Appendix to Global Steel Industry Analysis 2025: Production Rankings, Research Policies, and Decarbonization Strategies

Based on World Steel Association Data and Global Policy Documents

October 2025

Abstract

This document provides an appendix to the comprehensive analysis of the global steel industry, featuring detailed examination of steel research funding and innovation policies across the world's major steel-producing regions. The analysis covers technological pathways, industry dynamics, and strategic perspectives from plantmakers, iron ore producers, and technology developers driving the decarbonization transition.

Contents

A Current Industrial Research Activities of Leading Plantmakers

This appendix details the ongoing and recently completed industrial research activities of the world's leading plantmaking companies, focusing on their contributions to steel industry decarbonization, process innovation, and digital transformation. The information is organized by technology domain to highlight collaborative and competitive dynamics in the sector.

A.1 Hydrogen-Based Steelmaking Research

A.1.1 Investment Magnitude

Current and planned R&D investments by leading plantmakers:

- Total annual R&D spending across top 10 plantmakers: EUR 1.5-2.0 billion
- Green steel technologies represent 40-60% of new R&D allocation
- Significant increase from 2020 baseline (2-3x growth in hydrogen/CCUS)
- Government co-funding leverages private investment effectively

A.1.2 Critical Success Factors

For research activities to successfully enable commercial deployment:

- **Scale-Up Capability:** Pilot projects must provide credible pathway to commercial scale
- **Economic Viability:** Technologies must achieve competitive costs within realistic timeframes
- **Operational Reliability:** Steel producers require high availability and predictable performance
- **Integration:** New technologies must integrate with existing infrastructure where possible
- **Knowledge Transfer:** Successful R&D must translate to capabilities across organization

Table 1: Major Hydrogen Research Projects by Plantmaker Involvement

Project	**Location**	**Key Plantmakers**	**Technology Focus**
GrInHy2.0	Germany	SMS/Paul Wurth, Tenova	SOEC electrolyzer, H2 processing
SALCOS	Germany	SMS Group, multiple	H2-DRI, EAF integration
HyREX	South Korea	Primetals Technologies	H2 reduction + electric melting
Energiron Plants	Multiple	Danieli, Tenova	H2-ready direct reduction
TenarisDalmine	Italy	Tenova, Snam	H2 combustion in furnaces
HYBRIT	Sweden	Multiple suppliers	H2-DRI shaft furnace
H2FUTURE	Austria	Various suppliers	PEM electrolyzer integration

B Iron Ore Companies and Their Decarbonization Research Programs

This appendix details the research and strategic initiatives undertaken by the world's leading iron ore producers to adapt their products and processes for the decarbonizing steel industry. The quality and processing requirements of iron ore are fundamental to the feasibility and economics of new steelmaking pathways, particularly hydrogen-based direct reduction and smelting reduction.

B.1 Strategic Imperative for Ore Producers

The shift from blast furnace (BF) to hydrogen-based direct reduction (DR) and other alternative technologies creates both a risk and an opportunity for miners:

- **Risk:** DR plants require high-grade (>67% Fe) lump ore or pellets with strict specifications on impurities (SiO, AlO, P, S). Many existing mines produce ore unsuitable for DR without extensive and costly beneficiation.
- **Opportunity:** Producers of high-grade DR-grade ore can command significant price premiums. There is a growing market for a new class of "green iron" products like Hot Briquetted Iron (HBI) and Cold Briquetted Iron (CBI), allowing miners to move up the value chain.

B.2 Major Iron Ore Producers' Research Portfolios

B.2.1 Vale (Brazil)

Strategy: "Green Pig Iron" supplier and developer of low-carbon processing technologies.

Key Research Projects:

- **Tecnored:**
  - **Technology:** Proprietary smelting reduction process using carbonaceous agglomerates.
  - **Advantage:** Can use a wide range of fuels (biomass, syn-gas, hydrogen) and lower-grade iron ore fines.
  - **Status:** Pilot plant operational. Research focuses on scaling and integrating with hydrogen and biomass.
  - **Decarbonization Potential:** Up to 100% CO reduction if powered by green hydrogen or biochar.
- **BRBF Fines and "Green Briquettes":**
  - Development of high-grade, low-impurity briquettes specifically designed for the DR and EAF markets.
  - Research on optimizing binder systems to achieve high-temperature strength without contaminating the metal.
- **Megahub Model:**
  - Research into large-scale industrial hubs co-locating mining, beneficiation, briquetting, and renewable energy generation to produce a certified low-carbon "green iron" product for export.

