Brazil's Strategic Position in Global Steel Decarbonization: A Comparative Analysis of Technology Pathways, Policy Frameworks, and Competitive Advantages

Claude*
Anthropic PBC, San Francisco, CA, USA

André Costa e Silva
Steel Industry Expert, Brazil

Fabio Miani†
Department of Polytechnic Engineering and Architecture (DPIA)
University of Udine, Italy

November 2025

Abstract

The steel industry accounts for 7-9% of global CO_2 emissions, making its decarbonization critical to achieving international climate targets. This paper examines Brazil's unique strategic position in the global transition toward low-carbon steel production, analyzing technology pathways, policy frameworks, and competitive advantages relative to major steel-producing nations. With 33.8 million tonnes of annual crude steel production (9th globally), Brazil possesses distinctive advantages: abundant renewable energy resources, unique biomass potential for carbon-neutral ironmaking, high-quality iron ore reserves, and advanced demonstration projects in breakthrough technologies. Through comparative analysis of decarbonization strategies across twelve major steel-producing countries and detailed examination of Brazilian initiatives including the CSN Selene hydrogen project, Vale's Tecnored technology, and the Boston Metal molten oxide electrolysis plant, this study demonstrates that Brazil can become a global leader in low-cost green steel production. However, realization of this potential requires coordinated policy action, dedicated

*AI Research Assistant, Anthropic
†Corresponding author: fabio.miani@uniud.it

financing mechanisms, and strategic technology development. The analysis identifies critical success factors, policy gaps, and actionable recommendations for positioning Brazil at the forefront of the steel industry's transformation. This research contributes to the growing literature on industrial decarbonization in emerging economies and provides a framework for leveraging natural resource advantages in the global energy transition.

Keywords: Steel decarbonization, Brazil, green hydrogen, biomass metallurgy, direct reduced iron, technology pathways, industrial policy, renewable energy, circular economy

Contents

1 Introduction

1.1 Global Context: The Steel Decarbonization Imperative

The steel industry stands at a critical inflection point. As one of the foundational materials of modern civilization—essential to construction, transportation, machinery, and countless manufactured goods—steel production also represents one of the most significant industrial sources of greenhouse gas emissions. Global steel production reached 1,884.6 million tonnes in 2024 [1], with associated CO_2 emissions of approximately 2.6 billion tonnes, representing 7-9% of total global emissions [3].

The conventional integrated steelmaking route, based on blast furnace-basic oxygen furnace (BF-BOF) technology, produces approximately 2.0 tonnes of CO_2 per tonne of crude steel. This carbon intensity derives from the fundamental chemistry of ironmaking: the reduction of iron oxide using carbon-based reductants (primarily metallurgical coke), which inevitably generates CO_2 as a byproduct. With global steel demand projected to remain stable or grow modestly through 2050 [2], achieving climate targets under the Paris Agreement requires fundamental transformation of steelmaking processes.

Multiple technology pathways are emerging globally: hydrogen-based direct reduction (H_2-DRI), carbon capture utilization and storage (CCUS) retrofitted to existing facilities, increased electric arc furnace (EAF) production using scrap, and potentially disruptive technologies such as molten oxide electrolysis. Each pathway presents distinct technical challenges, capital requirements, and regional applicability depending on resource availability, industrial structure, and policy frameworks.

1.2 Brazil's Position in Global Steel Production

Brazil ranks as the world's 9th largest steel producer with 33.8 million tonnes of crude steel production in 2024, representing 89.7% of South American production [1]. The Brazilian steel industry comprises both integrated BF-BOF facilities (76% of capacity) and electric arc furnace operations (24%), with major producers including Gerdau (EAF specialist), CSN (integrated), ArcelorMittal Brasil, and Usiminas.

Brazil's steel sector is characterized by several distinctive features:

- **Resource endowment:** High-quality iron ore reserves, primarily in Minas Gerais and Pará states
- **Energy profile:** Predominantly renewable electricity grid (¿80% hydroelectric, wind, and biomass)
- **Biomass availability:** Significant potential for sustainable charcoal production from planted forests
- **Export orientation:** Substantial steel and iron ore exports to global markets
- **Technological capability:** Established industrial infrastructure and engineering expertise

Despite these advantages, Brazil's steel industry faces decarbonization challenges common to emerging economies: capital constraints for large-scale technology transformation, competition from lower-cost/higher-emission producers, need for policy coordination across multiple governmental levels, and limited dedicated financing mechanisms for industrial decarbonization.

1.3 Research Objectives and Contributions

This paper addresses three primary research questions:

1. What technology pathways are available for steel decarbonization, and which are most suitable for Brazilian conditions given resource endowments and industrial structure?
2. How do Brazil's decarbonization strategies, policy frameworks, and research initiatives compare to approaches in other major steel-producing nations?
3. What policy interventions, technological investments, and strategic partnerships would enable Brazil to achieve leadership in low-cost green steel production?

The research makes several contributions to academic and policy literature:

Empirical contribution: Comprehensive documentation of Brazilian steel decarbonization initiatives, including detailed analysis of the CSN Selene hydrogen project, Vale Tecnored technology, and Boston Metal's molten oxide electrolysis demonstration plant—providing primary data on breakthrough technology deployment in emerging economy contexts.

Comparative analysis: Systematic comparison of steel decarbonization approaches across twelve major producing countries (China, India, Japan, USA, Russia, South Korea, Germany, Turkey, Brazil, Iran, Vietnam, Italy), identifying distinct policy models, technology preferences, and funding mechanisms.

Strategic framework: Development of a decision framework for leveraging natural resource advantages in industrial decarbonization, applicable beyond steel to other hard-to-abate sectors.

Policy recommendations: Actionable policy prescriptions grounded in international best practices and adapted to Brazilian institutional context, including specific proposals for financing mechanisms, research priorities, and international partnerships.

1.4 Paper Structure

The remainder of this paper is organized as follows: Section 2 reviews relevant literature on steel decarbonization technologies and policy approaches. Section 3 describes the methodology and data sources. Section 4 presents a comparative analysis of decarbonization strategies across major steel-producing nations. Section 5 examines Brazil's current position, including detailed analysis of major projects and initiatives. Section 6 discusses Brazil's unique competitive advantages and strategic opportunities. Section 7 identifies challenges and policy gaps. Section 8 presents policy recommendations and a roadmap for action. Section 9 concludes with implications for research and practice.

2 Literature Review

2.1 Steel Decarbonization Technologies

The academic and technical literature identifies four primary pathways for steel sector decarbonization, each at different stages of technological maturity and commercial deployment.

2.1.1 Hydrogen-Based Direct Reduction (H_2-DRI)

Direct reduction processes using hydrogen as the reductant represent the most widely discussed pathway for deep decarbonization of primary steel production. The fundamental chemistry replaces carbon-based reduction:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \tag{1}$$

compared to conventional carbon reduction:

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \tag{2}$$

Vogl et al. [4] provide comprehensive techno-economic assessment of hydrogen-based direct reduction in shaft furnaces, demonstrating technical feasibility but highlighting cost sensitivity to hydrogen price and electricity source. The HYBRIT project in Sweden [5] represents the most advanced commercial-scale demonstration, targeting fossil-free steel production by 2026.

Key technical challenges include: hydrogen embrittlement of equipment and products, different reduction kinetics compared to carbon monoxide requiring process optimization, ore quality requirements (¿67% Fe content, low gangue), and integration with intermittent renewable energy sources [6].

2.1.2 Carbon Capture, Utilization, and Storage (CCUS)

CCUS retrofitted to existing BF-BOF facilities offers an incremental pathway, particularly relevant for assets with significant remaining operational life. Multiple capture technologies are under development: post-combustion amine scrubbing, pre-combustion syngas shift, oxy-fuel combustion, and calcium looping [7].

The economics of CCUS for steel remain challenging. Capture costs range from $40-120 per tonne CO_2 depending on concentration and capture technology, with additional transport and storage costs [8]. Energy penalties (15-30% additional energy requirement) reduce plant productivity. Long-term storage liability and public acceptance present additional barriers.

Several large-scale demonstration projects are underway: ArcelorMittal's Carbon2Carb project in Germany (blast furnace gas to synthetic crude), the Porthos project in Rotterdam (industrial cluster CCUS), and various initiatives in China and Japan [9].

2.1.3 Scrap-Based Electric Arc Furnace (EAF) Expansion

Increased steel production through EAF using scrap as feedstock offers immediate emissions reduction (0.4-0.5 tonnes CO_2 per tonne steel vs. 2.0 for BF-BOF) and leverages circular economy principles [10]. Global EAF capacity represents approximately 30% of total steel production, with significant growth potential.

However, EAF expansion faces constraints: scrap availability growing slower than steel demand, quality limitations from tramp elements (copper, tin, nickel), inability to produce certain high-quality steel grades from 100% scrap, and regional disparities in scrap generation (abundant in developed economies, scarce in rapidly industrializing nations) [11].

To address scrap constraints, DRI (produced via H_2 or natural gas) can supplement scrap in EAF operations, enabling production of high-quality steel grades while maintaining lower emissions than BF-BOF [12].

2.1.4 Breakthrough and Disruptive Technologies

Several early-stage technologies promise radical transformation if successfully commercialized:

Molten Oxide Electrolysis (MOE): Boston Metal's technology dissolves iron ore in molten oxide electrolyte, using electricity to separate iron and oxygen with zero direct CO_2 emissions [13]. Key advantages include ore flexibility, modular scaling, and high-purity iron output. Technology readiness level (TRL) 5-6, with commercial-scale demonstration plant under construction in Brazil.

Electrochemical processes: Electra's low-temperature aqueous electrolysis produces ultra-pure iron at 60°C, enabling integration with intermittent renewables [14]. TRL 4-5, with pilot operations demonstrated.

Biomass-based reduction: Rio Tinto's BioIron process uses raw biomass as reductant in a low-temperature chemical process, offering carbon-neutral pathway using agricultural waste [15]. Laboratory-scale proof of concept, targeting pilot plant.

Flash reduction: Calix's ZESTY process uses rapid hydrogen reduction of fine ore in proprietary flash calciner, eliminating pelletizing step [16]. Early pilot stage (TRL 3-4).

2.2 Policy Frameworks for Industrial Decarbonization

Academic literature identifies several key policy instruments for facilitating steel sector transformation:

2.2.1 Carbon Pricing Mechanisms

Carbon pricing through emissions trading systems (ETS) or carbon taxes creates economic incentive for emissions reduction. The EU ETS represents the most mature system, with current carbon prices of €60-90 per tonne CO_2 [17]. However, effectiveness depends on price level, free allocation mechanisms, and coordination with trade policy to prevent carbon leakage [18].

China launched national ETS in 2021, initially covering power sector with plans to expand to steel [19]. The system's impact remains uncertain given administrative price controls and limited trading activity.

2.2.2 Border Adjustment Mechanisms

The EU's Carbon Border Adjustment Mechanism (CBAM), entering implementation phase in 2026, represents novel approach to preventing carbon leakage while maintaining domestic climate ambition [20]. CBAM requires importers to purchase certificates reflecting carbon content of products, with deductions for carbon pricing in country of origin.

Legal challenges regarding WTO compatibility are anticipated. Administrative complexity and potential retaliation from trading partners present risks. Effectiveness depends on carbon price differential and ability to accurately measure embedded emissions [21].

2.2.3 Public Research Funding

Government-funded R&D plays critical role in de-risking breakthrough technologies and enabling industry learning-by-doing. Comparative analysis reveals diverse approaches:

- **Mission-oriented programs:** Japan's Green Innovation Fund (¥449.9 billion for steel sector hydrogen projects) [22]
- **Tax incentives:** US Inflation Reduction Act production and investment tax credits [23]
- **Public-private partnerships:** EU Clean Steel Partnership (€600 million total) [24]
- **Competitive demonstration funding:** EU Innovation Fund (€2+ billion allocated to steel projects) [42]

Research by Rodrik [25] emphasizes importance of "green industrial policy" that combines climate objectives with competitiveness and development goals, particularly relevant for emerging economies.

2.2.4 Procurement and Demand-Side Policies

Public procurement preferences for low-carbon steel can create early markets and price discovery. Germany's Steel Action Plan mandates consideration of embodied carbon in public infrastructure projects [41]. Similar approaches are emerging in France, Netherlands, and several US states.

Buy Clean programs, green building codes, and product standards incorporating lifecycle carbon represent additional demand-side instruments [26].

2.3 Resource Advantages and Industrial Strategy

Literature on resource-based industrial strategy provides relevant framework for analyzing Brazil's position. Mazzucato and Rodrik [27] argue that natural resource endowments can drive innovation and development when combined with appropriate policy frameworks—challenging traditional "resource curse" narratives.

Specific to renewable energy and green industrial transformation, Meckling and Nahm [28] demonstrate how countries with renewable energy advantages can capture value through energy-intensive manufacturing rather than simply exporting electricity. Brazil's renewable energy abundance positions it advantageously for hydrogen production and electrification pathways.

2.4 Research Gaps

Despite growing literature on steel decarbonization, several gaps remain:

1. **Emerging economy perspectives:** Most analysis focuses on Europe, Japan, or USA. Limited research on decarbonization strategies for major emerging producers (India, Brazil, Vietnam, Iran).

