Technical and Scientific Guide: Technology Readiness Levels (TRLs) of Steelmaking Processes Related to Mini Instant Fall School on A Journey through Steel Decarbonization Policies Worldwide

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Abstract

This LLM assisted prelimiary technical guide has been created in the framework of a Mini Instant Fall School on Steel Decarbonization. It has the aim of providing a comprehensive and understandable overview of steelmaking decarbonization technologies organized by Technology Readiness Level (TRL). The steel industry accounts for approximately 7-9% of global CO_2 emissions, making decarbonization critical for climate goals. This document categorizes emerging and established technologies from fundamental research (TRL 1-2) through commercial deployment (TRL 9), offering steel producers, researchers, and policymakers a structured framework for understanding the maturity landscape of steel decarbonization and green steel technologies.

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1 Introduction: Steel Industry Decarbonization Challenge

1.1 Global Context

The steel industry is responsible for producing approximately 1.9 billion tonnes of crude steel annually, generating 2.6 billion tonnes of CO_2 emissions. Traditional blast furnace-basic oxygen furnace (BF-BOF) routes account for roughly 70% of global steel production and are carbon-intensive, emitting 1.8-2.3 tonnes of CO_2 per tonne of crude steel produced.

Achieving net-zero emissions by 2050 requires transformative technologies across the entire steelmaking value chain, from iron ore reduction to final steel processing. This guide maps these technologies according to NASA's Technology Readiness Level (TRL) framework, adapted for industrial applications.

1.2 TRL Framework Explained

Technology Readiness Levels provide a systematic metric for assessing technology maturity:

- **TRL 1-2:** Basic principles observed and technology concept formulated
- **TRL 3-4:** Analytical and experimental critical function proof-of-concept
- **TRL 4-5:** Technology validated in laboratory and relevant environment
- **TRL 6-7:** Technology demonstrated in relevant/operational environment
- **TRL 7-8:** System complete and qualified through test and demonstration
- **TRL 9:** Actual system proven in operational environment

1.3 Document Structure

This guide is organized into six chapters corresponding to TRL ranges, with each chapter detailing specific technologies, their scientific basis, current development status, challenges, and industrial implications.

2 Chapter 1: Fundamental Research (TRL 1-2)

2.1 Overview

Technologies at TRL 1-2 are in early conceptual and fundamental research stages. Scientific principles are being observed and documented, with initial laboratory experiments validating basic concepts. These technologies may reach industrial application in 15-30 years.

2.2 Electrochemical Iron Ore Reduction

2.2.1 Technical Description

Direct electrochemical reduction of iron oxides using molten salt electrolytes or solid oxide electrolysis cells (SOEC). Electrons directly reduce Fe_2O_3 or Fe_3O_4 to metallic iron at cathodes, with oxygen evolution at anodes. Reaction occurs at 800-1200°C.

Key reaction: $Fe_2O_3 + 6e^- \rightarrow 2Fe + 3O^{2-}$

2.2.2 Current Status

Laboratory-scale proof-of-concept with small sample masses (grams to kilograms). Research focuses on electrode materials, electrolyte composition, and current efficiency optimization. Several universities and research institutes conducting fundamental studies.

2.2.3 Challenges

- Electrode degradation and material selection
- Scale-up from milligram to industrial tonnage scale
- Energy efficiency and current density optimization
- Integration with renewable electricity systems
- Economic viability compared to established routes

2.3 Hydrogen Plasma Smelting Reduction

2.3.1 Technical Description

Ultra-high temperature (>5000°C) hydrogen plasma for rapid direct reduction of iron ore. Plasma-assisted processes provide extreme reaction kinetics and potential for continuous operation. Combines thermal plasma generation with hydrogen reducing atmosphere.

2.3.2 Current Status

Fundamental research at plasma physics laboratories. Small-scale batch experiments demonstrating feasibility. Energy balance calculations and thermodynamic modeling underway.