B.2.2 Rio Tinto (UK/Australia)

Strategy: Partnering with steelmakers to develop integrated decarbonization pathways using Pilbara ores.

Key Research Projects:

- **BioIron™ Process:**

  - **Technology:** Uses raw biomass (e.g., agricultural waste) instead of coal as a reductant in a low-temperature chemical process.
  - **Advantage:** Leverages abundant biomass and lower-grade ores; the process is carbon-neutral if sustainably sourced.
  - **Status:** Proven at laboratory scale; ongoing pilot plant research in Germany.
  - **Partners:** Various steelmakers and research institutions.
- **Pilbara Ore Beneficiation for DR:**
  - Extensive R&D to upgrade Pilbara ores to DR-grade quality through advanced crushing, screening, and beneficiation circuits to reduce silica and alumina content.
- **Partnership with POSCO:**
  - Joint development of a "reduced emissions steelmaking process" from mine to metal, likely focusing on adapting Rio's ores for POSCO's HyREX technology.

B.2.3 BHP (Australia)

Strategy: Collaborative ecosystems and funding for breakthrough technologies.

Key Research Projects:

- **BHP Xplor Program:**
  - A venture-style program to identify and fund early-stage companies developing technologies critical for the energy transition, including green steel pathways.
- **Partnerships with China Baowu, HBIS, and JFE Steel:**
  - Multi-million dollar partnerships focused on:
    * BF energy efficiency and carbon capture readiness.
    * Increasing scrap utilization in BOFs.
    * Developing pathways for using BHP's iron ore in EAF and DRI processes.

B.2.4 Fortescue Metals Group (FMG) (Australia)

Strategy: Vertical integration into green energy and green iron production.

Key Research Projects:

- **Fortescue Future Industries (FFI):**
  - **Goal:** To become a major global producer of green hydrogen.
  - **Relevance:** FMG aims to use its own green hydrogen to produce green iron on-site at its mining operations, effectively exporting "green HBI" instead of just iron ore.
- **Green Iron Trial Plants:**
  - Planning and R&D for commercial-scale plants in Western Australia that will combine FMG iron ore with FFI green hydrogen in a DRI process.

B.2.5 LKAB (Sweden)

Strategy: The world's first and most ambitious transition to fossil-free iron ore products.

Key Research Projects:

- **HYBRIT (Hybrid Reduction of Iron Ore with fossil-free energy):**

  - **Role:** LKAB is the iron ore partner, responsible for producing fossil-free pellets and developing the processes for direct reduction with hydrogen.
  - **Innovation:** Developing a new class of "super-pellets" optimized for the specific reduction kinetics of hydrogen.

- **Transformation Plan:**
  - Investing billions to convert entire production system from traditional pellets to fossil-free sponge iron (DRI/HBI) by 2045.
  - This involves building large-scale electrolysis and DRI plants at its mining sites in Kiruna and Malmberget.

Table 2: Research Focus of Leading Iron Ore Producers

Company	**Primary Strategy**	**Key Research & Technology Initiatives**
Vale	Value-Added Green Iron	Tecnored smelting reduction, DR-grade briquettes, MegaHubs.
Rio Tinto	Process Innovation	BioIron™, Pilbara ore DR-upgrading, partnerships with steelmakers.
BHP	Collaborative Ecosystems	BHP Xplor, R&D partnerships with Baowu, HBIS, JFE.
Fortescue (FMG)	Vertical Integration	Fortescue Future Industries (green H2), on-site green iron plants.
LKAB	Fossil-Free Transformation	HYBRIT partnership, fossil-free pellet & sponge iron development.
Champion Iron (Canada)	High-Grade Specialist	Bloom Lake DR-grade concentrate, feasibility of HBI production.

B.3 Emerging Trends in Iron Ore Research

- **Ore Characterization for H Reduction:** Intensive research into the fundamental reduction kinetics of various ores using hydrogen, as it behaves differently from CO.
- **Advanced Beneficiation:** Development of dry processing, sensor-based ore sorting, and advanced magnetic separation to produce ultra-pure concentrates with minimal water and energy use.
- **Alternative Binders for Agglomeration:** Moving away from traditional bentonite clay, which adds silica, towards organic or synthetic binders that improve quality and reduce impurities.
- **Digital Mine-to-Metal Integration:** Using digital twins and AI to optimize the entire chain from ore extraction to steel production, ensuring consistent quality for sensitive new processes.

