

A Call for Collaborative Analysis Integrating  
Policy Architecture, Market Realities, and Regional Dynamics

# Steel Decarbonization in India: Balancing Rapid Growth with Climate Ambitions

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## Abstract

This preliminary study examines India’s steel decarbonization strategy within the context of its ambitious capacity expansion plans and net-zero commitment by 2070. India presents a unique challenge: as the world’s second-largest steel producer with the youngest fleet of blast furnaces globally, the nation must simultaneously accommodate surging domestic demand while navigating a complex energy transition away from coal-based production. This analysis synthesizes recent policy developments, including the September 2024 Ministry of Steel roadmap, the December 2024 Green Steel Taxonomy, and the National Green Hydrogen Mission allocations, alongside ground-level implementation realities. We identify three strategic tensions shaping India’s approach: the “build now, decarbonize later” paradigm versus immediate green investment; the role of coal-based Direct Reduced Iron (DRI) as both a technical advantage and carbon burden; and the challenge of coordinating federal policy with state-level industrial execution. Unlike China’s state-coordinated consolidation model, India’s approach emphasizes enabling frameworks for private sector innovation while managing a highly fragmented production landscape. This comparative perspective reveals fundamental differences in institutional capacity, resource endowments, and strategic priorities that have significant implications for global green steel competitiveness and technological pathways.

## 1 Introduction

India’s steel sector occupies a paradoxical position in the global decarbonization landscape. As the world’s second-largest crude steel producer with 179.5 million tonnes capacity in FY 2023-24, India combines massive scale with profound structural challenges. The sector accounts for approximately 12% of India’s total carbon emissions while supporting critical economic development goals in infrastructure, construction, and manufacturing.

The urgency of India’s steel transition is underscored by three converging realities. First, *aggressive capacity expansion*: the government’s National Steel Policy 2017 targets 300 million tonnes capacity by 2030, representing a near-doubling from current levels. Second, *a young asset base*: India has one of the youngest fleets of blast furnaces globally, with significant new BF-BOF capacity either recently commissioned or in advanced planning stages. Third, *climate commitments*: India’s pledge to achieve net-zero emissions by 2070 and reduce emissions intensity by 45% from 2005 levels by 2030 creates binding constraints on carbon-intensive growth pathways.

### 1.1 India’s Unique Technological Context

India’s steel production landscape differs fundamentally from both China and European producers in three critical dimensions:

**Coal-based DRI dominance:** India is the world’s largest producer of sponge iron (Direct Reduced Iron), with 55 million tonnes capacity produced predominantly through coal-based rotary kilns and coal-based shaft furnaces. This reflects India’s abundant domestic coal reserves and limited access to natural gas, creating a production pathway unique in global steel manufacturing.

**Fragmented production structure:** Unlike China’s increasingly consolidated industry, India maintains a highly dispersed production landscape. Alongside integrated steel plants (ISPs) operated by major producers like Tata Steel, JSW Steel, and SAIL, India has thousands of small and medium secondary producers using induction furnaces and mini blast furnaces, many with capacities below 0.5 million tonnes annually.

**Low per capita consumption with rapid growth trajectory:** India’s per capita steel consumption of 97.7 kg (FY 2024) remains far below the global average of 221.8 kg and dramatically lower than China’s peak consumption levels. This implies decades of sustained demand growth, making “demand reduction” strategies politically and economically untenable.

## 1.2 The September 2024 Policy Milestone

In September 2024, India’s Ministry of Steel released “*Greening the Steel Sector in India: Roadmap and Action Plan*”, following recommendations from 14 specialized Task Forces examining various decarbonization levers. This document represents India’s first comprehensive sectoral decarbonization strategy, followed by the December 2024 release of the *Taxonomy for Green Steel*, establishing a star-rating system for low-emission steel products.

These policy documents signal a qualitative shift from aspirational goals to actionable implementation frameworks. However, the effectiveness of these initiatives depends critically on budgetary allocations in federal budgets, regulatory enforcement capacity, and coordination between multiple ministries and state governments.

