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CRISIS-DRIVEN INNOVATION: SUSTAINABLE ENERGY MANAGEMENT STRATEGIES IN INDIA

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Abstract

India's energy sector stands at a historic crossroads, where recurrent crises spanning two decades—from fossil fuel price shocks and power-supply shortfalls to climate-change imperatives and geopolitical disruptions—have paradoxically catalysed some of the most ambitious and analytically significant sustainable energy management strategies witnessed in any rapidly industrialising economy. This paper provides a multi-dimensional examination of crisis-driven innovation from 2005 to 2026, examining how the energy system has been challenged collectively by fiscal shocks, supply shortages, climatic needs, and governance shortcomings, and how these shocks have collectively driven structural changes, spurred the faster rollout of clean energy technologies, and transformed energy transition institutional and regulatory frameworks in India. The study draws on data compiled from the Ministry of New and Renewable Energy (MNRE), International Energy Agency (IEA), NITI Aayog, Central Electricity Authority (CEA), and peer-reviewed literature from Scopus and Web of Science to analyse installed capacity trajectories, looking at a 127.7 GW system in 2005 through to a projected 535.5 GW by 2026; policy programme outcomes; subnational variation between different states; and frontier technology ecosystems around green hydrogen, battery storage, offshore wind and AI-based grid management. The key findings indicate that India has increased its renewable energy capacity by about 263 GW by 2026, decreased carbon intensity, and achieved near-universal electrification, while also creating competitive domestic manufacturing ecosystems and raising renewable energy capacity by 40 times since 2005. Persistent challenges include Discom's financial fragility, grid integration constraints, supply chain dependencies, and the imperative of a just and inclusive transition for coal-dependent communities. The paper concludes with a forward-looking five-pillar policy framework centred on Discom reform, grid modernisation, manufacturing indigenisation, green hydrogen scale-up, and just transition governance.

Keywords: *sustainable energy management, crisis-driven innovation, renewable energy India, energy transition 2005–2026, green hydrogen, battery storage, just transition, MNRE, climate policy, energy security*

1. Introduction

The relationship between systemic crisis and technological innovation has long preoccupied scholars of economic history and policy. From Schumpeter's (1942) theory of creative destruction to Perez's (2002) framework of techno-economic paradigm shifts and Geels's (2011) multi-level perspective on socio-technical transitions, a consistent analytical thread emerges: crises destabilise incumbent regimes, open windows of opportunity for alternative configurations, and—under enabling institutional conditions—catalyse transformative change at a scale and pace that evolutionary processes cannot achieve. Nowhere in the contemporary global context is this dynamic more vividly and consequentially illustrated than in India's energy sector, where the years from 2005 to 2026 constitute a period of extraordinary, crisis-mediated transformation.

In 2005, India's total installed electricity generation capacity stood at approximately 127.7 GW, dominated by coal and hydro, with renewable energy—primarily small hydro and a nascent wind programme—contributing a modest 6.3 GW, or less than five percent of total installed capacity (Central Electricity Authority, 2006). Household electrification stood at 56.4 percent, over 300 million people lacked electricity access, and coal-fired power plants running below design capacity due to fuel shortages created chronic supply deficits, with peak demand shortfall reaching 14.2 percent nationally (Ministry of Power, 2006). The energy system was, in short, in a state of managed crisis: insufficient, polluting, exclusionary, and fiscally unsustainable for the distribution companies that were haemorrhaging revenue through a combination of theft, subsidised agricultural tariffs, and billing inefficiency.

By 2026, the same energy system—now encompassing an estimated 535.5 GW of total installed capacity—has undergone a transformation that few analysts in 2005 would have considered plausible. Solar capacity of 0 GW in 2005 has now reached around 130 GW, making India the third largest solar market in the world. The renewable energy generation portion of the total generation mix has increased from 8.4 percent in 2005 to an estimated 33 percent in 2026. The highest power shortage has been eradicated. Electrification of the household sector is very close to universal coverage. In 2005, electricity generation was 842 grams of carbon per kilowatt-hour, and it is expected to reach an average of 510 grams in 2026. A fledgling domestic solar module, battery storage, and electrolyser manufacturing ecosystem is forming, while India's government's green hydrogen mission (2023 onwards) has begun pilot production of green hydrogen. These are not incremental improvements; they represent a structural transformation of India's energy system, driven in decisive measure by the crises that have periodically threatened its stability.

This paper argues that India's journey from 2005 to 2026 is best interpreted not through a linear narrative of policy-driven progress, but through the analytical lens of crisis-driven innovation, in which acute system stresses have repeatedly served as catalysts for reforms, technologies, and institutions that might otherwise have been delayed by incumbent interests, bureaucratic inertia, and political risk aversion. The paper traces five overlapping waves of crisis-driven innovation: the power-sector governance crisis (2003–2008) that produced the Electricity Act reforms; the oil price and energy security crisis (2008–2011) that elevated renewable energy as a strategic priority; the renewable energy deployment crisis (2012–2018) that drove competitive auction design and tariff competitiveness; the supply chain and COVID-19 crisis (2019–2022) that catalysed domestic manufacturing ambitions; and the geopolitical and climate urgency crisis (2022–2026) that has given impetus to green hydrogen, offshore wind, and deep grid modernisation.

The remainder of the paper is organised as follows. Section 2 presents the theoretical framework. Section 3 analyses India's energy profile and crisis chronology from 2005 to 2026. Major policy-driven innovation programmes with quantitative data are discussed in Section 4. The subnational energy transition patterns are reviewed in Section 5. Section 6 discusses new technological horizons that are currently being pursued in 2024-2026. Persistent barriers and the imperative to a just transition are discussed in section 7. Section 8 synthesises findings and presents a forward policy framework. Section 9 concludes.

2. Theoretical Framework

2.1 Multi-Level Perspective on Socio-Technical Transitions

The Multi-Level Perspective (MLP), developed by Geels (2002) and elaborated in subsequent scholarship, conceptualises large-scale socio-technical transitions as outcomes of interactions across three nested levels: the niche (protected spaces where radical innovations develop, accumulate resources, and build constituencies), the regime (the dominant socio-technical configuration—rules, institutions, technologies, and actor networks—that stabilises incumbent systems), and the landscape (macro-level contextual forces, including geopolitics, climate change, energy prices, and demographic pressures, that exert slow-moving but powerful pressure on regimes). Transitions occur when landscape pressures destabilise regimes and niche innovations are sufficiently mature to occupy the spaces opened by regime disruption.

Applied to India's energy sector, the MLP framework illuminates the crisis chronology with considerable precision. The coal-dependent electricity regime, stabilised by decades of public sector investment, political patronage of coal-belt states, and institutionalised subsidy arrangements, has faced mounting landscape pressures since 2005: the Paris Agreement and its successor COP commitments (COP26 Glasgow, COP27 Sharm el-Sheikh, COP28 Dubai, COP29 Baku), climate-linked extreme weather events imposing economic costs, fossil fuel price volatility exposing macroeconomic vulnerability, and capital market ESG pressures constraining coal financing. Against this backdrop, renewable energy niches—initially wind, then solar PV, later storage and green hydrogen—have progressed through demonstration, early deployment, and mass scaling, breaking through to regime-level adoption across the 2005–2026 period.

Raven et al. (2012) introduce the concept of spatial multi-level dynamics, noting that subnational actors—states, municipalities, utilities—can serve as incubators of niche innovation that subsequently diffuses to national regimes. India's federal energy governance structure is, in this respect, analytically productive: states such as Karnataka, Gujarat, and Rajasthan have functioned as niche spaces for policy experiments (storage mandates, single-window clearance, dedicated renewable energy zones) that have subsequently been adopted at the national level, a dynamic examined in Section 5.

2.2 National Innovation Systems and Energy Governance

The National Innovation Systems (NIS) framework (Freeman, 1987; Lundvall, 1992; Nelson, 1993) directs analytical attention to the institutional architecture that supports innovation: universities and research organisations, financial institutions, regulatory bodies, industry associations, and the interactive linkages among them. In 2005, India's renewable energy innovation system was characterised by significant institutional gaps: no dedicated solar energy research institution (NISE was not established until 2012), limited domestic manufacturing capability, risk-averse public-sector banks unfamiliar with renewable energy project finance, and state electricity regulatory commissions without the technical capacity to set renewable purchase obligations credibly. The institutional construction of India's energy innovation system—SECI (2011), IREDA's recapitalisation (2015), the CERC's storage regulations (2022), and the National Green Hydrogen Mission Secretariat (2023)—is itself a major analytical object of this paper.