C DRI Technology Providers and Plantmakers

This appendix profiles the leading companies that design, engineer, and supply Direct Reduction (DRI) plants and technology. Their R&D efforts are central to scaling up hydrogen-based steelmaking, as the DRI shaft furnace is the core reactor for this pathway.

C.1 The DRI Technology Landscape

The market is dominated by a few key technology providers, each with proprietary process designs. The current R&D race focuses on adapting these well-established natural gas-based processes for operation with 100% hydrogen.

C.2 Major DRI Technology Providers

C.2.1 Midrex Technologies, Inc. (A Kobe Steel Group Company)

Market Position: The global leader, responsible for 60% of the world's DRI production capacity.

Core Technology: The MIDREX® Process, a shaft furnace using reformed natural gas (a mixture of H and CO) as the reductant.

Key R&D Projects and Offerings:

- **MIDREX H™:**
  - **Technology:** A flexible process designed to use any mixture of hydrogen and natural gas, from 0% to 100% H.
  - **Innovation:** Process control systems and furnace design modifications to handle the different thermodynamics and kinetics of pure hydrogen reduction.
  - **Status:** Offered as a standard design for new plants. Multiple plants are being built or planned with "H-ready" capability.
- **Megamod® Design:**
  - A standardized, large-scale (2.0+ Mtpa) plant design that reduces capital cost and construction time, making DRI more economically attractive.
- **COLIMET® and MXCOL® Processes:**
  - Technologies for using CO-rich gases from other processes (e.g., coke oven gas), demonstrating flexibility in reductant sources.

C.2.2 Energiron (A Joint Venture of Tenova and Danieli)

Market Position: The main competitor to Midrex, known for its flexibility.

Core Technology: The ENERGIRON® ZR process, which directly injects zinc-free reductant gas into the shaft furnace.

Key R&D Projects and Offerings:

- **The "ZR" (Zero Reformer) Advantage:**
  - **Technology:** When using hydrogen or a hydrogen-rich gas, the ENERGIRON process can operate without a catalytic reformer, simplifying the plant and reducing capital and operating costs.
  - **Hydrogen Readiness:** This design makes it inherently more adaptable to high hydrogen percentages.
- **Hytemp® System:**

  - A pneumatic transport system for hot DRI (at 600°C) directly to the EAF, resulting in significant energy savings in the meltshop.

- **Commercial Deployment:**
  - The Vulcan Green Steel project in the USA is a flagship example of a hydrogen-ready ENERGIRON plant designed for natural gas start-up with a seamless transition to hydrogen.

C.2.3 Primetals Technologies (A Joint Venture of Mitsubishi Heavy Industries and Partners)

Market Position: A full-line plantmaker with a strong focus on integrating DRI with downstream EAF and BOF processes.

Core Technology: Licenses and further develops the MIDREX technology.

Key R&D Projects and Offerings:

- **Hydrogen-Based DRI Integration:**
  - Focuses on the overall plant integration, including hydrogen production, gas conditioning, and the interface with the EAF.
  - Developing digital twins for optimizing the entire H2-DRI-EAF chain.
- **HIsarna Smelting Reduction:**
  - While not a DRI technology, HIsarna is a complementary ironmaking technology being developed with Tata Steel. It is a cyclone converter furnace that can potentially be injected with hydrogen and offers inherent CO capture.
- **HyREX Technology Support:**
  - Key engineering partner for POSCO's HyREX technology, which is a fluidized bed hydrogen-based reduction process, an alternative to shaft furnace DRI.

C.2.4 SMS group / Paul Wurth

Market Position: A traditional leader in BF technology now aggressively developing hydrogen-based solutions.

Core Technology: Developing their own DRI shaft furnace design alongside hydrogen injection for blast furnaces.

Key R&D Projects and Offerings:

- **smelter DRI:**
  - A concept that combines a DRI shaft furnace with an electric smelter. This is particularly useful for ores with high gangue content, as the smelter separates the pure iron from the slag.
  - Can be powered by hydrogen and renewable electricity.
- **Hydrogen Blast Furnace (H2-BF):**
  - While not DRI, this is a major R&D area. SMS/Paul Wurth is researching the injection of hydrogen into existing BFs as a bridge technology, reducing coke consumption and CO emissions by up to 20%.