2.3.3 Challenges

- Extremely high energy consumption
- Plasma torch electrode lifetime
- Process control at extreme temperatures
- Material handling in plasma environment
- Economic competitiveness uncertain

2.4 Biological and Microbial Iron Reduction

2.4.1 Technical Description

Use of iron-reducing bacteria (e.g., *Geobacter* and *Shewanella* species) or enzymatic processes to reduce iron oxides at ambient or moderate temperatures. Bio-electrochemical systems combining microbial activity with electrical current.

2.4.2 Current Status

Basic laboratory research demonstrating microbial iron reduction. Extremely low reaction rates (micrograms to milligrams per day). Fundamental studies on electron transfer mechanisms and metabolic pathways.

2.4.3 Challenges

- Reaction kinetics orders of magnitude too slow for industrial application
- Scale-up from microscale to industrial scale unclear
- Product purity and morphology control
- Integration with steelmaking infrastructure
- Likely limited to niche applications or hybrid processes

2.5 Photocatalytic and Solar-Thermal Reduction

2.5.1 Technical Description

Direct solar energy utilization for iron ore reduction through concentrated solar thermal processes or photocatalytic reduction mechanisms. Solar concentrators achieve temperatures >1500°C or provide photon energy for chemical reactions.

2.5.2 Current Status

Conceptual studies and small-scale solar furnace experiments. Thermodynamic analyses of solar-to-chemical energy conversion. Limited experimental data on continuous operation.

2.5.3 Challenges

- Intermittency of solar resource
- Energy storage for continuous operation
- Scale and land requirements for industrial tonnages
- Geographic limitations to high-insolation regions
- Capital cost of solar concentrator infrastructure

3 Chapter 2: Technology Development (TRL 3-4)

3.1 Overview

TRL 3-4 technologies have demonstrated analytical and experimental proof-of-concept. Laboratory validation is underway with increasing scale and sophistication. These technologies may reach commercialization in 10-20 years with sustained development.

3.2 Hydrogen-Based Flash Ironmaking

3.2.1 Technical Description

Ultra-rapid reduction of fine iron ore particles suspended in high-temperature hydrogen atmosphere. Reduction occurs in seconds to minutes rather than hours, utilizing flash reactor technology. Temperatures 800-1100°C, reaction time <5 minutes.

Reaction: $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$ (flash kinetics)

3.2.2 Current Status

Pilot-scale flash reactors processing 10-100 kg/hour demonstrated. Research institutions and companies testing various ore types and hydrogen concentrations. Kinetic models validated against experimental data.

3.2.3 Challenges

- Ore preparation and particle size control
- Product collection and separation systems
- Reactor design for industrial scale (1000+ tonnes/day)
- Heat integration and energy efficiency
- Hydrogen supply infrastructure requirements

3.3 Molten Oxide Electrolysis (MOE)

3.3.1 Technical Description

Electrolysis of iron ore dissolved in molten oxide electrolyte (typically mixed iron-silicon oxides) at 1500-1600°C. Produces molten iron at cathode and oxygen gas at anode. Direct ore-to-steel process bypassing reduction and melting steps.

3.3.2 Current Status

Laboratory-scale cells (10-100 kg batches) operated successfully. Companies like Boston Metal advancing technology with demonstration-scale facilities under construction. Current densities and energy consumption being optimized.

3.3.3 Challenges

- Electrode material durability at high temperatures
- Electrolyte management and recycling
- Scale-up to continuous industrial operation
- Capital cost of electrolytic cells
- Renewable electricity integration and cost

3.4 Methane Pyrolysis with Iron Ore Reduction

3.4.1 Technical Description

Simultaneous methane decomposition ($CH_4 \rightarrow C + 2H_2$) and hydrogen-based iron ore reduction. Produces metallic iron, solid carbon, and minimal CO_2. Carbon product may have commercial value. Process temperature 800-1000°C.

3.4.2 Current Status

Laboratory reactors demonstrating concept with various catalysts. Research on carbon morphology control and separation. Energy balance studies showing potential advantages. Several patents filed.