2. **Biomass pathways:** Systematic analysis of sustainable biomass-based steelmaking largely absent from academic literature, despite Brazil's unique potential.

3. **Breakthrough technology scaling:** Limited empirical data on commercial deployment challenges for MOE, electrochemical processes, and other disruptive approaches.

4. **Policy coordination:** Insufficient attention to multi-level governance challenges in federalist systems (relevant to Brazil, USA, India).

5. **Just transition:** Minimal research on workforce and community impacts of steel transformation in developing country contexts.

This paper addresses these gaps through detailed analysis of Brazil's position, biomass pathways, breakthrough technology deployment, and policy coordination challenges.

3 Methodology

3.1 Research Design

This study employs a mixed-methods approach combining:

1. **Comparative policy analysis:** Systematic comparison of steel decarbonization strategies across twelve major producing countries

2. **Technology assessment:** Evaluation of technology pathways based on technical literature, industry reports, and project documentation

3. **Case study analysis:** Detailed examination of Brazilian initiatives including CSN Selene, Vale Tecnored, and Boston Metal MOE projects

4. **Stakeholder insights:** Integration of perspectives from industry, government, and research institutions (where available through public statements and publications)

3.2 Data Sources

3.2.1 Production and Emissions Data

- World Steel Association statistical yearbooks (2023-2024) for production rankings and trends [1]
- International Energy Agency (IEA) Iron and Steel Technology Roadmap for emissions data and scenarios [3]
- National statistical offices and industry associations for country-specific data

3.2.2 Policy Documents

- Government publications: Five-Year Plans (China), National Steel Policies (India, Brazil), Industrial Strategies (EU, Germany, USA, Japan)
- Regulatory frameworks: EU ETS and CBAM regulations, US IRA provisions, carbon trading schemes
- Research funding program documents: NEDO Green Innovation Fund (Japan), EU Clean Steel Partnership, DOE Industrial Decarbonization programs (USA)

3.2.3 Technical and Project Information

- Company sustainability reports and investor presentations from major steel producers (POSCO, ArcelorMittal, CSN, Tata Steel, Thyssenkrupp, etc.)
- Technology provider documentation (Midrex, Energiron, Primetals, SMS group)
- Academic publications and conference proceedings (AISTech, ICSTI, ESTAD)
- Patent databases for innovation tracking

3.2.4 Expert Analysis

This research benefited from consultation with artificial intelligence analytical systems (Anthropic Claude, Deepseek) for systematic analysis of policy documents in multiple languages, institutional mapping, and comparative framework development. All AI-generated insights were validated against primary sources and filtered through expert metallurgical and policy analysis.

3.3 Analytical Framework

The comparative analysis employs a structured framework examining six dimensions across countries:

1. **Technology pathway preferences:** Primary and secondary approaches to decarbonization
2. **Funding mechanisms:** Public research support, demonstration funding, tax incentives, industry co-funding requirements
3. **Policy instruments:** Carbon pricing, regulations, standards, procurement policies
4. **Institutional structures:** Government agencies, industry associations, research institutions, coordination mechanisms
5. **Timelines and targets:** Near-term emissions reduction commitments, long-term net-zero targets
6. **International positioning:** Trade policy, technology cooperation, competitiveness concerns

For Brazil specifically, additional dimensions include resource endowment assessment, comparative advantage analysis, project-level technical evaluation, and policy gap identification.

3.4 Limitations

Several methodological limitations should be noted:

- **Data availability:** Inconsistent reporting across countries, particularly for Russia, Iran, and Vietnam. Some commercial project data proprietary.
- **Rapidly evolving field:** Policy frameworks and technology projects changing faster than academic publication cycles. Analysis reflects status as of November 2025.
- **Uncertainty in projections:** Technology costs, hydrogen prices, carbon prices, and policy trajectories inherently uncertain. Scenario analysis used where appropriate.
- **Language barriers:** Primary sources in Chinese, Japanese, Korean, Portuguese, and other languages accessed through translation (increasing risk of misinterpretation).
- **Complexity of causation:** Difficult to isolate effects of specific policies from broader economic and technological trends.

Despite these limitations, the comprehensive scope and multiple data sources provide robust foundation for analysis and recommendations.

4 Comparative Analysis of Global Decarbonization Strategies

4.1 Overview of Major Steel Producers

Table 1 presents production data and technology mix for the twelve countries examined in this study.

Table 1: Steel Production and Technology Mix by Country (2024)

Country	Production (MT)	Global Share (%)	BF-BOF Share (%)	EAF Share (%)
China	1,005.1	53.3	90	10
India	149.4	7.9	55	45
Japan	84.0	4.5	75	25
USA	79.5	4.2	30	70
Russia	71.0	3.8	65	35
South Korea	63.6	3.4	70	30
Germany	37.2	2.0	70	30
Turkey	36.9	2.0	35	65
Brazil	**33.8**	**1.8**	**76**	**24**
Iran	31.4	1.7	55	45
Vietnam	22.0	1.2	30	70
Italy	20.0	1.1	40	60
Total (12)	**1,633.9**	**86.7**	–	–
World Total	**1,884.6**	**100.0**	–	–

These twelve countries represent 86.7% of global steel production, providing comprehensive coverage for comparative analysis. The diversity in technology mix reflects different industrial development paths, resource endowments, and market structures.

4.2 Technology Pathway Comparison

4.2.1 Hydrogen-Based Approaches

European Leaders (Germany, Sweden): Most aggressive hydrogen strategies, leveraging policy support and early-mover advantages. Germany's tkH2Steel (Thyssenkrupp) and SALCOS (Salzgitter) projects targeting conversion of integrated mills to H_2-DRI-EAF by 2030-2035. Sweden's HYBRIT project most advanced, with H2 Green Steel commercial plant under construction.

Policy support: EU Innovation Fund (€2+ billion steel allocations), national co-funding (Germany €2 billion hydrogen strategy), carbon contracts for difference, and CBAM protection.

Asian Approaches (Japan, South Korea): Hybrid strategies combining hydrogen with CCUS. Japan's Super COURSE50 injects hydrogen into blast furnaces while capturing CO_2, targeting 30% emissions reduction by 2030 [22]. South Korea developing proprietary HyREX technology (hydrogen reduction in fluidized bed) through POSCO-Primetals partnership [39].

Substantial government funding: Japan's Green Innovation Fund doubled to ¥449.9 billion. However, critics note continued BF-BOF focus limits deep decarbonization potential [40].

Emerging Economy Pilots (India, Brazil): Early-stage hydrogen initiatives. India's SAIL, Tata Steel, and JSW planning H_2-DRI pilots leveraging National Green Hydrogen Mission ($2.5 billion) [37]. Brazil's CSN Selene project progressing through phased implementation (Section 5.2.1).

Challenge: Hydrogen cost competitiveness. Green H_2 production costs $4-7/kg in most regions vs. $1-2/kg for gray hydrogen from natural gas [30]. Brazil's renewable energy advantage could enable $2-3/kg green H_2 by 2030.

4.2.2 Carbon Capture Strategies

Incremental Retrofit Focus (USA, Japan, China): CCUS emphasized where existing integrated mills have long operational life remaining. USA steel producers (US Steel, Cleveland-Cliffs) exploring CCUS leveraging 45Q tax credits ($85/tonne CO_2 stored) [23]. Japan integrating CCUS into COURSE50 program. China piloting various capture technologies at state-owned enterprises.

Economics remain challenging without high carbon prices or substantial subsidies. Energy penalty (15-30%) reduces competitiveness. Long-term viability questioned by some analysts viewing CCUS as transition technology rather than endpoint.

Limited Adoption in EAF-Dominant Regions: Turkey, Italy, Vietnam focus on EAF efficiency rather than CCUS, given lower baseline emissions from scrap-based production.

4.2.3 EAF Expansion Strategies

Already EAF-Dominant (USA, Turkey, Vietnam, Italy): These countries leverage existing EAF expertise and scrap availability. USA 70% EAF (Nucor, Steel Dynamics industry leaders), Turkey 65%, Vietnam 70%, Italy 60%. Decarbonization focuses on renewable electricity sourcing and operational efficiency.

Constraint: Scrap quality and availability. USA increasingly imports premium scrap; Turkey sources from Europe and Russia; Vietnam developing domestic collection infrastructure.

Planned Expansion (China, India, Japan): Major capacity shifts announced:

- China targeting 15-20% EAF share by 2030 (from 10%) [35]
- India 45% by 2030 (from 35%) [36]
- Japan large-scale EAF projects announced by JFE and Nippon Steel [38]

Challenge: Scrap availability growing slower than steel demand in industrializing economies. DRI supplementation necessary for quality requirements, increasing dependence on hydrogen/natural gas access.

4.2.4 Biomass and Alternative Carbon Sources

Brazil's Unique Position: Only major producer with significant biomass-based steelmaking. Charcoal use in BF-BOF operations already practiced at some facilities. Vale's Tecnored technology enables flexible fuel use (biomass, syngas, hydrogen) [32]. Sustainable plantation forestry provides feedstock without food-crop competition.

Carbon accounting complexity: Biomass considered carbon-neutral if sustainably sourced, but methodology and certification standards still developing. Brazilian advantage: abundant land for reforestation without displacing agriculture.

Limited International Adoption: Rio Tinto's BioIron technology (using agricultural waste) in pilot stage for Australian operations [**?**]. Otherwise, minimal biomass focus in global strategies due to feedstock constraints and logistics challenges.

4.3 Policy Instrument Comparison

Table 2 summarizes key policy instruments across examined countries.

Table 2: Comparison of Policy Instruments for Steel Decarbonization

Country/Region	Carbon Pricing	Public Funding	Trade Measures
EU (Germany, Italy)	ETS (€60-90/tCO_2), CBAM (2026+)	Innovation Fund (€40B+), RFCS, national programs	CBAM, safeguards, anti-dumping
China	National ETS (steel inclusion 2025+, price controls)	Undisclosed state funding, policy-directed lending	Capacity controls, export restrictions
India	PAT scheme (energy efficiency), voluntary carbon markets	National Green H_2 Mission ($2.5B), Steel Development Fund	Import tariffs, trade agreements
Japan	Voluntary action plans, limited carbon tax	Green Innovation Fund (¥450B steel), subsidies	Technology partnerships, export of BAT
USA	No federal carbon price (state/regional only)	DOE programs ($136M), IRA tax credits (45V, 45Q, 45X)	Section 232 tariffs, anti-dumping
South Korea	K-ETS (steel not included), planned inclusion	K-Steel Act framework, R&D investment	Trade agreements, technology partnerships
Brazil	No carbon pricing	Limited dedicated funding, blended finance schemes	Import tariffs, regional integration (Mercosur)
Russia, Iran	No carbon pricing	State research centers, limited funding	Trade restrictions (sanctions)
Turkey, Vietnam	No carbon pricing	Limited public funding	Export orientation, trade agreements

4.4 Funding Mechanisms and Levels

4.4.1 High-Resource Countries

Japan: Most aggressive public funding in absolute terms. Green Innovation Fund for steel: ¥449.9 billion (approximately $3 billion USD) over 2021-2030 [22]. 50% industry co-funding typical. Managed by NEDO (New Energy and Industrial Technology Development Organization).

European Union: Multi-source approach. Innovation Fund €2+ billion allocated to steel projects (2020-2024). Clean Steel Partnership €600 million total (2021-2027). RFCS €55 million annually (transitioning to Horizon Europe). National programs (Germany €2B hydrogen strategy, France similar). Carbon contracts for difference emerging.

United States: Tax credit approach via IRA rather than direct R&D grants. 45V (clean hydrogen production credit $3/kg for greenest), 45Q (CCUS credit $85/tonne), 45X (advanced manufacturing credit). DOE Industrial Decarbonization Office $136 million annual R&D budget. Total leverage significantly higher through tax credits.

4.4.2 Emerging Economy Approaches

India: Steel Development Fund established with $150+ million annual allocation. National Green Hydrogen Mission $2.5 billion total (across all sectors, steel priority area). Production-Linked Incentive (PLI) scheme for specialty steel. Tax benefits and preferential financing for green investments.

China: State funding levels not publicly disclosed. Policy-directed lending through state banks. Capacity swap mechanisms create implicit subsidy for modernization. Carbon trading revenues (when steel included) to support transformation.

Brazil: No dedicated steel decarbonization fund. Industrial Deep Decarbonization Initiative participation (announced July 2023). Blended finance schemes through development banks. EMBRAPII (Brazilian Company for Industrial Research and Innovation) as intermediary. Reliance on private sector and international partnerships for major projects.

4.5 Timeline Comparison and Net-Zero Targets

Table 3 compares decarbonization timelines across countries.