## 2 Methodological Approach

This analysis employs a comparative framework, contrasting India’s approach with China’s state-coordinated model documented in parallel research. The methodology integrates:

- **Policy document analysis:** Systematic review of Ministry of Steel roadmaps, the National Green Hydrogen Mission, and state-level industrial policy frameworks
- **Industry data synthesis:** Compilation of capacity tracking from Global Energy Monitor’s Global Steel Plant Tracker, industry association data, and company sustainability reports
- **Expert consultation:** Integration of perspectives from climate policy organizations (CPI, IEEFA, RMI) and industry stakeholders
- **Comparative institutional analysis:** Examining governance structures, policy instruments, and implementation capacity relative to China’s model

As with the China analysis, this research transparently acknowledges the integration of AI-assisted analysis alongside human expertise, recognizing both the opportunities and limitations of this methodological approach.

### 3 The Indian Policy Architecture: A Framework for Private Sector Enablement

India’s steel decarbonization policy operates through a fundamentally different institutional model than China’s state-coordinated approach. Rather than direct capacity mandates and forced consolidation, India emphasizes creating enabling conditions for private sector innovation while providing targeted support for critical technologies.

#### 3.1 The Institutional Landscape

Steel decarbonization policy in India involves complex coordination across multiple ministries, each with distinct mandates:

- **Ministry of Steel:** Sector-specific policy leadership, including the Green Steel Roadmap, Steel Scrap Recycling Policy 2019, and coordination of the 14 Task Forces on decarbonization levers
- **Ministry of New and Renewable Energy (MNRE):** Leads the National Green Hydrogen Mission, with 30% of pilot project budget (Rs 14.66 billion / \$177 million) allocated to steel sector applications
- **Ministry of Power:** Administers the Perform, Achieve and Trade (PAT) scheme for energy efficiency, with steel as a designated sector
- **Ministry of Environment, Forest and Climate Change:** Environmental clearances, emissions standards, and climate policy coordination
- **NITI Aayog:** National planning coordination and long-term strategy development

This multi-ministry structure creates both opportunities for comprehensive policy integration and challenges in implementation coordination, particularly when state governments exercise significant regulatory authority over industrial operations.

#### 3.2 Policy Instrument Portfolio

India’s decarbonization toolkit differs markedly from China’s command-and-control mechanisms:

**Definitional and Standards Frameworks** The December 2024 *Taxonomy for Green Steel* establishes a star-rating system defining green and low-carbon steel categories. This creates market differentiation mechanisms rather than mandatory production targets, enabling premium pricing for cleaner products while avoiding disruption to mainstream production.

**Financial Enablement Mechanisms** Rather than direct subsidies, India emphasizes:

- *Performance-Linked Incentives (PLI):* Under consideration for decarbonization technology adoption, though mechanisms remain under development
- *Transition finance frameworks:* Recognizing that steel lacks commercially viable “green alternatives,” policymakers are developing financial instruments specifically for “transitional activities” in hard-to-abate sectors
- *Green hydrogen production incentives:* The Strategic Interventions for Green Hydrogen Transition (SIGHT) programme under NGHM provides production-linked support for electrolyser manufacturing and hydrogen production

**Scrap and Circular Economy** The Steel Scrap Recycling Policy 2019 addresses a critical constraint in India’s transition: limited scrap availability. By establishing frameworks for metal scrapping centers and end-of-life vehicle processing, the policy aims to increase domestic scrap generation from current low levels toward levels that can support expanded EAF production.

**Energy Efficiency Mandates** The PAT scheme sets specific energy consumption improvement targets for designated industrial facilities, with tradeable certificates creating market mechanisms for efficiency investments. However, enforcement remains variable across states and plant sizes.

## 4 Five Strategic Tensions in India’s Decarbonization Pathway

Unlike China’s relatively linear consolidation and modernization approach, India’s steel transition is characterized by fundamental strategic tensions that shape policy choices and implementation realities.

### 4.1 Tension 1: Build Now vs. Invest Green

India faces a critical temporal dilemma. With steel demand projected to grow from 136 million tonnes in 2024 to 221–275 million tonnes by 2034, the nation must add massive production capacity. Two competing strategic pathways emerge:

**The “Build Now, Decarbonize Later” Approach:** This pathway prioritizes meeting immediate demand through conventional BF-BOF technology, which has lower capital costs and established operational knowledge. Proponents argue that India cannot sacrifice economic growth while technologies like green hydrogen remain commercially unviable. This approach dominates current investment patterns, with approximately 123 million tonnes of new BF-BOF capacity in various stages of development.

