant effects are new coal additions face carbon-intensity scrutiny, not outright bans. Existing coal plants are pushed toward Higher efficiency, Lower heat rates and Flexible operation. Carbon cost increasingly enters dispatch, investment, and financing decisions, especially through the Carbon Credit Trading Scheme (CCTS).

Implications of the second constraint:

- The power sector must **reduce emissions per unit of output without constraining growth**.
- This is solved via **renewables first, efficiency second, absolute reduction later-** not abrupt coal phase-out.

3) Affordability vs Financial Viability Constraint: DISCOMs and consumers- The present Scenario

DISCOMs already operate under High legacy power costs , Cross-subsidies, payment delays, and Transition technologies (storage, grid upgrades, peaking capacity) are **capital-intensive**, even if energy is cheap**.**

Limitations Imposed

Passing full transition costs directly to consumers, risks Tariff shock, Political resistance, Industrial competitiveness loss and conversely, suppressing tariffs weakens DISCOM balance sheets.

Implications of this third constraint

Transition must occur **without sustained tariff inflation**, while preserving DISCOM solvency. This pushes India toward gradual deployment, intensity-based carbon pricing (CCTS) and Time-of-day tariffs instead of flat hikes.

The Interactions of The Three Constraints (the real challenge)

Constraint	If prioritised alone	What it breaks
Reliability	Build lots of firm fossil capacity	NDC carbon targets
Carbon	Push RE aggressively	Grid stability, peak reliability
Affordability	Suppress tariffs	DISCOM finances, investment

NDC-2035 forces the power sector to solve all three simultaneously, not sequentially.

India's Strategy is "Different" from Global.

India's response makes sense once the triple constraint is recognised:

- No absolute cap on power sector emissions (unlike EU)
- Intensity-based carbon market (CCTS) instead of hard ETS
- Coal retained as capacity, not baseload energy
- Renewables dominate energy growth
- Storage and flexibility valued as system assets
- Tariffs reshaped by Time-of-Day, not across-the-board hikes

This is not policy inconsistency- it is **constraint-driven design**.

So, we see that under NDC-2035, India's power sector must simultaneously guarantee **reliability for rising peaks**, **deliver emissions-intensity reduction**, and **keep electricity affordable**- with failure on any one dimension threatening the entire transition.

This creates a classic **least-cost optimisation under reliability and carbon constraints**, rather than a simple "coal versus renewables" choice**. The correct question is not *how fast coal is phased out*, but *which mix minimises total system cost while meeting energy security and climate objectives.***

3. Research Gap

While the literature on India's energy transition is extensive, several critical dimensions remain underexplored. Much of the existing scholars have tended to reduce the transition narrative to a binary contest between coal and renewables, overlooking the nuanced system-level interactions that define least-cost pathways. Specifically, four gaps can be identified:

1) **Coal's evolving role in system adequacy and flexibility:** Current studies often frame coal as a fuel to be phased out, rather than examining its transformation into a reliability and flexibility provider. The implications of declining plant load factors, flexible operation retrofits, and coal's repositioning as **"system insurance**" have not been adequately integrated into transition models.
2) **Integration of Marginal Abatement Cost (MAC) curves into planning frameworks:** Although MAC curves are widely used in global energy economics, their systematic application to India's power sector remains limited. Few studies explicitly quantify the hierarchy of negative-cost (renewables, demand response), low-cost (coal efficiency), and medium-cost (storage) options in shaping least-cost decarbonisation strategies.
3) **Carbon Credit Trading Scheme (CCTS) and tariff design:** The emerging intensity-based carbon market in India introduces new dynamics for dispatch, investment, and tariff structures. Yet, the literature has not sufficiently examined how CCTS alters merit order dispatch, reshapes DISCOM procurement strategies, or drives the shift toward time-of-day tariffs. This represents a significant gap in linking carbon pricing mechanisms with consumer affordability and financial viability.
4) **Socio-economic pathways for coal-dependent states:** Research has largely neglected the fiscal, employment, and regional development challenges faced by coal-rich states such as Jharkhand, Odisha, Chhattisgarh, and West Bengal. The absence of detailed frameworks for revenue recycling, asset repurposing, and labour reskilling leaves a gap in understanding how just transition policies can mitigate socio-economic disruption.