3.4.3 Challenges

- Catalyst deactivation by carbon deposition
- Separation of iron and carbon products
- Methane source (natural gas) still fossil-based unless renewable methane used
- Carbon product market and utilization pathways
- Process economics and competitiveness

3.5 Ammonia-Based Direct Reduction

3.5.1 Technical Description

Use of ammonia (NH_3) as reducing agent and hydrogen carrier. Ammonia decomposes to nitrogen and hydrogen in-situ: $2NH_3 \rightarrow N_2 + 3H_2$. Hydrogen reduces iron ore while nitrogen acts as inert carrier gas. Temperature 700-900°C.

3.5.2 Current Status

Bench-scale experiments with reduction kinetics studies. Thermodynamic modeling and process simulation underway. Potential advantages in hydrogen storage and transport via ammonia infrastructure.

3.5.3 Challenges

- Nitrogen contamination in iron product
- Ammonia handling and safety considerations
- Decomposition catalyst requirements
- Green ammonia production capacity and cost
- Process efficiency compared to direct hydrogen use

4 Chapter 3: Technology Validation (TRL 4-5)

4.1 Overview

Technologies at TRL 4-5 have been validated in laboratory settings and are transitioning to relevant industrial environments. Pilot plants and demonstration facilities are operating or planned. Commercialization potential within 5-15 years with successful scaling.

4.2 Hydrogen Direct Reduction of Iron (H-DRI)

4.2.1 Technical Description

Replacement of natural gas with pure hydrogen in direct reduction shaft furnaces. Iron ore pellets or lump ore reduced by hydrogen at 800-1000°C producing direct reduced iron (DRI) and water vapor. Can be retrofitted into existing DRI plants.

Reaction: $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$

4.2.2 Current Status

Multiple pilot plants operating globally (HYBRIT, H2 Green Steel, Thyssenkrupp). Production capacities 1-10 tonnes/hour. Successful continuous operation demonstrated. Industrial partners committed to scale-up. TRL approximately 5-6.

4.2.3 Challenges

- Green hydrogen supply availability and cost ($2-5/kg currently)
- Reformulation of reduction models for pure hydrogen
- Furnace refractory compatibility with high water vapor content
- DRI handling and transport (pyrophoric nature)
- Economic competitiveness dependent on carbon pricing

4.3 Carbon Capture and Storage (CCS) for Blast Furnaces

4.3.1 Technical Description

Post-combustion CO_2 capture from blast furnace off-gases using chemical absorption (amines), physical adsorption, or membrane separation. Captured CO_2 compressed and transported for geological storage or utilization. Captures 80-95% of CO_2 emissions.

4.3.2 Current Status

Demonstration projects at integrated steel mills (e.g., Tata Steel, ArcelorMittal). Capture capacities 50,000-500,000 tonnes CO_2/year. Technology adapted from power generation sector. Economic feasibility dependent on policy support.

4.3.3 Challenges

- Energy penalty (15-30% additional energy consumption)
- Capital and operating costs ($60-120/tonne CO_2)
- CO_2 transport and storage infrastructure development
- Long-term storage site availability and monitoring
- Public acceptance and regulatory frameworks
- Not a zero-emission solution, only emission reduction

4.4 Top Gas Recycling Blast Furnace (TGR-BF)

4.4.1 Technical Description

Advanced blast furnace with CO_2 removal from top gas and recycling of CO-rich gas back into furnace. Oxygen enrichment increases reducing gas efficiency. Reduces coke consumption by 20-30% and CO_2 emissions by similar magnitude.

4.4.2 Current Status

Commercial demonstration plants operating in China and Europe. Technology proven at scale but limited adoption. Integration with CCS considered for deeper decarbonization. TRL approximately 6-7.

4.4.3 Challenges

- Requires oxygen plant infrastructure
- Higher capital investment than conventional BF
- Still produces significant CO_2 emissions (1.2-1.4 t CO_2/t steel)
- Limited decarbonization potential as standalone technology
- May be bridging technology rather than ultimate solution

4.5 Smelting Reduction with Hydrogen Injection

4.5.1 Technical Description

Partial replacement of coal/coke in smelting reduction processes (e.g., HIsarna, COREX) with hydrogen injection. Maintains high-temperature molten bath while reducing carbon input. Hybrid approach enabling gradual transition.

