Steel Decarbonization in India:
State-Level Implementation Strategies and
the Path to Net-Zero by 2070

A Comparative Analysis with China's Provincial Approach

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Abstract

This comprehensive study analyzes India's steel decarbonization strategy through state-level implementation during the 15th Finance Commission period (2025-2030) and beyond to the 2070 net-zero target. Drawing explicit parallels with China's provincial approach, this document examines how India's federal structure, diverse state capabilities, and different governance model create both opportunities and challenges for industrial transformation.

India's steel sector encompasses approximately 130-140 million tonnes of annual crude steel production (7-8% of global output), making it the world's second-largest producer after China. The analysis reveals fundamental operational challenges: (1) balancing rapid production growth with decarbonization imperatives, (2) managing transformation across highly diverse state contexts with varying resources and political will, (3) mobilizing capital estimated at $80-120 billion through 2040 in an economy with more constrained fiscal capacity than China, and (4) navigating democratic governance structures where national mandates face greater state-level resistance than in China's unified system.

State-level analysis demonstrates striking parallels and contrasts with Chinese provinces. Odisha (25-28 Mt/a, similar to China's Liaoning) possesses abundant iron ore and renewable potential but lacks hydrogen infrastructure. Jharkhand (18-20 Mt/a) faces severe environmental pressure like China's Hebei but with less policy enforcement capacity. Gujarat (12-15 Mt/a, parallel to Guangdong) leads in EAF adoption and market integration. Chhattisgarh (15-18 Mt/a) resembles Shanxi with coal-based infrastructure challenges.

Critical success factors include: achieving green hydrogen costs of 150-180/kg by 2030 (from current 300-400/kg), securing approximately 50-60 Mt scrap availability against current 35-40 Mt, maintaining policy coherence across electoral cycles in democratic governance, mobilizing finance through blended mechanisms, and managing just transition for 200,000-300,000 at-risk workers.

The study contextualizes India's approach against China's model, identifying key differences: market-driven versus state-coordinated transformation, federal versus unitary governance, capital-constrained versus capital-abundant environments, and democratic accountability versus technocratic implementation. India's pathway emphasizes gradual technology adoption, reliance on international partnerships, and alignment with export competitiveness requirements driven by EU's Carbon Border Adjustment Mechanism (CBAM).

Investment requirements are substantial but more manageable than China's scale: 6.0-8.5 trillion (approximately $75-105 billion) through 2040, with Odisha requiring 1.2-1.8 trillion and Jharkhand 1.0-1.5 trillion. Social dimensions are equally profound but complicated by weaker social safety nets compared to China.

Scenario analysis projects three pathways: (1) "Green Steel Leader" (15-20% probability) achieving 55-65% national emissions reduction by 2040 through rapid H2-DRI and EAF scaling; (2) "Steady Transformation" (55-60% probability) reaching 40-50% reduction with moderate delays; (3) "Slow Transition" (20-25% probability) limited to 25-35% reduction if financing fails or policy coherence breaks down.

Keywords: Steel decarbonization, India, hydrogen direct reduction, state policy, Odisha, Jharkhand, Gujarat, Chhattisgarh, Karnataka, net-zero 2070, National Steel Policy, CCUS, EAF, green hydrogen, just transition, CBAM, federal governance

This document represents a comprehensive analysis of India's steel decarbonization approach, explicitly structured to enable comparison with China's provincial strategies. The analysis was completed through human-AI collaboration between Prof. Fabio Miani and Anthropic's Claude system.

The opinions presented here do not reflect those of any specific organization in Italy—specifically the University of Udine—or India, and are presented solely for teaching and research purposes. Success probability assessments should be considered as illustrative scenarios rather than precise predictions.

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1 Introduction: India's Steel Decarbonization Challenge

1.1 Scale and Significance of India's Steel Sector

India's steel industry represents a critical component of the nation's economic development trajectory and global climate commitments. With approximately 130-140 million tonnes of crude steel production in 2024, India ranks as the world's second-largest steel producer, accounting for 7-8% of global output—substantially smaller than China's dominant 54% share but nonetheless globally consequential.

The sector generates approximately 260-300 Mt CO_2 annually, representing roughly 12-14% of India's total CO_2 emissions and approximately 2-2.5% of global steel sector emissions. While India's per-capita steel consumption remains significantly below developed economy levels (approximately 80 kg/capita versus 500+ kg/capita in China, 300-400 kg/capita in EU/Japan/USA), the growth trajectory is steep, with government targets aiming for 300 Mt production capacity by 2030-2031.

This growth imperative creates a fundamental tension absent in China's approach: India must simultaneously expand production to support infrastructure development while initiating decarbonization, whereas China decarbonizes while managing capacity reduction. This "grow and green" dual mandate fundamentally shapes India's transformation pathway.

1.2 Comparison with China's Context

Several critical differences distinguish India's steel decarbonization context from China's:

Production Scale: India's 130-140 Mt represents approximately 12-13% of China's 1,065 Mt, making India's challenge more manageable in absolute terms but still globally significant.

Technology Mix: India currently operates approximately 55-60% BF-BOF and 40-45% EAF/DRI routes, versus China's 87-90% BF-BOF dominance. India's higher existing EAF/DRI share provides a head start on cleaner technology adoption.

Governance Model: India's federal democratic structure contrasts sharply with China's unified authoritarian system. State governments possess substantial autonomy, unlike Chinese provinces operating under central directives. This creates both flexibility and coordination challenges.

Capital Availability: India's constrained fiscal capacity and less developed green finance ecosystem contrast with China's massive state-directed investment capacity. India must rely more heavily on private capital and international partnerships.

Regulatory Enforcement: India's regulatory enforcement capacity is generally weaker than China's, with compliance often inconsistent across states and dependent on political will.

Social Safety Nets: India's social safety nets are significantly less comprehensive than China's, complicating just transition programs for displaced workers.

1.3 Institutional Framework and National Policy

India's steel sector governance operates through multiple overlapping authorities:

Ministry of Steel: Formulates National Steel Policy, production targets, and sector development strategies. Recent focus on achieving 300 Mt capacity by 2030-2031 while improving competitiveness and sustainability.

Ministry of Environment, Forest and Climate Change (MoEFCC): Administers environmental clearances, emissions regulations, and climate commitments under Paris Agreement and national net-zero 2070 pledge.

Central Pollution Control Board (CPCB): Sets emissions standards and monitors compliance, though enforcement primarily through State Pollution Control Boards.

Ministry of New and Renewable Energy (MNRE): Coordinates green hydrogen development through National Green Hydrogen Mission, critical for steel decarbonization.

State Governments: Control land allocation, industrial licensing, electricity tariffs, and environmental enforcement—possessing substantial leverage over steel sector transformation.

1.4 Key National Policies and Commitments

National Steel Policy 2017 (updated 2022-2023): Establishes production targets, quality improvement goals, and sustainability principles, though specific decarbonization mandates remain less prescriptive than China's policies.

National Green Hydrogen Mission (2023): Targets 5 Mt green hydrogen production by 2030, with steel sector identified as priority consumer. Provides production-linked incentives and mandates for green hydrogen usage in hard-to-abate sectors.

Energy Conservation (Amendment) Act 2022: Establishes carbon trading mechanism and energy efficiency mandates for industrial sectors including steel.

Paris Agreement NDC Commitments: India pledges to reduce emissions intensity of GDP by 45% by 2030 (from 2005 levels) and achieve net-zero by 2070, though sectoral targets remain less specific than China's.

1.5 Structure of This Document

This analysis is organized to enable systematic comparison with China's provincial approach:

Section 2: National policy framework and regulatory mechanisms

Section 3: State-by-state analysis with explicit parallels to Chinese provinces:

- Odisha (parallel to Liaoning): Renewable energy advantages
- Jharkhand (parallel to Hebei): Environmental pressure and transformation urgency
- Gujarat (parallel to Guangdong): EAF leadership and market integration
- Chhattisgarh (parallel to Shanxi): Coal infrastructure challenges
- Karnataka (parallel to Jiangsu): Scrap availability and coastal access

Section 4: Technology pathways: H2-DRI, CCUS, EAF expansion

Section 5: Economic analysis and investment requirements

Section 6: Social dimensions and just transition

Section 7: International context: CBAM compliance and export competitiveness

Section 8: Scenario analysis and success probability assessment

Section 9: Comparative synthesis: India versus China models

Section 10: Conclusions and strategic recommendations

1.6 Research Questions

This study addresses five core research questions, structured to enable comparison with China:

1. **Governance Efficacy:** How does India's federal democratic governance model compare to China's unified authoritarian approach in driving steel sector transformation? What are the relative advantages and disadvantages?
2. **State Differentiation:** Which Indian states show the most promising transformation pathways, and how do their strategies compare to analogous Chinese provinces?
3. **Technology Economics:** Under what conditions can India achieve cost-competitive green steel, given more constrained capital access than China?
4. **Finance Mobilization:** Can India mobilize necessary capital ($80-120 billion through 2040) through market mechanisms and international partnerships, without China-style state-directed investment?
5. **CBAM Impact:** How does EU's Carbon Border Adjustment Mechanism create different incentive structures for India versus China, and does this accelerate or complicate transformation?

2 National Policy Framework

2.1 National Steel Policy and Production Targets

India's National Steel Policy framework establishes ambitious production expansion goals while incorporating sustainability principles, creating inherent tension between growth and decarbonization:

Production Targets:

- 2024 baseline: 130-140 Mt annual production
- 2030-2031 target: 300 Mt capacity (130-140% increase)
- Finished steel consumption target: 160 Mt by 2030
- Long-term vision: Maintain position as global cost-competitive producer

Key Policy Principles:

- Promote domestic value addition and reduce finished steel imports
- Enhance quality standards and specialty steel production
- Improve competitiveness through technology upgradation
- Incorporate environmental sustainability and circular economy principles
- Develop coastal steel plants leveraging imported ore and export markets

Comparison with China: Unlike China's October 2025 policy establishing mandatory 1.5:1 capacity replacement ratios forcing absolute capacity reduction, India's policy emphasizes capacity expansion with gradual emissions intensity improvement—a fundamentally different strategic orientation reflecting growth-stage economics.

2.2 National Green Hydrogen Mission

Launched in January 2023, the National Green Hydrogen Mission represents India's most consequential policy for steel decarbonization, though implementation timeline lags China's hydrogen initiatives:

Mission Targets:

- 5 Mt annual green hydrogen production by 2030
- 125 GW associated renewable energy capacity
- $100 billion expected investment through 2030
- Steel sector identified as priority consumption segment

Financial Incentives:

- Strategic Interventions for Green Hydrogen Transition (SIGHT): 17,490 crore ($2.1 billion) for production-linked incentives
- Electrolyzer manufacturing support: 4,440 crore ($530 million)
- Green hydrogen production incentives: 13,050 crore ($1.56 billion)
- Declining incentive structure: Higher subsidies in initial years to accelerate deployment

Steel Sector Implications:

- Mandates for green hydrogen usage in hard-to-abate industries being developed
- Hydrogen purchase obligations under consideration for steel producers
- Green hydrogen cost targets: 150-180/kg by 2030 (from current 300-400/kg)
- Critical challenge: Current costs make H2-DRI economically unviable without sustained subsidies

Comparison with China: China's hydrogen strategy features more aggressive scaling (targeting 2-3 Mt green H2 for steel sector alone by 2030 versus India's 5 Mt across all sectors), more developed pipeline infrastructure, and tighter integration with specific provincial steel transformation plans (e.g., Hebei's HBIS Zhangjiakou). India's approach relies more on market incentives rather than mandates.

2.3 Carbon Pricing and Emissions Trading

India's carbon pricing mechanisms remain less developed than China's ETS:

Energy Conservation (Amendment) Act 2022:

- Establishes framework for carbon trading mechanism
- Carbon Credit Trading Scheme (CCTS) launched 2023
- Steel sector not yet included in mandatory compliance phase
- Voluntary participation encouraged through renewable energy certificates

Current Status:

- Pilot phase focusing on power sector and large industrial emitters
- Carbon prices in voluntary markets: 800-1,500/t CO_2 ($10-18/t)
- Mandatory steel sector inclusion expected 2026-2027 timeframe
- Proposed cap-and-trade mechanism with free allocation followed by auction system

Comparison with China: China's ETS already operational for power sector with steel inclusion by 2025, carbon prices exceeding 100/t (700-800 at exchange rates), and more comprehensive enforcement. India's delayed implementation reduces immediate economic pressure for transformation.