C.3 Emerging and Alternative DRI Technologies

- **HyREX (POSCO/Primetals):** A fluidized bed process using hydrogen fines. Avoids the need for pelletizing, potentially lowering cost.

Table 3: Comparison of Leading DRI Technology Providers

Provider	**Core Technology**	**H2 Integration Approach**	**Key R&D Focus**
Midrex	Shaft Furnace (NG reformer)	MIDREX H™ (0-100% H flexibility)	Large-scale Megamod® design, process control for H2, use of alternative gases.
Energiron (Danieli/Tenova)	Shaft Furnace (Zero Reformer option)	Inherently H2-ready; ZR process eliminates reformer.	Hot DRI transport (Hytemp®), overall plant energy optimization, flexible ore feed.
Primetals Technologies	MIDREX License	Focus on system integration and digitalization.	Digital twin for H2-DRI-EAF, HyREX engineering, HIsarna development.
SMS group / Paul Wurth	New Shaft Furnace & Smelter	smelter DRI for low-grade ores; H2-BF injection.	Combining DRI with melting, CO2 capture from process gases.

- **CALIX ZESTY:** Uses a proprietary flash calciner for rapid hydrogen reduction of fine ores. Still at pilot stage but promises high efficiency.
- **CIRCORED (Metso Outotec):** A fine-ore reduction process using hydrogen in a circulating fluidized bed. Has been demonstrated at pilot scale.

The R&D competition is no longer just about efficiency in natural gas operation, but about **hydrogen flexibility, capital cost reduction, and integration with a volatile renewable energy grid**.

D BF vs. EAF Technology Dynamics: A Plantmaker Perspective

This appendix analyzes the strategic response of leading plantmaking companies to the fundamental technological shift from the integrated Blast Furnace - Basic Oxygen Furnace (BF-BOF) route to the Electric Arc Furnace (EAF) route. For these companies, this transition represents a profound reshaping of their product portfolios, R&D priorities, and business models.

D.1 The Paradigm Shift

The traditional business of building massive, multi-billion dollar integrated steel plants is giving way to a market demanding flexible, modular, and digitally advanced EAF-based "mini-mills." Plantmakers are adapting along two parallel tracks:

1. **Sustain and Decarbonize the BF-BOF Fleet:** Providing upgrade and life-extension solutions for the vast existing base of integrated plants.
2. **Lead the EAF Revolution:** Developing next-generation EAFs and DRI plants that form the core of the new green steel mills.

D.2 Plantmaker Strategies and Technology Portfolios

D.2.1 Primetals Technologies

Strategy: Technology agnosticism, offering solutions for all pathways while pushing digital integration.

- **BF-BOF Sustainment:**
  - **Blast Furnace Optimization:** AI-based burden distribution control, predictive maintenance for hearths and stoves, high-oxygen injection systems.
  - **Environmental Upgrades:** Gas cleaning systems, waste heat recovery, and integration of CCUS-ready components.
- **EAF Growth:**
  - **Ultimate EAF:** High-productivity, large-diameter furnaces with scrap preheating and advanced chemical energy injection.
  - **Quality EAF:** Focused on producing high-quality steel from high DRI/HBI charges, with precise control of carbon and temperature.
  - **Digital Twin:** The "Digital EAF" simulates the entire melting process to optimize energy use, electrode consumption, and productivity in real-time.

D.2.2 SMS group

Strategy: Leveraging core strength in metallurgical plant engineering to bridge both worlds.

- **BF-BOF Sustainment:**
  - **EcoBlast™:** A package of BF upgrades for lower coke rate and higher productivity.
  - **Hydrogen Injection (H2-BF):** A key R&D area, with pilot projects to demonstrate the safe and efficient injection of hydrogen into BFs.
- **EAF Growth:**
  - **Quantum EAF:** An ultra-high power (UHP) furnace focused on minimizing tap-to-tap time and specific energy consumption (targets below 350 kWh/t).
  - **Consteel®:** A continuous scrap charging process that improves efficiency and stability. SMS is researching integration with hot DRI from its *smelter* technology.

D.2.3 Danieli

Strategy: A clear champion of the EAF/mini-mill route, with a focus on compact, efficient, and automated plants.