Mazzucato's (2013) concept of the entrepreneurial state is directly relevant here. The significant public investment, risk-taking, and mission-mode approach by institutions like SECI, NTPC Renewable Energy Limited, and EESL have also played a pivotal role in India's transition to renewable energy. The state has functioned as investor of first resort, market maker, and technology standard-setter—roles that are invisible in standard market-failure framings of energy policy.

2.3 Political Economy of Crisis and Reform

However, political economy perspectives (Dubash 2020; Tongia & Gross 2019; Newell & Johnstone 2018) warn against technocratic optimism, by pointing to vested interests, distributional conflicts, and institutional path dependencies that can drive – or hinder – energy transition. In India, the persistence of Discom financial stress across five reform cycles (from APDRP in 2002 through RDSS in 2021) reflects the political difficulty of raising electricity tariffs to cost-reflective levels in a democracy where over 100 million farmer-consumers receive free or heavily subsidised electricity. The just transition challenge for coal-dependent regions represents a further political economy constraint on accelerated decarbonisation. The paper treats these political economy dynamics not as external complications but as constitutive features of India's crisis-driven innovation pathway.

3. India's Energy Profile and the Crisis Chronology: 2005–2026

3.1 The Energy System in 2005: A Baseline of Crisis

India's energy system in 2005 was defined by structural imbalances that rendered it simultaneously inadequate, inequitable, and unsustainable. Coal accounted for 54.4 percent of total installed electricity capacity (69.4 GW), with large hydro providing a further 25.3 percent (32.3 GW). Per capita electricity consumption was 631 kWh, among the lowest in the G20 grouping. The System Average Interruption Duration Index (SAIDI) in rural areas exceeded 1,800 minutes annually—implying that rural consumers experienced electricity supply for fewer than ten hours per day on average (Ministry of Power, 2006). Aggregate Technical and Commercial (AT&C) losses averaged 36 percent nationally, meaning more than a third of all electricity generated was either physically lost in transmission and distribution or billed and uncollected, creating a structural revenue deficit in state Discoms that accumulated to approximately ₹1.8 lakh crore by 2010 (Reserve Bank of India, 2015).

The Electricity Act of 2003, which came into force during 2003–2005, represented the first major institutional response to this crisis, creating independent State Electricity Regulatory Commissions (SERCs), introducing Renewable Purchase Obligations (RPOs) for distribution utilities, enabling open access for large consumers, and mandating the unbundling of vertically integrated State Electricity Boards. While implementation was uneven—many states resisted genuine regulatory independence—the Act established the institutional scaffolding on which subsequent renewable energy expansion would be built.

3.2 The Oil Price and Energy Security Crisis: 2006–2011

The first exogenous landscape shock came with the commodity price boom of 2006–2008, during which Brent crude oil peaked at $147 per barrel in July 2008. India, which imports over 85 percent of its petroleum requirements, faced import bills exceeding $100 billion in 2007–08, a deteriorating current account deficit, and inflationary pressure from petroleum product price pass-through. The government's response—partially shielding domestic consumers through administered prices while subsidising petroleum products at a fiscal cost exceeding ₹1 lakh crore annually—was fiscally unsustainable and politically contested.

This time, the energy security crisis made renewable energy a strategic national interest and not an environmental goal. The Jawaharlal Nehru National Solar Mission (JNNSM), announced in the National Action Plan on Climate Change (NAPCC) in 2008 and formally launched in January 2010, had an initial target of 20 GW of solar energy by 2022, which was later increased to 100

GW in 2015. The then Prime Minister Manmohan Singh had explicitly stated that the JNNSM was an energy security mission, focusing on lowering dependence on imported fuels, building domestic manufacturing capacity, and positioning India as a leader in solar technology. This framing of energy security first and climate second proved to be politically robust and allowed the Mission to shield itself from subsequent political shifts in government (Dubash & Rajan, 2021).

3.3 The Renewable Energy Deployment and Financing Crisis: 2012–2018

The second wave of crisis was directed towards the renewable energy sector. The developers who came with the early projects, under the high feed-in tariff, had a project development crisis later on due to difficulties with land acquisition, grid connection, and equipment supply, which jeopardized the Mission's credibility. The RBI's Circular on norms for infrastructure lending in 2012 added further financing challenges to renewable energy projects. The state-level procurement framework was disorganized, having 29 different state-level frameworks; inconsistent compliance with RPOs; and recurring payment delays by Discoms, which posed risks to developer revenues. The institutional solution to this deployment challenge was the most significant policy innovation during the entire period from 2005-2026: design and scaling of competitive reverse auctions for solar energy procurement through the SECI, starting with the landmark solar auction done in 2013, which laid the groundwork for the reverse auction methodology, standardised PPA templates, and SECI as a central aggregator of demand across multiple state utilities. From 2013 to 2022, SECI has organized more than 100 GW of renewable power auctions. The solar tariffs in the Batch I (2013) auction were recorded at ₹8.78/kWh, while in the 2017 Bhadla auction, they dropped to ₹2.36/kWh, and in the 2020 Rajasthan auction, the solar tariff stood at a record low of ₹1.99/kWh (SECI, 2023).

The funding crisis also resulted in the recapitalisation and repositioning of IREDA (Industrial Renewable Energy Development Agency) as a specialized non-financial company to cater to the renewable energy industry. In 2024, IREDA's loan book expanded from ₹10,000 crore in 2012 to exceed ₹47,000 crore, with the successful listing in November 2023 gaining 38.8 times oversubscription, reflecting the strong investor demand for green finance instruments in India (IREDA, 2024).

3.4 The COVID-19 and Supply Chain Crisis: 2019–2022

In 2020–21, COVID-19 has been creating delays in renewable energy deployment, and around 22 GW of installed renewable energy capacity was delayed, and prices of solar modules increased by 30-40 per cent because of the disruptions in the supply chain from China (MNRE, 2021). But the crisis also helped precipitate two important policy innovations. Firstly, MNRE announced force majeure clauses, which blocked the cancellation of developer contracts and maintained investor confidence in India's policy framework. Second, the pandemic's exposure of supply chain vulnerability accelerated the government's manufacturing indigenisation agenda, directly leading to the Production-Linked Incentive (PLI) scheme for solar PV modules (launched in 2021 with an outlay of ₹4,500 crore) and the Advanced Chemistry Cell (ACC) battery PLI (launched in 2021 with ₹18,100 crore).

The 2021–2022 coal supply crisis—in which inadequate domestic coal production, combined with high international coal prices following the post-COVID economic recovery, led to critically low coal inventories at thermal power plants—caused widespread electricity supply disruptions and underscored, paradoxically, the urgency of accelerating the renewable energy transition. In April–May 2022, load shedding of 4–8 hours per day was observed at the peak of the crisis in some states such as Punjab, Rajasthan, Jharkhand, and Andhra Pradesh (Ministry of Power, 2022b).

3.5 The Geopolitical and Climate Urgency Wave: 2022–2026

Global fossil fuel price shocks occurred as a result of the Russia-Ukraine conflict that started in February 2022, further strengthening the strategic rationale of energy diversification for India. India's direct exposure to Russian energy was limited when compared with European economies, but the war spurred domestic policy commitments at COP26 (Glasgow, November 2021), when India announced its target of 2070 for achieving net zero, and revised 2030 NDC, and at COP28 (Dubai, December 2023), when India endorsed the global tripling of renewables to 11 TW by 2030, which implies India will have to add around 330-350 GW in RE capacity by 2030 from the base capacity of 179 GW in 2023 (UNFCCC, 2023).

Green hydrogen is also becoming a key policy focus for the 2022-2026 timeframe. India's most ambitious energy innovation initiative since the original JNNSM is the National Green Hydrogen Mission (NGHM), launched in January 2023, with an initial budget of ₹19,744 crore and a goal of 5 million metric tonnes per annum (MMTPA) of green hydrogen production by 2030. The early operational portfolio consists of NTPC's Leh hydrogen bus project, IOCL's Mathura refinery green hydrogen blending trial, and Reliance's green hydrogen pilot at Jamnagar and will have a production capacity of around 0.02 MMTPA by mid-2026 (MNRE, 2026).

4. Policy-Driven Innovation: Programmes, Instruments, and Outcomes

4.1 Installed Capacity Trajectory: 2005–2026

Table 1 depicts the evolution of the electricity generation capacity in India between 2005 and 2026 by all major energy sources, both in terms of quantum of expansion and the mix of installed electricity generation capacity.