2.4 Environmental Standards and Enforcement

Emissions standards for steel sector administered through Central and State Pollution Control Boards:

Current Standards:

- Particulate matter limits: 50 mg/Nm^3 (stack emissions)
- SO_2 limits: 200-600 mg/Nm^3 depending on process
- NO_x limits: 500-750 mg/Nm^3
- Water consumption norms: 3.5-5.0 m^3/t crude steel

Enforcement Challenges:

- Inconsistent implementation across states
- Limited continuous emissions monitoring systems (CEMS) deployment

- Penalties often insufficient to drive compliance
- Regulatory capacity constraints in State PCBs

Comparison with China: China's ultra-low emissions (ULE) retrofitting mandates (PM 10 mg/Nm^3, SO_2 35 mg/Nm^3, NO_x 50 mg/Nm^3) are 5-10x stricter than India's standards, with 80%+ compliance achieved through rigorous enforcement. India's weaker enforcement creates less immediate pressure for technology upgradation.

3 State-Level Analysis: Divergent Pathways

3.1 Framework for State Comparison

India's steel production is concentrated in five major states accounting for approximately 75-80% of national output. This section examines each state's transformation strategy with explicit parallels to Chinese provinces.

Analytical Dimensions:

- Production scale and technology mix
- Raw material endowment (iron ore, coal, scrap)
- Environmental pressure and air quality status
- Renewable energy resources and grid infrastructure
- State government political will and fiscal capacity
- Major producers and ownership structure
- Cost competitiveness for different technology pathways

3.2 Odisha: The Renewable Energy Enabler (Parallel: Liaoning)

3.2.1 Strategic Position and Production Profile

Odisha emerges as India's most advantaged state for green steel transformation, comparable to China's Liaoning Province in renewable energy potential:

Production Characteristics:

- Annual capacity: 25-28 Mt (18-20% of India's total)
- Current technology: 65% BF-BOF, 35% DRI-EAF
- Major producers: JSW Steel (Angul), JSPL (Angul), Tata Steel (Kalinganagar), SAIL (Rourkela)
- Annual emissions: 55-65 Mt CO_2
- Direct employment: 80,000-100,000 workers

Comparative Advantages:

1. **Iron Ore Abundance:** Odisha possesses 50-55% of India's iron ore reserves (5.5-6.0 billion tonnes), ensuring long-term feedstock security without dependence on imports—similar to Liaoning's resource position but more dominant nationally.
2. **Renewable Energy Potential:**
   - Solar: 25-30 GW identified potential
   - Wind: 3-4 GW potential (coastal and hilly areas)
   - Hydropower: 2.5 GW (existing + potential)
   - Current renewable installed capacity: 2.5 GW (target 10-12 GW by 2030)
   - Levelized cost of electricity: 2.5-3.0/kWh (among India's lowest)
3. **Coastal Access:** Paradip Port (one of India's largest) enables efficient exports and imports, similar to Liaoning's Dalian Port.

4. **Lower Labor Costs:** Approximately 30-40% lower than China's Liaoning, providing cost advantage for capital-intensive projects.

3.2.2 Transformation Strategy

Odisha pursues a hydrogen-centered strategy leveraging renewable advantages:

Phase 1 (2025-2028): Foundation

- Green hydrogen production: 50,000-75,000 tonnes/year through dedicated solar/wind projects
- H2-DRI demonstration: 0.5-1.0 Mt capacity (likely JSW or Tata Steel pilot)
- Electrolyzer capacity: 500-750 MW
- Investment: 15,000-20,000 crore ($1.8-2.4 billion)

Phase 2 (2028-2035): Scaling

- Green hydrogen: 250,000-350,000 tonnes/year
- H2-DRI capacity: 5-7 Mt (20-25% of state production)
- Electrolyzer capacity: 3-4 GW
- Renewable energy: 8-10 GW dedicated to hydrogen
- CCUS retrofit: 3-5 Mt BF-BOF capacity
- Investment: 60,000-80,000 crore ($7.2-9.6 billion)

Projected Technology Mix Evolution:

Technology	2024	2030	2035	2050
BF-BOF (conventional)	65%	50%	30%	5%
BF-BOF with CCUS	0%	10%	20%	15%
Coal-based DRI-EAF	30%	20%	15%	5%
H2-DRI-EAF	0%	8%	20%	50%
Scrap-EAF	5%	12%	15%	25%
Total Capacity (Mt)	27	35	40	42
Emissions (Mt CO_2)	60	58	42	15
Intensity (t CO_2/t)	2.22	1.66	1.05	0.36

Table 1: Odisha Steel Technology Evolution

3.2.3 Critical Success Factors and Risks

Success Enablers:

- **Lowest Projected LCOS in India:** 50,000-55,000/t for H2-DRI by 2030 (versus 60,000-70,000/t in other states)
- **State Government Support:** Proactive industrial policy, streamlined approvals
- **Corporate Commitment:** Major producers (JSW, Tata) with strong ESG commitments
- **Export Competitiveness:** CBAM-compliant green steel production positions for EU exports

Critical Risks:

- **Hydrogen Cost (High Risk):** Current 300-400/kg requires 50-60% reduction; delays in National Hydrogen Mission implementation would increase costs
- **Grid Infrastructure (Medium Risk):** Requires 8,000-12,000 crore grid upgrades for hydrogen production and steel electrification
- **Water Availability (Medium Risk):** Hydrogen production water-intensive; coastal desalination may be required
- **DRI Pellet Supply (Low-Medium Risk):** Must expand pellet production capacity from current 8-10 Mt to 15-18 Mt

3.2.4 Comparison with Liaoning Province

Dimension	Odisha, India	Liaoning, China
Production scale	25-28 Mt (20% national)	70-75 Mt (7% national)
Renewable energy	25-30 GW solar, 3-4 GW wind	60+ GW wind, nuclear power
LCOS advantage	50,000-55,000/t ($600-660/t)	$900-1,000/t (RMB 6,500-7,200)
Hydrogen cost target	150-180/kg by 2030	RMB 8-12/kg by 2030
State support	Moderate, market-driven	Strong, state-coordinated
Infrastructure readiness	Developing	Advanced
Success probability	45-55%	55-65%

Table 2: Odisha versus Liaoning Comparison

Key Insight: Odisha possesses superior natural advantages (iron ore, lower costs) but faces greater infrastructure and governance challenges than Liaoning. Success depends on sustained private sector investment and state government effectiveness—less certain than China's coordinated approach.

3.3 Jharkhand: Environmental Pressure and Transformation Urgency (Parallel: Hebei)

3.3.1 Strategic Position and Challenge Scale

Jharkhand represents India's most environmentally stressed steel-producing state, analogous to China's Hebei Province:

Production Profile:

- Annual capacity: 18-20 Mt (13-15% of India's total)
- Current technology: 70% BF-BOF, 30% DRI-EAF
- Major producers: Tata Steel (Jamshedpur legacy plant), SAIL (Bokaro), smaller integrated mills
- Annual emissions: 40-45 Mt CO_2
- Direct employment: 100,000-120,000 workers

The Quadruple Crisis (paralleling Hebei):

1. **Air Quality Emergency:** Cities like Jamshedpur and Bokaro frequently exceed PM2.5 and PM10 standards by 2-3x, with steel contributing significantly
2. **Economic Dependency:** Steel and related industries contribute 25-30% of state GDP

3. **Technology Lock-in:** Aging BF infrastructure (some facilities 40-50 years old at SAIL Bokaro)
4. **Social Stability Risk:** Capacity transformation threatens 30,000-40,000 direct jobs in a state with limited alternative employment

3.3.2 Transformation Strategy

Unlike China's Hebei with its well-funded hydrogen demonstration (HBIS Zhangjiakou), Jharkhand faces constrained resources:

Phase 1 (2025-2028): Survival and Stabilization

- Ultra-low emissions retrofitting: 8-10 Mt capacity (matching basic air quality standards)
- Modest EAF expansion: 2-3 Mt capacity addition
- Energy efficiency improvements: Waste heat recovery, process optimization
- Investment: 12,000-18,000 crore ($1.4-2.2 billion)—lower per tonne than Odisha due to retrofitting focus

Phase 2 (2028-2035): Technology Transition

- BF-BOF capacity reduction: 5-7 Mt (approximately 30-35% of current BF capacity)
- CCUS retrofit: 3-4 Mt capacity (utilizing coal gasification infrastructure)
- H2-DRI pilot: 1-2 Mt (dependent on national hydrogen infrastructure)
- EAF expansion: Additional 4-5 Mt
- Investment: 45,000-65,000 crore ($5.4-7.8 billion)

Technology Pathway:

Unlike Hebei's hydrogen-centric approach, Jharkhand will rely more heavily on:

- **CCUS on existing BF-BOF:** Leveraging existing coal infrastructure and potential CO_2 utilization in coal seam methane extraction
- **Progressive EAF expansion:** As national scrap availability grows
- **Limited H2-DRI:** Only if national hydrogen pipeline infrastructure extends to Jharkhand (currently uncertain)

3.3.3 Critical Challenges and Risks

Jharkhand faces more severe challenges than Hebei:

1. **Weaker Enforcement Capacity:** State Pollution Control Board less resourced and effective than Hebei's environmental authorities. Historical non-compliance by some producers.
2. **Limited Fiscal Resources:** State government cannot provide subsidies at scale comparable to Hebei's 200-300 billion allocation. Must rely on central government schemes and private capital.
3. **Older Asset Base:** Significant portion of capacity approaching end-of-life, requiring either major retrofit investment or retirement—neither financially attractive to owners.
4. **Scrap Shortage:** Jharkhand generates less industrial scrap than coastal states, limiting EAF expansion potential without scrap imports.

5. **Renewable Energy Deficit:** Limited solar/wind potential compared to Odisha or Gujarat, making green hydrogen production locally uneconomical.

Risk Assessment: 35-45% probability of achieving 30-40% emissions reduction by 2035 (versus 50-55% for Hebei). Higher risk of "locked-in" emissions from retrofitted rather than replaced infrastructure.

3.3.4 Comparison with Hebei Province

Dimension	Jharkhand, India	Hebei, China
Production scale	18-20 Mt (15% national)	225-250 Mt (23% national)
Environmental pressure	Severe (PM2.5: 80-120 μg/m^3)	Critical (PM2.5: 60-100 μg/m^3)
Transformation approach	CCUS + gradual EAF	H2-DRI + aggressive reduction
Investment capacity	60,000-80,000 crore	RMB 200-300 billion (25-30x)
H2-DRI demonstration	None currently	1.2 Mt operational (HBIS)
Policy enforcement	Weak-moderate	Very strong
Just transition funding	5,000-8,000 crore	RMB 60-90 billion
Success probability	35-45%	50-55%

Table 3: Jharkhand versus Hebei Comparison

Key Insight: Jharkhand faces Hebei-scale environmental urgency without Hebei-scale resources or enforcement capacity. Transformation will be slower, more incremental, and more dependent on retrofitting existing assets rather than revolutionary technology adoption.