**The “Green from the Start” Counter-Argument:** Critics, including organizations like Global Energy Monitor, emphasize the stranded asset risk. With 86% of India’s planned BOF capacity not yet in construction phase, a strategic pivot remains feasible. Young blast furnaces commissioned today will operate for 30–40 years, potentially locking India into high-emission pathways incompatible with 2070 net-zero goals. The estimated stranded asset risk: \$124–187 billion.

*Current resolution:* Policy documents acknowledge both imperatives without definitively choosing. The Green Steel Taxonomy creates market signals favoring cleaner production without prohibiting conventional capacity expansion. This ambiguity may reflect political realities but creates uncertainty for long-term investment planning.

### 4.2 Tension 2: The Coal-DRI Paradox

India’s massive coal-based DRI capacity (60.5 million tonnes installed) represents both a technological advantage and a profound decarbonization challenge.

**The Advantage:** DRI-EAF routes are more easily decarbonizable than BF-BOF. Replacing coal with natural gas in DRI production significantly reduces emissions, and ultimate substitution with green hydrogen creates a pathway to near-zero emissions steel. India’s established DRI infrastructure and operational expertise could accelerate the transition if appropriate fuels become available.

**The Challenge:** Current coal-based DRI is extremely carbon-intensive, with emission intensities often exceeding conventional BF-BOF routes. India’s abundant coal and limited natural gas access create strong economic incentives to continue coal-based operations. The transition to natural gas-based DRI requires massive infrastructure investment in LNG import

terminals, pipeline networks, and plant retrofits. Green hydrogen substitution faces even greater technical and economic barriers.

*Current resolution:* The roadmap identifies natural gas as a transitional fuel, but actual infrastructure development and gas pricing policies remain underdeveloped. Most policy attention focuses on green hydrogen pilot projects, potentially underestimating the importance of the natural gas transition phase.

### 4.3 Tension 3: Integrated vs. Secondary Producers

India's production landscape is split between integrated steel plants (ISPs) and a vast secondary sector of small producers using induction furnaces and mini blast furnaces.

#### **ISP Characteristics:**

- Large scale (typically > 3 million tonnes capacity)
- Sophisticated environmental management
- Access to capital markets and international technology
- Subject to comprehensive regulatory oversight
- Capable of implementing advanced decarbonization technologies

#### **Secondary Sector Characteristics:**

- Highly fragmented (thousands of units with < 0.5 million tonnes capacity)
- Limited capital for major technology investments
- Variable product quality and environmental performance
- Minimal regulatory oversight for smallest units
- Critical for employment and regional economies

*Current resolution:* Most policy initiatives and decarbonization discussions focus exclusively on ISPs. The vast secondary sector, accounting for substantial production and emissions, remains largely unaddressed. This asymmetry creates competitive distortions and limits the effectiveness of national decarbonization efforts.

### 4.4 Tension 4: Federal Policy vs. State Implementation

India's constitutional structure grants states significant authority over industrial regulation, land use, and resource allocation. Steel plants require state-level environmental clearances, power supply agreements, and regulatory compliance monitoring.

This creates implementation variability: progressive states with strong administrative capacity can effectively enforce energy efficiency standards and environmental requirements, while states competing for industrial investment may offer regulatory leniency. The result is a highly uneven implementation landscape that complicates national decarbonization strategies.

*Current resolution:* The central government provides policy frameworks and incentive programs, but lacks direct enforcement mechanisms over state-regulated facilities. Coordination mechanisms like inter-state councils and chief minister conferences play critical roles but produce variable outcomes.

## 4.5 Tension 5: Domestic Standards vs. Global Competitiveness

India’s Green Steel Taxonomy may adopt definitions and emission intensity thresholds that differ from European standards or potential U.S. frameworks. This reflects legitimate concerns: Indian producers face different resource endowments, capital costs, and competitive conditions than European steelmakers.

However, divergent standards create potential trade complications, particularly regarding Europe’s Carbon Border Adjustment Mechanism (CBAM). If Indian “green steel” fails to meet EU criteria, it cannot benefit from preferential treatment under CBAM, disadvantaging Indian exports and potentially triggering trade disputes.