Table 3: Decarbonization Timeline Commitments by Country

Country	2030 Target	2040-2045 Target	Net-Zero
China	Peak emissions	–	2060
India	–	–	2070 (national)
Japan	60% reduction	73% reduction	2050
USA	Variable by admin	–	2050 (Paris)
Russia	No commitment	–	No target
South Korea	Pathway dev.	–	2050
Germany	55% reduction	65% (2045)	2045
Turkey	–	–	2053 (national)
Brazil	**42% (SDS)**	**–**	**2050 (implied)**
Iran	No commitment	–	No target
Vietnam	–	–	2050 (national)
Italy	55% reduction	–	2050

Key observations:

- European countries most aggressive with binding 2030 interim targets
- Asian economies (Japan, Korea) detailed mid-century pathways
- China peak-before-2030 strategy distinct from net-zero approach
- Brazil lacks sector-specific steel targets despite national commitments
- Sanctioned countries (Russia, Iran) no international commitments

4.6 Synthesis: Distinct National Models

Analysis reveals four distinct approaches to steel decarbonization:

Model 1: EU Comprehensive Coordination

- Strong carbon pricing plus border adjustment
- Substantial public funding with industry co-investment
- Coordinated across 27 member states

- Technology preference: H_2-DRI-EAF transition
- Example: Germany, Netherlands, Sweden, Italy

Model 2: Asian State-Coordinated

- Government-industry coordination without heavy carbon pricing
- Mission-oriented R&D programs
- Capacity management and structural adjustment
- Technology preference: Multiple pathways (H_2, CCUS, EAF)
- Example: Japan, South Korea, China

Model 3: Market-Driven with Incentives

- Tax incentives rather than direct regulation
- Limited federal coordination
- Industry-led technology selection
- Technology preference: Natural gas DRI, EAF, opportunistic CCUS
- Example: USA

Model 4: Emerging Economy Pragmatic

- Limited public funding, international partnerships
- Focus on leveraging natural resource advantages
- Incremental progress with pilot projects
- Technology preference: Context-dependent
- Example: India, Brazil, Turkey, Vietnam

Brazil's current positioning aligns with Model 4, but unique resource advantages suggest potential for hybrid approach combining elements of Models 1-3 with distinctive biomass pathway.

5 Brazil's Current Position: Projects, Policies, and Capabilities

5.1 Industry Structure and Emissions Profile

5.1.1 Production Capacity and Companies

Brazilian steel production reached 33.8 million tonnes in 2024, representing 5.6% growth over 2023 [1]. The industry comprises four major integrated producers and numerous EAF specialty mills:

Integrated BF-BOF Facilities (76% of capacity):

- **CSN (Companhia Siderúrgica Nacional):** Largest integrated producer, Volta Redonda (Rio de Janeiro). Capacity 5.8 MT annually. Owns iron ore mines. Leading hydrogen initiatives.
- **Usiminas:** Integrated facilities in Ipatinga and Cubatão. Capacity 4.8 MT. Joint venture with Nippon Steel (minority stake). Focus on flat products.
- **ArcelorMittal Brasil:** Part of global group. Integrated mills in Minas Gerais and Espírito Santo. Capacity 4.5 MT. Benefits from global R&D.
- **Ternium Brasil:** Integrated and semi-integrated facilities. Capacity 2.1 MT. Regional focus.

EAF Producers (24% of capacity):

- **Gerdau:** Largest EAF producer globally. Multiple facilities across Brazil. Total capacity 11.0 MT (including integrated). Specializes in long products, specialty steel. Strong scrap management capabilities.
- Numerous smaller regional EAF producers serving local markets.

5.1.2 Current Emissions Profile

Brazilian steel industry emissions estimated at 60-65 million tonnes CO_2 annually (calculated from production and technology mix). Breakdown by source:

- BF-BOF operations: 50-54 MT CO_2 (83-87%)
- EAF operations: 6-8 MT CO_2 (10-13%)
- Auxiliary operations: 2-3 MT CO_2 (3-5%)

Carbon intensity: Approximately 1.8-1.9 tonnes CO_2 per tonne steel (weighted average), slightly below global average (2.0) due to partial EAF capacity and some biomass use.

Decarbonization challenge: Achieving 2050 net-zero requires 85-95% emissions reduction, equivalent to 52-62 MT CO_2 annually from 2024 baseline.

5.2 Major Decarbonization Initiatives

5.2.1 CSN Selene Hydrogen Project

The Selene Project represents Brazil's most advanced green hydrogen initiative for steelmaking [33].

Project Structure (Three Phases):

Phase 1: Initial Implementation (Completion December 2025)

- Small-scale electrolyzer deployment (capacity not disclosed)
- Integration with existing operations
- Learning and process optimization
- Workforce training and capability development

Phase 2: Medium-Scale Deployment (2027-2028)

- Location: Araucária, Paraná state (southern Brazil)
- Capacity: 40 MW electrolyzer
- Application: Steel rolling and coating line facilities
- Renewable electricity sourcing from regional grid (high hydro/wind penetration)
- Estimated H_2 production: 1,600-1,800 tonnes/year

Phase 3: Integrated Steelmaking Application (2029-2030)

- Location: Rio de Janeiro (proximity to Volta Redonda integrated mill)
- Integration with BF-BOF operations (likely hydrogen injection or future DRI)
- Scale-up based on Phase 2 learnings
- Commercial viability demonstration

CSN-Petrobras Partnership (December 2024):
Protocol of intent for commercial-scale low-carbon hydrogen plant:

- Technology: Water electrolysis powered by renewable electricity
- Location: Paraná state (southern Brazil)
- Application: Industrial process fuel and feedstock for steelmaking
- Leverages Petrobras energy infrastructure and CSN steel expertise
- Potential for hydrogen export to regional markets (Argentina, Uruguay)

Technical Significance:
Selene demonstrates phased scale-up approach appropriate for capital-constrained contexts. Three-phase structure enables:

1. Risk mitigation through incremental investment
2. Learning-by-doing at each scale
3. Workforce capability development
4. Technology adaptation to Brazilian conditions (high humidity, tropical climate)
5. Economic validation before major capital commitment

Partnership with Petrobras brings complementary capabilities: energy sector expertise, project finance experience, government relationship management, and potential for integrated energy-industry hubs.

5.2.2 Vale Tecnored Technology

Tecnored represents proprietary Brazilian innovation in carbon-flexible ironmaking [32].

Technology Description:

Smelting reduction process using carbonaceous agglomerates (briquettes) rather than metallurgical coke:

- **Feedstock flexibility:** Accepts iron ore fines (no pelletizing required), reducing capital and operating costs
- **Reductant flexibility:** Can use biomass (charcoal, wood chips), syngas, hydrogen, or coal in various combinations
- **Lower temperature operation:** 1300-1400°C vs. 1500-1600°C for conventional BF
- **Direct pig iron output:** Molten iron suitable for steelmaking
- **Smaller scale viability:** Modular design enables 100,000-300,000 tonne/year plants (vs. 2-3 MT for modern BF)

Decarbonization Potential:

With 100% sustainable biomass: Near-zero net CO_2 emissions (carbon neutral if sustainably sourced). With hydrogen blend: Pathway to zero emissions while maintaining operational flexibility. Compared to conventional BF: 30-50% emissions reduction even with fossil fuel mix.

Development Status:

- Pilot plant operational since 2014
- Demonstration scale: 75,000 tonnes/year capacity
- Commercial scale design completed
- Research focus: Scaling to 300,000+ tonne/year units, optimizing biomass utilization, integrating hydrogen, long-term refractory performance

Strategic Implications:

Tecnored uniquely positions Vale to:

1. Move up value chain from ore exporter to green iron producer
2. Establish "Megahub" model: integrated mining, beneficiation, green iron production at single site
3. License technology to other producers (technology export revenue)
4. Supply certified low-carbon feedstock to EAF producers globally

Brazilian advantage: Abundant sustainable biomass from eucalyptus plantations (short rotation, high productivity, no food-crop displacement). Potential for circular integration with steel slag use in plantation fertilization.

5.2.3 Boston Metal Molten Oxide Electrolysis Plant

Boston Metal's commercial demonstration plant in Brazil represents first large-scale deployment of potentially disruptive MOE technology [13].

Technology Overview:

Molten oxide electrolysis dissolves iron ore in molten oxide electrolyte (1600°C). Electric current separates:

$$\text{Anode: } 2\text{O}^{2-} \rightarrow \text{O}_2 + 4e^- \quad (3)$$

$$\text{Cathode: } \text{Fe}^{2+} + 2e^- \rightarrow \text{Fe} \quad (4)$$

Key advantages:

- Zero direct CO_2 emissions (only byproduct: oxygen)
- Ore flexibility: Accepts low-grade, high-impurity ores
- Modular design: Cells added incrementally
- High-purity iron: Suitable for any steelmaking route
- Lower temperature than BF (though higher than DRI)

Brazil Plant Details:

- **Location:** Coronel Xavier Chaves, Minas Gerais (southwest Brazil, near ore sources)
- **Construction start:** 2023
- **Initial operations:** Small-scale 2024
- **Full operations:** Commercial demonstration scale 2026
- **Target capacity:** 10,000-20,000 tonnes/year initially (demonstration scale)

Financing and Partnerships:

- Series C funding: $122 million (September 2023)
- Series C2: $20 million (January 2024)
- Total raised: $300+ million
- Key investors: Aramco Ventures, Breakthrough Energy Ventures (Bill Gates), Marunoichi Innovation Partners (Japan), BHP Ventures
- Strategic partner: ArcelorMittal (consortium member, potential offtake agreement)

Technology Readiness:

Current TRL 5-6 (pilot to demonstration). Brazil plant critical milestone for advancement to TRL 7-8 (pre-commercial). Success factors: Cell durability at industrial scale, electricity consumption competitiveness (¡3 MWh per tonne iron target), operational reliability and uptime, economic viability at commercial scale.

Significance for Brazil:

1. Positions Brazil at frontier of breakthrough technology deployment
2. Attracts international cleantech investment
3. Creates high-skill jobs in advanced manufacturing
4. Potential for technology cluster development around plant
5. If successful, establishes Brazil as preferred location for green iron innovation

Risk: Technology unproven at commercial scale. Many promising steelmaking innovations failed at scale-up. However, international investor confidence and ArcelorMittal partnership provide validation.

5.3 Policy Frameworks and Government Support

5.3.1 National Policy Context

Brazil's steel decarbonization policy operates within broader industrial and climate frameworks:

Nationally Determined Contribution (NDC) - Updated October 2023:

- National target: 50% emissions reduction by 2030 (vs. 2005 baseline)
- Net-zero by 2050 commitment
- Sectoral targets: Focus on deforestation, energy, agriculture
- **Gap:** No specific steel industry mitigation measures or quantitative targets

Nova Indústria Brasil (NIB) Strategy - January 2024:

- National reindustrialization strategy
- Recognition of "green superpower" potential
- Structural investments in education and innovation
- **Weakness:** Overly broad mission orientation, lacks clear sector-specific roadmaps
- Steel mentioned favorably by President Lula but not in concrete action plan

5.3.2 Industrial Deep Decarbonization Initiative

Brazil joined the Industrial Deep Decarbonization Initiative in July 2023 at the Clean Energy Ministerial in India [34].

Significance:

- Initiative now represents 19% of global steel production
- Priority sectors: Steel, cement, petrochemicals
- Framework for international collaboration and knowledge exchange

Components:

1. Technology innovation and capacity building
2. Policy development for just transition
3. Social safety nets and workforce reskilling
4. Community engagement prioritization
5. Knowledge exchange through ISO 50001 training
6. Support for micro, small, and medium enterprises
7. Demonstration pilot projects

Funding Mechanisms:

- Co-funded blended finance schemes
- Seed funding for low-carbon technology entrepreneurs
- Collaboration with 80+ technology parks (20 state-run)
- Partnership with Brazilian research institutions and universities

5.3.3 Recent International Support

UNIDO Partnership: Industry, Cement, and Steel Sectoral Mitigation Plans development. Technical assistance for policy formulation. Aimed at readiness for COP30 (Brazil host, November 2025).

UK-Brazil Industrial Decarbonization Hub: Bilateral collaboration on technology transfer. Best practices sharing from UK industrial clusters. Focus on hydrogen, CCUS, and energy efficiency.

5.3.4 Research and Innovation Infrastructure

EMBRAPII (Brazilian Company for Industrial Research and Innovation):

- Intermediary organization connecting industry and research institutions
- Co-funding model: 1/3 EMBRAPII, 1/3 research institution, 1/3 industry partner
- Network of accredited research units in universities and institutes
- Steel-relevant units: Materials science, process engineering, energy systems

University-Industry Collaboration:
Historically weak linkages, but successful cases exist:

- Federal University of Minas Gerais (UFMG): Metallurgy programs, partnerships with local steel industry
- University of São Paulo (USP): Materials engineering, research collaboration with Gerdau and others
- COPPE/Federal University of Rio de Janeiro: Energy systems, hydrogen research

Challenge: Systematic, sustained collaboration remains exception rather than norm. Need for stronger knowledge transfer mechanisms and incentive alignment.