3.4 Gujarat: EAF Leadership and Market Integration (Parallel: Guangdong)

3.4.1 Strategic Position and Distinctive Characteristics

Gujarat represents India's most advanced state for circular economy-based steel transformation, directly analogous to China's Guangdong Province:

Production Profile:

- Annual capacity: 12-15 Mt (9-11% of India's total)
- Current technology: **55% EAF, 45% BF-BOF** (India's highest EAF share)
- Major producers: Essar Steel (Hazira), JSW (Vijayanagar extension), multiple secondary producers
- Annual emissions: 22-26 Mt CO_2 (lowest intensity among major states)
- Direct employment: 45,000-55,000 workers

Comparative Advantages:

1. **EAF Dominance:** Already 55% EAF versus national average of 40-45%, providing 10-15 year head start on transition pathway
2. **Scrap Ecosystem:**
    - Vibrant ship-breaking industry (Alang): 5-7 Mt/year scrap generation
    - Automotive manufacturing scrap: 2-3 Mt/year (Tata, Suzuki facilities)
    - Construction and industrial scrap: 3-4 Mt/year
    - Total availability: 10-14 Mt/year (expandable to 18-22 Mt by 2030)

3. **Coastal Access:** Multiple ports (Kandla, Mundra, Hazira) enable scrap imports and finished steel exports
4. **Renewable Energy Leadership:**
   - Solar: 10 GW installed (target 30 GW by 2030)
   - Wind: 9 GW installed (especially in Kutch region)
   - India's first state to achieve 100% village electrification
   - Aggressive renewable energy PPAs for industrial consumers
5. **Industrial Diversification:** Lower steel sector GDP dependency (8-12%) reduces political resistance to transformation

3.4.2 Transformation Strategy: EAF-Centric Circular Economy

Gujarat pursues a scrap-based pathway closely paralleling Jiangsu/Guangdong in China:

Phase 1 (2025-2028): EAF Expansion

- Retire: 2-3 Mt oldest BF-BOF capacity
- Add: 4-5 Mt new EAF capacity (net addition 2 Mt)
- Target EAF share: 65-70%
- Scrap processing infrastructure: 3,000-5,000 crore investment in sorting, cleaning, logistics
- Renewable PPAs: 15-20 TWh annually for steel sector
- Investment: 18,000-25,000 crore ($2.2-3.0 billion)

Phase 2 (2028-2035): Circular Economy Integration

- Further BF-BOF reduction: 3-4 Mt
- Additional EAF: 6-8 Mt
- Target EAF share: 80-85% (among India's highest)
- Closed-loop partnerships: Automotive OEMs, ship-breaking standardization
- Renewable electricity: 40-50 TWh for steel sector
- Hybrid DRI-scrap EAF: 2-3 Mt capacity (30% green H2-DRI, 70% scrap)
- Investment: 40,000-55,000 crore ($4.8-6.6 billion)

Projected Outcomes (2035):

- Capacity: 20-22 Mt (from current 13 Mt)
- Technology mix: 80-85% EAF, 10-15% CCUS-BF, 5% H2-DRI
- Emissions: 12-15 Mt CO_2 (from current 24 Mt)
- Emissions reduction: 40-50% despite 50% production growth
- Emissions intensity: 0.6-0.7 t CO_2/t steel (versus current 1.85)

Technology & Location	Capital (/tonne)	Operating (/tonne)	Total LCOS (/tonne)
Gujarat - EAF (grid mix)	26,000	28,000	54,000
Gujarat - EAF (renewable)	28,000	29,500	57,500
Gujarat - H2-DRI	70,000	33,000	103,000
Odisha - H2-DRI	68,000	30,000	98,000
Jharkhand - CCUS-BF	42,000	38,000	80,000
China Jiangsu - EAF	29,000	31,000	60,000
China Guangdong - EAF	30,000	32,500	62,500

Table 4: Levelized Cost of Steel Comparison (2030 Projections, 85 = $1)

3.4.3 Cost Competitiveness Analysis

Gujarat's EAF pathway offers India's most economically attractive transformation:

Key Insights:

- Gujarat EAF achieves LCOS competitive with Chinese coastal provinces
- 45-50% cost advantage over H2-DRI routes
- Even renewable-powered EAF (57,500) substantially cheaper than any hydrogen route
- Lower capital intensity (26,000-28,000 vs 68,000-70,000 for H2-DRI) critical in capital-constrained India

3.4.4 Green Steel Market Leadership

Gujarat positions itself as India's green steel export hub, leveraging CBAM compliance:

Target Markets:

1. **EU Exports (CBAM-driven):**
    - Current steel exports to EU: 1.5-2.0 Mt/year (primarily specialty products)
    - CBAM implementation (2026-2034) creates 30-50% cost penalty for carbon-intensive steel
    - Gujarat's low-carbon EAF steel: **0.6-0.8 t CO_2/t versus 2.0-2.2 t for conventional Indian BF**
    - Potential CBAM cost advantage: 3,000-5,000/t ($35-60/t at €80/t CO_2)
    - Target: 4-5 Mt EU exports by 2030 (from current 1.5-2.0 Mt)
2. **Domestic Premium Markets:**
    - Automotive: Partnerships with Tata Motors, Maruti Suzuki for low-carbon steel
    - Construction: Mumbai/Bangalore/Pune high-end projects with sustainability mandates
    - Renewable energy: Wind turbine towers, solar mounting structures
3. **Green Steel Certification:**
    - EPD (Environmental Product Declaration) adoption leadership
    - ResponsibleSteel certification pursuit

- SteelZero commitments from downstream customers

3.4.5 Comparison with Guangdong Province

Dimension	Gujarat, India	Guangdong, China
EAF share (current)	55%	70%
Production scale	12-15 Mt	40 Mt
Scrap availability	10-14 Mt/year	30-35 Mt/year
Renewable energy	19 GW (solar+wind)	25 GW (solar+wind)
LCOS (EAF renewable)	57,500 ($675)	RMB 5,000 ($690)
Export orientation	High (15-20% exports)	High (10-15% exports)
Market integration	Advanced automotive	Leading automotive/electronics
Success probability	65-70%	70-75%

Table 5: Gujarat versus Guangdong Comparison

Key Insight: Gujarat demonstrates that EAF-centric transformation can achieve deep decarbonization while supporting production growth, with economics superior to hydrogen routes. This pathway is most replicable for other emerging economies with scrap availability and renewable energy access.

3.5 Chhattisgarh: Coal Infrastructure Challenges (Parallel: Shanxi)

3.5.1 Strategic Context and Production Profile

Chhattisgarh represents India's coal-dependent steel production base, directly analogous to China's Shanxi Province:

Production Characteristics:

- Annual capacity: 15-18 Mt (11-13% of India's total)
- Current technology: 40% BF-BOF, **60% coal-based DRI-EAF** (India's highest DRI share)
- Major producers: SAIL (Bhilai), JSP, multiple coal-based DRI plants
- Annual emissions: 36-42 Mt CO_2 (high intensity due to coal-DRI)
- Direct employment: 70,000-85,000 workers

Coal Infrastructure Lock-in:

1. **Coal Abundance:** Chhattisgarh possesses 17-18% of India's coal reserves, creating strong path dependency
2. **Coal-based DRI Dominance:** Approximately 15-18 DRI plants using coal gasification, with recent capital investment (5-10 years old)
3. **Thermal Power Integration:** Steel plants often co-located with coal power plants for captive electricity
4. **Political Economy:** Coal mining employs 150,000-200,000 workers; steel transformation intersects with coal transition politics

3.5.2 Transformation Challenges

Chhattisgarh faces India's most complex transformation challenge, paralleling Shanxi's difficulties:

Technical Challenge: Coal-DRI to H2-DRI Conversion

- Current coal-DRI emissions: 2.5-3.0 t CO_2/t steel (versus 2.0-2.2 for BF-BOF)
- **Conversion difficulty:** Coal gasification infrastructure not readily adaptable to hydrogen
- Two pathways considered:
  1. **CCUS on coal-DRI:** Capture CO_2 from coal gasification ($60-80/t capture cost)
  2. **Replace coal-DRI with H2-DRI:** Requires complete plant retirement and rebuild

Economic Challenge:

- Recent coal-DRI investments (15,000-25,000 crore in past 5-7 years) create stranded asset risk
- Green hydrogen production locally uncompetitive (limited solar/wind, must import H2)
- CCUS capture costs ($60-80/t) + transport/storage ($20-30/t) = 7,000-9,000/t steel
- Owners face choice: operate inefficiently for 15-20 years (asset life), or write off recent investments

3.5.3 Proposed Transformation Strategy

Phase 1 (2025-2030): CCUS Retrofitting and Efficiency

- CCUS pilot: 2-3 Mt coal-DRI capacity (1-2 plants)
- CO_2 utilization: Industrial gas, enhanced oil recovery in nearby fields
- Efficiency improvements: Reduce coal consumption 10-15% through process optimization
- Renewable electricity substitution: Replace 20-30% captive thermal power with solar PPAs
- Investment: 20,000-30,000 crore ($2.4-3.6 billion)

Phase 2 (2030-2040): Gradual Asset Turnover

- Retire oldest coal-DRI plants (8-10 Mt capacity) as they reach end-of-life
- Replace with: 50% H2-DRI (if hydrogen costs decline sufficiently), 50% scrap-EAF
- Expand CCUS: 5-7 Mt capacity with CO_2 pipeline infrastructure
- Investment: 65,000-90,000 crore ($7.8-10.8 billion)

Projected Outcomes (2040):

- Capacity: 18-20 Mt (modest growth from current 16 Mt)
- Technology: 25% CCUS coal-DRI, 25% H2-DRI, 30% scrap-EAF, 20% CCUS-BF
- Emissions: 22-28 Mt CO_2 (from current 38 Mt)
- Emissions reduction: 30-40% (India's slowest transformation)
- Emissions intensity: 1.2-1.4 t CO_2/t (versus current 2.4)

3.5.4 Critical Risks and Political Economy

Risk Factors:

1. **Stranded Assets (Very High Risk):** 15,000-25,000 crore recent coal-DRI investments could become economically unviable if carbon pricing strengthens

2. **Political Resistance (High Risk):** Coal mining employment (150,000-200,000) creates political opposition to aggressive transformation
3. **Technology Uncertainty (Medium-High Risk):** CCUS on coal-DRI not yet demonstrated at commercial scale in India
4. **Hydrogen Import Dependency (Medium Risk):** Local green H2 production uneconomical; requires pipeline from Rajasthan/Gujarat (1,000+ km)

Comparison with Shanxi Province:

Dimension	Chhattisgarh, India	Shanxi, China
Coal dependency	Very high (60% coal-DRI)	Very high (coal + BF-BOF)
Production scale	15-18 Mt	60 Mt
Recent investment	15,000-25,000 crore	RMB 100-150 billion
Transformation approach	CCUS + gradual turnover	CCUS + some H2-DRI
Political sensitivity	Extreme (coal employment)	Extreme (coal + steel jobs)
CCUS infrastructure	Minimal (pilot only)	Developing (5-10 Mt)
Success probability	30-40% (slowest)	40-50%
Stranded asset risk	Very high	High

Table 6: Chhattisgarh versus Shanxi Comparison

Key Insight: Chhattisgarh demonstrates that recent capital investment in carbon-intensive technology creates powerful lock-in effects. Transformation will be slowest where stranded asset risks are highest and political opposition strongest—a cautionary lesson for other regions considering coal-based industrial expansion.

3.6 Karnataka: Scrap Availability and Coastal Integration (Parallel: Jiangsu)

3.6.1 Strategic Position

Karnataka represents an emerging EAF hub leveraging scrap generation and coastal access:

Production Profile:

- Annual capacity: 8-10 Mt (6-7% of India's total)
- Current technology: 55% BF-BOF, 45% EAF
- Major producers: JSW Steel (Vijayanagar/Toranagallu), multiple secondary producers
- Annual emissions: 17-20 Mt CO_2
- Direct employment: 35,000-45,000 workers

Comparative Advantages (parallel to Jiangsu):

1. **Scrap Ecosystem:**
   - Bangalore automotive/aerospace manufacturing: 2-3 Mt/year scrap
   - Construction/demolition (Bangalore, Mysore): 1.5-2.5 Mt/year
   - Industrial manufacturing: 1-2 Mt/year
   - Total: 5-7 Mt/year (expandable to 10-12 Mt by 2030)
2. **Coastal Access:** New Mangalore Port enables scrap imports and exports (though less developed than Gujarat's ports)

3. **High-Value Manufacturing Integration:** Aerospace, automotive, electronics sectors create demand for specialty steels and close supply chain relationships
4. **Renewable Energy:** 20+ GW solar+wind potential, aggressive state RE policies

3.6.2 Transformation Strategy

Phase 1-2 (2025-2035): EAF Expansion

- Retire: 3-4 Mt BF-BOF capacity
- Add: 6-8 Mt EAF capacity
- Target EAF share: 70-75% (from current 45%)
- Scrap processing: 2,000-3,500 crore investment
- Renewable PPAs: 20-25 TWh for steel sector
- Investment: 35,000-50,000 crore ($4.2-6.0 billion)

Projected Outcomes (2035):

- Capacity: 12-14 Mt (40% growth)
- EAF share: 70-75%
- Emissions: 10-12 Mt CO_2 (40-45% reduction despite production growth)
- Emissions intensity: 0.8-0.9 t CO_2/t

Success Probability: 60-65%, slightly lower than Gujarat due to less developed port infrastructure and smaller scrap base, but following proven EAF expansion pathway.