4.5.2 Current Status

Pilot-scale testing with hydrogen injection rates up to 30-40% of total reducing agent. Process modeling and optimization ongoing. Industrial demonstrations planned for 2024-2027 timeframe.

4.5.3 Challenges

- Limited decarbonization depth (30-50% reduction maximum)
- Complex process control with mixed reducing agents
- Hydrogen injection technology and distribution
- Still requires some carbon for thermal energy
- Economic benefit requires high carbon prices

5 Chapter 4: System Development and Demonstration (TRL 6-7)

5.1 Overview

TRL 6-7 technologies are demonstrated in operational or near-operational environments at industrially relevant scales. First-of-a-kind commercial plants are under construction or planned. These technologies could achieve significant market penetration within 5-10 years.

5.2 Electric Arc Furnace (EAF) with High Scrap Rates

5.2.1 Technical Description

Melting of steel scrap and/or DRI using electric arc furnaces powered by renewable electricity. Modern EAFs can process 100% scrap or DRI-scrap mixtures. Power consumption 350-500 kWh per tonne of liquid steel. Emissions primarily from electricity source.

5.2.2 Current Status

Mature technology representing 30% of global steel production. Hundreds of EAF facilities operating worldwide. New installations increasingly powered by renewable electricity contracts. When using renewable electricity and DRI from green hydrogen, near-zero emissions achievable.

5.2.3 Challenges

- Scrap availability limited (cannot meet 100% of global demand)
- Scrap quality and tramp element contamination
- DRI availability for primary steel production
- Grid capacity and renewable electricity availability
- Higher capital cost than BF-BOF for primary production
- Regional differences in scrap availability and electricity costs

5.3 Natural Gas-Based DRI (Transitional Technology)

5.3.1 Technical Description

Direct reduction using natural gas-derived syngas ($CO + H_2$) in shaft furnaces (MIDREX, HYL/Energiron). Produces DRI with 85-95% metallization. CO_2 emissions approximately 0.7-1.0 tonnes per tonne of DRI. Can be transitioned to hydrogen with modifications.

5.3.2 Current Status

Well-established commercial technology with over 100 million tonnes annual capacity globally. Operating plants in Middle East, India, North America. Technology fully proven at industrial scale (TRL 9), but included here as transition pathway to H-DRI.

5.3.3 Challenges

- Still fossil fuel-based (not ultimate decarbonization solution)
- Natural gas price volatility
- CH_4 slip and upstream emissions considerations
- Need for retrofit to hydrogen or replacement with H-DRI
- May represent stranded asset risk without hydrogen conversion pathway

5.4 Carbon Capture and Utilization (CCU)

5.4.1 Technical Description

Captured CO_2 from steelmaking used as chemical feedstock for producing methanol, synthetic fuels, chemicals, or building materials. Reduces net emissions if utilizing renewable energy. Various conversion pathways including Power-to-X technologies.

5.4.2 Current Status

Several demonstration projects coupling steel plant CO_2 capture with utilization pathways. Commercial plants producing methanol from steel mill gases operating in China and Europe. Scale limited by CO_2 utilization market size.

5.4.3 Challenges

- Limited market size for CO_2-derived products relative to steel emissions
- Energy intensity of conversion processes
- Economics dependent on product prices and carbon pricing
- Life-cycle emissions accounting complexity
- Not scalable to eliminate all steel sector emissions

5.5 Advanced Process Control and AI Optimization

5.5.1 Technical Description

Machine learning and artificial intelligence for optimizing steelmaking process parameters to minimize energy consumption and emissions. Real-time monitoring and control systems. Predictive maintenance and quality optimization.

5.5.2 Current Status

Increasingly deployed across steel industry for BF-BOF and EAF operations. 5-15% energy savings demonstrated. Multiple vendors offering solutions. Integration with existing plant control systems.