5.4 Critical Policy Gaps

Analysis reveals several significant gaps in Brazil's steel decarbonization policy framework:

1. **Absence of sector-specific targets:** NDC lacks quantitative goals for steel industry emissions reduction
2. **No dedicated financing mechanism:** Unlike India (Steel Development Fund), Japan (Green Innovation Fund), or EU (Innovation Fund), Brazil has no substantial public funding specifically for steel decarbonization
3. **Limited coordination across government:** Multiple ministries (Mines and Energy, Science and Technology, Industry, Environment) operate in silos without integrated steel strategy
4. **Unclear regulatory roadmap:** Industry lacks visibility on future carbon pricing, emissions standards, or green steel definitions
5. **Insufficient integration with energy policy:** Hydrogen strategy development not yet fully coordinated with industrial decarbonization needs
6. **Weak demand-side policies:** No public procurement preferences for low-carbon steel, limited green building codes incorporating embodied carbon
7. **Absence of competitiveness protection:** No border adjustment mechanism or safeguards specifically for green steel, exposing domestic producers to unfair competition

These gaps represent both challenge and opportunity. COP30 hosting (November 2025) creates political imperative and visibility for addressing deficiencies.

6 Brazil's Competitive Advantages and Strategic Opportunities

6.1 Renewable Energy Endowment

6.1.1 Current Energy Profile

Brazil's electricity matrix stands among the cleanest globally:

- **Hydroelectric:** 60-65% of generation
- **Wind:** 12-15% and rapidly growing
- **Biomass (sugarcane bagasse, etc.):** 8-10%
- **Solar:** 3-5% and fastest growing
- **Natural gas and other fossils:** ¡15%

Total renewable share: 83-87%, compared to global average of 28-30% [29].

Implications for steelmaking:

- EAF operations already low-carbon with grid electricity
- Green hydrogen production cost-competitive: Electricity cost dominates electrolyzer economics (60-70% of levelized cost). Brazil's renewable electricity costs ($30-50/MWh in many regions) enable $2-3/kg green H_2 by 2030 vs. $4-7/kg in most other countries [30]
- Grid reliability and capacity: Existing infrastructure supports industrial load; expansion needed for massive hydrogen production but technically feasible

6.1.2 Renewable Energy Potential

Brazil ranks in top 3 globally for prospective utility-scale solar and wind capacity [31]:

Solar potential:

- Northeast region: Among world's best irradiation levels (1900-2400 $kWh/m^2/year$)
- Capacity factor: 24-28% for fixed-tilt PV
- Land availability: Abundant semi-arid areas unsuitable for agriculture
- Cost trajectory: Declining rapidly with scale

Wind potential:

- Onshore: Northeastern coast and southern regions, excellent wind resources
- Offshore: Beginning exploration, vast potential along 7,400 km coastline
- Capacity factor: 35-45% onshore (world-class), potential 50

Hydroelectric:

- Existing: 109 GW installed capacity
- Additional potential: 100+ GW unexploited, primarily in Amazon basin (environmental concerns limit development)
- Role: Provides baseload and flexibility to balance variable solar/wind

Biomass/bioenergy:

- Sugarcane bagasse: 15-20 GW potential from existing ethanol industry
- Purpose-grown energy crops: Vast additional potential
- Forest residues: Sustainable harvest from managed forests

Strategic implication: Brazil can produce abundant low-cost renewable electricity for both electrification pathways (MOE, EAF) and green hydrogen production (H_2-DRI), providing fundamental cost advantage in green steel production.

6.2 Biomass Resources for Carbon-Neutral Steelmaking

6.2.1 Sustainable Biomass Potential

Brazil's biomass advantage for steelmaking unique globally:

Eucalyptus plantations:

- Fast-growing: 7-8 year rotation (vs. 20-40 years temperate forests)
- High productivity: 30-40 m^3/hectare/year
- Charcoal yield: 1 tonne charcoal from 3-4 tonnes eucalyptus wood
- Current scale: 9+ million hectares planted eucalyptus (primarily for pulp/paper)
- Additional land available: Degraded pasture (60-80 million hectares), no displacement of food crops or natural forest

Charcoal properties for steelmaking:

- Higher fixed carbon content than coal (75-80% vs. 60-70%)
- Lower sulfur content (beneficial for steel quality)
- Lower ash content
- Renewable if sustainably sourced: Net-zero CO_2 over plantation rotation cycle

Current charcoal use in Brazilian steel:

Approximately 6-8 million tonnes charcoal used annually in steel production, primarily in small-scale BF and ferro-alloy production in Minas Gerais. Some integrated mills use partial charcoal injection. Challenge historically: Sustainable sourcing, productivity, and consistency. Opportunity: Scale sustainable charcoal production integrated with modern steelmaking technology.

6.2.2 Tecnored Integration with Biomass Strategy

Vale's Tecnored technology specifically designed for biomass utilization:

- Accepts charcoal in briquette form (no pelletizing of ore required)
- Can blend biomass with other reductants for operational flexibility
- Lower temperature operation (vs. BF) better suited to charcoal properties
- Modular scale enables distributed production near biomass sources

Economic analysis: With sustainable plantation forestry:

- Charcoal cost: $150-250/tonne (depending on scale and logistics)
- Steelmaking requirement: approximately 500-600 kg charcoal per tonne iron
- Charcoal cost per tonne steel: $75-150
- Comparable to metallurgical coal cost in many regions

- Carbon credit value: $40-100 per tonne steel CO_2 avoided (at €40-100/tonne carbon price) improves competitiveness

Environmental considerations:
Sustainable biomass steelmaking requires rigorous certification:

- FSC (Forest Stewardship Council) or equivalent certification for plantations
- Avoidance of land-use change emissions
- Biodiversity protection in plantation management
- Water resource management
- Social and labor standards

Properly managed, offers genuinely carbon-neutral pathway unavailable to most steel-producing nations.

6.3 High-Quality Iron Ore Reserves

Brazil possesses world-class iron ore resources:

Reserves and quality:

- Total reserves: 34 billion tonnes (2nd globally after Australia)
- Average Fe content: 62-68% (high-grade)
- Low impurities: Phosphorus, sulfur content favorable for steelmaking
- Primary deposits: Carajás (Pará), Quadrilátero Ferrífero (Minas Gerais)

Relevance for decarbonization pathways:
H_2-DRI requirements:

- Requires ¿67% Fe, low gangue (SiO_2, Al_2O_3)
- Brazilian ores generally meet or exceed these specifications
- Advantage vs. lower-grade producers (China, India in some regions) requiring extensive beneficiation

MOE (Boston Metal) advantage:

- MOE technology accepts wide range of ore qualities
- Brazil's high-grade ores enable higher productivity and lower electricity consumption
- Flexibility to use lower-grade domestic ores in MOE if economically attractive

Vertical integration opportunity:

- Vale, BHP Brasil, others control both mining and processing
- Enables "Megahub" model: Integrated mining, green energy, green iron production at single site
- Reduces logistics costs and emissions from ore transport
- Creates opportunity for upstream carbon accounting and certified green iron products

6.4 Strategic Geographic Position

6.4.1 Domestic Market and Regional Integration

Domestic demand:

- Per capita steel consumption: 130-140 kg/year (2024)
- Below developed economy levels (300-500 kg) and Chinese peak (700+ kg)
- Growth potential: Infrastructure investment, urbanization, industrialization
- Provides domestic market for green steel as transformation proceeds

Mercosur integration:

- Regional trade bloc: Brazil, Argentina, Uruguay, Paraguay (Chile, Bolivia, others as associates)
- Combined steel market: 50+ million tonnes
- Opportunity for regional green steel hub: Brazil production supplying regional markets
- Hydrogen export potential: Argentina and Uruguay also developing renewable H_2 projects, potential for coordinated development

6.4.2 Export Market Access

Traditional export markets:

- USA: Significant destination for semi-finished and specialty steel
- Europe: Imports Brazilian steel, increasingly carbon-sensitive due to CBAM
- Latin America: Regional leader position
- Asia: Ore exports to China, potential for green iron/steel as markets develop

Green steel market positioning:

As carbon border mechanisms expand (EU CBAM operational 2026, potential similar measures in USA, Japan, others):

- Brazilian low-carbon steel avoids CBAM charges
- Potential for premium pricing in carbon-constrained markets
- "Made with Brazilian renewable energy and sustainable biomass" brand differentiation
- First-mover advantage in establishing certification and supply relationships

6.5 Innovation and Technology Development Capacity

6.5.1 Industrial and Engineering Capabilities

Brazil possesses sophisticated industrial capacity:

- Large-scale industrial project experience (offshore oil and gas, hydroelectric, ethanol/biofuels, aviation - Embraer)
- Engineering and construction firms capable of complex industrial projects
- Skilled workforce in metallurgy, chemical engineering, process control
- Academic strengths in materials science, metallurgical engineering, energy systems

Successful technology development examples:

- Flexfuel vehicles: World leader in ethanol-gasoline flex technology
- Deep-water oil extraction: Petrobras pre-salt technology
- Embraer regional aircraft: Global competitive aerospace industry
- Agricultural technology: Embrapa innovations in tropical agriculture

Pattern: Brazil succeeds when leveraging unique resource advantages (biofuels, deep-water oil, tropical crops) through sustained R&D investment and strong university-industry collaboration. Steel decarbonization opportunity follows similar template.

6.5.2 Potential for Technology Leadership

Strategic positioning for green steel technology development:

Biomass metallurgy expertise:

- Vale's Tecnored proprietary technology developed in Brazil
- Decades of experience with charcoal-based ironmaking (small-scale)
- Opportunity to become global knowledge center for sustainable biomass steelmaking
- Potential for technology licensing and consulting exports

Renewable hydrogen integration:

- Combining world-class renewable resources with industrial applications
- Learning from ethanol industry experience (distributed production, integration with agriculture)
- Pilot projects (CSN Selene) generating operational knowledge
- Potential leadership in hydrogen storage, transport in tropical/subtropical conditions

Breakthrough technology deployment:

- Boston Metal selected Brazil for first commercial-scale MOE plant
- Demonstrates international confidence in Brazilian industrial capabilities
- Potential to attract additional breakthrough technology developers
- Could establish innovation cluster around green steel technologies

6.6 COP30 Window of Opportunity

Brazil will host COP30 in November 2025 in Belém (Amazon region), creating unique strategic opportunity:

Political visibility and commitment:

- Global attention on Brazilian climate leadership
- Domestic political imperative for concrete achievements
- Opportunity to launch national green steel strategy with international support
- Platform for announcing major projects and attracting investment commitments

International partnership development:

- Bilateral technology cooperation agreements (EU, Japan, USA, others)
- Multilateral initiative engagement (Mission Innovation, Industrial Deep Decarbonization)
- Climate finance mobilization (Green Climate Fund, multilateral development banks)
- Private sector offtake agreements and investment commitments

Precedent: COP host country initiatives:

- Egypt COP27: Renewable energy initiatives, green hydrogen partnerships
- UAE COP28: Industrial decarbonization focus, technology cooperation
- Pattern: Host countries use COP as launching platform for signature initiatives

Optimal timing:
COP30 (late 2025) aligns well with:

- CSN Selene Phase 1 completion (December 2025)
- Boston Metal plant initial operations (2024-2025)
- Vale Tecnored commercial scale readiness
- Global green steel market development (EU CBAM implementation 2026)
- Brazilian electoral cycle (presidential election 2026) - establishes commitments before transition

Brazil could position itself as "green steel superpower" analogous to its established leadership in biofuels and renewable energy.

7 Challenges and Barriers to Realization

7.1 Policy and Institutional Challenges

7.1.1 Fragmented Governance Structure

Brazil's federalist system and institutional complexity create coordination challenges:

Multiple governmental levels:

- Federal ministries: Mines and Energy, Science and Technology, Industry, Environment, Economy (each with partial jurisdiction)
- State governments: Environmental licensing, tax incentives, energy policy
- Municipal governments: Zoning, local environmental regulation

Coordination deficit:

- No single agency with clear steel decarbonization mandate
- Limited inter-ministerial coordination mechanisms
- Risk of conflicting policies and regulatory uncertainty
- Slower decision-making compared to centralized systems (China, South Korea)

Recommendations:

- Establish high-level inter-ministerial working group with clear mandate
- Designate lead agency (likely Ministry of Mines and Energy or newly created industrial transition authority)
- Formalize consultation mechanisms with industry, labor, research institutions
- Develop integrated national steel decarbonization roadmap with quantitative targets and timelines

7.1.2 Absence of Carbon Pricing

Unlike EU, UK, South Korea, and other countries, Brazil lacks economy-wide carbon pricing:

Implications:

- No market-based incentive for emissions reduction
- Clean technologies must compete on cost alone without carbon price support
- Difficulty in business case justification for large capital investments
- Potential competitive disadvantage vs. producers in carbon-priced jurisdictions (if border adjustments applied)

Options for Brazil:

1. **National ETS:** Comprehensive cap-and-trade system covering major industrial sectors. Advantages: Flexibility, economic efficiency. Challenges: Political feasibility, administrative complexity.

2. **Carbon tax:** Direct price on emissions. Advantages: Simplicity, predictable price signal. Challenges: Political opposition, distributional concerns.

3. **Sectoral mechanisms:** Targeted schemes for industry (similar to India's PAT scheme). Advantages: Lower political barrier, sectoral buy-in. Challenges: Limited scope, potential inefficiency.

4. **Implicit carbon pricing:** Regulatory standards, technology mandates achieving similar effect without explicit price. Advantages: Politically feasible. Challenges: Less economically efficient, harder to optimize.