3.7 State Comparison and Strategic Insights

3.7.1 Divergent Pathways Synthesis

India's state-level transformation strategies demonstrate necessary adaptation to local conditions:

State	Capacity (Mt)	Primary Pathway	Secondary Pathway	Chinese Parallel
Odisha	25-28	H2-DRI (25%)	CCUS (20%)	Liaoning
Jharkhand	18-20	CCUS (25%)	EAF (30%)	Hebei
Gujarat	12-15	EAF (60%)	H2-DRI (15%)	Guangdong
Chhattisgarh	15-18	CCUS (40%)	Gradual turnover	Shanxi
Karnataka	8-10	EAF (50%)	H2-DRI (15%)	Jiangsu
Others	45-50	Mixed	–	Various
National	**130-140**	**Distribution: H2-DRI 18% CCUS 25% EAF 40% Conventional 17%**		

Table 7: India State Technology Specialization (2035 Projection)

3.7.2 Critical Insights for National Policy

1. No One-Size-Fits-All Approach:

- Like China, India requires differentiated state strategies
- Gujarat/Karnataka EAF pathway: Most economically attractive, fastest deployment
- Odisha H2-DRI pathway: Highest long-term potential but technology/cost risk
- Jharkhand/Chhattisgarh CCUS pathway: Necessary but slowest, managing legacy assets

2. Capital Allocation Priorities:

- **Highest ROI:** Gujarat, Karnataka EAF expansion (28,000-30,000/t LCOS)
- **Strategic Importance:** Odisha H2-DRI demonstration (future technology leadership)
- **Social Necessity:** Jharkhand just transition programs (preventing instability)
- **Cautious Investment:** Chhattisgarh CCUS (high stranded asset risk)

3. Inter-State Synergies (paralleling China):

- **Odisha → Jharkhand/Chhattisgarh:** Potential hydrogen pipeline (600-800 km)
- **Gujarat → Karnataka:** Scrap trading network, technology sharing
- **Renewable Energy Corridors:** Rajasthan/Gujarat solar → Chhattisgarh/Jharkhand via green hydrogen

4 Technology Pathways and Economics

4.1 Hydrogen Direct Reduced Iron (H2-DRI) in India

4.1.1 Technical Approach and Current Status

India's H2-DRI development lags China's HBIS Zhangjiakou demonstration but shows emerging momentum:

Current Demonstrations:

- **JSW Steel - Vijayanagar (announced 2024):** Plans for 0.5 Mt H2-DRI pilot by 2027-2028, utilizing mix of grey and green hydrogen
- **Tata Steel - Kalinganagar (feasibility study):** Evaluating 1.0-1.5 Mt H2-DRI by 2028-2030
- **ArcelorMittal Nippon Steel (AMNS):** Exploring H2-DRI options for Gujarat facility

Technology Approach:

- Shaft furnace DRI technology adapted from natural gas-based systems
- Hydrogen source (Phase 1): Grey hydrogen from industrial by-products, coke oven gas
- Hydrogen source (Phase 2): Green hydrogen from dedicated solar/wind electrolysis
- Target metallization: 92-95%
- Integration: DRI fed to electric arc furnaces for steelmaking

4.1.2 Economic Analysis

Levelized Cost of Steel (LCOS) for H2-DRI (2030 Projection):

Cost Component	Odisha (/t)	Gujarat (/t)	Jharkhand (/t)	China Hebei (/t equiv.)
Capital (annualized)	68,000	70,000	75,000	85,000
Green hydrogen	27,000	30,000	35,000	30,000
Iron ore pellets	14,000	14,500	13,500	15,000
Electricity (EAF)	8,000	8,500	9,500	9,000
Other operating	6,000	6,500	7,000	7,500
Total LCOS	**98,000**	**103,000**	**115,000**	**108,000**

Table 8: H2-DRI Levelized Cost Comparison (assumes green H2 at 180/kg)

Critical Cost Drivers:

1. **Hydrogen Cost Dominance:** At 180/kg (2030 target), hydrogen represents 27-30% of LCOS. Each 10/kg change in H2 price alters LCOS by 1,500/t.
2. **Sensitivity Analysis:**
    - H2 at 150/kg: LCOS = 93,000/t (Odisha)
    - H2 at 200/kg: LCOS = 103,000/t (Odisha)
    - H2 at 250/kg: LCOS = 113,000/t (Odisha) — economically unviable

3. **Capital Cost Premium:** H2-DRI requires 2.5-2.8x capital investment versus EAF (68,000-75,000 vs 26,000-30,000), creating financing challenge in capital-constrained India.

4.1.3 Critical Success Factors

Factor 1: Green Hydrogen Cost Trajectory (Probability: 40-50%)

Achieving 150-180/kg by 2030 requires:

- Renewable electricity: 2.0-2.5/kWh (achievable in Odisha, Gujarat through large-scale solar/wind)
- Electrolyzer CAPEX: 40,000-50,000/kW (from current 60,000-80,000) through manufacturing scale-up
- Capacity utilization: 4,000-5,000 hours/year (requires grid integration or hybrid RE+storage)
- National Green Hydrogen Mission subsidies: 30-50/kg in initial years

India faces greater challenges than China:

- Less developed electrolyzer manufacturing (China produces 70-80% of global electrolyzers)
- More fragmented renewable energy deployment
- Weaker grid infrastructure for large-scale electrolysis (requires dedicated RE+electrolyzer sites)
- Lower subsidy capacity than China's state-directed support

Assessment: 40-50% probability of achieving cost targets by 2030 (versus 50-60% for China), rising to 60-70% by 2035.

Factor 2: Infrastructure Development

Required by 2035 for 25-30 Mt H2-DRI capacity nationally:

- Electrolyzers: 8-12 GW capacity
- Hydrogen pipelines: 1,500-2,000 km (Rajasthan/Odisha/Gujarat → consumption centers)
- DRI-grade pellet plants: 30-35 Mt/year capacity (from current 20-25 Mt)
- Renewable energy: 40-60 GW dedicated to hydrogen production

Investment Required: 1.5-2.2 trillion ($18-26 billion) for infrastructure alone

Challenge: India's infrastructure development timelines typically 30-50% longer than China's due to land acquisition, regulatory approvals, and financing constraints.

4.2 Carbon Capture, Utilization, and Storage (CCUS)

4.2.1 India's CCUS Status and Potential

CCUS represents critical pathway for Jharkhand, Chhattisgarh, and transitional capacity elsewhere:

Current Status:

- **No commercial-scale CCUS on steel in India** (versus China's multiple pilots)
- **Limited CO_2 storage characterization:** Geological surveys incomplete

- **Utilization focus:** India emphasizes CO_2 utilization over storage due to limited offshore storage options

Potential CCUS Applications:

1. **BF-BOF Retrofit:** Capture from blast furnace top gas and BOF off-gas (70-80% capture possible)
2. **Coal-DRI Retrofit:** Capture from coal gasification (85-90% capture possible)
3. **Integrated Steel Plants:** Capture from multiple point sources with shared infrastructure

4.2.2 Economic Analysis

CCUS-BF-BOF Levelized Cost (2030):

Cost Component	Jharkhand (/t steel)	Chhattisgarh (/t steel)	China Shandong (/t equiv.)
Base BF-BOF production	42,000	43,000	40,000
CO_2 capture ($50-60/t)	9,000	9,500	8,000
Transport (100-200 km)	3,000	3,500	2,500
Storage/utilization	4,000	4,500	3,500
Additional OPEX	2,000	2,500	2,000
Total LCOS with CCUS	**60,000**	**63,000**	**56,000**
Emissions intensity	0.6 t CO_2/t	0.7 t CO_2/t	0.5 t CO_2/t

Table 9: CCUS-Equipped Steel Production Economics

Critical Challenges:

1. **CO_2 Storage Uncertainty (High Risk):**
    - India lacks extensive offshore sedimentary basins comparable to North Sea or Gulf of Mexico
    - Onshore storage faces land availability and public acceptance challenges
    - Geological characterization requires 5-10 years and 5,000-10,000 crore investment
2. **CO_2 Utilization Markets:**
    - Enhanced oil recovery (EOR): Limited potential in India's mature fields
    - Industrial gases: Market limited to 2-3 Mt CO_2/year
    - Building materials: Emerging but unproven at scale
    - Chemical feedstock: Requires additional energy input
3. **Cost Competitiveness:**
    - CCUS-BF (60,000-63,000/t) more expensive than EAF (54,000-58,000/t)
    - Only justified where BF assets are young (< 10 years) and EAF/H2-DRI not viable
    - Requires carbon pricing of 4,000-6,000/t CO_2 (40-60 per tonne) to achieve parity

Strategic Role: CCUS serves as "bridge technology" for 2030-2045 period in states with young BF-BOF assets (Chhattisgarh, parts of Jharkhand), allowing emissions reduction of 60-75% while avoiding stranded assets. Not a long-term solution for 2070 net-zero target.

4.3 Electric Arc Furnace (EAF) Expansion

4.3.1 India's EAF Advantages

EAF represents India's most economically attractive and rapidly deployable pathway:

Current Status:

- EAF+DRI share: 40-45% (versus China's 10-13%)
- Historical use of DRI-EAF route due to limited coking coal availability
- Strong secondary steel sector with EAF expertise
- Growing scrap availability from infrastructure buildout and end-of-life vehicles

Scrap Availability Projection:

Scrap Source	2024 (Mt)	2030 (Mt)	2040 (Mt)
Manufacturing scrap	12-15	20-25	35-40
End-of-life vehicles	6-8	12-15	25-30
Construction/demolition	10-12	18-22	35-45
Ship-breaking	6-7	8-10	10-12
Imports (potential)	3-5	8-12	15-20
Total Available	**37-47**	**66-84**	**120-147**
Steel production (Mt)	130	180	250
Scrap ratio (%)	28-36%	37-47%	48-59%

Table 10: India Steel Scrap Availability Projection

Key Insight: By 2030, India's scrap availability (66-84 Mt) could support 70-90 Mt EAF production, representing 40-50% of projected national capacity—significantly higher than China's 32-36% target despite lower per-capita steel stock.

4.3.2 EAF Economic Competitiveness

Comparative LCOS (2030, renewable electricity):

Location	Capital (/t)	Operating (/t)	Total (/t)	Emissions (t CO_2/t)
Gujarat EAF	28,000	29,500	57,500	0.15
Karnataka EAF	28,500	30,000	58,500	0.18
Odisha EAF	27,000	28,500	55,500	0.12
Jharkhand EAF	29,000	32,000	61,000	0.25
India Average	**28,000**	**30,000**	**58,000**	**0.18**
China Average	29,000	31,000	60,000	0.15
Comparison with other routes:				
India H2-DRI	70,000	32,000	102,000	0.20
India CCUS-BF	42,000	38,000	80,000	0.65
India Conventional BF	35,000	40,000	75,000	2.20

Table 11: EAF Competitiveness versus Alternative Routes

Strategic Advantages:

1. **Lowest LCOS:** 55,500-61,000/t versus 98,000-115,000 for H2-DRI
2. **Lowest capital intensity:** 27,000-29,000/t versus 68,000-75,000 for H2-DRI—critical in capital-constrained India
3. **Proven technology:** Minimal technology risk, established supply chains
4. **Fastest deployment:** 24-36 months project timeline versus 48-60 months for H2-DRI
5. **Low emissions:** 0.12-0.25 t CO_2/t with renewable electricity (90-95% reduction)

4.3.3 EAF Expansion Strategy and Targets

National EAF Roadmap:

	2024	2028	2032	2040	2050
EAF capacity (Mt)	55-60	75-85	95-110	130-150	170-190
% of total capacity	42-45%	45-50%	48-55%	52-60%	60-70%
Scrap input (Mt)	35-40	50-60	65-80	95-115	130-160
DRI input (Mt)	20-25	25-30	30-35	35-40	40-50
EAF emissions (Mt CO_2)	12-15	15-18	18-22	22-28	25-32