*Current resolution:* The taxonomy document acknowledges international compatibility challenges but prioritizes domestic industrial reality. This pragmatic approach may face future revision as international carbon pricing mechanisms mature.

## 5 Four Technological Pathways Under Development

India’s decarbonization strategy acknowledges multiple technological pathways, recognizing that no single approach will address the sector’s diverse production landscape.

### 5.1 Pathway 1: Best Available Technologies (BAT) for Existing Assets

For the existing and near-term BF-BOF fleet, India emphasizes retrofitting with proven efficiency technologies:

- **Pulverized Coal Injection (PCI):** Reduces coke consumption in blast furnaces, lowering both emissions and operating costs. Many Indian plants operate below optimal PCI rates.
- **Coke Dry Quenching (CDQ):** Recovers waste heat from coke production, reducing energy consumption with negative cost of CO<sub>2</sub> abatement (economically beneficial).
- **Top Pressure Recovery Turbine (TRT):** Recovers energy from blast furnace top gas pressure, generating electricity with negative abatement costs.
- **Waste heat recovery systems:** Comprehensive integration of heat recovery across multiple process stages, estimated to reduce specific energy consumption from 6–6.5 Gcal/tonne to levels approaching international best practice (4.5–5 Gcal/tonne).

These technologies offer immediate emissions reductions with favorable economics, making them attractive for transition finance. Estimates suggest over \$13 billion investment required for BAT adoption across small and medium mills.

### 5.2 Pathway 2: Natural Gas Transition in DRI Production

The shift from coal-based to natural gas-based DRI represents a critical intermediate step toward hydrogen-based production:

**Technical advantages:** Natural gas-based DRI using Midrex or HYL processes reduces CO<sub>2</sub> emissions by approximately 50% compared to coal-based routes while maintaining product quality and production efficiency.

**Infrastructure requirements:** Success depends on:

- Expanded LNG import terminal capacity
- Gas pipeline network extension to steel production centers

- Price competitiveness relative to coal (currently unfavorable without carbon pricing)
- Plant retrofits or new gas-based DRI facility construction

**Current status:** Major producers like JSW Steel and Tata Steel have announced exploration of natural gas-based DRI, but actual construction commitments remain limited pending resolution of gas supply and pricing issues.

### 5.3 Pathway 3: Green Hydrogen Integration

Green hydrogen represents the ultimate decarbonization pathway for DRI-EAF routes, but faces substantial technical and economic barriers:

**National Green Hydrogen Mission (NGHM) allocations:** The Ministry of Steel received 30% of pilot project budget (Rs 14.66 billion), indicating serious policy commitment. SIGHT programme tenders focus on electrolyser manufacturing scale-up and technology development.

**Technical challenges:**

- Green hydrogen production costs currently 3–4x natural gas on energy-equivalent basis
- Electrolyser manufacturing capacity remains limited domestically
- DRI shaft furnace technology requires adaptation for pure hydrogen operation
- Massive renewable energy capacity addition required (estimates suggest 300+ TWh annually for full sector decarbonization)

**Timeline expectations:** Policy documents and industry analysis suggest green hydrogen will achieve meaningful penetration (25–30% of hydrogen needs) only in the 2030–2040 period, with full adoption not expected until 2045–2050. This timeline depends critically on cost reduction trajectories and carbon pricing mechanisms.

**Pilot projects:** Several companies, including JSW Steel and Tata Steel, have announced small-scale pilot projects, but at capacities (typically 0.01–0.05 million tonnes) far below commercial scale.

### 5.4 Pathway 4: Scrap-Based EAF Expansion

Increasing scrap-based production offers immediate emissions reductions, as EAF routes using scrap have approximately 70% lower emissions than BF-BOF.

**Current constraints:**

- India generates approximately 20–25 million tonnes of steel scrap annually, far below demand potential
- Scrap collection infrastructure remains underdeveloped, particularly for end-of-life vehicles and construction demolition
- Scrap quality variability and contamination issues affect product specifications
- Cultural and economic factors limit scrap generation and collection efficiency

**Steel Scrap Recycling Policy 2019:** Establishes frameworks for:

- Authorized metal scrapping centers with quality standards
- End-of-life vehicle processing guidelines
- Scrap grading and certification systems



- Integration with circular economy initiatives

**Growth projections:** Optimistic scenarios project domestic scrap availability could reach 40–50 million tonnes by 2030, supporting EAF capacity expansion from current 10% to 15–20% of total production. This remains modest compared to global averages (30–40%) in developed economies.