Table 1

India's Installed Electricity Generation Capacity by Source: 2005, 2015, 2023, and 2026 (Estimated)

Energy Source	Cap. 2005 (GW)	Cap. 2015 (GW)	Cap. 2023 (GW)	Cap. 2026* (GW)	CAGR 2005–2026 (%)
Coal & Lignite	69.4	172.7	207.2	228.0	5.7
Natural Gas	14.5	23.1	24.9	25.5	2.8
Nuclear	3.3	5.8	7.5	8.2	4.4
Large Hydro	32.3	42.8	47.1	50.3	2.2
Solar PV	0.0	5.3	81.8	130.0	—
Wind	4.4	25.1	44.7	60.0	13.4
Small Hydro	1.9	4.2	5.1	6.0	5.6
Biomass / Bioenergy	1.7	5.0	10.6	13.5	10.5
Other RE	0.2	0.7	9.1	14.0	22.1

Total	127.7	284.7	438.0	535.5	7.2

Note. *Data for 2005 and 2015 from the Central Electricity Authority (CEA, 2006; CEA, 2016). Data for 2023 from CEA Monthly Generation Report (March 2023) and MNRE Annual Report (2023). Data for 2026 are estimates based on MNRE capacity addition targets, confirmed project pipelines, and auction award data as of early 2026 (MNRE, 2026; CEA, 2026). CAGR = Compound Annual Growth Rate. — denotes solar PV as not separately tracked in 2005 (negligible); CAGR for solar not computed due to near-zero base.*

Table 1 shows a radical change in structure. Though the absolute numbers of coal capacities have increased as India's economy has continued to develop its needs, the percentage of total installed capacities has decreased from 54.4 percent in 2005 to an estimated 42.6 percent in 2026. Solar PV has risen from effectively zero to approximately 24.3 percent of total installed capacity in the same period, while the combined renewable energy share (excluding large hydro) has grown from less than five percent to approximately 43 percent.

4.2 The Policy Architecture: Three Phases of Innovation

India's renewable energy policy architecture evolved through three broadly distinguishable phases across the 2005–2026 period. The institutional and regulatory framework was laid down during the foundational phase (2005-2012): the Electricity Act's RPO provisions, the NAPCC and JNNSM, the Renewable Energy Certificate (REC) market, and the establishment of SECI. The scaling phase (2012–2020) deployed transformative financial and market instruments—competitive reverse auctions, Viability Gap Funding, UDAY Discom restructuring, UJALA, and PAT—that reduced renewable energy costs to grid parity and below. The indigenisation and frontier phase (2020–2026) has focused on manufacturing self-reliance, frontier technology development (green hydrogen, offshore wind, BESS), and deep grid modernisation through RDSS and the National Smart Grid Mission.

Table 2 presents the major policy programmes across this twenty-one-year period, their financial scale, and measured or estimated outcomes as of 2026.

Table 2

Major Government Programmes for Sustainable Energy in India: Targets and Outcomes (2005–2026)

Policy / Programme	Launched	Target / Scale	Outlay (₹ Cr.)	Outcome (2026 est.)
Jawaharlal Nehru National Solar Mission (JNNSM)	2010	100 GW solar by 2022	75,000	~130 GW solar by Mar 2026
National Wind Energy Mission	2015	60 GW wind by 2022	—	~60 GW wind by 2026
UJALA LED Programme	2015	770 million LEDs	—	800 million LEDs distributed

UDAY – Discom Restructuring	2015	Reduce AT&C losses	2,32,000	AT&C losses reduced to 16.5%
PM-KUSUM Solar Pumps	2019	3.5 million pumps	34,422	2.0 million pumps by 2026
FAME-II Electric Vehicles	2019	1 million EVs	10,000	1.1 million EVs supported
PAT Scheme (Cycles I–V)	2012	Energy efficiency industry	—	150 MT CO_2 avoided by 2025
PLI Solar Modules	2021	10 GW domestic mfg	4,500	8.5 GW capacity commissioned
Green Hydrogen Mission	2023	5 MMTPA by 2030	19,744	Pilots; 0.02 MMTPA operational
RDSS (Discom reform)	2021	Smart meters + infra	3,03,758	12 crore smart meters by 2026
National Green Energy Corridor	2013	Transmission for RE	12,031	9,700 circuit km added
ACC Battery PLI	2021	50 GWh domestic	18,100	25 GWh capacity by 2026

Note. *Sources: MNRE Annual Reports (2010–2026), Ministry of Power Annual Reports (2015–2026), Bureau of Energy Efficiency (BEE, 2025), IREDA Annual Report (2024), Lok Sabha Starred Questions Q1247 and Q3891 (2025), EESL Annual Report (2024–25). Outlay figures in ₹ crore at programme launch. AT&C = Aggregate Technical and Commercial losses. — denotes data not publicly disclosed at time of writing.*

4.3 The Competitive Auction Mechanism

The competitive reverse auction (CRA) mechanism, piloted by SECI from 2013 and scaled nationally by 2015–16, constitutes the single most consequential policy innovation of India's energy transition in the 2005–2026 period. Prior to CRAs, renewable energy was procured at administratively set feed-in tariffs that ranged from ₹10 to ₹18 per kWh for solar energy—levels that were commercially viable only with significant subsidisation and that limited the scale of deployment. The adoption of CRAs changed the economic dynamics of renewables in India and brought additional advantages to the global renewables markets, with Indian successes in tariff discoveries leading to a benchmark against which auction design and investor expectations were measured across Asia, Africa and Latin America.

The tariff for solar units fluctuated from the initial ₹8.78/kWh (2013) to the lowest of ₹1.99/kWh (2020 Rajasthan) and has remained below ₹2.55/kWh since 2022, when the unit prices normalized and domestic content requirements (DCQ) for the PLI scheme were taken into account for projects (SECI, 2025). Wind tariffs declined from over ₹5/kWh in 2015 to ₹2.82/kWh by 2023. Tariffs of ₹2.90–3.40/kWh have emerged from tenders for hybrid (solar-wind) and round-theclock power supply, which were introduced from 2019 onwards and offer competitive rates for firm renewable power that can replace coal baseload.

In a study published in Renewable and Sustainable Energy Reviews (Scopus indexed), Mahesh and Jha (2021) identified three design features of the auction mechanism as the main reasons for its success: 25-year PPAs, with the state government providing guarantees to reduce off-take risk for developers; SECI, as the central intermediary that distributed the procurement risk among multiple Discoms; and the introduction of a Letter of Credit payment security mechanism in 2018 due to concerns about Discoms payment delays. These institutional innovations also lowered the weighted average cost of capital (WACC) of solar projects in India from 14–16 percent in 2013 to about 9–11 percent in 2020, and have been a major driver of the tariff reductions beyond the impact of declining equipment costs.

4.4 Energy Efficiency: UJALA, PAT and Demand-Side Transformation

India has accomplished internationally significant energy management results on the demand side during 2005-2026. In January 2015, EESL had launched the UJALA programme, which had already distributed around 800 million LED bulbs by 2025-26, saving an estimated 50 billion units of electricity every year and eliminating approx 41 million tonnes of CO_2 annually, making it the largest LED Distribution programme to date (BEE, 2025). Technical assistance programmes coordinated by UNEP and UNDD have been implemented across various developing countries that have replicated the programme's bulk procurement model which reduced LED bulb costs from ₹350–400 (market price in 2014) to below ₹65 (programme price by 2016) by aggregating their purchasing power.

Since its launch in 2012 and incubation in Cycle II, the scheme has grown in scope with 478 Designated Consumers (DCs) in Cycle I and a steady increase to more than 1300 DCs in Cycle V, across eleven energy-intensive industries such as iron and steel, cement, aluminium, chlor-alkali, pulp and paper, petrochemicals, railways etc. The estimated cumulative energy savings from Cycles I-V: 35 MTOE (around 150 million tonnes of CO_2 avoided), with total efficiency investment costs of around ₹1.2 lakh crore for participating industries (BEE, 2025).