This paper addresses these gaps by combining **technical (MAC and system modelling), economic (CCTS and tariff impacts), and social (just transition pathways)** dimensions into a unified framework.

Objectives

1) To evaluate India's least-cost power sector transition to 2035 under the triple constraint of reliability, carbon reduction, and affordability.
2) To construct and interpret **Marginal Abatement Cost (MAC) curves** for coal efficiency, renewables, storage, and CCUS.
3) To analyze the role of **Real-Time Market (RTM) liquidity** as a price signal for system flexibility.
4) To assess the impact of the **Carbon Credit Trading Scheme (CCTS)** on dispatch, tariff design, and DISCOM procurement strategies.
5) To propose a **just transition framework** for coal-dependent states, integrating fiscal, employment, and asset repurposing pathways.

4. Methodology

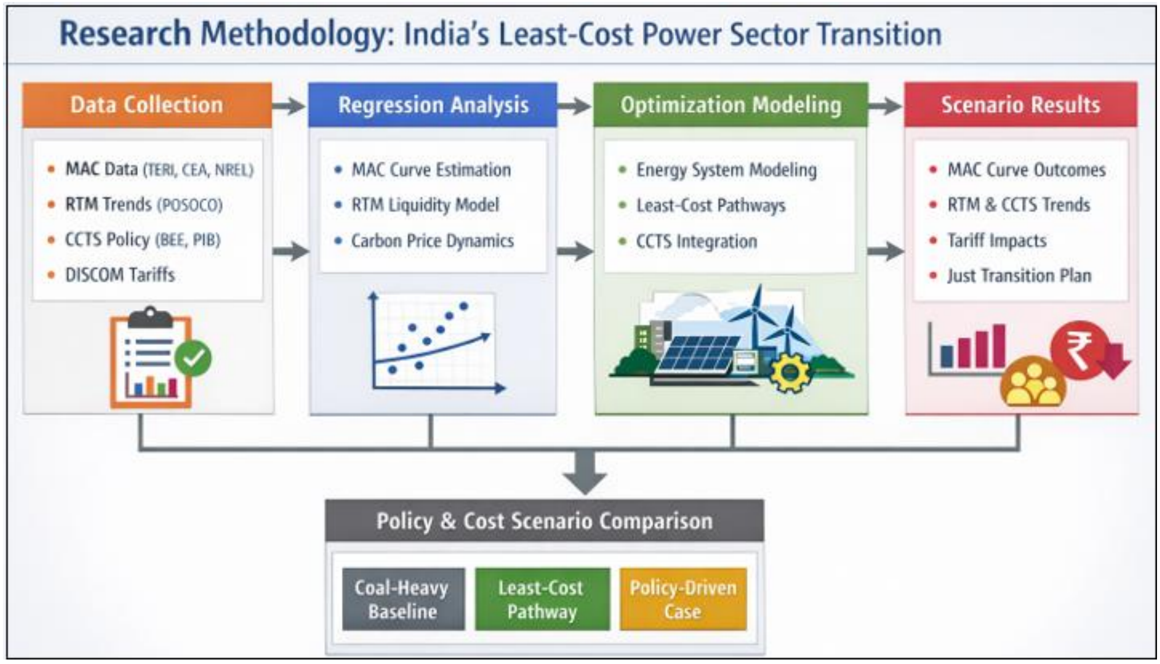

Figure 1

1) Model Type and Analytical Framework

This study employs a hybrid optimization–simulation framework integrating Marginal Abatement Cost (MAC) modeling, Real-Time Market (RTM) liquidity analysis, and Carbon Credit Trading Scheme (CCTS) simulation. The optimization component minimizes total system cost under reliability and carbon constraints using linear programming principles, while the simulation component models dynamic interactions between dispatch, carbon pricing, and tariff evolution across the 2024–2035 horizon. The combined approach captures both static cost hierarchies (MAC) and dynamic market signals (RTM, CCTS).

2) Data Inputs and Sources

Empirical and secondary datasets were synthesized from institutional sources, including:

- TERI (2023): technology-specific capital cost and efficiency data for renewables and coal retrofits.
- CEA (2024): operational parameters such as Plant Load Factor (PLF), ramping capability, and heat rate for coal and hydro assets.
- NREL (2020): cost benchmarks for solar, wind, and battery storage.
- World Bank (2023): global MAC hierarchies for CCUS and long-duration storage.
- POSOCO/GRID-India (2025): RTM liquidity indices and volatility trends.
- BEE and PIB (2025): CCTS compliance benchmarks and carbon pricing guidelines.