- **BF-BOF Sustainment:** Limited focus. Danieli's strategy is predicated on the decline of the BF route.
- **EAF Growth:**
  - **Digimelter:** A highly publicized technology combining the Consteel continuous charging with optimized oxy-fuel burners and a sophisticated digital control system. Marketed as achieving 330-350 kWh/t energy consumption.
  - **Q-Melt:** A compact, fast-melting EAF designed for high productivity in smaller footprints.
  - **Automation:** Heavy investment in Q-Robot systems for automated slagging, tap-hole opening, and sampling, reducing labor costs and improving safety.

D.2.4 Tenova

Strategy: Specialization in the "soft" areas of the process: heating, combustion, and environmental technologies applicable to both routes.

- **BF-BOF Sustainment:**
  - **iRecovery:** Waste heat recovery systems for BOF and coke oven gases.
  - **Burner Technology:** Developing hydrogen-capable burners for reheating furnaces (e.g., TenarisDalmine project).
- **EAF Growth:**
  - **EAF Optimization:** Advanced oxy-fuel burner systems, foamy slag control, and fume extraction systems.
  - **Energiron DRI:** As a co-owner, Tenova provides the core process technology for the hydrogen-ready DRI plants that feed modern EAFs.

Table 4: Plantmaker R&D Focus: BF-BOF vs. EAF-DRI (Qualitative Assessment)

Plantmaker	**BF-BOF R&D Focus (Sustain)**	**EAF-DRI R&D Focus (Growth)**
Primetals Technologies	AI optimization, CCUS readiness, life extension.	Digital EAF, H2-DRI integration, quality EAF for auto steel.
SMS group	Hydrogen BF injection, EcoBlast upgrades.	Quantum EAF, Consteel with hot DRI, *smelter* technology.
Danieli	Minimal.	Digimelter, Q-Melt, full-plant automation (Q-Robot), Energiron.
Tenova	H2-burners for reheat furnaces, waste heat recovery.	EAF efficiency, Energiron DRI, environmental systems.

D.3 The Emerging Business Model: "Greenfield vs. Brownfield"

- **Brownfield (BF-BOF):** The business is now primarily about **services, upgrades, and digital solutions**. The goal is to help existing assets run more efficiently, with lower emissions, for longer. The profit is in margins on technology packages and long-term service contracts.
- **Greenfield (EAF-DRI):** The business is returning to **building new plants**, but of a different kind. These are smaller, more modular, and highly automated EAF-based mills. The competitive advantage comes from offering a complete, integrated, and digitally native "Green Steel Plant" solution.

The plantmakers that thrive will be those that successfully manage this portfolio transition, leveraging their legacy knowledge while aggressively capturing the new market for flexible, digital, and green steel production technologies.

E Alternative Iron and Steelmaking Technology Developers

This appendix profiles companies and consortia developing disruptive, non-conventional pathways for iron and steel production. These technologies aim to leapfrog incremental improvements to the BF-BOF and conventional EAF routes, potentially offering step-change reductions in capital cost, energy use, and carbon emissions.

E.1 The Case for Disruption

While hydrogen-DRI represents a major evolution, it still requires large-scale agglomeration (pelletizing) plants and shaft furnaces. The following technologies seek to redefine the process itself, with common goals of:

- Eliminating coking and sintering entirely.
- Operating at lower temperatures.
- Using electricity as the primary energy and reductant source.
- Processing low-grade or complex ores without extensive beneficiation.

E.2 Molten Oxide Electrolysis (MOE)

E.2.1 Boston Metal (USA)

Technology: Molten Oxide Electrolysis (MOE).

- **Process:** Dissolves iron ore in a molten oxide electrolyte. Passing an electric current through this solution splits the iron oxide into liquid iron and oxygen. No carbon reductant is used.
- **Key Advantages:**
  - **Zero Direct CO Emissions:** The only by-product is oxygen.
  - **Ore Flexibility:** Can process a wide range of iron ores, including low-grade and high-impurity ores that are problematic for other processes.
  - **Modular Design:** Cells can be added incrementally, unlike a massive blast furnace or shaft furnace.
  - **High-Purity Iron:** Produces liquid iron suitable for any steelmaking furnace.
- **Status and R&D:**
  - **TRL:** 5-6 (Pilot to Demonstration).
  - Successfully demonstrated production of high-value metals (tantalum, niobium). The steel application is now the primary focus.
  - Raised $262M (Series B, C, C2) from investors including ArcelorMittal, BHP Ventures, and Breakthrough Energy Ventures.
  - Building a commercial-scale demonstration plant in Brazil, with initial operations targeted for 2024-2025.
- **Challenges:** Scaling up cell durability and achieving competitive electricity consumption at an industrial scale.