Table 12: India EAF Expansion Trajectory

Investment Requirements (2025-2040):

- EAF capacity addition: 90-100 Mt
- Capital investment: 2.5-2.8 trillion ($30-34 billion)
- Scrap collection/processing infrastructure: 30,000-45,000 crore ($3.6-5.4 billion)
- Grid upgrades: 20,000-30,000 crore ($2.4-3.6 billion)
- Renewable energy PPAs: 80,000-120,000 crore ($9.6-14.4 billion)
- **Total: 3.6-4.2 trillion ($43-50 billion)**

4.4 Technology Portfolio Recommendations

Prioritization Matrix for India:

Technology	Economic Viability	Deployment Speed	Emissions Reduction	Strategic Priority
EAF Expansion	**Excellent** (55-61k/t)	**Fast** (2-3 years)	**85-95%** (0.1-0.3 tCO_2)	**Highest** (60% capacity)
H2-DRI (Odisha)	Promising (98-105k/t)	Moderate (4-5 years)	85-90% (0.2-0.3 tCO_2)	High (Pilot+scale)
CCUS-BF	Challenging (60-65k/t)	Slow (5-7 years)	60-75% (0.5-0.8 tCO_2)	Medium (Bridge tech)
CCUS-DRI	Very Difficult (68-75k/t)	Very Slow (6-8 years)	70-80% (0.4-0.6 tCO_2)	Low (Limited cases)

Table 13: Technology Prioritization for India

Recommended National Strategy:

1. **Foundation (60% investment): EAF Expansion**
    - Deploy 60-70 Mt additional EAF capacity by 2035
    - Focus in Gujarat, Karnataka, Odisha, Maharashtra
    - Leverage lowest cost, fastest deployment, proven technology
2. **Strategic (25% investment): H2-DRI Demonstration**
    - 5-8 Mt pilot capacity in Odisha by 2030
    - Prove technology and build supply chains
    - Position for post-2035 scaling if hydrogen costs decline
3. **Bridge (15% investment): Selective CCUS**
    - 8-12 Mt CCUS retrofits in Jharkhand/Chhattisgarh
    - Manage stranded asset risk on young BF-BOF capacity
    - Buy time for EAF/H2-DRI scaling

Comparison with China: China invests more heavily in H2-DRI (25% of strategy) due to greater hydrogen infrastructure and state-directed capital. India's market-driven, capital-constrained context favors EAF emphasis (60% versus China's 40%), accepting slower long-term decarbonization for more certain near-term economics.

5 Economic Analysis and Investment Requirements

5.1 National Investment Needs (2025-2040)

Comprehensive Investment Estimate:

Investment Category	Amount (crore)	US Dollar (Billion)
Production Technology:		
EAF capacity addition	250,000-280,000	30-34
H2-DRI capacity	120,000-150,000	14-18
CCUS retrofits	50,000-70,000	6-8
BF-BOF efficiency upgrades	30,000-40,000	3.5-5
Subtotal Production	**450,000-540,000**	**54-65**
Infrastructure:		
Scrap collection/processing	30,000-45,000	3.6-5.4
Grid upgrades	20,000-30,000	2.4-3.6
Hydrogen pipelines	25,000-35,000	3.0-4.2
CO_2 transport/storage	15,000-25,000	1.8-3.0
Port/logistics	10,000-15,000	1.2-1.8
Subtotal Infrastructure	**100,000-150,000**	**12-18**
Enabling Investments:		
Renewable energy (dedicated)	80,000-120,000	9.6-14.4
Electrolyzers	35,000-50,000	4.2-6.0
R&D and pilots	10,000-15,000	1.2-1.8
Skills/training	5,000-8,000	0.6-1.0
Just transition programs	20,000-30,000	2.4-3.6
Subtotal Enabling	**150,000-223,000**	**18-27**
TOTAL INVESTMENT	**700,000-913,000**	**84-110**

Table 14: India Steel Decarbonization Investment (2025-2040)

Annual Investment Pace:

- 2025-2030: 25,000-35,000 crore/year ($3-4 billion/year)
- 2030-2035: 45,000-60,000 crore/year ($5.4-7.2 billion/year)
- 2035-2040: 50,000-70,000 crore/year ($6-8.4 billion/year)

5.2 Financing Mechanisms and Capital Mobilization

India faces greater financing challenges than China due to more constrained public capital and less developed green finance:

5.2.1 Public Sector Financing

Central Government Mechanisms:

- **National Green Hydrogen Mission:** 19,744 crore allocated (2023-2030), insufficient for steel sector alone

- **Production-Linked Incentives (PLI):** Potential extension to green steel (20,000-30,000 crore)
- **National Investment and Infrastructure Fund (NIIF):** 40,000 crore corpus, can co-invest in steel infrastructure
- **Sovereign Green Bonds:** 8,000 crore issued in 2023, scalable to 25,000-40,000 crore/year

State Government Mechanisms:

- Capital subsidies: 15-25% of project cost for priority investments (Odisha, Gujarat models)
- Land at concessional rates
- Electricity duty waivers for renewable-powered facilities
- Accelerated depreciation allowances

Estimated Public Contribution: 20-30% of total investment (140,000-270,000 crore)

5.2.2 Private Sector Financing

Corporate Balance Sheets:

- Major producers (Tata Steel, JSW, SAIL, JSPL) combined EBITDA: 60,000-80,000 crore/year
- Debt capacity: 2-3x EBITDA = 120,000-240,000 crore
- Equity raising: 30,000-50,000 crore feasible through rights issues/QIPs
- **Challenge:** Recent sector profitability pressures (net margins 2-4%) constrain self-financing

Commercial Bank Lending:

- Project finance: 60-70% debt typical for steel projects
- Green finance norms requiring climate risk assessment
- Interest rates: 9-11% for investment-grade borrowers
- **Challenge:** Banks' steel sector exposure limits (10-15% of loan book typically)

Estimated Private Contribution: 50-60% of total investment (350,000-550,000 crore)

5.2.3 International Financing

Multilateral Development Banks:

- **Asian Development Bank (ADB):** Energy Transition Mechanism, potential 20,000-30,000 crore
- **World Bank/IFC:** Green financing facility, 15,000-25,000 crore
- **New Development Bank (BRICS):** Infrastructure focus, 10,000-15,000 crore

Bilateral Climate Finance:

- EU-India partnerships (Green Deal alignment): €2-3 billion potential
- US DFC (Development Finance Corporation): $1-2 billion
- Japan JBIC (Japan Bank for International Cooperation): $1.5-2.5 billion

Green Bonds and Climate Funds:

- International green bond markets: 40,000-60,000 crore potential

- Climate Investment Funds: 8,000-12,000 crore
- Sovereign wealth fund co-investments: 15,000-25,000 crore

Estimated International Contribution: 15-20% of total investment (105,000-180,000 crore)

5.3 State-Level Investment Distribution

State	Total Investment (crore)	Per Tonne (/t capacity)	Primary Technology	Success Probability
Odisha	120,000-180,000	42,000-65,000	H2-DRI	45-55%
Gujarat	80,000-120,000	55,000-80,000	EAF	65-70%
Jharkhand	100,000-150,000	50,000-75,000	Mixed	35-45%
Chhattisgarh	90,000-130,000	50,000-72,000	CCUS	30-40%
Karnataka	60,000-90,000	50,000-75,000	EAF	60-65%
Others	250,000-343,000	Varied	Mixed	40-55%
National	**700,000-1,013,000**	**48,000-70,000**	**Portfolio**	**45-55%**

Table 15: State-Level Investment Requirements and Risk Assessment

5.4 Comparison with China's Investment Scale

Dimension	India	China
Total investment (2025-2040)	$84-110 billion	$280-350 billion
Per tonne capacity	$580-785/t	$260-330/t
% of sector revenue (annual)	8-12%	6-9%
Public sector share	20-30%	40-50%
Private sector share	50-60%	35-45%
International finance	15-20%	5-10%
Financing challenge	**High**	**Moderate**

Table 16: India-China Investment Comparison

Key Insights:

1. **Absolute Scale:** India's $84-110 billion is 30-35% of China's $280-350 billion, but represents *higher* burden relative to sector revenue and fiscal capacity
2. **Per-Tonne Intensity:** India's $580-785/t is 2-3x China's $260-330/t because:
   - Higher capital costs in India
   - Less economies of scale
   - More expensive international technology licensing
   - Lower state subsidy offsetting capital requirements
3. **Financing Mix:** India must rely more heavily on private capital (50-60% vs China's 35-45%) and international finance (15-20% vs 5-10%), creating greater execution risk
4. **Timeline Implications:** Financial constraints likely extend India's transformation timeline 5-8 years beyond China's, even for equivalent technology pathways

6 Social Dimensions and Just Transition

6.1 Employment Impact Assessment

6.1.1 Direct Steel Sector Employment

Current Employment (2024):

- Direct steel production workers: 450,000-500,000
- Ancillary services (logistics, maintenance, administration): 150,000-180,000
- Total direct steel employment: 600,000-680,000

Employment by State:

State	Direct Steel Workers	Ancillary Services	Total Employment
Jharkhand	100,000-120,000	35,000-40,000	135,000-160,000
Odisha	80,000-100,000	28,000-35,000	108,000-135,000
Chhattisgarh	70,000-85,000	25,000-30,000	95,000-115,000
Gujarat	45,000-55,000	15,000-20,000	60,000-75,000
Karnataka	35,000-45,000	12,000-16,000	47,000-61,000
Others	120,000-145,000	40,000-52,000	160,000-197,000
National	**450,000-550,000**	**155,000-193,000**	**605,000-743,000**

Table 17: Steel Sector Employment by State

6.1.2 Projected Job Displacement (2025-2040)

Technology-Driven Displacement:

Technology Transition	Capacity Change (Mt)	Job Intensity (per 1000t)	Jobs Displaced	Jobs Created
BF-BOF → EAF	-40 to -50	8-10 → 4-5	160,000-250,000	80,000-125,000
BF-BOF → H2-DRI	-15 to -20	8-10 → 5-6	45,000-80,000	25,000-40,000
BF-BOF → CCUS retrofit	-8 to -12	8-10 → 7-8	8,000-24,000	0-6,000
Capacity reduction	-20 to -30	8-10	160,000-300,000	0
Total			**373,000-654,000**	**105,000-171,000**
Net Displacement			**268,000-483,000**	

Table 18: Employment Displacement Projection (2025-2040)

Key Findings:

- **Net job displacement: 268,000-483,000 workers** (44-72% of current direct employment)
- **Geographic concentration:** 60-70% of displacement in Jharkhand, Chhattisgarh, Odisha
- **Timeline:** 50-60% of displacement occurs 2028-2035 (peak transformation period)
- **Skill mismatch:** New jobs require different skills (electrical, automation, hydrogen handling vs traditional blast furnace operation)

6.2 India's Just Transition Challenges vs China

Critical Differences:

Dimension	India	China
Social safety net	Weak-moderate (limited unemployment insurance, informal economy large)	Strong (comprehensive unemployment, retraining, early retirement)
Alternative employment	Limited in steel-concentrated regions	State creates alternative industries
Retraining capacity	Fragmented, underfunded	Comprehensive vocational system
Early retirement	Minimal provisions	Generous packages (80-90% salary)
Political sensitivity	Extreme (electoral consequences immediate)	High (stability priority, less electoral pressure)
Union strength	Strong in public sector, fragmented private	State-controlled, coordinated
Funding capacity	20,000-30,000 crore ($2.4-3.6B)	RMB 100-150 billion ($14-21B)

Table 19: Just Transition Capacity: India versus China

India's Greater Challenges:

1. **Weaker Social Safety Nets:** India's unemployment insurance covers only organized sector (10-15% of workforce), provides minimal benefits (5,000-8,000/month for 6-12 months), versus China's comprehensive system (70-80% wage replacement for 12-24 months)
2. **Electoral Sensitivity:** Democratic accountability makes job losses politically costly. State elections every 5 years create short-term political horizons incompatible with 15-year transformation timelines. China's longer political timelines allow sustained pressure despite short-term pain.
3. **Limited Fiscal Capacity:** Central+state governments can mobilize 20,000-30,000 crore ($2.4-3.6 billion) for just transition, versus China's RMB 100-150 billion ($14-21 billion)—a 5-7x difference
4. **Informal Economy:** 30-40% of steel-related workers in informal contracts, excluded from formal retraining/transition programs
5. **Regional Concentration:** Jharkhand, Chhattisgarh have 25-30% state GDP from steel+related industries, versus China's Hebei at 15-20%. Alternative employment creation more difficult.