## 6 Carbon Capture, Utilization and Storage (CCUS): The Uncertain Lever

CCUS receives significant attention in India’s decarbonization discussions, with analysis suggesting:

**Technical potential:** BF-BOF plants have concentrated CO<sub>2</sub> streams suitable for capture, with large point sources enabling economies of scale in capture equipment.

**Economic challenges:** Current cost estimates suggest \$50–60/tonne CO<sub>2</sub> abatement costs, uncompetitive without carbon pricing or subsidies. Total investment requirements for comprehensive CCUS deployment exceed \$150 billion.

**Utilization focus:** Indian approaches emphasize CCU (carbon capture and utilization) over geological storage, exploring conversion of captured CO<sub>2</sub> into:

- Methanol and other chemical feedstocks
- Synthetic fuels
- Mineralization for construction materials

This focus on utilization reflects limited geological storage site characterization in India and the need to create economic value from captured carbon to improve project economics.

**Policy support:** CCUS features prominently in Ministry of Steel roadmaps, but concrete implementation mechanisms (tax incentives, mandates, infrastructure support) remain under-developed. The technology is positioned as a long-term option rather than near-term priority.

## 7 Financing the Transition: The \$300 Billion Challenge

Ministry of Steel estimates indicate comprehensive steel sector decarbonization will require approximately \$300 billion in capital investment through 2070. This massive sum encompasses:

- Technology upgrades at small and medium mills: \$13+ billion
- Advanced technology deployment (H<sub>2</sub>-DRI, CCUS): \$150+ billion
- Renewable energy infrastructure: \$50+ billion
- Scrap collection and processing infrastructure: \$10+ billion
- Natural gas infrastructure: \$30+ billion
- R&D and pilot projects: \$5+ billion

## 7.1 Transition Finance as a Critical Instrument

Traditional “green finance” instruments (green bonds, sustainability-linked loans) require allocation to demonstrably green technologies aligned with Paris Agreement pathways. This creates a paradox for steel: the sector needs capital to transition, but lacks commercially viable “green alternatives” that meet green finance criteria.

**Transition finance** addresses this gap by:

- Accepting “transitional activities” that provide incremental emissions reductions even if not fully Paris-aligned
- Enabling financing for BAT adoption, natural gas transitions, and other intermediate steps
- Requiring credible transition plans demonstrating pathway to eventual net-zero
- Creating market mechanisms that reward progress rather than demanding perfection

Organizations like Climate Policy Initiative (CPI) are developing transition finance frameworks specifically for Indian steel, working with financial institutions and steel producers to operationalize these concepts.

## 7.2 Policy Mechanisms Under Consideration

**Performance-Linked Incentives (PLI):** The Steel Ministry is exploring PLI schemes specifically for decarbonization investments, though design parameters and funding commitments remain in development. PLI models used successfully in electronics and other sectors could be adapted for steel technology adoption.

**Carbon pricing mechanisms:** India currently lacks comprehensive carbon pricing for industry. The PAT scheme creates limited incentives through energy efficiency certificates, but does not directly price CO<sub>2</sub> emissions. Future carbon pricing (whether through taxation or emissions trading) is widely recognized as essential for making green technologies economically competitive.

**Import protection and green procurement:** Discussions include:

- Increasing import duties (from 7.5% to 10–12%) to protect domestic industry during transition
- Mandatory green steel procurement targets for government infrastructure projects
- Preferential treatment in public procurement for certified green steel products

These measures could create domestic market pull for green steel without requiring subsidy expenditure, though they raise concerns about international trade obligations.

# 8 Regional and Company-Level Dynamics

## 8.1 Leading Producers and Their Strategies

**Tata Steel:** India’s oldest and most internationally connected producer, with operations spanning India, UK, and Netherlands. Tata Steel has announced commitments to net-zero by 2045 (ahead of India’s national 2070 target) and is actively piloting hydrogen technology. European operations provide technology transfer opportunities, though their planned closures create strategic challenges.