E.3 Electrochemical-Hydrometallurgical Processes

E.3.1 Electra (USA)

Technology: Low-temperature electrochemical process.

- **Process:** Dissolves iron ore in an acid solution at low temperature (60°C). Uses an electrochemical cell to plate out high-purity iron (99.98%) onto a cathode. The acid is regenerated and reused.
- **Key Advantages:**
  - **Ultra-Low Temperature:** Operates at 60°C vs. >1500°C for conventional processes.
  - **Renewable Electricity:** Can be powered directly by intermittent solar and wind without the need for thermal inertia.
  - **Gangue-Free Iron:** Produces a pure iron product, eliminating slag and impurity removal steps.
  - **Distributed Production:** The modular and low-temperature nature could enable smaller, distributed plants.
- **Status and R&D:**
  - **TRL:** 4-5 (Lab to Pilot).
  - Successfully operated a pilot plant in 2023.
  - Raised $85M in funding from Breakthrough Energy Ventures, Amazon Climate Pledge Fund, and others.
  - Focused initially on the iron ore market before targeting steelmaking.
- **Challenges:** Scaling the electrochemical cells, managing reagent flows, and the economics of producing a solid iron product that must still be melted for steelmaking.

E.4 Flash Reduction Using Hydrogen

E.4.1 Calix (Australia) - ZESTY Process

Technology: ZESTY (Zero Emissions Steel TechnologY) - Flash reduction in a suspended state.

- **Process:** Fine iron ore is rapidly heated and reduced by hydrogen in a proprietary calciner (the same technology used in their CO capture process). The fast reaction kinetics avoid the need for pelletizing.
- **Key Advantages:**
  - **Direct Use of Ore Fines:** Eliminates the energy and cost of pelletizing.
  - **Fast Kinetics:** Reduction occurs in seconds.
  - **Integration with Renewables:** Designed for intermittent operation.
- **Status and R&D:**
  - **TRL:** 3-4 (Lab to small Pilot).
  - Conducting pilot-scale testing and seeking industrial partners for demonstration.

E.5 Other Notable Approaches

E.5.1 Limelight Steel (USA)

Technology: Industrial heating using high-efficiency laser diodes.

- **Concept:** Replace fossil fuel burners in various high-temperature industrial processes, including steel reheating and potentially direct ore reduction, with precise, zero-emission laser energy.
- **Status:** Early stage (TRL 2-3), focusing on proving the economic viability of laser heating for industrial throughput.

E.5.2 MIT Spin-offs (e.g., Form Energy)

Technology: While focused on batteries, the development of ultra-low-cost, long-duration energy storage (e.g., iron-air batteries) is a critical enabling technology for the widespread electrification of steelmaking, which requires stable, 24/7 power.

Table 5: Overview of Alternative Ironmaking Technologies

Company / Process	**Core Principle**	**TRL**	**Potential Impact and Challenges**
Boston Metal (MOE)	Electrolysis of molten oxides	5-6	Highest disruption potential; handles any ore; zero direct emissions. Challenge: Scaling cell technology and energy cost.
Electra	Low-temperature electroplating	4-5	Radical efficiency gain; enables distributed production. Challenge: Scaling electrochemical cells and downstream melting.
Calix (ZESTY)	Flash reduction with H2	3-4	Eliminates pelletizing; fast and flexible. Challenge: Gas-solid separation, scaling the calciner reactor.
CIRCORED (Metso)	Fluidized bed H2 reduction	5-6	Proven for fine ores. Challenge: Gas consumption, sticking in the bed. Not as novel but a viable alternative to shaft furnaces.

E.6 Strategic Implications

The success of any of these technologies could reshape the industry's geography, capital requirements, and value chains. They represent a long-term, high-risk/high-reward bet for investors and steelmakers. While the BF and conventional DRI/EAF routes will dominate for decades, these alternatives provide the technological options for a truly transformative second wave of decarbonization post-2040.

References and Comprehensive Sitography

Academic Journals and Conference Proceedings

[1] **Fischedick, M., et al.** (2024). "Techno-economic assessment of hydrogen-based steelmaking pathways: A global perspective." *International Journal of Hydrogen Energy*, 49(3), 1123-1145.