Even modest carbon price (\$20-40/tonne CO_2) would substantially improve economics of clean steel investments. Revenue recycling to support industrial transformation could gain political support.

7.1.3 Regulatory Uncertainty

Industry stakeholders cite regulatory uncertainty as major barrier to investment:

Key uncertainties:

- Future emissions standards and compliance timelines
- Definition and certification of "green steel" for domestic and export markets
- Environmental licensing process duration and requirements
- Grid connection and renewable energy procurement rules
- Tax treatment of decarbonization investments

Impact:

- Investors demand higher returns to compensate for policy risk
- Delays in final investment decisions pending regulatory clarity
- Competitive disadvantage vs. countries with clear, stable policy frameworks

Best practice (international):

- Germany: 10-year roadmap with binding interim targets
- UK: Carbon Budget system with five-year cycles
- South Korea: K-Steel Act with five-year master plans and annual roadmaps

Brazil should adopt similar approach: Multi-year national steel decarbonization plan with legislated framework providing stability across electoral cycles.

7.2 Financing and Investment Challenges

7.2.1 Capital Requirements

Steel decarbonization extremely capital-intensive:

Technology-specific capital costs (per tonne annual capacity):

- H_2-DRI plant + EAF: $600-900 (including electrolyzer)
- BF-BOF CCUS retrofit: $300-500 additional
- MOE (Boston Metal): Unknown, likely $400-700 (estimated)
- Tecnored: $250-400 (smaller scale, modular)
- New EAF (scrap-based): $150-300

Brazil total transformation cost estimate:

To decarbonize 76% BF-BOF capacity (25.7 MT):

- Full H_2-DRI conversion: $15-23 billion
- Mixed strategy (H_2, biomass, CCUS, EAF): $10-18 billion
- Phased implementation (2025-2040): $600 million - $1.2 billion annually

Additional costs: Hydrogen production infrastructure, renewable energy generation, transmission and distribution, R&D and workforce training.

7.2.2 Financing Gap

Current financial resources inadequate:

Industry capacity:

- Brazilian steel industry 2024 revenues: $20 billion (estimated)
- Profit margins: 5-10% historically (cyclical)
- Internal cash flow generation: $300-600 million annually available for major transformation investments (after sustaining capex, dividends)
- Gap: Cannot self-finance required $600 million - $1.2 billion annual transformation spending

Public funding:

- Current dedicated funding: Minimal
- BNDES (National Development Bank) lending capacity: Substantial, but requires clear policy direction and risk-sharing mechanisms
- International climate finance: Potential source, underutilized

Gap analysis:

Annual investment need: $600 million - $1.2 billion. Current mobilization: $100-200 million (estimated, from private sector). Financing gap: $400 million - $1.0 billion annually.

7.2.3 Proposed Financing Mechanisms

1. National Industrial Decarbonization Fund
Model: EU Innovation Fund, Indian Steel Development Fund

- Capitalization: $3-5 billion initial (10-year program)
- Sources: Government budget allocation, international climate finance, carbon auction revenues (if ETS implemented), dedicated tax on fossil fuels
- Function: Competitive grants for demonstration projects, Capital grants and soft loans for commercial deployment, Risk guarantees for first-of-kind facilities
- Co-funding: 30-50% industry contribution required

2. Green Steel Investment Tax Credits
Model: US Inflation Reduction Act

- Production tax credits: $50-100 per tonne CO_2 avoided for certified low-carbon steel
- Investment tax credits: 30-40% of qualified decarbonization capital expenditure
- Transferability: Credits tradeable to improve accessibility for tax-constrained firms
- Duration: 10 years to provide investment certainty

3. BNDES Green Steel Facility
Dedicated lending program through national development bank:

- Loan volume: $5-8 billion over 10 years
- Terms: Below-market interest rates, extended tenors (15-20 years)
- Eligibility: Projects meeting emissions reduction thresholds
- Risk-sharing: Partial government guarantee for early projects

4. International Climate Finance Mobilization
Leverage global funds:

- Green Climate Fund: $200-500 million potential
- World Bank and IFC: Lending and equity participation
- Bilateral development finance institutions: EU, Japan, USA development banks
- Private sector co-investment: Blended finance structures

Combined, these mechanisms could mobilize required $10-18 billion total investment over 2025-2040 period.

7.3 Technical and Operational Challenges

7.3.1 Hydrogen Supply and Infrastructure

Production scale-up:

Current Brazilian hydrogen production: ¡100,000 tonnes annually (primarily gray hydrogen for refining, ammonia). Required for steel decarbonization (full H_2-DRI pathway): 2-3 million tonnes annually green hydrogen by 2040.

Scale-up challenge: 20-30x increase requiring:

- 15-25 GW electrolyzer capacity deployment
- 30-50 GW additional renewable electricity generation (dedicated to hydrogen)
- Investment: $20-35 billion (electrolyzers and renewable generation)

Infrastructure requirements:

- Pipelines: H_2 embrittlement requires dedicated pipelines or repurposed natural gas lines with modification. Brazil's natural gas pipeline network limited (unlike USA, Europe). Likely need new dedicated hydrogen infrastructure connecting production (renewable energy hubs) to consumption (steel mills).
- Storage: Hydrogen storage (compressed, liquid, or underground) needed for renewable intermittency buffering. Technology exists but limited Brazilian experience at scale.
- Safety and standards: Hydrogen more energetic and diffusive than natural gas, requiring stringent safety protocols. Need for updated codes, standards, workforce training.

Phasing strategy:

Phase 1 (2025-2030): On-site hydrogen production at steel facilities (smaller scale, avoiding transport). CSN Selene model.

Phase 2 (2030-2040): Regional hydrogen hubs with pipeline connections. Leveraging renewable energy zones (Northeast solar/wind).

Phase 3 (2040+): National hydrogen network integrated with steel, other industries, potential exports.

7.3.2 Scrap Availability and Quality

EAF expansion limited by scrap constraints:

Current scrap generation: Brazil generates approximately 10-12 million tonnes steel scrap annually (from end-of-life products, manufacturing scrap). Current collection rate: 70-75% (vs. 85-90% in developed economies).

Growth potential: Scrap generation correlated with historical steel consumption (20-30 year lag for construction, 10-15 years for automotive). Brazilian steel consumption growth 2000-2020 creates scrap availability increase 2020-2050. Projected: 15-18 million tonnes by 2030, 20-25 million tonnes by 2040.

Quality challenges:

- Tramp elements (copper from wiring, tin from coatings) contaminate scrap, limiting use in high-quality steel grades

- Sorting and processing infrastructure underdeveloped
- Regional disparities (scrap abundant in industrialized Southeast, scarce in other regions)

Implications: EAF capacity can expand from current 24% to perhaps 35-40% by 2040 based on domestic scrap. Beyond that, requires:

- DRI supplementation (increasing dependence on hydrogen/natural gas)
- Scrap imports (economically marginal given transport costs)
- Advanced scrap sorting and cleaning technologies (research priority)

7.3.3 Workforce Transition and Skills Gap

Current workforce:

Brazilian steel industry directly employs approximately 80,000 workers. Indirect employment (mining, transport, supplies): 200,000+.

Skill requirements for new technologies:

- Hydrogen systems: Safety protocols, process control, maintenance
- Advanced materials: DRI handling, EAF operation, MOE (if deployed)
- Digital systems: Industry 4.0, AI-based process optimization, predictive maintenance
- Environmental management: Emissions monitoring, carbon accounting, certification

Current gaps:

- Limited Brazilian experience with industrial-scale hydrogen
- Traditional BF-BOF skills not directly transferable
- Shortage of specialized engineers and technicians
- Risk of brain drain (skilled workers attracted to higher-wage countries)

Training and education needs:

- University curriculum updates in metallurgical engineering programs
- Technical school programs for hydrogen technicians
- Industry-led training for existing workforce retraining
- International exchange programs (learn from early adopters in Europe, Japan)

Social transition concerns:

Steel-dependent communities (Volta Redonda, Ipatinga, others): Employment disruption during transformation could create social resistance. Just transition framework needed:

- Early retirement packages for workers near retirement age
- Retraining and placement assistance
- Regional economic diversification support
- Community engagement and consultation

International precedent: Germany's coal phase-out with substantial worker support ($40 billion program), UK's industrial transition funds.

7.4 Market and Competitiveness Challenges

7.4.1 Green Steel Price Premium Uncertainty

Economic viability depends on price premium for low-carbon steel:

Cost differential:

Green steel production costs estimated $100-300 per tonne higher than conventional BF-BOF (depending on hydrogen price, capital cost allocation). Requires either:

- Sufficient carbon price differential (if border adjustments applied)
- Market premium from willing buyers
- Public subsidies to bridge cost gap during transition

Current premium evidence:

Limited transactions to date make price discovery difficult:

- H2 Green Steel (Sweden): Offtake agreements with automotive customers (Mercedes, BMW, Volvo) at undisclosed premium
- Thyssenkrupp: Pilot sales of low-CO_2 steel at €50-100 per tonne premium
- ArcelorMittal XCarb: Premium products marketed but volumes small

Buyer willingness to pay:

- Automotive sector: Strong commitment (Scope 3 targets), willing to pay moderate premiums
- Construction: More price-sensitive, limited premium willingness except public procurement
- Appliances and machinery: Minimal premium currently

Risk for Brazil:

If premiums fail to materialize, green steel investments may not achieve returns. Mitigation: Phased approach, starting with cost-competitive biomass pathways, expanding to hydrogen as costs decline.

7.4.2 Competition from Low-Cost/High-Emission Producers

Global overcapacity and trade dynamics threaten Brazilian competitiveness:

Chinese competition:

- China 1 billion tonnes annual capacity, 900 million tonnes domestic consumption
- Persistent overcapacity drives exports at low prices
- State subsidies and policy-directed lending create non-market competition
- Brazilian imports from China: Limited currently due to freight costs, but threat in low-value products

Regional competition:

- Mexican steel (NAFTA preferential access to USA)
- Argentinian producers (Mercosur integration)
- Colombian, Venezuelan capacity (when operational)

Export market access:

If Brazil invests heavily in decarbonization while competitors do not:

- Higher costs could reduce export competitiveness
- Domestic market could face import competition from lower-cost/higher-emission producers
- Risk of "carbon leakage" (production shifting to less-regulated jurisdictions)

Mitigation strategies:

1. Border adjustment mechanism (Brazilian version of CBAM) to protect domestic market
2. Trade agreements with carbon intensity provisions
3. Anti-dumping and countervailing duties against subsidized imports
4. Focus on premium markets and customers valuing sustainability
5. Cost competitiveness through renewable energy advantage (offset higher capital costs)

7.4.3 Technology Risk and Uncertainty

First-of-kind technology deployment carries inherent risks:

Technical performance risk:

- MOE unproven at commercial scale; could face unexpected challenges
- H_2-DRI at scale may encounter operational issues not apparent in pilots
- Biomass steelmaking productivity and consistency questions at large scale

Cost escalation risk:

- Actual capital and operating costs may exceed estimates
- Learning curve benefits uncertain
- Alternative technologies could emerge, rendering early investments obsolete

Integration challenges:

- New technologies integrating with existing infrastructure may face unforeseen difficulties
- Supply chain for specialized equipment and materials may be constrained
- Operational expertise development takes time

Risk management approaches:

- Phased deployment: Pilot → demonstration → commercial
- Portfolio approach: Pursue multiple pathways simultaneously
- International partnerships: Share risks and learn from global experiences
- Flexible capital investment: Avoid premature lock-in to single technology
- Government risk-sharing: Public funding for early projects reduces private risk

8 Policy Recommendations and Strategic Roadmap

8.1 Short-Term Priorities (2025-2027)

8.1.1 Recommendation 1: Establish National Steel Decarbonization Roadmap

Action: Federal government should publish comprehensive sectoral decarbonization roadmap by Q2 2026 (aligned with COP30 commitments).

Content:

- Quantitative emissions reduction targets: 25% by 2030, 50% by 2035, 80-95% by 2050 (from 2024 baseline)
- Technology pathway analysis and priorities for Brazilian context
- Phasing timeline for different steel production technologies
- Infrastructure requirements (hydrogen, renewable energy, grid)
- Investment estimates and financing strategy
- Workforce transition plan
- Research and innovation priorities

Process:

- Inter-ministerial working group (Mines and Energy lead)
- Stakeholder consultation (industry, labor, environmental groups, researchers)
- International expert review (leverage partnerships with IEA, UNIDO, bilateral)
- Legislative endorsement for stability across electoral cycles

Expected impact: Provides clarity for industry investment decisions, coordinates government actions across ministries, establishes Brazil's credibility in international climate forums.

8.1.2 Recommendation 2: Launch National Industrial Decarbonization Fund

Action: Establish dedicated financing mechanism for steel and other hard-to-abate sectors by end of 2026.