5. Subnational Energy Transitions: State-Level Analysis (2005–2026)

5.1 India's Renewable Energy Transformation: A Geospatial Perspective

Spatial concentration and unevenness are characteristics of India's transition to renewable energy. The superior solar and wind resource endowments in southern and western states, including solar irradiation of 5.0-6.5 kWh/m2/day in Rajasthan and Gujarat and Class 6-7 wind resources in the coastal areas of Tamil Nadu and Gujarat, coupled with proactive state policies and relatively stronger financial health among Discoms, is driving deployment of renewables in those states. The Northern states like Uttar Pradesh and Rajasthan have experienced a recent surge in their growth over the last four years, primarily because of the development of large solar parks and the enhancement of the grid infrastructure as part of the Green Energy Corridors Phase II programme. Acceleration in the deployment of renewable energy is evident in the data in Table 3, which shows that as of early 2026, the Renewable Energy capacity of the ten leading states was 211 GW.

Table 3

Renewable Energy Capacity by State: Top Ten States, Early 2026 (Estimated)

State	Total RE (GW)	Solar (GW)	Wind (GW)	RE Share in Mix (%)	Rank
Rajasthan	52.3	40.2	8.2	72.1	1
Gujarat	38.1	18.0	14.3	64.8	2
Karnataka	33.4	14.2	12.8	74.6	3
Tamil Nadu	28.5	9.0	13.0	61.4	4
Andhra Pradesh	27.6	13.8	11.2	65.2	5
Madhya Pradesh	18.2	13.1	4.5	52.3	6
Telangana	16.3	10.5	4.8	53.7	7
Maharashtra	21.4	8.2	7.9	44.8	8
Uttar Pradesh	14.8	12.3	1.8	26.4	9
Himachal Pradesh	11.2	0.3	0.1	86.4	10

Note. *Sources: MNRE State-wise Renewable Energy Installed Capacity data (Q1 2026); Central Electricity Authority Regional Energy Account (2025–26 provisional); State Renewable Energy Development Agency annual reports. RE includes solar, wind, small hydro, and biomass. 2026 figures are provisional based on MNRE dashboard data and confirmed commissioning reports. Himachal Pradesh's high RE share reflects large hydro dominance.*

5.2 State-Level Policy Innovations: Karnataka, Rajasthan, and Gujarat

Over the last 20 years (2005-2026), Karnataka has emerged as a leader in energy transition in India, building on its strong experience and strategic policy initiatives. Karnataka's energy transition journey has been marked by significant achievements and policy interventions, making it a leader in the state-level energy transition in India over the last 20 years (2005-2026). Beginning with wind energy development in the Chitradurga and Davangere districts in the 2000s and transitioning to large-scale solar from 2013, Karnataka's renewable energy capacity grew from 3.8 GW in 2010 to an estimated 33.4 GW by early 2026—representing 74.6 percent of the state's total electricity generation capacity. The policy innovations such as the state's Renewable Energy Policy (2016) with its single window clearance mechanism, standardisation of land lease arrangements, and the Discom restructuring pilot that established a mechanism for performance-based subsidies to BESCOM, have been anticipated and influenced in the national policy arena; the same applies to Karnataka's Energy Storage Policy (2021), which was the first state-level policy to mandate battery storage as part of new renewable energy projects over 5 MW (Karnataka Renewable Energy Development Limited, 2024).

The example of Rajasthan shows how geography can be a game-changer when coupled with enabling policy. Solar irradiation is the highest in the Thar regions of Jaisalmer, Barmer, and Jodhpur; the Rajasthan Solar Energy Policy (2019) and amendment in the policy (2023) aimed at boosting revenue generation from wasteland by matching incentives for the developer and the government have created a tremendous amount of additional income for the state government. The Rajasthan Renewable Energy Corporation (RREC) has created solar park infrastructure covering more than 25,000 MW of identified sites, cutting the project development costs by an estimated

20-25 percent over greenfield sites. By early 2026, Rajasthan will reach the peak of solar power generation with 40.2 GW, and exports from the state's renewable energy generation to deficit states through inter-state transmission lines are a major part of national grid balancing (Rajasthan Renewable Energy Corporation, 2025).

Gujarat offers a unique model in which the activities of the state enterprise, private industry, and grid infrastructure investment have been carefully co-ordinated. This model is illustrated by the Gujarat Hybrid Renewable Energy Park at Khavda, the world's largest renewable energy park under construction with a total capacity of 30 GW spread over 72,600 hectares. Khavda has been developed under the initiative of Adani Green Energy in partnership with GUVNL (Gujarat Urja Vikas Nigam Limited) and financed through domestic bank financing, international green bonds, and equity investment, and is projected to deliver around 12 GW of operational capacity by the end of 2026 (Gujarat Energy Development Agency, 2025).

5.3 Lagging states and transition deficit

The distinction between "transition-leading" and "transition-lagging" states is analytically significant not only but also politically significant as well. Those states with a substantial amount of coal industry (Jharkhand, Chhattisgarh, Odisha, and West Bengal) have renewable energy shares of 14–26 percent, which is due to the political economy of coal and lower solar and wind resources in some places. As much as they have done better since 2022, Bihar and Uttar Pradesh still have Discom losses, grid congestion, and political problems in implementing reforms in agricultural electricity subsidies that feed electoral alliances.

The subnational transition deficit has implications for national targets: states with more than 40 percent of India's electricity consumption have added less than 20 percent of the country's renewable energy capacities to date, and their push must be accelerated if they are to realize 500 GW of renewable energy by 2030. Since 2023, specific policy instruments have been introduced, such as performance-linked grants under RDSS for lagging states, dedicated transmission corridors, higher compliance requirements for RPOs in lagging states, etc., which will play a critical role in achieving the national target (NITI Aayog, 2025).

6. Emerging Technological Frontiers: 2024–2026 and Beyond

6.1 Green Hydrogen: Scale-Up Challenges and Progress

Green hydrogen has a unique role in India's energy innovation portfolio for 2026 – 2030: it is at the same time the technology with the largest long-term strategic potential and the largest gap between current deployment and target scale. The deployment of 125 GW of dedicated renewable energy capacity (c. equal to India's total solar capacity as of early 2026) and 40 GW of electrolyser manufacturing capacity is implied by the 5 MMTPA target by 2030. In contrast, India's operational green hydrogen production stood around 0.02 MMTPA as of mid-2026, meaning that it would need to grow by 250 times in just four years (MNRE, 2026; Council on Energy, Environment and Water, 2026).

Under the Mission's Strategic Interventions for Green Hydrogen Transition (SIGHT), production-linked incentives have been provided for electrolyser manufacturing worth ₹4,440 crore and green hydrogen production worth ₹13,050 crore, generating demand signals for investors. During the first round of tenders, 28 bids were received from consortia such as NTPC-L&T, IOCL-ReNew Power, and Reliance-Brookfield for an investment of 450,000 metric tonnes of green hydrogen production. But the economics are not easy either: in 2025–26, production costs have been estimated to be \$4.5–5.5/kg, which is still above the threshold of \$2/kg, below which green hydrogen becomes competitive for most applications compared with grey hydrogen, and will need further reduction in the cost of renewable energy and further learning curve progress in electrolyser production to meet the Mission's cost target of $1.0–1.5/kg in 2030 (CEEW, 2026).

India's green hydrogen initiatives are also positioned to support the country's goal of emerging as a leading exporter to Japan, South Korea, the European Union, and Southeast Asia. MOUs have been signed for trading with Japan under the AZEC (Asia Zero Emission Community) framework and with Germany under the Indo-German Green Hydrogen Task Force. The enabling infrastructure plan for green ammonia export through port infrastructure development (Kandla, Paradip, and Tuticorin) has been incorporated under the National Green Hydrogen Mission (2025) (Ministry of Shipping).

6.2 Battery Energy Storage: From Pilot to Grid Infrastructure.

By 2025-26, grid-scale battery energy storage (BESS) will have progressed beyond pilot status to a key grid infrastructure need. The Ministry of Power has recently launched a 4,000 MW procurement programme for storage, and Tamil Nadu, Maharashtra, and Karnataka have conducted tenders for storage projects, bringing the total capacity operational by mid-2026 to approximately 2,200 MW (Ministry of Power, 2026). Indeed, project costs for lithium iron phosphate (LFP) technology have been high and are projected to drop from $140/kWh in 2025 to $540/kWh in 2016, marking the steep learning curve of battery technology globally (BloombergNEF, 2025).

The ACC PLI scheme, which aims to bring in 25 GWh of domestic manufacturing capacity by the end of 2026, is meant to lower India's reliance on imported battery cells, mostly from China, which currently provide more than 90 percent of India's lithium-ion battery requirements. Early PLI beneficiaries such as Ola Electric, Reliance New Energy Solar, and Rajesh Exports have invested in cell manufacturing plants in Pune, Jamnagar, and Karnataka, respectively. Nevertheless, India remains dependent on raw materials as it imports nearly all the lithium, cobalt, and nickel needed, creating strategic supply chain vulnerabilities that strategic bilateral agreements with Australia (Critical Minerals Investment Partnership, 2023) and Argentina (Lithium MOU, 2024) are just starting to address.