5.5.3 Challenges

- Data quality and sensor infrastructure requirements
- Integration with legacy systems
- Model training and validation requirements
- Incremental improvement only (not transformational)
- Cybersecurity considerations

6 Chapter 5: System Commissioning and Pre-Commercial (TRL 7-8)

6.1 Overview

Technologies at TRL 7-8 have completed system demonstration and are being qualified for commercial deployment. First commercial plants are under construction or commissioning. These represent the leading edge of steel decarbonization deployment today.

6.2 Hydrogen-Based Direct Reduction (H-DRI) - Commercial Scale

6.2.1 Technical Description

Full-scale hydrogen direct reduction facilities producing 1-2+ million tonnes of DRI annually using green hydrogen from electrolysis. Integrated with EAF melting for complete primary steel production. Near-zero CO_2 emissions when using renewable electricity throughout value chain.

6.2.2 Current Status

HYBRIT pilot plant (Sweden) successfully producing fossil-free steel since 2021. H2 Green Steel constructing first large-scale plant (5 Mt/year capacity by 2030). Multiple projects announced globally with FID (Final Investment Decision) or under construction. TRL advancing from 7 to 8.

6.2.3 Deployment Timeline

- 2024-2026: First commercial plants start production
- 2027-2030: Multiple gigascale facilities operational
- 2030-2040: Technology becomes mainstream for primary steel in regions with renewable electricity

6.2.4 Remaining Challenges

- Green hydrogen supply chain development (100+ TWh electricity needed globally)
- Capital financing for first movers ($3-5 billion per plant)
- Premium pricing for green steel and customer acceptance
- Grid infrastructure for gigawatt-scale renewable electricity
- Iron ore pellet supply suited for hydrogen reduction

6.3 HIsarna Smelting Reduction with CCS

6.3.1 Technical Description

Molten bath smelting reduction process eliminating coke ovens and sinter plant. Direct use of coal and iron ore fines. High CO_2 concentration in off-gas ($>95\%$) facilitating CCS. Pilot plant demonstrated 20-30% CO_2 reduction vs. conventional BF-BOF.

6.3.2 Current Status

Pilot plant operated successfully at Tata Steel IJmuiden (Netherlands) for several years. Technology demonstration completed. Commercial-scale deployment decision pending. With CCS integration, could achieve 80-90% emission reduction.

6.3.3 Challenges

- Scale-up from 60,000 t/year pilot to multi-million tonne commercial plant
- CCS infrastructure requirement for full decarbonization
- Capital cost competitiveness
- Still requires fossil carbon input
- Uncertain competitive position vs. H-DRI-EAF route

6.4 HYBRIT Hydrogen Storage and Distribution

6.4.1 Technical Description

Large-scale hydrogen production via water electrolysis (100+ MW), seasonal storage in lined rock caverns, and distribution to DRI facility. Demonstration of complete hydrogen value chain for steelmaking. Storage capacity enables buffering renewable electricity variability.

6.4.2 Current Status

HYBRIT project in Sweden operating pilot-scale system. Rock cavern hydrogen storage demonstrated. Commercial-scale hydrogen production facilities under construction. End-to-end system validation completed.

6.4.3 Challenges

- Geological suitability for underground hydrogen storage
- Hydrogen compression and storage costs
- Electrolyzer cost reduction (target <$300/kW)
- Renewable electricity procurement and pricing
- Replication to regions without suitable geology

6.5 Digital Twins and Real-Time Optimization

6.5.1 Technical Description

Comprehensive digital models of entire steelmaking facilities enabling simulation, optimization, and predictive control. Integration of process data, thermodynamic models, and machine learning. Real-time adjustment of operating parameters to minimize emissions and energy consumption while maintaining product quality.

6.5.2 Current Status

Advanced digital twin systems deployed at leading steel facilities. Integration with emission monitoring and reporting. Demonstrated 3-8% additional energy savings beyond conventional control systems. Vendor ecosystem established.