Design parameters:

- Initial capitalization: R$15-25 billion ($3-5 billion USD equivalent) over 10 years
- Funding sources: Government budget allocation (R$5-8 billion), International climate finance (R$3-5 billion), Carbon revenues if ETS implemented (R$5-10 billion), Debt issuance (green bonds) (R$2-3 billion)
- Disbursement mechanisms: Competitive grants for R&D and demonstration (30%), Capital grants for commercial deployment (40%), Concessional loans and guarantees (30%)
- Eligibility criteria: Minimum emissions reduction threshold (e.g., 50% vs. conventional), Technical and financial viability assessment, Employment and just transition plan, Sustainability certification

Governance:

- Independent board with industry, government, civil society representation
- Transparent project selection process
- Regular reporting and evaluation
- Sunset clause requiring renewal based on performance

Expected impact: Bridges financing gap, de-risks early investments, catalyzes private sector capital, demonstrates government commitment.

8.1.3 Recommendation 3: Leverage COP30 for International Partnerships

Action: Use COP30 (November 2025) as launching platform for Brazilian green steel initiative.

Deliverables for COP30:

1. Launch national steel decarbonization roadmap
2. Announce major project commitments (CSN Selene Phase 2, Tecnored commercialization, Boston Metal plant inauguration)

3. Sign bilateral technology cooperation agreements (Target: EU, Japan, USA, Australia)
4. Secure international climate finance commitments ($500 million - $1 billion target)
5. Establish "Green Steel Alliance" with other emerging producers (India, South Africa, Indonesia)
6. Showcase Brazilian renewable energy and biomass advantages through high-profile events

Post-COP follow-through:

- Establish bilateral working groups with technology partner countries
- Negotiate offtake agreements with international steel buyers
- Participate in green steel certification and standards development
- Position Brazil as knowledge hub for biomass metallurgy and tropical/subtropical hydrogen systems

Expected impact: International visibility and credibility, Accelerated technology transfer, Catalyzed investment (domestic and foreign), Established leadership position in global green steel transition.

8.2 Medium-Term Priorities (2028-2035)

8.2.1 Recommendation 4: Develop Hydrogen Infrastructure

Action: Build out hydrogen production and distribution infrastructure integrated with steel production hubs.

Phase 1: On-site production (2025-2030)

- Electrolyzers at major steel facilities (5-10 sites)
- Capacity: 500 MW - 1 GW total
- Renewable energy: On-site solar/wind or dedicated PPAs
- Demonstration and workforce training focus

Phase 2: Regional hubs (2030-2037)

- Large-scale production in optimal renewable resource zones (Northeast solar/wind, South hydropower backup)
- Pipeline connections to industrial clusters
- Capacity: 5-10 GW electrolyzers
- Shared infrastructure reduces per-unit costs

Financing strategy:

- Public-private partnerships for infrastructure

- Anchor contracts from steel industry providing revenue certainty
- Integration with broader hydrogen economy (transport, ammonia production, exports)

Policy enablers:

- Streamlined permitting for hydrogen projects
- Grid connection priority for hydrogen-linked renewables
- Safety standards and codes development
- Hydrogen blending mandate for natural gas (phased introduction)

8.2.2 Recommendation 5: Strengthen University-Industry Collaboration

Action: Build robust research ecosystem for green steel technologies.
Institutional mechanisms:

1. **Centers of Excellence:** Establish 3-5 university-based centers focusing on: Hydrogen metallurgy, Biomass steelmaking, Electrochemical ironmaking, Carbon capture and utilization, Digital manufacturing and AI optimization
2. **Industrial PhD programs:** Co-supervised by university and industry, Students embedded in steel companies, Funding from Industrial Decarbonization Fund, Target: 50-100 PhDs by 2035
3. **EMBRAPII expansion:** Increase steel-focused research units, Enhanced funding for pre-commercial development, Faster technology transfer mechanisms
4. **International research networks:** Partnerships with leading institutions (MIT, RWTH Aachen, University of Tokyo, etc.), Researcher exchange programs, Joint projects leveraging complementary strengths

Funding:

- Government research grants: R$200-300 million annually
- Industry co-funding: Matching requirement
- International collaboration grants

Expected outcomes:

- Technology development and adaptation to Brazilian conditions
- Workforce training (master's and PhD students)
- Publication and IP generation
- Spin-off company creation
- International recognition as green steel research hub

8.2.3 Recommendation 6: Implement Green Steel Certification System

Action: Establish national framework for low-carbon steel certification compatible with international standards.

System design:

- **Carbon intensity tiers:** Ultra-low (¡0.2 t CO_2/t steel), Low (0.2-0.8), Medium (0.8-1.4), Standard (¿1.4 - current BF-BOF baseline)
- **Methodology:** Lifecycle assessment (LCA) approach following ISO 14040/14044, Scope 1 and 2 emissions (direct and electricity), Cradle-to-gate boundary (mine to steel mill gate), Third-party verification required
- **Certification body:** Independent organization with multi-stakeholder governance, Accreditation by national standards body (INMETRO), Mutual recognition agreements with international schemes (ResponsibleSteel, EU standards)
- **Digital product passport:** Blockchain or similar for traceability, QR code on products linking to certificate, Enables supply chain transparency for downstream buyers

Integration with policy:

- Public procurement preference for certified low-carbon steel (10-20% price premium accepted)
- Tax incentives linked to certification tier
- Eligibility for Industrial Decarbonization Fund based on certification
- Trade policy: Expedited customs for certified exports, Border adjustment exemptions for certified imports (if mechanism implemented)

Timeline:

- 2026: Stakeholder consultation and methodology development
- 2027: Pilot phase with volunteer companies
- 2028: Full launch and mandatory for public procurement
- 2029: Integration with trade policy

8.3 Long-Term Vision (2036-2050)

8.3.1 Recommendation 7: Strategic Technology Portfolio Management

Action: Maintain diversified technology portfolio through 2050 transition.

Technology-specific strategies:

Biomass-based steelmaking:

- Comercialize Tecnored at scale (target: 15-20% of capacity by 2040)
- Develop sustainable plantation forestry supply chains

- Pursue premium markets valuing unique carbon-neutral pathway
- License technology internationally for revenue and knowledge leadership

Hydrogen-DRI-EAF:

- Follow global cost reduction curve (green H_2 reaching $1-2/kg by 2040s)
- Deploy at large integrated mills as capital stock turns over
- Target: 40-50% of capacity by 2045-2050
- Focus on high-quality steel grades for premium markets

Advanced EAF with scrap:

- Expand from 24% to 35-40% by 2040 as scrap availability grows
- Invest in scrap sorting and processing technologies
- Develop advanced EAF designs for high productivity and efficiency
- Target: Construction and lower-grade applications

Breakthrough technologies (MOE, etc.):

- Monitor Boston Metal and other demonstrations
- If technically successful, deploy at 5-15% of capacity by 2045-2050
- Advantage: Ore flexibility and potential low cost with cheap renewable electricity
- Risk: Technology may not achieve commercial viability

Residual BF-BOF with CCUS:

- Limited role (10-15% capacity) for assets with long remaining life
- CCUS retrofit where economically justified
- Primarily bridge technology to 2040-2050
- Phase out as newer technologies become cost-competitive

2050 target capacity mix:

- Biomass-based: 15-20%
- H_2-DRI-EAF: 40-50%
- Scrap-EAF: 35-40%
- Breakthrough (MOE, etc.): 5-15%
- BF-BOF with CCUS: ¡5% or phased out

Total capacity: 35-45 MT (maintaining current scale or modest growth with demand).

8.3.2 Recommendation 8: Position as Green Steel Exporter

Action: Develop export strategy capitalizing on low-carbon advantage.

Target markets:

- **European Union:** CBAM creates strong incentive for low-carbon imports. Brazilian steel avoids border adjustment charges. Premium market for high-quality, certified green steel.
- **North America:** Growing climate consciousness, potential US carbon border mechanism. Existing trade relationships and proximity advantage.
- **Japan and South Korea:** Limited domestic resources, import-dependent. Potential for long-term supply agreements.
- **Latin America:** Regional leadership position. Lower transportation costs. Integration through Mercosur and other agreements.

Product focus:

- High-value specialty steels (automotive, machinery)
- Certified green steel with full traceability
- Semi-finished products for further processing
- Green HBI/DRI for export to EAF producers globally

Branding strategy:

- "Brazilian Green Steel" certification mark
- Marketing emphasis on renewable energy and sustainable biomass
- Differentiation from competitors on carbon intensity
- Sustainability storytelling (connection to Amazon preservation, renewable energy leadership)

Trade policy integration:

- Negotiate green steel provisions in trade agreements
- Mutual recognition of carbon certification with major markets
- Export credit agency support for green steel transactions
- Trade missions and buyer-seller matchmaking

Volume targets:

- 2030: 5-7 MT green steel exports (from 10-12 MT total exports)
- 2040: 10-15 MT green steel exports (from 15-20 MT total)
- 2050: 15-20 MT premium green steel exports

8.4 Enabling Policies and Institutional Reforms

8.4.1 Carbon Pricing Implementation

Recommendation: Introduce carbon pricing by 2028-2030 to provide market-based incentive.

Preferred approach: Sectoral emissions trading system (ETS) for industry:

- Coverage: Steel, cement, chemicals, pulp and paper, oil refining (major industrial emitters)
- Initial price: R$50-100 per tonne CO_2 ($10-20 USD)
- Price trajectory: Gradual increase to R$200-300 ($40-60) by 2035
- Free allocation: Phased reduction from 90% (initial) to 30% (2040)
- Revenue recycling: 100% of auction revenues to Industrial Decarbonization Fund

Competitiveness protection:

- Border carbon adjustment on imports (Brazilian CBAM equivalent)
- Export rebates for carbon costs embedded in products
- Benchmarking and free allocation for trade-exposed sectors
- Regular review and adjustment to maintain competitiveness

Political economy:

- Build coalition with environmental groups, progressive industry leaders
- Emphasize revenue recycling (no net tax increase)
- Frame as competitiveness measure (preparing for global carbon border adjustments)
- Pilot with voluntary phase before mandatory implementation

8.4.2 Regulatory Modernization

Recommendation: Streamline permitting and regulatory processes for green steel investments.

Key reforms:

1. **Fast-track environmental licensing:** Expedited review for projects with demonstrated emissions reductions. Single federal-state coordinated process (avoiding duplication). Defined timelines with automatic approval if deadlines missed. Pre-approved technology list (standardized review for proven approaches).
2. **Grid connection priority:** Renewable energy projects linked to industrial decarbonization receive priority grid connection. Streamlined interconnection studies and approvals. Cost-sharing for grid reinforcement needed for hydrogen hubs.

3. **Hydrogen safety codes:** Adopt international standards (ISO, NFPA) with Brazilian adaptations. Training and certification programs for hydrogen workers. Inspection and enforcement capacity building.

4. **Land use and zoning:** Industrial zoning reforms to accommodate hydrogen infrastructure, biomass logistics, renewable energy integration. Coordination across federal, state, and municipal jurisdictions.

Implementation:

- Legislative package introduced 2026, enacted 2027
- Regulatory agency capacity building (training, staffing)
- Stakeholder working groups to develop implementing regulations
- Monitoring and continuous improvement based on experience

8.4.3 Just Transition Framework

Recommendation: Comprehensive worker and community transition support.

Worker support programs:

- **Retraining:** Technical education in hydrogen systems, advanced steelmaking, digital technologies. Tuition-free programs with living stipends. Partnerships with companies guaranteeing interviews/placement.
- **Early retirement:** Voluntary early retirement for workers within 5 years of eligibility. Enhanced pension benefits (80-90% of final salary). Health insurance continuation.
- **Job placement:** Career counseling and placement services. Priority hiring at new green steel facilities. Relocation assistance if necessary.
- **Income support:** Transition allowances during retraining or job search (6-12 months at 70% of previous salary). Extension for older workers with difficulty transitioning.

Community transition:

- Economic diversification grants for steel-dependent regions
- Infrastructure investment to attract new industries
- Small business development support
- Education and healthcare facility upgrades

Financing:

- R$2-4 billion Just Transition Fund over 15 years
- Combination of federal budget, carbon pricing revenues, international climate finance

- Modeled on European Just Transition Mechanism

Governance:

- Tripartite structure (government, industry, labor unions)
- Regional transition committees in affected areas
- Transparent monitoring of outcomes (employment, income, community indicators)

8.5 International Cooperation Priorities

8.5.1 Technology Partnerships

European Union:

- Focus: H_2-DRI technology transfer, CCUS, certification standards
- Mechanisms: Joint R&D projects under Horizon Europe, Industrial decarbonization working group, Brazilian participation in Clean Steel Partnership (observer or associate status)
- Companies: Partnerships with Thyssenkrupp, ArcelorMittal, SSAB, Salzgitter

Japan:

- Focus: COURSE50 technology, energy efficiency, quality steel production
- Mechanisms: NEDO-Brazilian counterpart collaboration, JCM (Joint Crediting Mechanism) for carbon credits, Technology demonstration projects with JISF members
- Companies: Nippon Steel (already invested in Usiminas), JFE Steel, Kobe Steel

Australia:

- Focus: Green hydrogen development, iron ore to green iron value chain
- Mechanisms: Bilateral hydrogen partnership, HYSUPPLY consortium participation (if applicable)
- Companies: Fortescue Future Industries (FFI), Rio Tinto (BioIron), BHP

United States:

- Focus: Breakthrough technologies, digital manufacturing, market access
- Mechanisms: DOE-Brazilian ministry collaboration, Research partnerships with national laboratories (NREL, Argonne)
- Companies: Boston Metal (already in Brazil), technology provider partnerships

South Korea:

- Focus: HyREX and other proprietary technologies, heavy industry transformation experience
- Mechanisms: Bilateral industrial cooperation agreement, Technology licensing discussions
- Companies: POSCO, Hyundai Steel

8.5.2 South-South Cooperation

Green Steel Alliance with Emerging Producers:

Establish coalition with India, South Africa, Indonesia, and other emerging economy steel producers:

Objectives:

- Share experiences and best practices in industrial transformation
- Coordinate positions in international climate negotiations
- Joint technology development (pooling resources)
- Collective advocacy for differentiated responsibilities and support
- Market cooperation (avoiding destructive competition)

Activities:

- Annual ministerial meeting on steel decarbonization
- Technical working groups on specific challenges
- Joint research projects and pilot demonstrations
- Capacity building and training exchanges
- Development of common certification and standards

Financing:

- Coalition seeking dedicated international climate finance
- World Bank or regional development bank facility
- Technology transfer on concessional terms from developed countries

8.5.3 Standards and Certification Harmonization

Recommendation: Active participation in international green steel standards development.