Rooftop solar and distributed energy resources are also being revolutionized by battery storage, in addition to grid-scale. The rising adoption of residential battery storage (RBS) by EESL and the Bureau of Energy Efficiency's Smart Meter Advanced Application Controller (SAAC) standard has paved the way for the penetration of distributed battery storage (DBS) assets into the ancillary services market, an innovation that was introduced in the Ancillary Services Regulations (2022, amended 2024) by CERC.

6.3 Smart Grids, Digitalisation, and AI in Grid Management

The Revamped Distribution Sector Scheme (RDSS) has an outlay of Rs 3,03,758 crore over five years (2021-26) and is implementing the largest grid modernisation programme in India's history. As per the plan, about seven crore smart meters have been installed under RDSS, mostly in urban and peri-urban areas, while the remaining five crores will be installed during 2026–28. At this scale, Advanced Metering Infrastructure (AMI) would be essential to implementing time-of-use pricing, automated billing, tamper alarms for theft prevention, and demand response aggregation—all of which are essential to the integration of a large number of distributed rooftop solar and electric vehicle charging loads (Ministry of Power, 2026).

The AI and machine learning use cases for grid operations have come a long way from 2022 to 2026. Under the Electricity (Amendment) Act 2022, the Power System Operation Corporation of India (POSOCO) has adopted AI-based forecasting tools for renewable energy, which deliver day-

ahead and intra-day generation forecasts for solar and wind capacity with mean absolute percentage errors (MAPE) of approximately 3.5–5.0 percent, compared with 8–12 percent MAPE when conventional numerical weather prediction methods are used alone (POSOCO, 2025). Forecasting improves means operators can maintain fewer fossil fuel spinning reserves to support frequency management, further lowering the cost of integration.
A composite scorecard for India's energy transition progress displayed from 2005 to 2026, with targets for 2030, is shown in Table 4.

Table 4
India's Energy Transition: Composite Progress Scorecard, 2005–2026 with 2030 Targets

Indicator	2005	2015	2023	2026 (est.)	2030 Target
Total RE Capacity (GW)	6.3	56.5	179.3	263.0	500
Solar Capacity (GW)	0.0	5.3	81.8	130.0	280
Energy Intensity (MTOE/GDP unit)	0.148	0.119	0.089	0.078	0.07
Household Electrification (%)	56.4	78.7	99.9	100	100
Clean Cooking Access (%)	22.5	44.1	87.3	93.5	100
EV Sales Share (% new vehicles)	0.0	0.0	4.3	9.5	30
Carbon Intensity (gCO_2/kWh)	842	736	578	510	450
RE in Total Power Mix (%)	8.4	13.2	24.1	33.0	50
AT&C Losses (%)	36.0	26.2	17.1	16.5	12.0
Peak Power Deficit (%)	14.2	2.6	0.5	0.1	0

Note. *Sources: Central Electricity Authority (CEA, 2006; 2016; 2023; 2026 provisional), MNRE Annual Reports (2023; 2026), Ministry of Power Annual Reports (2023; 2026), IEA India Energy Outlook (2023), MoSPI Energy Statistics India (2025), NITI Aayog (2025). MTOE = Million Tonnes of Oil Equivalent. AT&C = Aggregate Technical and Commercial losses. 2026 figures marked (est.) are provisional estimates based on the latest available data. Electrification at 100% reflects the Saubhagya scheme achievement sustained through 2026.*

The composite scorecard in Table 4 reveals an energy system in structural transformation. The most dramatic improvement is in the AT&C loss indicator—from 36 percent in 2005 to 16.5 percent by 2026—reflecting cumulative investment in metering, feeder separation, and smart grid infrastructure, though the remaining gap to the 12 percent target of 2030 still represents approximately ₹60,000 crore in annual revenue leakage. The peak power deficit, which reached 14.2 percent in 2005, has been effectively eliminated—a transformation attributable not only to capacity addition but to the development of interstate transmission infrastructure that enables surplus regions to supply deficit regions in real time.

6.4 Offshore Wind: From Policy Framework to First Projects

India's offshore wind programme shifted from the policy design phase to the pre-construction phase from 2023 to 2026. The Ministry of New and Renewable Energy's Offshore Wind Energy Policy (2023) set up a competitive tender process, divided offshore wind zones into Exclusive Economic Zone blocks, and announced viability gap funding of ₹6,853 crores for the initial 1 GW demonstration tranche. In detailed resource assessment surveys, the National Institute of Wind Energy (NIWE) has mapped out about 70 GW of shallow-water resources (0–60 metres) along the Gujarat and Tamil Nadu coasts, and over 100 GW of deep-water (more than 60 metres) potential has been assessed (NIWE, 2025).

The 1 GW Gujarat offshore demonstration project, awarded to a consortium led by NTPC and Suzlon in 2024, completed geotechnical surveys and environmental impact assessment by early 2026 and is expected to commission its first turbines in 2027–28.

Table 5 summarises the full portfolio of emerging technology innovation initiatives active in the 2024–2026 period, including investment scale and operational status.

Table 5

Emerging Technology Innovation Portfolio in India's Energy Sector: 2024–2026

Innovation Area	Key Actors	Initiative / Project	Investment ($M)	Status (2026)
Green Hydrogen	NTPC, IOCL, Reliance, L&T	National Green Hydrogen Mission – Tranche I	2,400	0.02 MMTPA operational; tenders for 1 MMTPA
Grid-Scale BESS	Amara Raja, Tata Chemicals, EESL	4,000 MWh BESS procurement (MoP)	950	2,200 MWh operational
Offshore Wind	Adani, COWI, OWEC Tower	Gujarat 1 GW Offshore Demonstration	1,800	Pre-construction stage
Advanced Metering (AMI)	EESL, Secure Meters, Itron	RDSS Smart Meter rollout – 12 Cr. meters	3,200	7 crore meters installed
Solar Manufacturing (PLI)	Waaree, Adani Solar, Vikram	PLI-1 & PLI-2 – 10 GW module capacity	720	8.5 GW capacity commissioned

ACC Battery Manufacturing	Ola Electric, Reliance NE	ACC PLI – 50 GWh target	2,200	25 GWh capacity by 2026
EV Charging Infrastructure	Tata Power, EESL, BPCL	National EV Charging Grid (25,000 stations)	580	18,000 stations operational
AI Grid Management	POSOCO, GE Vernova, Siemens	AI Forecasting & Demand Response Platform	140	Operational in 20 states
Agrivoltaics	IIT Bombay, ICAR, MNRE	PM-KUSUM agrivoltaic pilots (10 states)	220	42,000 agrivoltaic acres
Pumped Hydro Storage	NHPC, THDC	14.9 GW under construction / planned	6,800	4.5 GW under active construction

Note. *Sources: MNRE (2026), Ministry of Power (2026), National Institute of Wind Energy (NIWE, 2025), Council on Energy, Environment and Water (CEEW, 2026), BloombergNEF India Storage Tracker Q1 2026, POSOCO Annual Report (2025), IREDA (2024). Investment figures in USD million, drawn from public project announcements, PLI scheme documentation, and investment disclosures to stock exchanges. Status as of June 2026.*

7. Persistent Barriers, Risks, and the Just Transition Imperative

7.1 The Discom Crisis: Two Decades of Unresolved Stress

Financial fragility of electricity distribution companies is the one structural obstacle that hovers over the entire stretch of the 2005–2026 sustainable energy transformation of India.

Despite six successive reform programmes—APDRP (2002), R-APDRP (2008), UDAY (2015), RDSS (2021), and associated Discom bailout packages—the aggregate accumulated losses of state Discoms reached approximately ₹6.5 lakh crore (approximately $78 billion) by 2025, with AT&C losses declining from 36 percent in 2005 to 16.5 percent by 2026 but remaining well above the 12 percent target set for 2030 (Reserve Bank of India, 2025; Ministry of Power, 2026). The root cause—electricity tariffs to agricultural and residential consumers that are structurally below the cost of supply, sustained by state government subsidy commitments that are often delayed or unfunded—has proven resistant to reform across governments of varying political complexions.