6.5.3 Challenges

- Model accuracy and validation across operating conditions
- Integration with decarbonization technologies (H-DRI, CCS)
- Data infrastructure and connectivity requirements
- Workforce training and change management
- Enabling technology rather than primary decarbonization solution

7 Chapter 6: Commercial Operation (TRL 9)

7.1 Overview

TRL 9 technologies are fully commercial and proven in operational environments. While representing established approaches, many require scaling or combination with emerging technologies for deep decarbonization. This chapter covers deployed technologies forming the foundation of near-term steel sector emission reductions.

7.2 Electric Arc Furnace (EAF) Steelmaking

7.2.1 Technical Description

Melting of steel scrap, DRI, or hot briquetted iron (HBI) using high-power electric arcs (50-400 MW). Modern EAFs achieve tap-to-tap times of 35-50 minutes with 350-500 kWh/t energy consumption. Ultra-high power (UHP) designs maximize productivity. Secondary metallurgy for composition and temperature control.

7.2.2 Current Status

Approximately 700+ EAF facilities operating globally, producing 28-30% of world steel output (500 Mt/year). Technology continuously improving with larger transformers, advanced process control, and renewable electricity integration. When powered by renewables and using green DRI, lifecycle emissions <0.2 t CO_2/t steel.

7.2.3 Decarbonization Pathway

1. **Near-term (2024-2030):** Transition to renewable electricity contracts (power purchase agreements). Gradual increase in DRI/HBI use alongside scrap.
2. **Medium-term (2030-2040):** Large-scale deployment of H-DRI feeding EAFs. Scrap supplementation where available. Expansion of EAF capacity to replace BF-BOF.
3. **Long-term (2040-2050):** EAF becomes dominant steelmaking technology globally. Near-complete decarbonization achieved through green electricity and hydrogen-based feedstock.

7.2.4 Operational Considerations

- Grid connection requirements (stable high-power supply)
- Scrap management and quality control systems
- Dust collection and environmental systems
- Electrode consumption and costs
- Product quality control for high-grade applications

7.3 Energy Efficiency Improvements in BF-BOF

7.3.1 Technical Description

Package of proven technologies reducing energy consumption and emissions in conventional blast furnace routes: pulverized coal injection (PCI), top pressure recovery turbines (TRT), coke dry quenching (CDQ), waste heat recovery systems, oxygen enrichment, and optimized burden distribution.

7.3.2 Current Status

Widely deployed globally with best-practice plants achieving 320-340 kg coke/t hot metal. Emission intensity reduced from 2.0-2.3 to 1.7-1.9 t CO_2/t steel through efficiency measures. Incremental improvements continue with advanced process control and AI optimization.

7.3.3 Emission Reduction Potential

Best-practice BF-BOF plants demonstrate 15-20% emission reduction compared to global average. Further 5-10% reduction possible through full implementation of available technologies and optimizations. Represents important near-term emission reductions but insufficient for long-term decarbonization targets.

7.3.4 Implementation Status

- PCI technology: >95% of global BF capacity
- Coke dry quenching: 70% of global capacity
- Top pressure recovery: 60% of global capacity
- Waste heat recovery: Variable, 40-80% depending on region
- Significant improvement potential remains in emerging economies

7.4 Natural Gas-Based DRI (MIDREX/HYL)

7.4.1 Technical Description

Shaft furnace direct reduction using reformed natural gas (CO + H_2 syngas). Iron ore pellets or lump ore reduced at 800-1050°C producing DRI with 85-95% metallization. Off-gas recycled after CO_2 removal. Products include cold DRI, hot DRI (HDRI), and hot briquetted iron (HBI).

7.4.2 Current Status

Over 100 plants operating globally with 120 Mt/year capacity. Dominant technology in regions with low natural gas prices (Middle East, USA, Russia). Modern plants achieve 0.7-0.9 t CO_2/t DRI. MIDREX and Energiron (HYL) represent primary technology providers. Proven reliability and product quality.

7.4.3 Transition to Hydrogen

Natural gas DRI plants designed for potential hydrogen retrofit. Transitional pathway:

1. Current: 100% natural gas-based reduction
2. Phase 1: 20-30% hydrogen blending (minimal modifications)
3. Phase 2: 50-70% hydrogen (moderate equipment changes)
4. Phase 3: 100% hydrogen (significant modifications, equivalent to H-DRI)

Technology providers actively developing hydrogen-ready designs and retrofit pathways.