3) Time Horizon and Scenario Design

The model evaluates India's power sector transition from **2024 to 2035**, aligned with the NDC-2035 commitments. Three scenarios were analyzed:

- Baseline: coal-heavy generation mix without carbon pricing.
- Least-cost transition: renewables + storage + efficiency retrofits under carbon intensity targets.
- Policy-driven: inclusion of CCTS and time-of-day (ToD) tariffs.

4) Constraints

The optimization is subject to the following constraints:

- Reliability constraint: firm capacity ≥ peak demand × reserve margin.
- Carbon constraint: emissions intensity ≤ 0.53 × 2005 baseline by 2035.
- Affordability constraint: average tariff growth ≤ 2% annually in real terms.

These ensure system adequacy, decarbonization, and tariff stability.

5) Assumptions

Key assumptions include:

- Technology learning rates: 3–5% annual cost decline for renewables and batteries.
- Carbon price trajectory: ₹300/tCO_2 in 2026 rising to ₹1,500/tCO_2 by 2035.
- Exchange rate and inflation held constant in real terms.

- No abrupt coal phase-out; efficiency and flexibility retrofits prioritized.

6) MAC Curve Formulation

- MAC values were derived from empirical data and literature synthesis, validated through regression modeling. For each technology i:
- MAC_i=C_i/A_i
- where C_i is the incremental capital cost (₹ million/MW) and A_i is the abatement potential (MtCO_2 avoided). The cumulative abatement potential A_c and marginal cost MAC_i were plotted to form the curve.
- Technologies were ranked by ascending MAC_i, producing a stepwise curve from negative-cost (renewables, demand response) to high-cost (CCUS, hydrogen).

7) Sample Scope

The sample scope includes Geographic coverage: pan-India, aggregated across regional grids (ER, WR, SR, NR). Plant types: coal (subcritical, supercritical, retrofit), solar PV, wind, hybrid RE, pumped storage, battery storage, CCUS. System boundary includes grid-connected generation and storage assets only; off-grid excluded.

8) Reproducibility

All computations were performed using **Python** (pandas, statsmodels, matplotlib) for regression and curve generation. The dataset and code are structured for replication, enabling future researchers to update cost parameters or extend the time horizon.

MAC Curve Construction:

- **Definition**: A MAC curve plots the ***marginal cost*** **(the cost of reducing one additional tonne of CO_2 equivalent) against the *abatement potential* (the total emissions reduction possible from a measure).**
- **Purpose:** It provides a structured way to compare different mitigation strategies—such as renewable energy deployment, energy efficiency upgrades, carbon capture, or afforestation—based on both cost and impact.
- **Origin:** The concept was popularized by McKinsey in the mid-2000s as a decision-support tool for governments and corporations**.**

Interpretation:

Bars below the horizontal axis indicate *negative-cost measures* (i.e., they save money while reducing emissions, such as energy efficiency improvements).

Bars above the axis represent measures that require additional investment but may be necessary for deeper decarbonization**.**

Uses of MAC Curves

- **Policy design:** Helps governments prioritize low-cost, high-impact measures in climate action plans.
- **Corporate strategy:** Guides companies in selecting cost-effective decarbonization pathways.
- **Investment planning:** Identifies where subsidies, carbon pricing, or technology support may be needed.
- **Academic research:** Provides a comparative framework for analyzing sectoral or national mitigation strategies**.**
- **Limitations:** Static assumptions are made. MAC curves often assume fixed costs and technologies, which may change rapidly.

Ranked mitigation options by ₹/tCO_2 avoided.
Data from TERI, CEA, and modeled system costs.

RTM Analysis

Indexed liquidity trends (2024=100). Captures volatility from solar-heavy supply and evening peaks**.**

CCTS Modelling: Intensity-based carbon pricing with credit trading**. Benchmarks ti ghten gradually, avoiding shocks.**

Tariff Assessment: DISCOM tariff projections under least-cost mix. Focus on time-of-day differentiation.