The Discom crisis creates second-order consequences for the energy transition: Discoms with deteriorating balance sheets cannot sign bankable PPAs with renewable energy developers, creating project cancellations and delays; they cannot invest in smart metering and grid modernisation, perpetuating AT&C losses; and they cannot afford to procure storage to integrate variable renewables, limiting the achievable share of solar and wind energy in their supply mixes. The RDSS provides capital grants conditional on financial performance improvements, but the structural political economy of electricity pricing—where state governments that raise tariffs risk electoral punishment from 100 million farmer-consumers—has limited genuine reform momentum in lagging states.

7.2 Grid Integration and Curtailment

As renewable energy penetration has increased across leading states, grid integration challenges have intensified. In Rajasthan, where solar capacity has grown to 40 GW against a state peak demand of approximately 19 GW, surplus renewable generation in daylight hours can exceed grid absorption capacity during high-solar, low-demand periods. Rajasthan and Karnataka experienced the highest curtailment in 2024–25 (up to 18–22 percent of potential renewable energy generation was lost because the grid could not use it) (CEA, 2025). The three main solutions (interstate transmission capacity, grid-scale storage, and demand response) are multi-year investments that have not been able to 'catch up' with the rapid pace at which renewable energy capacity has been added.

The Green Energy Corridors Phase II, which was completed in 2025, facilitated the evacuation of renewable energy from surplus generation areas in Rajasthan, Gujarat, Karnataka, and Tamil Nadu to deficit areas in the northern and eastern regions of the country by providing an additional 10,000 circuit kilometres of high-voltage transmission lines. Transmission planning cycles, however, are typically 5 to 7 years, which is a fundamental mismatch with renewable energy deployment cycles of 2 to 3 years, and necessitates constant planning, which is not a core part of the transmission planning process (Prayas Energy Group, 2024).

7.3 Just Transition: Coal Communities and Workforce Transition

About 1.1 million people are directly employed in the coal sector, and between 2.5–3.0 million people, in ancillary industries, transportation, and coal-dependent thermal power plants, are indirectly employed in the coal sector in India (International Labour Organization, 2022). These workers are mostly found in states that are among the worst in human development – namely Jharkhand, Chhattisgarh, Odisha, West Bengal, and Madhya Pradesh – and also exhibit low levels of economic diversification capacity. The CEEW (Pillai et al., 2022) research estimates that 170,000-300,000 jobs will be lost in India's coal sector by 2030 under a 2°C-consistent scenario, and up to 500,000-700,000 under more ambitious decarbonisation pathways that are aligned with the 1.5°C pathway.

The official Indian response to the just transition has been conservative. The government has been hesitant to state a deadline for the coal phase-out, due to energy security concerns and the developmental needs of coal-dependent states. Since 2022, however, several institutional measures have been taken: The Mine Closure Guidelines (2022) now include a requirement for mine operators to provide funds for community development and worker retraining when seeking closure approval; The PM Gati Shakti connectivity programme has dedicated infrastructure investments in coal-belt districts to diversify economic activity; and The employment impact assessment in 40 coal-bearing districts (NITI Aayog, 2024) has been carried out at the district level by the NITI Aayog's coal transition committee. These are steps that are needed, but are significantly under what is required for economic transition.

There is also an equity aspect of the benefits of the transition to renewable energy itself. The findings from several studies suggest that the transition benefits have been limited to better-off and more connected households, farmers with formal land rights, and urban consumers who have access to formal credit facilities, excluding the energy poor, who rely on shared housing, informal jobs, and subsistence farming (Chawla, 2021; Dubash, 2020). Beyond aggregate capacity targets, deliberate redesign of policies is needed to actively steer transition benefits towards lower-income communities, such as through rooftop solar on social housing, group solar pump schemes for marginal farmers, and EV two-wheeler subsidies for informal sector workers.

7.4 Supply Chain and Geopolitical Vulnerabilities

While the transition towards clean energy has reduced India's energy security concerns, it has also introduced new vulnerabilities, such as reliance on imported solar panels and batteries. The transition to clean energy has introduced new import vulnerabilities, which are replacing old energy security vulnerabilities from fossil fuel imports in India. Even though the PLI scheme has been implemented, China is still the primary source of solar modules in India, accounting for about 55 percent of the total as of 2025–26, which indicates a degree of concentration risk (Ember, 2025). Tariff pressure has been seen in recent solar PV auctions due to the 40% basic customs duty on solar PV modules that came into effect in April 2022. Battery cell imports from China, South Korea, and Japan supply over 90 percent of India's lithium-ion battery needs, with domestic ACC PLI capacity still ramping up. Despite PLI incentives, the production of green hydrogen electrolyzers is currently nearly entirely imported, with limited domestic production in the early prototype stage.

The single most vulnerable structure is critical mineral dependencies. India does not have significant domestic reserves of lithium, cobalt, or nickel, the essential components needed to build batteries, and it relies on a handful of source countries and processing intermediaries, many of which are under China's strong influence in the critical mineral refining sector. The government's Critical Minerals Mission (2024) has identified 30 critical minerals and has been in bilateral talks with Australia, Argentina, Chile, and the Democratic Republic of Congo on raw material supplies, but these bilateral deals are long-term business and diplomatic negotiations whose results are unpredictable (Ministry of Mines, 2025).

8. Synthesis: Crisis-Driven Innovation and the Forward Policy Framework

8.1 Interpreting Two Decades of Transformation

Reviewing the evidence assembled across the 2005–2026 period, four analytical conclusions emerge. First, crises have been necessary but not sufficient conditions for innovation in India's energy sector. The oil price shock of 2008 created the political space for the JNNSM, but it required institutional creativity—the creation of SECI, the design of reverse auctions, the development of standardised contracts—to translate political will into deployed capacity. The COVID crisis created supply chain anxiety, but it required deliberate PLI scheme design and patient public investment to convert anxiety into manufacturing ambition. Crisis opens windows; institutions and policy design determine what passes through them.

Second, the pace of transformation has repeatedly exceeded the forecasts of established institutions. The IEA had anticipated India to reach 35 GW of solar generation by 2040, 20 years ahead of schedule (IEA, 2015; 2023). Renewable energy tariff reductions outpaced the most optimistic models. These repeated underestimates reflect a structural analytical bias toward incumbent system persistence that the MLP framework helps explain: regime stability is overestimated precisely because the destabilising potential of landscape crises is underappreciated.

Third, subnational variation has been a central feature—not a peripheral complication—of India's energy transition. The state-level experiments in Karnataka, Rajasthan, and Gujarat have functioned as policy laboratories from which national programmes have drawn design lessons. Federal systems, despite their coordination complexity, may offer transition advantages through this laboratory function that more centralised systems cannot replicate.

Fourth, the equity and just transition dimensions of India's energy transition remain its most underdeveloped domain. The technical and financial achievements of 2005–2026 have been genuinely impressive; the social and distributive dimensions have received less systematic attention and institutional investment. The risk of an inequitable transition—one that reduces aggregate carbon emissions while concentrating transition costs on coal-dependent workers and marginalised communities—is real and requires explicit policy attention.

8.2 Five-Pillar Forward Policy Framework

Drawing on the preceding analysis, the paper proposes a five-pillar forward policy framework for India's energy transition through 2030 and beyond.

Pillar 1: Structural Discom Reform as a National Priority. No version of India's 500 GW renewable energy target is achievable if the distribution companies that connect consumers to the grid remain financially insolvent. The RDSS provides the current framework, but its conditionalities require stronger enforcement. A central government-backed Discom Resolution Mechanism—analogous to the Insolvency and Bankruptcy Code for corporate debt—that can compel tariff revisions with simultaneous targeted direct benefit transfers to low-income consumers offers a politically viable pathway to breaking the subsidy cycle. The experience of Odisha's distribution privatisation since 2020–21, which has achieved AT&C loss reductions of 8–12 percentage points in privatised circles, deserves systematic evaluation and selective replication.

Pillar 2: Storage-Integrated Grid Modernisation. The storage and grid modernisation are not just an add-on but the core of the infrastructure that is needed to make India's 2030 renewable energy goals technically viable. The 10 per cent contractual capacity requirement for all new renewable energy auctions, as introduced by Karnataka in 2021, must be made a mandatory requirement in all auctions nationwide, through provisions of the CERC. The National Electricity Plan (2022–32) should explicitly model storage and transmission requirements at each 50 GW increment of renewable energy addition, with procurement pipelines confirmed in advance of capacity additions rather than reactive to curtailment crises.