[2] **Wang, X., Zhang, L., & Chen, H.** (2024). "Digital twin implementation in electric arc furnace operations: Case studies from Chinese steel plants." *Journal of Cleaner Production*, 435, 134567.

[3] **Vogl, V., Åhman, M., & Nilsson, L. J.** (2023). "Assessment of hydrogen direct reduction for fossil-free steelmaking: Technical and economic analysis of the HYBRIT process." *Journal of Cleaner Production*, 203, 736-745.

[4] **Sohn, H. Y., & Fruehan, R. J.** (2023). "The potential emergence of molten oxide electrolysis for iron production: Fundamentals and scaling challenges." *Metallurgical and Materials Transactions B*, 54(2), 789-802.

[5] **Li, Y., et al.** (2023). "Iron ore quality requirements for hydrogen-based direct reduction: Implications for global mining operations." *Minerals Engineering*, 195, 108023.

[6] **Kim, J., Park, S., & Lee, H.** (2024). "HyREX technology development: Fluidized bed hydrogen reduction for steel decarbonization." *ISIJ International*, 64(1), 45-58.

[7] **European Commission, Joint Research Centre.** (2024). "Best Available Techniques (BAT) Reference Document for Iron and Steel Production." EUR 31690 EN.

[8] **Zhang, Q., et al.** (2023). "China's steel industry transformation: Pathways to carbon peak before 2030." *Energy Policy*, 182, 113745.

[9] **International Energy Agency (IEA).** (2024). "Iron and Steel Technology Roadmap: Towards more sustainable steelmaking." Paris: IEA Publications.

[10] **Bataille, C., et al.** (2023). "A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement." *Journal of Cleaner Production*, 187, 960-973.

Industry Reports and White Papers

[11] **World Steel Association.** (2025). *Steel Statistical Yearbook 2024*. Brussels: worldsteel.

[12] **McKinsey & Company.** (2024). *Decarbonization challenge for steel: Navigating the transformation.* Metals & Mining Practice.

[13] **Boston Consulting Group.** (2024). *The Green Steel Revolution: Strategies for a decarbonized steel industry.*

[14] **Material Economics.** (2023). *Industrial Transformation 2050: Pathways to net-zero emissions from EU heavy industry.* Stockholm.

[15] **Rocky Mountain Institute.** (2024). *Green hydrogen-based steelmaking: Economic analysis and policy requirements.*

[16] **CRU Group.** (2024). *Iron Ore Market Outlook: Quality requirements for the energy transition.*

[17] **BloombergNEF.** (2024). *Green Steel: Technology Outlook and Cost Analysis.*

[18] **Deloitte.** (2024). *The future of steel: Digitalization and sustainability convergence.*

Official Government and International Organization Publications

[19] **International Energy Agency (IEA).** (2024). *Energy Technology Perspectives 2024: Special Report on Clean Energy Innovation.*

[20] **European Commission.** (2023). *Clean Steel Partnership: Strategic Research and Innovation Agenda 2021-2027.*

[21] **United Nations Industrial Development Organization (UNIDO).** (2024). *Global Roadmap for Accelerating the Development of Green Hydrogen in Industry.*

[22] **U.S. Department of Energy.** (2024). *Industrial Decarbonization Roadmap.*

[23] **Ministry of Industry and Information Technology of China.** (2024). *Guidance on Promoting High-Quality Development of Steel Industry.*

[24] **Japan's Ministry of Economy, Trade and Industry (METI).** (2024). *Green Innovation Fund: Progress Report on Steel Sector Projects.*

[25] **Government of India, Ministry of Steel.** (2024). *National Green Hydrogen Mission: Steel Sector Implementation Plan.*

Corporate Technical Publications and Investor Materials

[26] **Midrex Technologies, Inc.** (2024). *MIDREX H2™: Technical White Paper on Hydrogen-ready Direct Reduction.*

[27] **Primetals Technologies.** (2024). *HyREX Technology Development: Partnership with POSCO.*

[28] **Boston Metal.** (2024). *Molten Oxide Electrolysis: Technology Overview and Commercial Scaling Strategy.*

[29] **ArcelorMittal.** (2024). *XCarb® Innovation Fund: Annual Portfolio Review.*

[30] **SSAB.** (2024). *HYBRIT: Fossil-free steel value chain progress report.*

[31] **Vale S.A.** (2024). *Tecnored Technology: Advancing low-carbon ironmaking.*

[32] **Rio Tinto.** (2024). *BioIron™ Process Development: Laboratory to Pilot Scale Results.*

Conference Presentations and Workshop Proceedings

[33] **AISTech 2024 Proceedings.** (2024). Association for Iron & Steel Technology.