Data Collection: The datasets for the MAC curve, RTM liquidity, and CCTS credit market indices are secondary data sets synthesized from multiple institutional sources: TERI, NREL, CEA, POSOCO/GRID-India, and Government of India (BEE, PIB). Each contributes specific data streams that underpin the graphs**.**

5. Results

1) MAC Curve (2030–2035) from Fig 2.

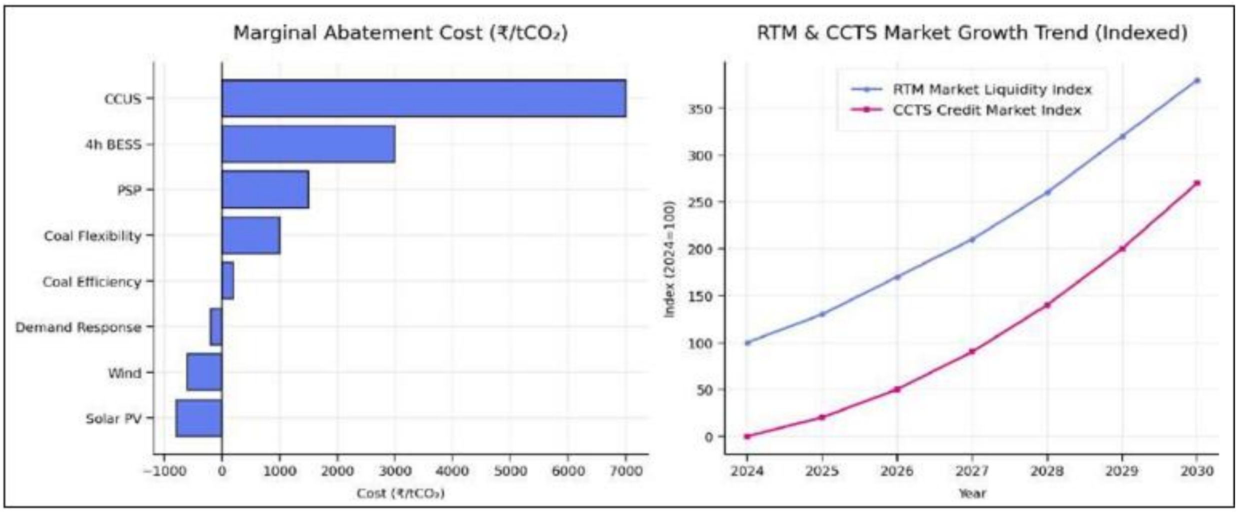

Figure 2

- Negative cost: Solar PV, wind, demand response.
- Low cost: Coal efficiency (₹300–1,000/tCO_2), flexibility retrofits (₹800–1,500/tCO_2).
- Medium cost: Pumped storage (₹1,000–2,000/tCO_2), BESS (declining).
- High cost: CCUS (>₹2,000–8,000/tCO_2).

2) RTM Liquidity
- Index rises from 100 (2024 baseline) to ~300 by 2030.
- RTM becomes primary price signal for flexibility.

3) CCTS Credit Market
- Starts slow in 2026 Oct, accelerates post-2028.
- Efficient coal plants neutralize carbon costs; inefficient units face penalties.
- Tariff Structure
- Average tariffs stable in real terms.
- Energy charges decline, capacity charges rise.
- ToD pricing becomes unavoidable.
- Discussion
- **Coal's role**: **From baseload to system insurance**. PLFs decline, but coal remains valuable for adequacy.
- Renewables: Backbone of least-cost abatement, structurally cheaper than coal.
- Storage: Indispensable for evening peaks, moderate cost but system-critical.

Carbon pricing: CCTS integrates carbon costs gradually, avoiding shocks.

RTM: Flexibility scarcity becomes the defining market signal.

Policy Implications

Avoid new coal investments beyond efficiency retrofits. Scale up storage and DSM to manage peaks. Strengthen transmission corridors for renewable integration. Enable market reforms for carbon-adjusted merit order. Design ToD tariffs to incentivize load shifting**.**

1) Just Transition

Coal-dependent states (Jharkhand, Odisha, Chhattisgarh, West Bengal) face fiscal and social risks. Strategies include Revenue recycling, Carbon-market revenues compensate states, Asset repurposing i.e. End-of-life coal assets converted to storage or RE parks. Labour reskilling for Transition to grid services, RE O&M, logistics. Economic diversification for Green hydrogen hubs, RE manufacturing in coal regions.