6.3 Just Transition Program Framework

6.3.1 Core Program Components

1. Skills Retraining and Reskilling (8,000-12,000 crore)

- Target: 150,000-200,000 workers
- Duration: 6-18 months technical training
- Focus areas:
  - Renewable energy installation and maintenance
  - Hydrogen handling and safety
  - EAF electrical systems and automation

    - CCS operations and monitoring
    - General manufacturing and logistics
- Partnership: Industry skill councils, technical institutes
- Stipend: 15,000-20,000/month during training
- Placement support: Guaranteed interviews, relocation assistance

2. **Early Retirement Schemes (15,000-20,000 crore)**
- Eligibility: Workers age

  55+ with 25+ years service
- Benefits:
    - 60-70% of final salary until retirement age (60-65)
    - Continued medical benefits
    - Pension bridge to state pension eligibility
    - One-time separation payment: 500,000-1,000,000
- Target: 80,000-100,000 workers
- **Challenge:** Cost per worker (1.5-2.0 crore present value) 3-4x higher than China due to longer life expectancy and weaker state pension system

3. **Income Support and Transition Assistance (5,000-8,000 crore)**
- Unemployment benefits extension: 12-18 months at 50-60% salary
- Relocation assistance: 100,000-200,000 per household for job-related moves
- Microcredit for self-employment: 200,000-500,000 loans at subsidized rates
- Education scholarships for workers' children: 50,000-100,000/year
- Mental health and counseling services

4. **Regional Economic Diversification (8,000-12,000 crore)**
- Alternative industry development in steel-dependent regions:
    - Renewable energy manufacturing (solar panels, wind turbines)
    - Automotive components (leveraging existing precision manufacturing)
    - Logistics and warehousing hubs
    - Agro-processing industries
- Infrastructure investments creating temporary construction employment
- SME development funds for local entrepreneurship
- Tourism development in historically industrial areas

6.3.2 State-Specific Just Transition Strategies

Jharkhand (Highest Risk):

- Projected displacement: 35,000-50,000 direct workers (30-40% of state steel employment)

- Just transition budget: 7,000-10,000 crore
- Strategy:
  - Prioritize early retirement for 15,000-20,000 workers age 55+
  - Retrain 10,000-15,000 for EAF operations (as capacity shifts from BF to EAF)
  - Regional diversification: Renewable energy hub (solar manufacturing), leveraging existing industrial infrastructure
  - Special economic zones for alternative manufacturing
- Political challenge: State elections 2029 coincide with peak displacement period

Chhattisgarh (Stranded Asset Risk):

- Projected displacement: 25,000-40,000 workers (coal-DRI closures)
- Just transition budget: 5,000-8,000 crore
- Strategy:
  - Extend operating life of coal-DRI through CCUS retrofits (buy 10-15 years transition time)
  - Gradual workforce reduction through attrition and early retirement
  - Coal mine rehabilitation and renewable energy projects on former mining land
  - Integration with national coal transition programs (separate but coordinated funding)
- Unique challenge: Must coordinate steel transition with concurrent coal mining decline

Odisha (Growth with Transformation):

- Projected displacement: 15,000-25,000 (despite capacity growth, due to automation)
- Just transition budget: 3,000-5,000 crore
- Strategy:
  - Skills upgrading rather than displacement (workers transition to H2-DRI operations)
  - Create 20,000-30,000 new jobs in hydrogen production, renewable energy
  - Net job creation possible if transformation managed well
  - Model state for ”just transition + growth” approach

6.4 Comparison with China’s Just Transition Approach

Key Insights:

1. **Scale vs Intensity:** China faces 3-4x more displaced workers in absolute terms, but India’s challenge is more intense relative to fiscal capacity and social safety net strength
2. **Democratic Accountability:** India’s electoral cycles create political incentives to delay painful transitions, whereas China can impose short-term costs for long-term goals
3. **Funding Gap:** India’s just transition programs are underfunded by 50-70% relative to need, versus China’s 20-30% gap

Element	India Approach	China Approach
Total affected workers	268,000-483,000	800,000-1,200,000
Per-worker support	40,000-60,000 ($5,000-7,000)	RMB 120,000-180,000 ($17,000-25,000)
Early retirement	60-70% salary, limited duration	80-90% salary, full until retirement
Retraining programs	Fragmented, 6-18 months	Comprehensive, 12-24 months
Alternative employment	Market-driven, limited support	State-created industries
Political management	Electoral vulnerability, protests likely	Stability priority, protests contained
Implementation timeline	2025-2040 (15 years)	2025-2035 (10 years, more compressed)
Success probability	35-45% (full implementation)	55-65%

Table 20: Just Transition: India versus China

4. **Regional Concentration Risk:** Both countries face extreme concentration in specific regions (India: Jharkhand/Chhattisgarh; China: Hebei/Shanxi), but India's weaker regional economic diversification capacity increases social instability risk

6.5 Social Stability Risks and Mitigation

High-Risk Scenarios:

1. **Labor Unrest (Probability: 40-50%):**
   - Mass layoffs without adequate support trigger strikes, protests
   - Particularly acute in Jharkhand 2028-2032 (peak displacement period coinciding with state elections)
   - Precedent: 2015-2017 demonetization protests, 2020-2021 farmer protests demonstrate mobilization capacity
   - Mitigation: Gradual timelines, generous early retirement, proactive communication
2. **Political Backlash (Probability: 50-60%):**
   - Opposition parties campaign against "job-killing green policies"
   - State governments delay implementation to avoid electoral costs
   - Central-state coordination breaks down
   - Mitigation: Bipartisan consensus-building, linking transformation to job creation in new sectors
3. **Inadequate Support Implementation (Probability: 45-55%):**
   - Retraining programs fail to secure meaningful employment
   - Early retirement funds exhausted, leaving workers without support
   - Regional diversification investments delayed or diverted
   - Mitigation: Ring-fenced funding, independent oversight, regular audits

Critical Success Factor: India's steel decarbonization ultimately depends as much on effective just transition management as on technology deployment. Unlike China, where social stability can be maintained through state control, India requires genuine social license through worker support—making just transition the binding constraint on transformation speed.

7 International Context: CBAM and Export Competitiveness

7.1 EU Carbon Border Adjustment Mechanism (CBAM)

7.1.1 CBAM Implementation Timeline and Impact

The EU's Carbon Border Adjustment Mechanism represents a critical external driver for India's steel decarbonization:

CBAM Timeline:

- **2023-2025: Reporting Phase** — Steel exporters report embedded emissions, no financial impact
- **2026-2030: Phase-in Period** — CBAM charges begin, phasing from 0% (2026) to 100% (2030) as EU ETS free allowances phase out
- **2030-2034: Full Implementation** — Full carbon pricing on imports, no free allowances
- **2034+: Scope Expansion** — Potential extension to downstream products (machinery, vehicles, consumer goods)

CBAM Carbon Pricing Assumptions:

- 2026: €50-60/t CO_2 (4,500-5,400/t)
- 2028: €70-80/t CO_2 (6,300-7,200/t)
- 2030: €90-100/t CO_2 (8,100-9,000/t)
- 2035: €120-140/t CO_2 (10,800-12,600/t)

7.1.2 Impact on Indian Steel Exports

Current Export Profile:

- Total steel exports: 6-8 Mt/year (4-6% of production)
- EU exports: 2.0-2.5 Mt/year (25-35% of total exports)
- Products: Flat products (hot-rolled coil, cold-rolled), long products (rebar, structural steel), specialty steels
- Export value: 25,000-35,000 crore/year ($3-4.2 billion)

CBAM Cost Impact (2030 Full Implementation):

Production Route	Emissions (t CO_2/t)	CBAM Cost (/t)	% of Price	Export Viability
Conventional BF-BOF	2.0-2.2	18,000-20,000	35-40%	**Non-viable**
CCUS-equipped BF	0.6-0.8	5,400-7,200	10-15%	Marginal
Coal-based DRI-EAF	2.3-2.6	21,000-23,000	40-45%	**Non-viable**
Gas-based DRI-EAF	1.2-1.4	10,800-12,600	20-25%	Challenging
H2-DRI-EAF	0.2-0.3	1,800-2,700	3-5%	Competitive
Scrap-EAF (renewable)	0.1-0.2	900-1,800	2-3%	**Highly competitive**
Assumes EU carbon price of €100/t CO_2 (9,000), typical export price 50,000/t				

Table 21: CBAM Impact on Indian Steel Export Economics (2030)

Critical Findings:

1. **Conventional Routes Become Non-Viable:** BF-BOF and coal-DRI steel faces 35-45% price penalty, eliminating export competitiveness
2. **Green Steel Gains Competitive Advantage:** H2-DRI and scrap-EAF routes face only 2-5% CBAM costs, creating **15,000-20,000/t ($180-240/t) cost advantage** over conventional steel
3. **Transformation Becomes Commercially Driven:** CBAM converts decarbonization from cost burden to competitive necessity for export-oriented producers
4. **State Differentiation Amplifies:** Gujarat and Odisha (leading EAF/H2-DRI) capture EU export opportunities, while Jharkhand and Chhattisgarh lose export markets

7.2 Export Strategy Under CBAM

7.2.1 Scenario Analysis: Export Evolution

Baseline Scenario (No Transformation):

- EU exports decline from 2.0-2.5 Mt (2024) to 0.3-0.5 Mt (2030)
- Revenue loss: 20,000-28,000 crore/year
- Market share captured by: Turkey (lower emissions intensity), Japan/Korea (CCUS-equipped), China (state-subsidized green steel)

Transformation Scenario (Successful Green Steel):

- EU exports expand from 2.0-2.5 Mt (2024) to 4.0-6.0 Mt (2035)
- Revenue: 50,000-75,000 crore/year
- Product mix shift: Higher-value specialty steels, automotive grades, premium construction steel
- Market positioning: Cost-competitive green steel supplier leveraging India's low renewable energy costs

7.2.2 State-Level Export Strategies

Gujarat (EAF Leadership):

- Target: 2.5-3.5 Mt EU exports by 2030 (from current 0.6-0.8 Mt)
- Strategy:
  - Leverage existing EAF infrastructure and scrap availability
  - Rapid renewable energy PPAs (target: 100% renewable electricity by 2028)
  - Port infrastructure optimization (Mundra, Hazira)
  - Quality upgrades for automotive/construction grades
- Investment: 8,000-12,000 crore (quality upgrades, certifications, logistics)
- Probability of success: 65-70%

Odisha (H2-DRI Demonstration):

- Target: 1.0-1.5 Mt EU exports by 2032-2035 (premium green steel)
- Strategy:

  - Position as ultra-low-carbon steel producer (<0.3 t CO_2/t)
  - Target premium segments: Aerospace, high-end automotive, renewable energy equipment
  - Premium pricing: 10-15% above conventional steel justified by carbon advantage
  - Partnerships with EU manufacturers seeking supply chain decarbonization
- Investment: 5,000-8,000 crore (H2-DRI pilot, quality systems, marketing)
- Probability of success: 45-55% (dependent on H2 cost trajectory)

Karnataka (Specialty Steel):

- Target: 0.8-1.2 Mt EU exports by 2030-2032
- Strategy:
  - Focus on specialty alloys and high-strength steels
  - Leverage Bangalore aerospace/automotive linkages for technical capability
  - EAF-based production with strict quality controls
- Investment: 4,000-6,000 crore
- Probability of success: 55-60%

7.3 Comparison with China's CBAM Response

Dimension	India	China
Current EU exports	2.0-2.5 Mt/year	2.5-3.5 Mt/year
CBAM vulnerability	High (70% BF-BOF + coal-DRI)	Very high (90% BF-BOF)
Transformation speed	Moderate (capital-constrained)	Fast (state-directed)
Green steel capacity (2030)	15-20 Mt	100-120 Mt
Export strategy	Increase exports 2-3x (4-6 Mt)	Maintain/grow (4-8 Mt)
Competitive advantage	Lower labor costs, RE costs	Scale, technology leadership
Government support	Limited subsidies, market-driven	Massive subsidies, state coordination
Probability of export growth	50-60%	65-75%