- "Digital Transformation in EAF Steelmaking: Case Studies from North America"
- "Hydrogen Injection in Blast Furnaces: Operational Experience and Scaling Challenges"
- "Advanced Process Control for DRI Plants: AI and Machine Learning Applications"

[34] **ICSTI 2024.** (2024). International Conference on Science and Technology of Ironmaking.

- "Fundamental Kinetics of Hydrogen Reduction: Implications for DRI Process Design"
- "Alternative Ironmaking Technologies: TRL Assessment and Commercial Pathways"

[35] **EUROPEAN STEEL TECHNOLOGY AND APPLICATION DAYS (ESTAD) 2024.** (2024).

- "EU Green Deal Implementation: Impact on Steel Technology Development"
- "Carbon Border Adjustment Mechanism: Technical Requirements and Compliance"

Online Resources and Databases

[36] **World Steel Association Statistics:** https://www.worldsteel.org/steel-by-topic/statistics.html

- Comprehensive global steel production data
- Sustainability indicators and environmental performance metrics

[37] **IEA Iron and Steel Technology Collaboration Programme:** https://www.iea.org/industry/iron-and-steel

- International collaboration on steel decarbonization
- Technology assessments and policy analysis

[38] **European Steel Technology Platform (ESTEP):** https://www.estep.eu/

- EU steel research coordination
- Clean Steel Partnership implementation

[39] **U.S. Department of Energy Industrial Efficiency & Decarbonization Office:** https://www.energy.gov/eere/iedo/industrial-decarbonization

- Funding opportunities and technical resources
- R&D project database

[40] **MIT Climate Portal - Steel Decarbonization:** https://climate.mit.edu/explainers/steel-production-and-

- Educational resources on steel decarbonization technologies
- Policy analysis and technology assessments

[41] **Global CCS Institute:** https://www.globalccsinstitute.com/

- Carbon capture projects database
- Technical reports on CCUS in steel industry

[42] **International Renewable Energy Agency (IRENA):** https://www.irena.org/

- Green hydrogen production cost data
- Renewable energy integration studies

Patent Databases and Intellectual Property Resources

[43] **European Patent Office (EPO) - Espacenet:** https://worldwide.espacenet.com/

- Search keywords: "hydrogen direct reduction," "molten oxide electrolysis," "electric arc furnace optimization"

[44] **United States Patent and Trademark Office (USPTO):** https://www.uspto.gov/

- Patent classification: C21B (manufacture of iron or steel), C22B (production or refining of metals)

[45] **World Intellectual Property Organization (WIPO):** https://www.wipo.int/

- PCT international patent applications in steel technology

Standards and Certification Bodies

[46] **International Organization for Standardization (ISO):**

- ISO 14404: CO emission intensity from iron and steel production

- ISO 20915: Life cycle inventory calculation methodology for steel products

[47] **ResponsibleSteel:** https://www.responsiblesteel.org/

- Sustainability certification standard for steel
- Chain of custody requirements

Research Institutions and Academic Centers

[48] **Max Planck Institute for Iron Research:** https://www.mpie.de/

[49] **RWTH Aachen University - Steel Institute:** https://www.stahl.rwth-aachen.de/

[50] **University of Science and Technology Beijing - Metallurgy:** https://en.ustb.edu.cn/

[51] **Carnegie Mellon University - Center for Iron and Steelmaking Research:** https://www.cmu.edu/engineering/materials/

[52] **Swerea MEFOS:** https://www.ri.se/en/mefos

[53] **CSIR-National Metallurgical Laboratory, India:** https://www.nmlindia.org/

Note on Currency: This references list includes publications through mid-2025, reflecting the most current research and industry developments available at the time of publication. Readers are encouraged to consult the online resources for the most recent updates, particularly in this rapidly evolving field.

Accessibility: Many of the industry reports and corporate publications are available through company websites and investor relations portals. Academic publications can typically be accessed through university libraries or research gateways.