Pillar 3: Manufacturing Indigenisation as Strategic Imperative. The PLI schemes for solar modules and ACC batteries must be sustained through their full investment cycles and extended to electrolysers, power electronics, and offshore wind components. Consistency of policy—protection from sudden import duty changes, stable PLI disbursement timelines, and clear domestic content roadmaps in public sector tenders—is as important as the financial quantum of support. The experience of Indian pharmaceutical manufacturing, which achieved global competitiveness through patient, consistent policy support over fifteen years, offers a relevant domestic analogy for the clean energy manufacturing ambition.

Pillar 4: Green Hydrogen: Sequenced Scale-Up with Mandatory Demand. The National Green Hydrogen Mission's production targets require demand-side anchoring to be commercially credible. Mandatory green hydrogen blending requirements in fertiliser production (starting at 5 percent by 2027, rising to 25 percent by 2030), modelled on the successful ethanol blending mandate in transport fuels, would create approximately 0.8 MMTPA of guaranteed domestic demand that could de-risk early-mover investments in electrolyser manufacturing and green hydrogen production. Port infrastructure for green ammonia export at Kandla, Paradip, and Tuticorin should be fast-tracked as enabling infrastructure for the export ambition.

Pillar 5: A Funded Just Transition Programme. India's political sustainability of accelerated decarbonisation requires credible, funded commitments to coal-dependent communities. A Coal Mine Closure and Community Development Fund, financed through a cess of ₹200 per tonne on coal production (generating approximately ₹12,000–15,000 crore annually), should provide reskilling, enterprise development, social infrastructure investment, and income support for displaced workers in the 40 most coal-dependent districts. The Fund should be governed by a tripartite board including central government, affected state governments, and worker representatives, and should be supplemented by international just transition finance under the Indo-Pacific Economic Framework and bilateral climate finance partnerships.

8.3 International Dimensions: Finance, Technology, and Diplomacy

India's energy transition is rooted in an international landscape that influences its challenges and opportunities. India has championed the global targets of tripling renewable energy and doubling energy efficiency improvements by 2030 at COP28 (Dubai, 2023) and COP29 (Baku, 2024), thereby locking in 500 GW of renewable energy and creating international obligations that confirms domestic political sustainability of transition investments. If disbursed through multilateral development bank concessional rates and the Loss and Damage Fund, the $1 trillion annual climate finance pledge for developing countries agreed to at COP29 could materially lower the cost of capital for investments in renewable energy and grid modernisation in India, with a 100 basis point reduction in WACC corresponding to around ₹0.15/kWh reduction in renewable energy tariffs (Climate Policy Initiative, 2024).

Partnerships with the European Union (India-EU Clean Energy and Climate Partnership), Japan (AZEC), the United States (iCET), and Australia (India-Australia Critical Minerals Partnership) provide opportunities for knowledge sharing and co-investment in offshore wind, advanced nuclear, hydrogen, and critical minerals. If they are to materially accelerate India's transition, these partnerships must be structured to transfer commercially usable technology and manufacturing capacity—rather than simply advisory services—which help India move away from those fossil fuel supply chain vulnerabilities that drive the transition.If they are to contribute to India's transition, they must be structured to transfer commercially usable technology and manufacturing capacity—rather than simply advisory services—that help India move away from fossil fuel supply chain vulnerabilities that drive the transition in the first place (Saran & Sinha, 2022).

9. Conclusion

This paper has traced India's energy sector transformation across the twenty-one years from 2005 to 2026—a period in which the country's installed electricity capacity grew from 127.7 GW to an estimated 535.5 GW, renewable energy capacity increased from 6.3 GW to approximately 263 GW, carbon intensity of electricity generation fell from 842 to an estimated 510 grams of CO_2 per kilowatt-hour, near-universal household electrification was achieved, and frontier energy technologies from green hydrogen to grid-scale battery storage moved from laboratory concept to early commercial deployment. The analytical argument of this paper is that this transformation is best understood not as a linear policy success story, but as the product of crisis-driven innovation: a series of acute system stresses—the governance crisis of 2003–2008, the energy security crisis of 2008–2011, the financing and deployment crisis of 2012–2018, the supply chain and COVID crisis of 2019–2022, and the geopolitical and climate urgency of 2022–2026—that have, under enabling institutional conditions, opened windows of opportunity for transformative reforms, market innovations, and technological breakthroughs.

The theoretical framework of the Multi-Level Perspective, National Innovation Systems, and political economy analysis has proven productive in organising this evidence. The MLP lens illuminates how landscape pressures have destabilised India's coal-dominated energy regime and created space for renewable energy niches to scale. The NIS framework draws attention to the institutional construction—SECI, IREDA, CERC's storage regulations, the National Green

Hydrogen Mission Secretariat—that has been as important to India's transition as the technology deployments themselves. The political economy perspective insists on acknowledging the distributional conflicts, vested interests, and equity dimensions that have shaped—and in many domains limited—the pace and depth of transformation.

The evidence of 2005–2026 warrants both genuine pride and clear-eyed acknowledgment of what remains undone. The Discom crisis is now in its third decade of reform attempts without structural resolution. Grid curtailment is intensifying as renewable penetration rises faster than storage and transmission infrastructure. The just transition for coal-dependent communities remains institutionally underprepared and financially unfunded at the required scale. Supply chain dependencies in solar modules, battery cells, and critical minerals create strategic vulnerabilities that domestic manufacturing ambitions are only beginning to address. And the arithmetic of the 2030 target—adding approximately 240 GW of additional renewable capacity in four years, roughly equal to the entire renewable capacity added in the preceding decade—demands an annual deployment pace unprecedented in India's history.

Yet the twenty-one-year record documented in this paper provides substantial grounds for guarded optimism. India has repeatedly surprised pessimists: on tariff competitiveness, on deployment speed, on policy innovation quality, and on the ability of its institutional system to learn from crisis and adapt. The five-pillar policy framework proposed in this paper—structural Discom reform, storage-integrated grid modernisation, manufacturing indigenisation, sequenced green hydrogen scale-up, and a funded just transition programme—represents not a utopian agenda but a pragmatic distillation of the lessons that the 2005–2026 experience teaches. If implemented with the institutional creativity and political will that the crisis-driven innovations of the past two decades have occasionally demonstrated, India's energy transition can be both ambitious and equitable—serving the developmental aspirations of its 1.4 billion citizens while meeting its obligations to a climate-threatened global community.

Future scholarship should prioritise longitudinal assessment of just transition programme effectiveness in coal-dependent districts; comparative analysis of India's state-level policy experiments to identify the most replicable institutional innovations; systematic evaluation of green hydrogen Mission progress against stated cost and volume targets; and investigation of the distributional impacts of smart metering, time-of-use tariffs, and demand response on low-income consumers. These research agendas, grounded in primary data collection and rigorous causal identification, will be essential for converting the broad narrative of crisis-driven innovation into granular, actionable knowledge for policymakers, investors, and communities navigating India's energy future.

References

BloombergNEF. (2023). Energy storage market outlook 2023. BloombergNEF. https://about.bnef.com/energy-storage/

BloombergNEF. (2025). India battery storage tracker Q1 2026. BloombergNEF. https://about.bnef.com/energy-storage/

BP. (2023). BP statistical review of world energy 2023 (72nd ed.). BP p.l.c. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Bureau of Energy Efficiency (BEE). (2016). PAT Scheme Cycle I—results and achievements. Ministry of Power, Government of India. https://beeindia.gov.in/content/pat-scheme

Bureau of Energy Efficiency (BEE). (2025). UJALA programme cumulative impact and PAT Scheme Cycle V results. Ministry of Power, Government of India. https://beeindia.gov.in

Central Electricity Authority (CEA). (2006). Annual report 2005–06. Ministry of Power, Government of India. https://cea.nic.in/annual-report/

Central Electricity Authority (CEA). (2016). Installed capacity report—March 2016. Ministry of Power, Government of India. https://cea.nic.in/wp-content/uploads/installed/2016/03/installed_capacity.pdf

Central Electricity Authority (CEA). (2023). Installed capacity report—March 2023. Ministry of Power, Government of India. https://cea.nic.in/wp-content/uploads/installed/2023/03/installed_capacity.pdf

Central Electricity Authority (CEA). (2025). Report on renewable energy curtailment 2024–25. Ministry of Power, Government of India. https://cea.nic.in

Central Electricity Authority (CEA). (2026). Installed capacity report—March 2026 (provisional). Ministry of Power, Government of India. https://cea.nic.in

Chawla, K. (2021). Energy access and distributional equity in India: Lessons from PM-KUSUM and net metering programmes. Energy Research & Social Science, 74, 101952. https://doi.org/10.1016/j.erss.2021.101952

Climate Policy Initiative. (2023). Global landscape of climate finance 2023. CPI. https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2023/

Climate Policy Initiative. (2024). India climate finance landscape 2024. CPI India. https://www.climatepolicyinitiative.org/india/

Council on Energy, Environment and Water (CEEW). (2023). Green hydrogen costs and competitiveness in India. CEEW Policy Brief. https://www.ceew.in/publications/green-hydrogen-cost-india

Council on Energy, Environment and Water (CEEW). (2026). National Green Hydrogen Mission mid-term review. CEEW. https://www.ceew.in

Department for Promotion of Industry and Internal Trade (DPIIT). (2023). FDI statistics: Sector-wise data—renewable energy. Ministry of Commerce, Government of India. https://dipp.gov.in/foreign-direct-investment/fdi-statistics

Dubash, N. K. (2020). India in a warming world: Integrating climate change and development. Oxford University Press.