Table 22: CBAM Response: India versus China

Strategic Insights:

1. **India's Relative Advantage:** Lower labor costs (30-40% below China) and potentially lower renewable energy costs (especially in Gujarat, Odisha) create competitiveness opportunity if technology gap closes
2. **China's Structural Advantage:** Massive scale and state support enable faster transformation. China targets 100-120 Mt green steel capacity by 2030 versus India's 15-20 Mt, allowing China to compete on both cost and scale
3. **Market Positioning:** India should focus on niche segments (specialty steels, premium grades) rather than competing with China on commodity steel volumes
4. **Critical Timeline:** India must achieve significant green steel capacity by 2028-2030 to capture CBAM-driven market opportunities. Delays beyond 2032 risk permanent market share loss to China, Turkey, and domestic EU production

7.4 Beyond CBAM: Global Green Steel Standards

7.4.1 Emerging Standards and Certifications

CBAM represents first-mover regulation, but global green steel ecosystem developing rapidly:

ResponsibleSteel Certification:

- Comprehensive ESG standard covering carbon emissions, labor practices, governance
- Adoption: 70+ certified sites globally, including Tata Steel (Jamshedpur), JSW (Vijayanagar)
- Market access: Increasingly required by automotive, construction, appliance manufacturers
- India's advantage: Early adoption by major producers

SteelZero Initiative:

- Corporate commitments to procure net-zero steel by 2050
- Signatories include: BMW, Volvo, Schneider Electric (collectively purchasing 10-15 Mt/year)
- Near-term targets: 50% emissions reduction by 2030
- India's challenge: Must demonstrate credible pathway to meet procurement standards

ISO 14067 Carbon Footprint Standard:

- Life-cycle assessment (LCA) methodology for product carbon footprinting
- Increasingly required for public pro

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- Near-term targets: 50% emissions reduction by 2030
- India's challenge: Must demonstrate credible pathway to meet procurement standards

ISO 14067 Carbon Footprint Standard:

- Life-cycle assessment (LCA) methodology for product carbon footprinting
- Increasingly required for public procurement and corporate supply chains
- India's gap: Limited LCA expertise and verification capacity

7.5.2 Strategic Implications for India

Certification Priority:

- Focus on Gujarat and Odisha plants for early certification
- Target 8-10 Mt certified green steel capacity by 2030
- Leverage certification for premium pricing (5-15% green premium achievable)

Supply Chain Integration:

- Partner with EU manufacturers establishing green supply chains
- Joint ventures with European steel producers for technology transfer
- Position as reliable green steel supplier for European automotive transplants in India

8 Scenario Analysis and Success Probability Assessment

8.1 Methodology for Scenario Development

This analysis employs a multi-factor assessment framework to evaluate India's steel decarbonization prospects:

Assessment Dimensions:

- Policy implementation effectiveness (30% weight)
- Technology cost reduction trajectory (25% weight)
- Capital mobilization capacity (20% weight)
- Social/political stability (15% weight)
- International competitiveness (10% weight)

Data Sources:

- Historical policy implementation rates in India (2015-2024)
- Technology cost projections from NITI Aayog, IEA, industry associations
- Investment tracking from Ministry of Steel, RBI, corporate announcements
- Social stability indicators from labor ministry, state government reports
- Export competitiveness analysis from commerce ministry, WTO data

8.2 Three Primary Scenarios

8.2.1 Scenario 1: Green Steel Leader (15-20% Probability)

Defining Conditions:

- National Green Hydrogen Mission achieves 80%+ of targets by 2030
- EAF expansion accelerates to 70-75 Mt by 2035 (versus 55-60 Mt baseline)
- Carbon pricing reaches 2,000-3,000/t CO_2 by 2030
- International climate finance mobilizes $25-35 billion for steel transition
- State-level coordination remains strong across electoral cycles

Emissions Trajectory:

Year	Production (Mt)	Emissions (Mt CO_2)	Intensity (t CO_2/t)	Reduction (from 2024)
2024	135	285	2.11	-
2030	180	270	1.50	5%
2035	220	198	0.90	30%
2040	250	138	0.55	52%
2050	280	70	0.25	75%

Table 23: Green Steel Leader Scenario Emissions Pathway

Technology Mix Evolution:

- 2030: 50% EAF, 15% H2-DRI, 20% CCUS, 15% conventional

- 2040: 60% EAF, 25% H2-DRI, 15% CCUS, 0% conventional
- 2050: 65% EAF, 30% H2-DRI, 5% CCUS, 0% conventional

Success Enablers:

- Sustained policy commitment across government changes
- Private sector capital mobilization exceeds expectations
- International partnerships accelerate technology transfer
- Social consensus on just transition enables faster transformation

8.2.2 Scenario 2: Steady Transformation (55-60% Probability)

Defining Conditions:

- National Green Hydrogen Mission achieves 60-70% of targets by 2030
- EAF expansion reaches 65-70 Mt by 2035
- Carbon pricing reaches 1,000-2,000/t CO_2 by 2030
- International climate finance mobilizes $15-20 billion
- State-level coordination moderate, some implementation delays

Emissions Trajectory:

Year	Production (Mt)	Emissions (Mt CO_2)	Intensity (t CO_2/t)	Reduction (from 2024)
2024	135	285	2.11	-
2030	175	280	1.60	2%
2035	210	231	1.10	19%
2040	240	180	0.75	37%
2050	270	135	0.50	53%

Table 24: Steady Transformation Scenario Emissions Pathway

Technology Mix Evolution:

- 2030: 45% EAF, 10% H2-DRI, 25% CCUS, 20% conventional
- 2040: 55% EAF, 15% H2-DRI, 20% CCUS, 10% conventional
- 2050: 60% EAF, 20% H2-DRI, 15% CCUS, 5% conventional

Key Characteristics:

- Moderate pace consistent with historical industrial transformation in India
- Some states (Gujarat, Odisha) outperform while others (Jharkhand, Chhattisgarh) lag
- Export competitiveness maintained for 40-50% of current EU exports
- Just transition challenges managed with moderate social disruption

8.2.3 Scenario 3: Slow Transition (20-25% Probability)

Defining Conditions:

- National Green Hydrogen Mission achieves 40-50% of targets by 2030
- EAF expansion limited to 55-60 Mt by 2035
- Carbon pricing remains below 1,000/t CO_2 through 2030s
- International climate finance mobilizes $5-10 billion only
- State-level coordination weak, significant implementation delays

Emissions Trajectory:

Year	Production (Mt)	Emissions (Mt CO_2)	Intensity (t CO_2/t)	Reduction (from 2024)
2024	135	285	2.11	-
2030	170	306	1.80	-7%
2035	200	260	1.30	9%
2040	230	230	1.00	19%
2050	260	195	0.75	32%

Table 25: Slow Transition Scenario Emissions Pathway

Technology Mix Evolution:

- 2030: 40% EAF, 5% H2-DRI, 25% CCUS, 30% conventional
- 2040: 50% EAF, 8% H2-DRI, 22% CCUS, 20% conventional
- 2050: 55% EAF, 12% H2-DRI, 18% CCUS, 15% conventional

Risk Factors:

- Policy inconsistency across electoral cycles
- Capital constraints limit investment pace
- Social resistance slows plant closures and transformation
- EU export markets largely lost to competitors

8.3 State-Level Success Probability Assessment

State	Green Steel Leader	Steady Transformation	Slow Transition	Weighted Probability
Gujarat	25%	60%	15%	65%
Odisha	20%	55%	25%	52%
Karnataka	15%	60%	25%	50%
Jharkhand	10%	45%	45%	38%
Chhattisgarh	5%	40%	55%	32%
Other States	15%	55%	30%	48%
National Average	**15%**	**53%**	**32%**	**48%**

Table 26: State-Level Scenario Probability Assessment

8.4 Critical Uncertainties and Tipping Points

Positive Tipping Points (Accelerating Transformation):

1. **Green Hydrogen Cost Breakthrough (2026-2028):** Electrolyzer costs fall faster than expected, achieving 150/kg by 2028 instead of 2030
2. **CBAM Expansion (2028-2030):** Other major markets (UK, Japan, Canada) implement similar carbon border measures, increasing export pressure
3. **Technology Leapfrog (2027-2029):** Indian companies successfully deploy next-generation DRI technology with higher efficiency
4. **Climate Finance Mobilization (2025-2027):** Global climate funds allocate $15-20 billion specifically for Indian steel transition

Negative Tipping Points (Slowing Transformation):

1. **Policy Reversal (2029 elections):** New government reduces climate ambition, slows implementation
2. **Financial Crisis (2026-2028):** Economic downturn reduces steel demand and investment capacity
3. **Social Unrest (2028-2030):** Labor protests force slowdown of plant transformations
4. **Technology Failure (2027-2029):** H2-DRI pilots encounter operational problems, delaying scaling

9 Comparative Synthesis: India versus China Models

9.1 Governance and Implementation Comparison

Dimension	India	China
Governance Structure	Federal democracy	Centralized authoritarian
Policy coordination	Complex center-state	Unified national-provincial
Implementation speed	Moderate (3-5 year lags)	Fast (1-2 year implementation)
Policy consistency	Electoral cycle impacts	Long-term consistency
Local adaptation	High state autonomy	Provincial flexibility within bounds
Transformation Approach	Market-driven + incentives	State-directed + mandates
Private sector role	Primary investor and operator	State-owned enterprises dominant
Capital allocation	Market mechanisms + subsidies	State banking system directed
Technology choice	Economic viability driven	Strategic priorities driven
International integration	High (partnerships, exports)	Moderate (technology transfer focus)
Social Dimensions	Democratic accountability	Social stability priority
Just transition	Politically mandatory	State-managed transition
Labor impact	High electoral sensitivity	Contained through state control
Compensation	Limited fiscal capacity	Generous state-funded packages
Alternative employment	Market-driven creation	State-created industries

Table 27: Governance and Implementation Model Comparison

9.2 Technology Pathway Divergence

India's EAF-Centric Pathway:

- **Rationale:** Capital efficiency, scrap availability, proven technology
- **Advantage:** Lower LCOS (55,000-61,000/t vs 98,000-115,000 for H2-DRI)
- **Scale:** 60-70% of capacity by 2050 versus 40-45% in China
- **Emissions reduction:** 85-95% with renewable electricity
- **Timeline:** Rapid deployment (2025-2035) versus gradual H2-DRI scaling

China's H2-DRI Emphasis:

- **Rationale:** Technology leadership, hydrogen infrastructure, state capital
- **Advantage:** Ultimate decarbonization potential, strategic positioning
- **Scale:** 40-50% of capacity by 2050 versus 25-30% in India
- **Emissions reduction:** 90-95% with green hydrogen
- **Timeline:** Slower initial deployment but massive scaling post-2030

Comparative Technology Economics:

9.3 Capital Mobilization and Investment Patterns

Scale and Sources:

Key Differences:

Technology	India LCOS (/t, 2035)	China LCOS (/t equiv.)	India Share (2050)	China Share (2050)
EAF (renewable)	55,000-58,000	58,000-62,000	60-70%	40-45%
H2-DRI	85,000-95,000	80,000-90,000	25-30%	40-50%
CCUS-BF	60,000-65,000	55,000-60,000	5-10%	10-15%
Conventional	75,000-80,000	70,000-75,000	0-5%	0-5%

Table 28: Comparative Technology Economics and Deployment

Investment Dimension	India	China
Total (2025-2040)	$84-110 billion	$280-350 billion
Annual average	$5.6-7.3 billion	$18.7-23.3 billion
% of sector revenue	8-12%	6-9%
Public share	20-30%	40-50%
Private share	50-60%	35-45%
International	15-20%	5-10%
Green bonds	Emerging market	Established market
Return requirements	12-15% IRR	8-10% IRR

Table 29: Capital Mobilization Comparison

1. **Risk Pricing:** India's higher capital costs (12-15% vs 8-10% IRR requirements) disadvantage capital-intensive H2-DRI routes
2. **Public Role:** China's state-directed capital enables strategic investments despite lower returns; India's market-driven approach prioritizes economic viability
3. **International Integration:** India's greater reliance on international finance (15-20% vs 5-10%) creates both opportunity (technology transfer) and risk (currency, geopolitical)
4. **Implementation Efficiency:** China's lower per-tonne investment ($260-330/t vs $580-785/t) reflects scale advantages and lower capital costs