**JSW Steel:** India’s largest private producer, with aggressive capacity expansion plans. JSW has announced interest in natural gas-based DRI and green hydrogen pilots, but maintains

significant conventional capacity investments. The company emphasizes customer demand for green steel as a critical driver for major technology investments.

**Steel Authority of India Limited (SAIL):** The largest public sector producer, with aging assets requiring modernization. SAIL faces capital constraints but benefits from government support. Modernization programs include BAT adoption, with mixed progress on advanced decarbonization technologies.

**ArcelorMittal Nippon Steel India (AM/NS):** Joint venture between global leaders, with modern facilities in Gujarat. The company operates one of India’s most efficient integrated plants and has announced exploration of hydrogen technologies, leveraging parent company expertise.

## 8.2 Geographical Clusters

Steel production in India concentrates in several key regions, each with distinct characteristics:

**Odisha:** Proximity to iron ore resources makes this state a steel production hub. However, coal-based energy and inland location increase logistics costs for exports. Decarbonization here depends heavily on renewable energy grid integration and potentially green hydrogen production.

**Gujarat:** Coastal location with modern facilities (AM/NS) and strong industrial infrastructure. Better positioned for LNG imports and renewable energy integration. Gujarat’s proactive industrial policy creates favorable enabling environment for technology adoption.

**Jharkhand-West Bengal:** Historical steel heartland with older facilities (SAIL plants, Tata Steel Jamshedpur). These regions face modernization challenges but have skilled workforce and established supply chains. Urban pollution concerns create pressure for emissions controls.

**Karnataka:** JSW Steel’s primary base, with modern coastal facilities under development. Positioned to leverage Karnataka’s renewable energy targets and relatively progressive industrial policy environment.

## 9 Comparative Analysis: India vs. China

Understanding India’s approach requires comparison with China’s model, revealing fundamental differences in institutional capacity, strategic priorities, and implementation mechanisms.

### 9.1 Governance and Coordination

**China:** Centralized policy coordination through integrated national planning (Five-Year Plans), with NDRC and MIIT exercising direct authority over capacity allocations, major investments, and industry consolidation. State-owned enterprises dominant, enabling direct policy implementation.

**India:** Fragmented governance with multiple ministries and strong state-level authority. Policy framework emphasizes enablement rather than mandates. Private sector dominates production, limiting direct government control. Implementation depends on creating economic incentives rather than issuing directives.

### 9.2 Industry Structure

**China:** Forced consolidation creating mega-producers (China Baowu > 100 million tonnes capacity). Capacity swap mechanisms eliminate small, inefficient producers. Geographical concentration in modern coastal industrial clusters.

**India:** Highly fragmented, with top producers accounting for smaller market shares. Thousands of small secondary producers remain economically and politically significant. No equivalent capacity replacement mechanisms force consolidation.

### 9.3 Technological Pathways

#### China:

- Systematic retrofitting of massive BF-BOF fleet with ULE (Ultra-Low Emissions) requirements
- Strategic piloting of hydrogen-based DRI (HyDREI project)
- Focus on optimizing conventional pathways while de-risking future technologies
- State-coordinated R&D with substantial funding

#### India:

- Emphasis on “transition finance” for incremental improvements (BAT adoption)
- Unique challenge of coal-based DRI requiring fuel substitution
- Greater reliance on private sector R&D and international technology partnerships
- Longer timeline to green hydrogen adoption (2030–2050 vs. China’s more aggressive pilots)

### 9.4 Resource Endowments

**China:** Limited iron ore resources (high import dependence), coal abundance but air quality crisis driving energy transition, coastal concentration enables efficient logistics.

**India:** Abundant iron ore resources (export potential), massive coal reserves creating economic resistance to fuel switching, renewable energy potential (solar, wind) but grid integration challenges, geographical dispersion increases logistical complexity.

### 9.5 International Positioning

**China:** Views steel as strategic sector for technological leadership and industrial sovereignty. Massive investment in green steel R&D aimed at securing intellectual property and export technology markets. Less concerned with international standards compatibility.

**India:** Seeks to leverage steel growth for economic development while avoiding stranded assets. More sensitive to international standards (CBAM) given export ambitions. Emphasizes collaboration and technology transfer rather than technological sovereignty.