Forums:

- ISO technical committees on steel and carbon accounting
- ResponsibleSteel certification scheme (join as member)
- Global Steel Climate Council (if established)
- IEA Steel Technology Roadmap collaboration
- UNFCCC technology mechanism engagement

Priorities:

- Ensure biomass pathways recognized in international standards

- Methodology for carbon accounting in tropical/subtropical conditions
- Mutual recognition of Brazilian certification with EU, USA, Japan, others
- Avoid proliferation of incompatible standards (reducing trade barriers)

Expected benefits:

- Brazilian products accepted in global markets
- Influence on standards reflects Brazilian interests and capabilities
- Reduced compliance costs through harmonization
- Enhanced credibility and reputation

9 Conclusions

9.1 Summary of Key Findings

This comprehensive analysis of Brazil's position in global steel decarbonization reveals several critical insights:

1. Unique strategic advantages: Brazil possesses a distinctive combination of abundant renewable energy resources (83-87% clean electricity), sustainable biomass potential unavailable to most competitors, high-quality iron ore reserves, and advanced demonstration projects in breakthrough technologies. This positions Brazil to become a global leader in low-cost green steel production.

2. Technology pathway diversity: Unlike many countries pursuing single primary pathways (Europe: H_2-DRI; USA: natural gas DRI + EAF; China: EAF expansion), Brazil can leverage multiple approaches: biomass-based steelmaking (Tecnored), green hydrogen from renewable electrolysis, scrap-based EAF expansion, and potentially disruptive MOE technology. This diversification reduces risk and enables optimization for different market segments.

3. Critical policy gaps: Despite favorable resource endowments and promising projects, Brazil lacks essential policy infrastructure: sector-specific decarbonization targets in NDC, dedicated financing mechanisms comparable to international peers, coordinated governmental strategy across ministries, carbon pricing to incentivize emissions reduction, and competitiveness protection measures for transition period.

4. Substantial but achievable investment requirements: Full transformation of Brazil's steel sector requires $10-18 billion total investment over 2025-2040, equivalent to $600 million - $1.2 billion annually. This exceeds industry's self-financing capacity but is achievable through combined public-private mechanisms, international climate finance, and innovative financing structures.

5. Window of opportunity timing: The next 2-3 years represent critical decision period. COP30 hosting (November 2025) creates unique political visibility and momentum. Major technology demonstrations (CSN Selene, Boston Metal, Tecnored) reaching maturity. Global green steel market developing as EU CBAM implementation begins (2026). Delaying action risks missing first-mover advantages and falling behind competitors.

6. Comparative international context: Analysis of twelve major steel-producing countries reveals distinct national models. Brazil currently follows "Emerging Economy Pragmatic" approach (limited public funding, reliance on international partnerships, incremental progress). However, unique resource advantages suggest potential for hybrid model combining best elements of European coordination, Asian state support, and distinctive Brazilian biomass/renewable pathway.

9.2 Implications for Theory and Practice

9.2.1 Contributions to Industrial Decarbonization Literature

This research advances academic understanding in several domains:

Resource advantages in energy transitions: Challenges traditional "resource curse" narratives by demonstrating how natural resource endowments (renewable energy, biomass, minerals) can drive innovation and value capture when combined with appropriate policy frameworks. Extends work by Mazzucato, Rodrik, and others on resource-based industrial strategy.

Technology pathway selection in emerging economies: Contributes to literature on appropriate technology choices for developing countries. Demonstrates importance of context-specific factors (resource availability, industrial structure, institutional capacity) rather than one-size-fits-all prescriptions. Biomass pathway, for example, unsuitable for most countries but highly promising for Brazil.

Multi-level governance challenges: Provides empirical case study of coordination challenges in federal systems (relevant to USA, India, others). Shows necessity of vertical integration (federal-state-municipal) and horizontal integration (across ministries and agencies) for effective industrial transformation.

Just transition frameworks: Adds emerging economy perspective to predominantly European/North American literature on workforce and community transition. Highlights different constraints (limited fiscal capacity) and opportunities (younger workforce, growing economy) in developing country contexts.

International cooperation mechanisms: Analyzes technology transfer, financing, and standards harmonization challenges from recipient country perspective. Identifies tensions between intellectual property protection and technology diffusion, between competitiveness concerns and climate cooperation.

9.2.2 Policy Implications Beyond Brazil

Findings have relevance for other emerging economy steel producers and hard-to-abate sectors:

For other countries:

- India: Similar challenges (large BF-BOF capacity, capital constraints, federal system) but different resources (less renewable energy, limited biomass). Can learn from Brazilian financing mechanisms and international partnership approaches.

- Indonesia, Vietnam, South Africa: Smaller producers with growth potential. Brazilian model of leveraging natural advantages and breakthrough technology deployment applicable.

- Iran, Turkey: Resource-rich but politically constrained. Technical aspects of biomass integration and renewable hydrogen relevant despite limited international cooperation opportunities.

For other sectors:

- Cement: Parallel decarbonization challenge, similar policy instrument needs
- Chemicals: Hydrogen as feedstock, renewable energy integration
- Aluminum: Electrification pathway, renewable electricity crucial
- Heavy transport: Hydrogen and biofuels, infrastructure requirements

Brazilian steel decarbonization framework (multi-technology portfolio, phased implementation, international partnerships, just transition integration) transferable with adaptations.

9.3 Limitations and Future Research

9.3.1 Study Limitations

Data constraints:

- Proprietary project information limited public availability
- Inconsistent reporting across countries hinders precise comparisons
- Rapidly evolving field means analysis quickly dated

Uncertainty in projections:

- Technology costs, particularly hydrogen and breakthrough approaches, highly uncertain
- Carbon pricing and green steel premiums difficult to forecast
- Political and policy trajectories unpredictable (electoral cycles, international relations)

Scope limitations:

- Focus on production-side transformation; limited analysis of demand-side policies and consumption patterns
- Domestic focus; limited treatment of global trade dynamics and geopolitical dimensions
- Primary emphasis on CO_2; other environmental impacts (water, biodiversity, circular economy) mentioned but not deeply analyzed

9.3.2 Future Research Agenda

Technology-specific studies:

1. Detailed techno-economic analysis of Tecnored at commercial scale (sensitivity to biomass costs, productivity, product quality)
2. Brazilian-specific H_2-DRI modeling (tropical climate effects, seasonal renewable variations, infrastructure requirements)
3. MOE scaling challenges and economics in Brazilian context
4. Advanced scrap processing technologies for quality improvement

Economic and financial analysis:

1. Detailed cost-benefit analysis of proposed financing mechanisms
2. Assessment of green steel price premium evolution and market development
3. Analysis of stranded asset risks for existing BF-BOF capacity
4. Evaluation of carbon leakage risks and border adjustment effectiveness

Social and environmental dimensions:

1. Worker transition pathways and retraining effectiveness studies
2. Community impacts in steel-dependent regions (Volta Redonda, Ipatinga)
3. Sustainable biomass supply chain development and certification
4. Water resource implications of hydrogen production in semi-arid regions
5. Biodiversity impacts of renewable energy and plantation forestry expansion

Policy and governance:

1. Comparative analysis of federal coordination mechanisms in steel decarbonization
2. Assessment of carbon pricing design options for Brazilian context
3. Analysis of regulatory barriers and reform priorities
4. Evaluation of public procurement as market-making instrument

International dimensions:

1. Brazil-EU trade implications of CBAM and potential responses
2. South-South cooperation mechanisms for industrial decarbonization
3. Technology transfer barriers and enabling policies
4. Green steel certification and standards harmonization challenges

9.4 Final Reflections

The global steel industry's decarbonization represents one of the most significant industrial transformations of the 21st century. Success requires unprecedented coordination among governments, industry, academia, and civil society, sustained over multiple decades, in the face of substantial technical and economic uncertainties.

Brazil stands at a unique historical juncture. The combination of world-class renewable energy resources, distinctive biomass potential, high-quality mineral reserves, and advanced industrial capabilities positions the country to become a global leader in green steel production. The economic opportunity is substantial: capturing high-value export markets, developing and licensing proprietary technologies, creating high-skill jobs, and establishing knowledge leadership in a critical sector.

However, realization of this potential is not inevitable. It requires decisive policy action, substantial financial mobilization, sustained political commitment, and effective international partnerships. The next 2-3 years represent a critical window. Delays risk missing first-mover advantages as European, Japanese, and South Korean producers establish market positions and technology leadership.

The policy recommendations in this paper—national steel decarbonization roadmap, industrial decarbonization fund, COP30 launching platform, hydrogen infrastructure development, enhanced university-industry collaboration, green steel certification, carbon pricing, and just transition framework—provide an actionable agenda for positioning Brazil at the forefront of the steel sector transformation.

Success would reverberate beyond steel alone. It would demonstrate emerging economy capability to lead in advanced industrial technology development, validate the potential for resource-based green industrialization, provide templates for other hard-to-abate sectors, and contribute meaningfully to global climate change mitigation.

The choice is Brazil's to make. The resources, capabilities, and opportunities exist. What remains is the political will, strategic vision, and sustained implementation to transform potential into reality.

As Brazil prepares to host COP30 and stake its claim to global climate leadership, the steel industry presents a concrete opportunity to move from aspirational rhetoric to tangible achievement. The world is watching. The time for action is now.

Acknowledgments

The authors gratefully acknowledge the collaborative effort that made this comprehensive analysis possible. André Costa e Silva provided invaluable expertise on Brazilian steel industry dynamics and decarbonization initiatives. Fabio Miani of the University of Udine contributed academic rigor, comparative policy analysis, and the foundational research from his MIFUS project "A Journey through Policies of Steel Decarbonization." Claude (Anthropic AI) provided systematic literature review, data synthesis, and analytical framework development, with all outputs validated by the human co-authors. Special thanks to the professionals at CSN, Vale, Boston Metal, and other companies who have shared information about their projects through public channels. We also acknowledge the support of the Department of Polytechnic Engineering and Architecture at the University of Udine. Any errors or omissions remain the sole responsibility of the authors.

References

[1] World Steel Association (2025). *World Steel in Figures 2025*. Brussels: worldsteel.

[2] World Steel Association (2023). *Short Range Outlook October 2023*. Brussels: worldsteel.

[3] International Energy Agency (2023). *Iron and Steel Technology Roadmap*. Paris: IEA.

[4] Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, 203, 736-745.

[5] SSAB (2024). *HYBRIT: Towards fossil-free steel*. Available: https://www.hybritdevelopment.se/

[6] Fischedick, M. et al. (2024). Techno-economic analysis of hydrogen-based steelmaking pathways. *International Journal of Hydrogen Energy*, 49(15), 234-256.

[7] International Energy Agency (2023). *CCUS in Clean Energy Transitions*. Paris: IEA.

[8] Bellona Foundation (2023). *Carbon Capture and Storage in the Steel Industry*. Oslo: Bellona.

[9] ArcelorMittal (2024). *Climate Action Report 3*. Luxembourg: ArcelorMittal.

[10] Material Economics (2023). *Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry*. Stockholm: Material Economics.

[11] Cullen, J. M., Allwood, J. M., & Bambach, M. D. (2012). Mapping the global flow of steel. *Environmental Science & Technology*, 46(24), 13048-13055.

[12] Midrex Technologies (2024). *MIDREX H2™: Technical Overview*. Charlotte, NC: Midrex.

[13] Boston Metal (2024). *Molten Oxide Electrolysis: Technology and Commercialization*. Woburn, MA: Boston Metal.

[14] Electra (2024). *Breakthrough Iron Production*. Boulder, CO: Electra.

[15] Rio Tinto (2024). *BioIron Process Development Update*. Melbourne: Rio Tinto.

[16] Calix (2024). *ZESTY: Zero Emissions Steel Technology*. Sydney: Calix.

[17] Ember (2024). *European Carbon Market Analysis*. London: Ember.

[18] Dechezleprêtre, A., & Sato, M. (2022). The impacts of environmental regulations on competitiveness. *Review of Environmental Economics and Policy*, 11(2), 183-206.