9.4 Social Dimension Comparative Analysis

Just Transition Capacity:

Social Dimension	India	China
Workers affected	268,000-483,000	800,000-1,200,000
Per-worker support	$5,000-7,000	$17,000-25,000
Early retirement	Limited, modest benefits	Comprehensive, generous
Retraining	Fragmented, 6-18 months	Systematic, 12-24 months
Alternative jobs	Market-driven creation	State-created industries
Political management	Electoral vulnerability	Stability-focused control
Social unrest risk	High (40-50%)	Moderate (20-30%)
Funding adequacy	30-40% of need	70-80% of need

Table 30: Just Transition Capacity Comparison

Critical Implications:

- **Transformation Speed:** India's social constraints may limit pace despite technical feasibility

- **Regional Concentration:** Both countries face extreme concentration, but India's weaker regional diversification capacity increases risk
- **Political Economy:** Democratic accountability creates different incentives—short-term avoidance of pain versus China's long-term imposition of costs
- **Ultimate Outcome:** China likely achieves faster absolute emissions reduction; India potentially achieves more sustainable social outcome if managed effectively

9.5 International Competitiveness and Export Strategy

CBAM Response Comparison:

Competitiveness Dimension	India	China
Current EU exports	2.0-2.5 Mt/year	2.5-3.5 Mt/year
CBAM vulnerability	High (70% high-carbon)	Very high (90% high-carbon)
Green steel capacity (2030)	15-20 Mt	100-120 Mt
Export strategy	Niche focus, 2-3x growth	Volume maintenance, premium growth
Competitive advantage	Lower labor, potential RE costs	Scale, technology, state support
Transformation timeline	Moderate (capital-constrained)	Fast (state-directed)
Market positioning	Specialty steels, specific segments	Broad range, volume leadership
Probability of export growth	50-60%	65-75%

Table 31: International Competitiveness Comparison

Strategic Positioning:

- **India's Niche Opportunity:** Focus on specific segments where labor cost advantage and emerging green steel capability create competitive edge
- **China's Scale Advantage:** Massive capacity enables competition across broad product range, though potentially at lower margins
- **Technology Trajectory:** China's H2-DRI emphasis positions for ultimate low-cost green steel; India's EAF focus provides near-term competitiveness
- **Partnership Strategies:** India's greater openness to international partnerships may accelerate learning and market access

9.6 Overall Model Effectiveness Assessment

India's Democratic Market Model:

- **Strengths:** Adaptability, innovation potential, social feedback, international integration
- **Weaknesses:** Implementation inconsistency, capital constraints, slower decision-making
- **Suitability:** Better for incremental improvement, market-driven solutions, socially sustainable transitions
- **Success probability:** 45-55% for achieving 2040 targets

China's Authoritarian State Model:

- **Strengths:** Implementation speed, capital mobilization, long-term consistency, scale advantages

- **Weaknesses:** Innovation constraints, social tension risks, international skepticism, potential misallocation
- **Suitability:** Better for rapid transformation, capital-intensive pathways, technology leapfrogging
- **Success probability:** 55-65% for achieving 2040 targets

Hybrid Potential: India could benefit from selective adoption of China's strategic co-ordination approaches while maintaining democratic market strengths—particularly in state-level implementation and critical infrastructure development.

10 Conclusions and Strategic Recommendations

10.1 Key Findings and Conclusions

10.1.1 India's Distinctive Decarbonization Pathway

This analysis reveals that India's steel decarbonization pathway differs fundamentally from China's approach due to structural constraints and opportunities:

1. Economic Reality Drives Technology Choice:

- India's capital constraints and higher return requirements favor EAF expansion (55,000-61,000/t LCOS) over H2-DRI (98,000-115,000/t)
- This economic reality creates a more gradual, economically sustainable transformation pathway
- EAF focus leverages India's emerging scrap availability and lower labor costs

2. Federal Democracy Creates Implementation Challenges:

- State-level variation in capacity, resources, and political will produces highly divergent transformation trajectories
- Democratic accountability makes rapid, disruptive transformation politically difficult
- Social license through just transition becomes binding constraint on transformation speed

3. International Context Creates Both Pressure and Opportunity:

- CBAM threatens 35-45% of current EU exports but creates competitive advantage for green steel
- India's openness to international partnerships can accelerate technology learning
- Green steel exports represent significant economic opportunity if transformation succeeds

10.1.2 Comparative Advantage Assessment

India's Relative Strengths:

1. **EAF Expertise:** Existing 40-45% EAF/DRI share provides technology foundation and skilled workforce
2. **Scrap Trajectory:** Growing scrap availability (66-84 Mt by 2030) supports EAF expansion without dependence on imported technology
3. **Renewable Energy Costs:** Potential for among world's lowest renewable electricity costs (2.0-2.5/kWh in optimal locations)
4. **Labor Cost Advantage:** 30-40% lower labor costs than China provide competitiveness buffer during transition
5. **International Partnerships:** Greater openness to joint ventures, technology transfer, and climate finance

India's Critical Challenges:

1. **Capital Intensity:** Higher capital costs and constrained fiscal capacity limit investment pace

2. **Implementation Capacity:** Weaker regulatory enforcement and longer project timelines than China
3. **Social Transition:** More complex just transition management in democratic context with weaker safety nets
4. **Technology Risk:** Dependence on unproven-at-scale technologies (H2-DRI, CCUS) with higher risk premiums
5. **Scale Limitations:** Smaller individual projects lack China's economies of scale

10.2 Strategic Recommendations for India

10.2.1 National Policy Recommendations

1. Prioritize EAF Expansion as Foundation Strategy:

- Allocate 55-60% of public support to EAF-related investments (scrap processing, grid upgrades, quality improvements)
- Streamline approvals for EAF projects (24-36 month timeline versus 48-60 for H2-DRI)
- Target 70-75 Mt EAF capacity by 2035 (from current 55-60 Mt)
- Leverage EAF economics to drive near-term emissions reduction while building H2-DRI capability

2. Implement Differentiated State Strategies:

- **Gujarat/Karnataka:** Accelerate EAF expansion with export focus, target 80-85% EAF share by 2035
- **Odisha:** Develop as H2-DRI demonstration hub, target 25-30% H2-DRI by 2035
- **Jharkhand/Chhattisgarh:** Focus on CCUS retrofits and just transition, accept slower transformation pace
- Establish state-level transformation targets with flexibility in implementation pathways

3. Strengthen Carbon Pricing and CBAM Preparedness:

- Implement steel sector inclusion in carbon trading by 2026-2027
- Phase in carbon pricing gradually: 500-1,000/t (2026), 1,000-2,000/t (2028), 2,000-3,000/t (2030)
- Create CBAM response fund to support export-oriented green steel production
- Accelerate green steel certification (ResponsibleSteel, EPD) for major exporters

4. Enhance International Partnership Strategy:

- Target joint ventures with EU/Japanese/Korean steel producers for technology transfer
- Secure $15-20 billion in dedicated climate finance for steel transition
- Position India as green steel export hub for EU markets post-CBAM
- Participate actively in global green steel standards development

10.2.2 Investment and Financing Recommendations

1. Optimize Capital Allocation:

- **Priority 1 (60%):** EAF expansion and scrap infrastructure (highest ROI, lowest risk)
- **Priority 2 (25%):** H2-DRI demonstration and hydrogen infrastructure (strategic positioning)
- **Priority 3 (15%):** CCUS retrofits for young BF-BOF assets (bridge solution)
- Avoid major investments in new BF-BOF capacity that would create additional stranded asset risk

2. Develop Innovative Financing Mechanisms:

- Green steel transition bonds with partial government guarantees
- Blended finance structures combining commercial, development, and climate finance
- Production-linked incentives for green steel production (1,000-2,000/t for certified green steel)
- Risk-sharing facilities for first-of-a-kind technology deployments

3. Strengthen Public Finance Effectiveness:

- Ring-fence National Green Hydrogen Mission funds for steel sector applications
- Coordinate state government incentives to avoid beggar-thy-neighbor competition
- Use public funds to de-risk private investment rather than substitute for it
- Focus public investment on enabling infrastructure (grids, pipelines, ports) rather than direct production subsidies

10.2.3 Social Dimension Recommendations

1. Implement Proactive Just Transition Program:

- Establish national just transition fund with 30,000-40,000 crore initial capitalization
- Target early retirement for 80,000-100,000 workers age 55+
- Provide comprehensive retraining for 150,000-200,000 workers with placement support
- Develop regional economic diversification plans for Jharkhand, Chhattisgarh

2. Manage Transformation Timeline Realistically:

- Accept slower transformation in socially sensitive regions to maintain stability
- Sequence plant transformations to avoid concentrated regional impact
- Use CCUS retrofits to extend operating life where social impact would be severe
- Coordinate with state election cycles to minimize political disruption

3. Enhance Stakeholder Engagement:

- Establish tripartite forums (government, industry, labor) for each major steel region
- Develop plant-level transition plans with worker participation

- Create transparent monitoring and reporting on social impacts
- Build community support through local benefit sharing (infrastructure, services)

10.3 Final Comparative Assessment

10.3.1 India's Realistic Transformation Outlook

Expected Outcomes (2035):

- **Production:** 210-220 Mt (60-65% growth from 2024)
- **Emissions:** 200-230 Mt CO_2 (20-30% reduction from 2024 despite growth)
- **Technology mix:** 50-55% EAF, 10-15% H2-DRI, 20-25% CCUS, 10-15% conventional
- **Export competitiveness:** Maintain 40-60% of current EU exports through green steel production
- **Employment:** Net reduction of 200,000-300,000 direct jobs, partially offset by new jobs in green steel

Comparative Assessment with China:

- **Emissions reduction pace:** India 20-30% by 2035 vs China 40-50% (from respective baselines)
- **Economic efficiency:** India's lower-cost pathway but slower absolute reduction
- **Social sustainability:** Potentially more sustainable if just transition managed effectively
- **Technology leadership:** China likely maintains advantage in H2-DRI; India competitive in EAF-based green steel
- **International positioning:** Both countries face CBAM challenges; India potentially better positioned for partnership-based solutions

10.3.2 Broader Implications for Global Steel Decarbonization

Relevance for Other Developing Economies:

- India's EAF-centric, economically-driven pathway may be more replicable than China's capital-intensive approach
- Democratic governance challenges require different implementation strategies than authoritarian models
- Just transition complexity in contexts with weak safety nets requires greater attention
- International partnership and climate finance role more critical in capital-constrained environments

Global Climate Implications:

- India's growth-plus-decarbonization challenge represents common dilemma for emerging economies
- Success would demonstrate that industrial development and climate action can be compatible

- Failure would show limitations of market-driven approaches without strong state capacity
- India-China comparison provides crucial learning for global industrial decarbonization

10.4 Concluding Remarks

India's steel decarbonization journey represents one of the most significant tests of whether a major developing economy can simultaneously achieve industrial development and deep emissions reduction. The analysis presented here suggests a challenging but feasible pathway that differs fundamentally from China's approach due to India's democratic governance, market-driven economy, and capital constraints.

The EAF-centric pathway emerging as India's most viable option offers lower costs and faster deployment than hydrogen-based routes, though with ultimately higher residual emissions. This pragmatic approach recognizes economic realities while making substantial progress toward long-term decarbonization goals.

India's federal democracy creates both challenges—implementation inconsistency, slower decision-making—and strengths—adaptability, social feedback, innovation potential. Success will require leveraging these democratic advantages while developing stronger coordination mechanisms.

The international context, particularly CBAM, creates both existential threat and significant opportunity. India's response will determine not only its steel sector's future but also its position in the emerging global green economy.

Ultimately, India's steel decarbonization represents a microcosm of the broader developing country climate challenge: how to achieve wealth-creating industrialization while contributing to global climate solutions. The pathway outlined here—pragmatic, economically-driven, socially-aware—offers a model that, if successful, could guide other emerging economies facing similar dilemmas.

This analysis suggests a 45-55% probability of India achieving its stated transformation targets—a challenging but attainable goal that would represent a significant accomplishment in global industrial decarbonization.

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