Implications for The Indian Power Sector (2030–2035)
- Marginal abatement cost (MAC) curves rank mitigation options by **₹/tCO_2 avoided**, revealing the economic logic of the transition.
- **Coal-based abatement options: low-cost improvements first:** Contrary to popular perception, a significant share of coal-sector emissions can be reduced at low or even negative cost:
- **Operational efficiency, digital optimisation, and heat-rate improvements** often deliver negative or near-zero MACs because fuel savings outweigh investment costs.
- **Auxiliary power reduction, turbine retrofits, and coal quality optimisation** sit in the ₹300–1,000/tCO_2 range.
- **Flexibilisation retrofits** (enabling low-load and ramping operations to support renewables) typically cost ₹800–1,500/tCO_2 but are system-critical.
- High-capital options such as repowering or coal-based CCUS appear only at very high MACs (₹2,000–8,000+/tCO_2) and are not least-cost before the late 2030s.

Implication: Coal's first response to carbon constraint is **efficiency and flexibility**, not exit.

2) Renewable energy: structurally negative abatement costs

Utility-scale renewables in India sit firmly in the **negative MAC zone**:
- **Solar PV and onshore wind** remain cheaper than new coal on an energy basis, even without carbon pricing.
- Hybrid combinations (solar + wind) slightly raise costs but improve capacity utilisation.

Because renewables reduce both emissions and fuel expenditure, they continue to form the **backbone of least-cost abatement** through 2035.

3) Storage and flexibility: medium-cost but indispensable

Energy storage does not abate emissions directly; it **enables higher renewable penetration**:
- **Pumped storage** typically falls in the ₹1,000–2,000/tCO_2 range (effective MAC).
- **Battery energy storage systems (BESS)** for evening peaks start higher but decline steadily through the 2030s.
- **Demand response**, especially for cooling loads, often sits at very low or even negative MACs.
- **System insight:** Storage and flexible coal together minimise *total* system cost; excluding either increases costs elsewhere.

4) Overall MAC hierarchy (conceptual)
- Negative cost: Solar, wind, demand response
- Low cost: Coal efficiency and flexibility
- Medium cost: Pumped storage, short-duration BESS
- High cost: CCUS, long-duration storage, green hydrogen power

This hierarchy explains the reasons as to why **coal remains in the system while its role changes**.

Implications for DISCOM Tariffs under the Least-Cost 2035 Mix

1) **Average tariffs remain stable rather than escalated:** System-level modelling by Indian planning agencies consistently shows that falling renewable energy costs and efficiency gains **offset carbon-related costs**. Average bulk supply tariffs remain broadly stable (in real terms) into the early-to-mid-2030s. **The transition is not inflationary at the average tariff level.**
2) **Structural shift in tariffs: energy becomes cheap, peaks become expensive**

What changes materially is **tariff structure**, not headline averages:
- **Energy charges (₹/kWh)** decline as RE displaces fuel costs.
- **Capacity and fixed charges** rise due to storage, hydro, and flexible coal assets.
- **Time-of-Day (ToD) differentiation** becomes unavoidable, with sharp evening-peak price signals.

This reflects a system moving from an *energy-scarce* regime to a *flexibility-scarce* regime.

Result: Consumers who adapt (load shifting, efficiency, storage) benefit; inflexible peak users pay more.

Key messages

- **Solar, wind, demand response = negative cost abatement**
- **Coal efficiency s flexibility** deliver low-cost emissions reduction
- **Storage enables decarbonisation**, but at moderate cost **CCUS remains high cost** and non competitive pre 2040
- **Policy signal**
  India's least cost decarbonisation starts with **RE + efficiency**, not coal exit.

RTM and CCTS Market Growth Trend (Right Panel)

RTM Liquidity Index

a) Reflects rising **system volatility**
b) Driven by:
  - Solar-heavy daytime supply
  - Sharp evening peaks
  - Coal flexibility and storage arbitrage

c) RTM becomes the **primary price signal** for flexibility by 2030

CCTS Credit Market Index

a) Starts slow but accelerates as:
  - Intensity benchmarks tighten
  - More sectors enter compliance
  - Carbon price gets discovered through trading

b) Mirrors India's graduated transition strategy

Market insight

RTM prices value time, CCTS prices value carbon intensity. Together, they reshape dispatch, investment, and tariff design.