## 10 Implications for Global Collaboration

India’s steel decarbonization journey presents distinct opportunities and challenges for international cooperation, particularly for research initiatives like the Steel X Future framework.

### 10.1 Research Collaboration Opportunities

**Coal-to-hydrogen DRI transitions:** India’s unique position with massive coal-based DRI capacity creates opportunities for joint research on fuel substitution pathways, hydrogen injection rates, and metallurgical quality control. This work has limited relevance for European producers but high value for other developing economies.

**Scrap-based steelmaking in resource-constrained contexts:** Research on optimizing EAF operations with variable scrap quality, contamination management, and quality control for challenging feedstock conditions addresses issues common across developing economies.

**Financing mechanisms and policy design:** India’s exploration of transition finance frameworks, PLI schemes, and market-based mechanisms provides valuable case studies for other nations facing similar institutional and economic constraints.

**Digital transformation and Industry 4.0:** Indian companies are rapidly adopting digital technologies for process optimization, predictive maintenance, and energy management. Collaboration on data analytics, AI applications, and digital twin technologies offers mutual benefits.

## 10.2 Challenges for International Coordination

**Divergent standards and definitions:** If India adopts “green steel” definitions incompatible with European or American frameworks, it complicates joint research, technology transfer, and market development. Harmonization efforts face legitimate concerns about context-specific feasibility.

**Intellectual property and technology transfer:** Indian companies and policymakers emphasize affordable technology access, while technology developers seek IP protection and commercial returns. Balancing these interests requires innovative partnership structures.

**Timeline and urgency mismatches:** European steel faces existential pressure for rapid decarbonization, while India faces existential pressure for capacity expansion. These different timelines create challenges for joint research prioritization and technology development pathways.

## 10.3 Potential Partnership Frameworks

**Technical capacity building:** Student exchange programs, researcher mobility, and joint supervision of doctoral research could address talent development needs in both regions. Indian students could benefit from European expertise in hydrogen metallurgy and CCUS, while European programs could learn from Indian experience in resource-constrained innovation.

**Pilot project collaboration:** Joint funding and technical support for pilot-scale demonstration projects in India, with European technology providers and Indian operators sharing data and learning. This de-risks technology deployment while building operational knowledge.

**Policy learning networks:** Systematic exchange of policy experiences, regulatory approaches, and implementation lessons through workshops, joint publications, and policy dialogue. India can learn from European carbon pricing experience, while Europe can learn from India’s transition finance innovations.

**Pre-competitive research consortia:** Industry-academic partnerships addressing fundamental metallurgical challenges (hydrogen embrittlement, ore quality impacts, process modeling) where competitive concerns are limited and knowledge sharing benefits all parties.

# 11 Critical Assessment and Open Questions

This analysis reveals several critical gaps and ambiguities in India’s steel decarbonization strategy that warrant further investigation:

## 11.1 The Secondary Sector Knowledge Gap

Most policy analysis and decarbonization discussions focus exclusively on integrated steel plants, while thousands of small secondary producers remain largely invisible. Critical unknowns include:

- Actual production volumes and emissions profiles of the secondary sector
- Technical and economic feasibility of decarbonization interventions for small producers

- Social and employment implications of potential secondary sector consolidation
- Regulatory enforcement capacity for dispersed, small-scale operations

This knowledge gap undermines comprehensive emissions accounting and policy effectiveness assessment.

## 11.2 Natural Gas Infrastructure: The Missing Link?

Policy documents identify natural gas as a transitional fuel for DRI production, but concrete plans for gas infrastructure development, supply security, and pricing policies remain underdeveloped. Critical questions:

- Will India develop domestic natural gas production, or depend on LNG imports?
- What pipeline infrastructure investments are required, and who finances them?
- At what price point does natural gas become competitive with coal for DRI production?
- Does focus on green hydrogen cause policy neglect of this essential intermediate step?

Without answers to these questions, the natural gas transition pathway remains more aspirational than actionable.

## 11.3 State-Level Implementation: Variation and Capacity

The importance of state governments in industrial regulation creates implementation variability that is poorly understood. Research questions include:

- Which states have effective capacity to implement and monitor steel sector environmental regulations?
- How do states balance economic development priorities (attracting investment) against environmental enforcement?
- Can best practices from progressive states be effectively transferred to states with weaker administrative capacity?
- What coordination mechanisms work best for aligning state actions with national policy goals?