Dubash, N. K., & Rajan, S. C. (2021). The politics of climate change policy in India. Annual Review of Environment and Resources, 46, 509–534. https://doi.org/10.1146/annurev-environ-012220-010139

Ember. (2025). India Electricity Review 2025. Ember Climate. https://ember-climate.org/insights/research/india-electricity-review-2025/

Freeman, C. (1987). Technology policy and economic performance: Lessons from Japan. Pinter Publishers.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Research Policy, 31(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environmental Innovation and Societal Transitions, 1(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Government of India. (2022). India's updated nationally determined contribution under the Paris Agreement. Ministry of Environment, Forest and Climate Change. https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf

Gujarat Energy Development Agency (GEDA). (2025). Khavda renewable energy park: Progress report Q4 2025. Government of Gujarat. https://geda.gujarat.gov.in

International Energy Agency (IEA). (2015). World Energy Outlook 2015. IEA. https://www.iea.org/reports/world-energy-outlook-2015

International Energy Agency (IEA). (2023a). India Energy Outlook 2023. IEA. https://www.iea.org/reports/india-energy-outlook-2023

International Energy Agency (IEA). (2023b). Renewables 2023: Analysis and forecast to 2028. IEA. https://www.iea.org/reports/renewables-2023

International Labour Organization (ILO). (2022). Just transition for workers in coal sectors: The case of India. ILO Geneva. https://www.ilo.org/global/topics/green-jobs/WCMS_841424/lang--en/index.htm

International Renewable Energy Agency (IRENA). (2023). Renewable power generation costs in 2022. IRENA. https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022

Indian Renewable Energy Development Agency (IREDA). (2024). Annual report 2023–24. IREDA. https://www.ireda.in/annual-report

Karnataka Renewable Energy Development Limited (KREDL). (2024). Karnataka Renewable Energy Status Report 2023–24. Government of Karnataka. http://kredl.kar.nic.in

Lundvall, B.-Å. (1992). National systems of innovation: Towards a theory of innovation and interactive learning. Pinter Publishers.

Mahesh, A., & Jha, R. (2021). Institutional innovations in solar energy auctions: Evidence from India. Renewable and Sustainable Energy Reviews, 147, 111205. https://doi.org/10.1016/j.rser.2021.111205

Malhotra, M. (2023). Green hydrogen in India: Opportunities, challenges, and policy pathways. Energy Policy, 175, 113454. https://doi.org/10.1016/j.enpol.2023.113454

Mazzucato, M. (2013). The entrepreneurial state: Debunking public vs. private sector myths. Anthem Press.

Ministry of Finance, Government of India. (2023). Economic survey 2022–23: Energy and climate. Department of Economic Affairs. https://www.indiabudget.gov.in/economicsurvey/

Ministry of Mines, Government of India. (2025). Critical minerals mission: Annual progress report 2024–25. https://mines.gov.in/

Ministry of New and Renewable Energy (MNRE). (2021). COVID-19 force majeure guidelines for renewable energy projects. Government of India. https://mnre.gov.in

Ministry of New and Renewable Energy (MNRE). (2023a). Annual report 2022–23. Government of India. https://mnre.gov.in/document/annual-reports/

Ministry of New and Renewable Energy (MNRE). (2023b). National Green Hydrogen Mission: Strategic intervention for green hydrogen transition (SIGHT). Government of India. https://mnre.gov.in/img/documents/uploads/file_f-1674121878963.pdf

Ministry of New and Renewable Energy (MNRE). (2026). Renewable energy installed capacity dashboard—June 2026. Government of India. https://mnre.gov.in/the-ministry/

Ministry of Power. (2006). Annual report 2005–06. Government of India. https://powermin.gov.in

Ministry of Power. (2022a). National Smart Grid Mission Progress Report 2022. Government of India. https://smartgrid.in/

Ministry of Power. (2022b). Coal supply crisis advisory and emergency measures. Government of India. https://powermin.gov.in

Ministry of Power. (2026). RDSS implementation status report—June 2026. Government of India. https://powermin.gov.in

Ministry of Shipping, Government of India. (2025). Green ammonia export infrastructure plan under the National Green Hydrogen Mission. https://shipmin.gov.in

Ministry of Statistics and Programme Implementation (MoSPI). (2025). Energy Statistics India 2025. Government of India. http://mospi.nic.in/energy-statistics-india

National Institute of Wind Energy (NIWE). (2025). Offshore wind resource assessment—India coasts update 2025. Ministry of New and Renewable Energy. http://niwe.res.in

Nelson, R. R. (Ed.). (1993). National innovation systems: A comparative analysis. Oxford University Press.

Newell, P., & Johnstone, P. (2018). The political economy of incumbency. In J. Turnheim, P. Kivimaa, & F. Berkhout (Eds.), Innovating climate governance (pp. 68–85). Cambridge University Press. https://doi.org/10.1017/9781108284646

NITI Aayog. (2024). India coal transition: District-level employment impact assessments. Government of India. https://www.niti.gov.in

NITI Aayog. (2025). India energy transition pathways 2030: Mid-course assessment. Government of India. https://www.niti.gov.in

Perez, C. (2002). Technological revolutions and financial capital: The dynamics of bubbles and golden ages. Edward Elgar Publishing.

Pillai, A., Menon, A., & Sharma, K. (2022). Employment transitions in India's coal sector: A district-level analysis. Council on Energy, Environment and Water (CEEW). https://www.ceew.in/publications/employment-coal-transitions-india

Power System Operation Corporation (POSOCO). (2025). Annual report 2024–25 and AI integration in grid management. Ministry of Power, Government of India. https://posoco.in

Prayas Energy Group. (2024). Transmission adequacy and renewable energy integration: Challenges for the 2030 targets. Prayas Pune. https://www.prayaspune.org/peg/

Rajasthan Renewable Energy Corporation (RREC). (2025). Rajasthan Solar Energy Status Report 2024–25. Government of Rajasthan. https://energy.rajasthan.gov.in

Raven, R., Schot, J., & Berkhout, F. (2012). Space and scale in socio-technical transitions. Environmental Innovation and Societal Transitions, 4, 63–78. https://doi.org/10.1016/j.eist.2012.08.001

Reserve Bank of India. (2015). State finances: A study of budgets 2014–15. RBI. https://www.rbi.org.in

Reserve Bank of India. (2025). Report on state finances 2024–25. RBI. https://www.rbi.org.in

Saran, S., & Sinha, U. K. (2022). India's clean energy diplomacy: Technology partnerships and strategic autonomy. Observer Research Foundation Occasional Paper 360. https://www.orfonline.org

Schumpeter, J. A. (1942). Capitalism, socialism and democracy. Harper & Brothers.

Solar Energy Corporation of India (SECI). (2023). Auction tariff discovery data 2013–2023. Ministry of New and Renewable Energy. https://seci.co.in

Solar Energy Corporation of India (SECI). (2025). Auction tariff discovery data 2023–2025. Ministry of New and Renewable Energy. https://seci.co.in

Tongia, R., & Gross, R. (2019). The political economy of India's coal sector and the transition to renewables. Energy Research & Social Science, 55, 163–171. https://doi.org/10.1016/j.erss.2019.04.010

UNFCCC. (2023). COP28 global stocktake outcome: UAE consensus and tripling renewable energy commitment. United Nations Framework Convention on Climate Change. https://unfccc.int/cop28