[19] Ministry of Ecology and Environment, China (2025). *National Carbon Emissions Trading Market Report*. Beijing: MEE.

[20] European Commission (2023). *Carbon Border Adjustment Mechanism: Implementing Regulation*. Brussels: European Commission.

[21] Mehling, M. A., et al. (2019). Designing border carbon adjustments for enhanced climate action. *American Journal of International Law*, 113(3), 433-481.

[22] NEDO (2024). *Green Innovation Fund: Hydrogen Utilization in Iron and Steelmaking*. Tokyo: NEDO.

[23] U.S. Congress (2022). *Inflation Reduction Act of 2022*. Public Law 117-169.

[24] Clean Steel Partnership (2024). *Strategic Research and Innovation Agenda*. Brussels: Clean Steel Partnership.

[25] Rodrik, D. (2014). Green industrial policy. *Oxford Review of Economic Policy*, 30(3), 469-491.

[26] McKinsey & Company (2024). *Decarbonization Challenge for Steel*. New York: McKinsey.

[27] Mazzucato, M., & Rodrik, D. (2023). Industrial policy with conditionalities. *Oxford Review of Economic Policy*, 39(2), 217-235.

[28] Meckling, J., & Nahm, J. (2022). The politics of technology bans. *Energy Policy*, 159, 112627.

[29] EPE - Empresa de Pesquisa Energética (2024). *Balanço Energético Nacional 2024*. Brasília: EPE.

[30] IRENA (2024). *Green Hydrogen Cost Reduction: Scaling up Electrolysers*. Abu Dhabi: IRENA.

[31] IRENA (2023). *Renewable Energy Statistics 2023*. Abu Dhabi: IRENA.

[32] Vale S.A. (2024). *Tecnored Technology: Advancing Low-Carbon Ironmaking*. Rio de Janeiro: Vale.

[33] CSN - Companhia Siderúrgica Nacional (2024). *Projeto Selene: Hidrogênio Verde para Siderurgia*. São Paulo: CSN.

[34] Industrial Deep Decarbonization Initiative (2023). *Brazil Joins IDDI at CEM14*. Press Release, July 2023.

[35] Ministry of Industry and Information Technology, China (2025). *Steel Industry Growth Plan 2025-2026*. Beijing: MIIT.

[36] Ministry of Steel, India (2023). *National Steel Policy 2017 (Revised)*. New Delhi: Ministry of Steel.

[37] Ministry of New and Renewable Energy, India (2023). *National Green Hydrogen Mission*. New Delhi: MNRE.

[38] Japan Iron and Steel Federation (2024). *Carbon Neutrality Action Plan*. Tokyo: JISF.

[39] POSCO Holdings (2024). *HyREX Technology and Carbon Neutrality Strategy*. Pohang: POSCO.

[40] TransitionZero (2024). *Japan's Steel Decarbonization: Policy Gaps and Opportunities*. London: TransitionZero.

[41] Federal Ministry for Economic Affairs and Climate Action, Germany (2023). *Steel Action Plan 2.0*. Berlin: BMWK.

[42] European Commission (2024). *Innovation Fund: Large Scale Call Results 2023-2024*. Brussels: European Commission.

Appendix A: Sitography - MIFUS Project Resources

A Journey through Policies of Steel Decarbonization

Research project by Fabio Miani, University of Udine

This appendix provides a comprehensive sitography of key web resources, policy portals, industry platforms, and institutional databases that informed the MIFUS project research on global steel decarbonization policies. These resources are organized by category and region to facilitate further research and policy monitoring.

International Organizations and Multilateral Initiatives

International Energy Agency (IEA)

- Main portal: https://www.iea.org
- Iron and Steel Technology Roadmap: https://www.iea.org/reports/iron-and-steel-technol
- Industrial decarbonization reports: https://www.iea.org/topics/industry
- Energy Technology Perspectives: https://www.iea.org/reports/energy-technology-perspec

World Steel Association (worldsteel)

- Main portal: https://worldsteel.org
- Steel Statistical Yearbook: https://worldsteel.org/steel-topics/statistics/
- Climate Action: https://worldsteel.org/steel-topics/climate-change/
- Technology and Innovation: https://worldsteel.org/steel-topics/technology/

UNIDO - United Nations Industrial Development Organization

- Industrial decarbonization: https://www.unido.org/our-focus-safeguarding-environment-
- Industrial Deep Decarbonization Initiative (IDDI): https://www.unido.org/IDDI

Mission Innovation

- Net-Zero Industries Mission: https://mission-innovation.net/missions/net-zero-industr

Clean Energy Ministerial

- Industrial Deep Decarbonization Initiative: https://www.cleanenergyministerial.org/initiatives-campaigns/industrial-deep-decarbonization-initiative/

European Union - Policy and Programs

European Commission - Climate Action

- EU Green Deal: https://ec.europa.eu/clima/eu-action/european-green-deal_en
- Innovation Fund: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system innovation-fund_en
- Carbon Border Adjustment Mechanism (CBAM): https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en
- EU ETS: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-et en

Clean Steel Partnership

- Main portal: https://www.clean-steel.eu/
- Strategic Research Agenda: https://www.clean-steel.eu/what-we-do/strategic-research-

Research Fund for Coal and Steel (RFCS)

- Project database: https://ec.europa.eu/research/participants/docs/h2020-funding-gui cross-cutting-issues/research-fund-coal-steel_en.htm

Germany - National Initiatives

Federal Ministry for Economic Affairs and Climate Action (BMWK)

- Steel Action Plan: https://www.bmwk.de/Redaktion/EN/Dossier/steel.html
- National Hydrogen Strategy: https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html

Major German Projects

- Thyssenkrupp tkH2Steel: https://www.thyssenkrupp-steel.com/en/company/sustainability/climate-strategy/tkh2steel.html
- Salzgitter SALCOS: https://salcos.salzgitter-ag.com/en/
- ArcelorMittal Hamburg: https://corporate.arcelormittal.com/climate-action/decarbonisation-projects

Sweden and Nordic Region

HYBRIT Development

- Main portal: https://www.hybritdevelopment.se/en/
- Technology overview: https://www.hybritdevelopment.se/en/the-hybrit-initiative/

H2 Green Steel

- Company website: https://www.h2greensteel.com/

SSAB (Steel producer)

- Fossil-free steel: https://www.ssab.com/fossil-free-steel

Japan - National Programs

NEDO - New Energy and Industrial Technology Development Organization

- Green Innovation Fund: https://www.nedo.go.jp/english/activities/activities_ZZJP_100129.html
- Hydrogen projects: https://www.nedo.go.jp/english/introducing/what_is_hydrogen.html

Japan Iron and Steel Federation (JISF)

- Carbon Neutrality Action Plan: https://www.jisf.or.jp/en/activity/climate/index.html
- COURSE50 technology: https://www.jisf.or.jp/en/activity/climate/course50/index.html

Major Japanese Steel Companies

- Nippon Steel: https://www.nipponsteel.com/en/csr/env/warming.html
- JFE Steel: https://www.jfe-steel.co.jp/en/csr/environment/warming/

South Korea

POSCO Holdings

- Carbon Neutrality: https://www.posco.com/en/esg/environment/carbon-neutrality/
- HyREX Technology: https://www.posco.com/en/business/technology/

Korean Government

- K-ETS Information: http://www.gir.go.kr/home/index.do?menuId=36 (Korean)

United States

Department of Energy (DOE)

- Industrial Decarbonization Office: https://www.energy.gov/eere/iedo/industrial-decarbon
- Hydrogen Program: https://www.hydrogen.energy.gov/

Inflation Reduction Act Resources

- Tax credits overview: https://www.irs.gov/inflation-reduction-act-of-2022
- 45V Hydrogen credits: https://www.energy.gov/eere/fuelcells/inflation-reduction-act

U.S. Steel Industry

- American Iron and Steel Institute: https://www.steel.org/

China

Government Agencies

- Ministry of Ecology and Environment: https://english.mee.gov.cn/
- National ETS: http://www.tanjiaoyi.com/ (Chinese)
- Ministry of Industry and Information Technology: https://en.miit.gov.cn/

China Iron and Steel Association (CISA)

- Main portal: http://www.chinaisa.org.cn/ (Chinese)

India

Ministry of Steel

- National Steel Policy: https://steel.gov.in/national-steel-policy-2017
- Steel Development Fund: https://steel.gov.in/

Ministry of New and Renewable Energy

- National Green Hydrogen Mission: https://mnre.gov.in/green-hydrogen/

Indian Steel Companies

- Tata Steel: https://www.tatasteel.com/sustainability/climate-action/
- JSW Steel: https://www.jsw.in/jsw-steel-sustainability

Brazil - National Resources

Government Portals

- Ministry of Mines and Energy: https://www.gov.br/mme/pt-br
- Ministry of Science, Technology and Innovation: https://www.gov.br/mcti/pt-br
- EPE - Energy Research Company: https://www.epe.gov.br/pt

Brazilian Steel Industry

- IABr - Brazilian Steel Institute: https://www.acoabrasil.org.br/ (Portuguese)
- CSN: https://www.csn.com.br/en/
- Vale: https://www.vale.com/
- Gerdau: https://www.gerdau.com/

Research and Innovation

- EMBRAPII: https://embrapii.org.br/en/
- CNPq: https://www.gov.br/cnpq/pt-br

Brazilian Projects

- CSN Selene Project: https://www.csn.com.br/ (company reports)
- Boston Metal Brazil: https://www.bostonmetal.com/

Technology Providers and Industry Platforms

Direct Reduction Technologies

- Midrex Technologies: https://www.midrex.com/
- Energiron (Tenova-Danieli): https://www.energiron.com/
- Primetals Technologies: https://www.primetals.com/

Breakthrough Technologies

- Boston Metal (MOE): https://www.bostonmetal.com/
- Electra (aqueous electrolysis): https://www.electra.earth/
- Rio Tinto BioIron: https://www.riotinto.com/en/news/releases/BioIron

Electrolyzer Manufacturers

- NEL Hydrogen: https://nelhydrogen.com/
- ITM Power: https://itm-power.com/
- Plug Power: https://www.plugpower.com/
- Thyssenkrupp Nucera: https://www.thyssenkrupp-nucera.com/

Certification and Standards

ResponsibleSteel

- Main portal: https://www.responsiblesteel.org/
- Standard and certification: https://www.responsiblesteel.org/standard-certification/

ISO Standards

- ISO 14040/14044 (LCA): https://www.iso.org/standard/37456.html
- ISO 50001 (Energy Management): https://www.iso.org/iso-50001-energy-management.html

Research and Think Tanks

Agora Industry

- Steel decarbonization: https://www.agora-industry.org/

Material Economics

- Industrial transformation reports: https://materialeconomics.com/

Breakthrough Energy

- Hard-to-abate sectors: https://breakthroughenergy.org/

Institute for Industrial Productivity

- Steel efficiency database: https://www.iip-network.org/

Transition Zero

- Steel tracker: https://www.transitionzero.org/

Financial Institutions and Climate Finance

Green Climate Fund

- Main portal: https://www.greenclimate.fund/

World Bank Climate Change

- Climate finance: https://www.worldbank.org/en/topic/climatechange

IFC (International Finance Corporation)

- Green finance: https://www.ifc.org/en/what-we-do/sector-expertise/climate-business

Carbon Markets and Pricing

ICAP - International Carbon Action Partnership

- ETS map and data: https://icapcarbonaction.com/

Ember Climate

- EU ETS analysis: https://ember-climate.org/topics/carbon-pricing/

Carbon Pricing Dashboard (World Bank)

- Global overview: https://carbonpricingdashboard.worldbank.org/

Academic and Conference Resources

AISTech Conference

- Annual steel conference: https://www.aist.org/conferences-events/aistech

ESTAD - European Steel Technology and Application Days

- Conference proceedings: https://www.estad.org/

Journal of Cleaner Production

- Steel decarbonization papers: https://www.sciencedirect.com/journal/journal-of-cleaner

News and Industry Publications

SteelOrbis

- Steel industry news: https://www.steelorbis.com/

Kallanish

- Steel market intelligence: https://www.kallanish.com/

Metal Bulletin (S&P Global)

- Steel pricing and news: https://www.spglobal.com/commodityinsights/en/metals

Data Visualization and Tracking Tools

Climate TRACE

- Emissions tracking: https://climatetrace.org/

Global Energy Monitor - Global Steel Plant Tracker

- Steel facility database: https://globalenergymonitor.org/projects/global-steel-plant-t

MIFUS Project Documentation

University of Udine - Department of Polytechnic Engineering and Architecture

- Department website: https://www.uniud.it/en/uniud-dpia
- Research portal: Contact Dr. Fabio Miani (fabio.miani@uniud.it)

Note: All URLs were verified as of November 2025. Web resources may change over time. For broken links or additional resources, please contact the corresponding author.

This sitography represents the culmination of extensive research conducted for the MIFUS project "A Journey through Policies of Steel Decarbonization" at the University of Udine. It serves as a comprehensive resource for researchers, policymakers, and industry professionals engaged in steel sector transformation and industrial decarbonization policy analysis.