## 11.4 Carbon Pricing: The Elephant in the Room

Most techno-economic analyses of green steel technologies conclude they become commercially viable only with carbon pricing in the range of \$50–100/tonne CO<sub>2</sub>. India currently lacks such pricing mechanisms, and political resistance to carbon taxation remains strong given development priorities and energy poverty concerns.

Without carbon pricing or equivalent mechanisms (regulatory mandates, substantial subsidies), the business case for major decarbonization investments remains weak. Policy documents acknowledge this implicitly but avoid confronting the political challenge directly. This creates fundamental uncertainty about whether announced technology pathways will actually be implemented at scale.

## 11.5 The 2030–2040 Capacity Addition Dilemma

India will add approximately 100–150 million tonnes of steel capacity in the next decade. Current indications suggest the vast majority will be conventional BF-BOF technology. Key questions:

- At what point does the cumulative stranded asset risk become politically unacceptable?
- Could policy interventions (carbon pricing, green procurement mandates, import restrictions) shift investment decisions toward lower-carbon pathways?
- Is there a technological “wait and see” strategy that delays capacity additions until green technologies mature, or is demand pressure too urgent?
- How do company-level capital allocation decisions respond to ambiguous long-term policy signals?

The resolution of this dilemma in the coming 2–3 years will fundamentally determine India’s long-term emissions trajectory.

## 12 Conclusion: Pragmatism, Ambiguity, and the Challenge of Dual Imperatives

India’s steel decarbonization strategy reflects the profound complexity of managing simultaneous growth and climate imperatives in a developing economy context. Unlike China’s state-coordinated, engineering-focused approach that treats steel transformation as a national infrastructure project, India’s strategy emphasizes creating enabling conditions for private sector innovation while maintaining policy flexibility.

Several key insights emerge from this analysis:

**First, the primacy of dual imperatives:** India cannot sacrifice economic development for environmental goals, nor can it ignore climate commitments given both domestic air quality crises and international pressure. Policy documents attempt to reconcile these imperatives without definitively prioritizing either, creating strategic ambiguity that may reflect political wisdom but complicates long-term planning.

**Second, the challenge of fragmentation:** India’s dispersed industry structure, multi-ministry governance, and federal-state division of powers creates implementation challenges that contrast sharply with China’s centralized model. Success depends on coordination mechanisms and incentive structures rather than command-and-control mandates.

**Third, the resource endowment paradox:** India’s abundant coal and limited natural gas access create powerful economic incentives to continue carbon-intensive pathways, even as the nation pursues green hydrogen and renewable energy. The transition from coal-based DRI to hydrogen-based production requires navigating an uncertain intermediate phase that policy documents address inadequately.

**Fourth, the financing challenge:** The \$300 billion investment requirement exceeds the capacity of government subsidy programs or private sector balance sheets alone. Success requires innovative financial instruments, particularly transition finance mechanisms that reward incremental progress rather than demanding immediate transformation.

**Fifth, the importance of international collaboration:** India’s approach offers valuable lessons for other developing economies facing similar challenges, while Indian industry and researchers could benefit substantially from European and global expertise in green steel technologies. However, effective collaboration requires acknowledging different timelines, priorities, and constraints rather than imposing standardized solutions.

## 12.1 A Call for Collaborative Analysis

This preliminary analysis barely scratches the surface of India’s steel decarbonization challenge. Critical gaps remain in understanding the secondary sector, state-level implementation dynamics, scrap supply chain development, and the political economy of carbon pricing.

The author welcomes engagement from:

- Indian researchers and industry practitioners who can provide ground-level insights into implementation realities
- Policy experts who can clarify evolving regulatory frameworks and financing mechanisms
- International collaborators interested in comparative analysis and technology partnership opportunities
- Environmental and development scholars who can contextualize steel decarbonization within broader sustainability transitions

The challenge of steel decarbonization is global in scope but must be addressed through context-specific pathways. Understanding India’s approach—with all its complexities, contradictions, and pragmatic compromises—is essential for anyone engaged with the future of global steel production.

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This work was conceived as a comparative analysis alongside a parallel examination of China’s steel decarbonization strategy, with both studies intended to facilitate cross-regional learning and international research collaboration.

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