Integrated Interpretation (Why this graph and picture matters)

Signal	What it means
MAC curve shape	Coal survives via efficiency, not growth
RTM uptrend	Flexibility becomes the new scarcity
CCTS growth	Carbon cost becomes a balance-sheet item
Combined effect	Dispatch C investment go carbon- and time-aware

Carbon cost pass-through under CCTS

Under India's **intensity-based Carbon Credit Trading Scheme (CCTS)**:

- Efficient coal plants can earn or neutralise carbon costs.
- Inefficient generators face higher effective costs.

DISCOM power procurement therefore increasingly reflects **carbon-adjusted merit order**, reinforcing efficiency incentives without sudden tariff shocks.

The Role of Coal changes from Baseload to System Insurance By 2035:

- Coal's **installed capacity remains substantial**, supporting grid adequacy and seasonal security.
- Coal's **generation share declines**, but it becomes more valuable per MW as a flexibility and reliability provider.
- Plant Load Factors (PLFs) fall structurally, raising fixed-cost recovery challenges and the importance of capacity and ancillary service payments.

Coal survives not as a growth fuel, but as **insurance against variability and peak risk**.

Just Transition for Coal States under the CCTS Framework

The coal states are exposed in this transition. States such as Jharkhand, Odisha, Chhattisgarh, and West Bengal depend heavily on Coal royalties and taxes, Rail freight revenues and Public and quasi-public employment tied to mining and thermal power. An unmanaged transition risks fiscal stress and social disruption.

The Reason for different approach of India

India has deliberately avoided an absolute-cap ETS. Instead, CCTS has Target as **emissions intensity**, not output. This allows **credit banking,** starts with **moderate benchmarks.** This design **slows economic shocks**, buying time for adjustment rather than forcing abrupt closures.

Elements of a just transition pathway

An emerging consensus among Indian think tanks and policymakers includes:

- **Revenue recycling:** Use carbon-market revenues to compensate coal-dependent states.
- **Asset repurposing:** Convert end-of-life coal assets into pumped storage, solar parks, or grid infrastructure.
- **Labour transition:** Reskilling for grid services, renewables OCM, logistics, and industrial decarbonisation.
- **Economic diversification:** Location of RE manufacturing, green hydrogen hubs, and materials processing in coal regions.

The NDC-2035 is thus framed as a **developmental transition**, not a coal shutdown mandate.

Integrated thoughts

India's power-sector transition to 2035 is best understood as:

- **Economically rational** (guided by MAC curves, not ideology)
- **System-aware** (valuing flexibility as much as energy)
- **Socially negotiated** (using intensity-based carbon markets to manage change)

Coal does not disappear; it **changes character**. Renewables dominate energy, storage and coal together provide reliability, tariffs evolve rather than explode, and coal states are given time and policy space for adjustment.

In short, India's pathway is not *anti-coal,* it is **anti inefficiency and anti fragility**.

Takeaway for the Power Sector

India's power transition to 2035 is not about replacing coal with renewables, but about replacing inflexible megawatts with flexible, low-carbon megawatts. Coal units that are **efficient and also flexible** remain viable. RE along with storage dominate incremental capacity. DISCOM tariffs shift toward **ToD as well as carbon-adjusted pricing.** Coal states get time for **just, managed transition.**

6. Conclusion

This study demonstrates that India's power sector transition to 2035 is optimally characterised by a least-cost framework balancing reliability, emissions intensity reduction, and affordability. The analysis shows that renewable energy and demand-side measures provide cost-effective emissions reductions, while coal remains relevant through efficiency improvements and flexible operation. Energy storage plays a critical enabling role despite moderate costs, and tariff structures evolve toward time-sensitive pricing without increasing average consumer burden. The Carbon Credit Trading Scheme facilitates gradual decarbonisation by embedding carbon costs into operational decisions. Overall, the transition reflects a system-optimised pathway that prioritises flexibility, economic efficiency, and socio-economic stability. **This integrated pathway balances reliability, carbon reduction, and affordability, aligning with NDC-2035 and Net-Zero 2070.**

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