7.4.4 Strategic Considerations

- Asset life typically 30-40 years (investment decisions must consider decarbonization timeline)
- Natural gas price volatility and long-term availability
- Potential stranded asset risk if carbon prices increase significantly

- Opportunity for brownfield conversion to hydrogen
- Important bridging technology in energy transition

7.5 Scrap-Based Circular Steel Economy

7.5.1 Technical Description

Steel recycling through collection, sorting, processing, and remelting of post-consumer and manufacturing scrap. Steel is infinitely recyclable without quality degradation. Modern scrap processing includes shredding, magnetic separation, sensor-based sorting, and de-coating. Produces variety of scrap grades for different applications.

7.5.2 Current Status

Approximately 630 Mt of steel scrap recycled annually (global recycling rate 85% of available scrap). EAFs consume majority of scrap. Collection and processing infrastructure well-established in developed economies. Significant energy savings: recycling reduces energy consumption by 60-75% vs. primary production.

7.5.3 Decarbonization Role

Scrap-based steelmaking with renewable electricity represents lowest-emission production route (0.1-0.3 t CO_2/t steel including upstream). However, scrap availability constraints prevent 100% scrap-based production:

- Global steel demand growing faster than scrap generation
- Quality dilution from tramp elements (Cu, Sn, etc.)
- Regional imbalances in scrap availability
- Product applications requiring virgin steel (automotive, electrical applications)

Optimal future: Maximize scrap utilization supplemented by H-DRI for primary production needs.

7.5.4 Enhancement Technologies

- Advanced sorting (laser-induced breakdown spectroscopy, X-ray fluorescence)
- Tramp element removal technologies (under development)
- Digitalization of scrap supply chains
- Extended product lifetimes to maintain steel quality through cycles

7.6 Renewable Electricity Procurement

7.6.1 Technical Description

Contracting mechanisms for steel producers to procure renewable electricity: power purchase agreements (PPAs), renewable energy certificates (RECs), on-site generation (solar, wind), and grid renewable energy procurement. Critical enabler for EAF and H-DRI decarbonization.

7.6.2 Current Status

Increasing number of steel producers signing long-term renewable PPAs (10-25 year contracts). Examples include ArcelorMittal, Nucor, SSAB, and H2 Green Steel. On-site solar installations at steel facilities growing. Renewable electricity now cost-competitive in many regions.

7.6.3 Implementation Models

- **Corporate PPAs:** Direct contracts with renewable generators
- **Virtual PPAs:** Financial hedging instruments
- **On-site generation:** Solar PV on facility roofs and land
- **Green electricity tariffs:** Utility-provided renewable options
- **Co-location:** Steel facilities near major renewable resources

7.6.4 Critical Success Factors

- Grid infrastructure adequacy for high power loads
- Renewable resource availability and reliability
- Regulatory frameworks enabling long-term contracts
- Price competitiveness vs. fossil electricity
- Additionality considerations (driving new renewable capacity)

8 Cross-Cutting Analysis and Conclusions

8.1 Technology Maturity Landscape

The steel decarbonization technology portfolio spans the complete TRL spectrum from fundamental research to commercial deployment. Key observations:

- **Commercial solutions exist today:** EAF with renewable electricity and scrap recycling provides proven near-zero emission pathway, constrained by scrap availability.
- **Near-commercial breakthrough:** H-DRI-EAF route approaching large-scale deployment (2024-2030), offering primary steel production with <0.2 t CO_2/t steel.
- **Transition technologies deployed:** Natural gas DRI and BF-BOF efficiency improvements reduce emissions 20-50% while hydrogen and CCS technologies mature.
- **Emerging options under development:** Molten oxide electrolysis, flash reduction, and other TRL 3-5 technologies may provide alternative pathways post-2035.
- **Long-term research continues:** TRL 1-2 technologies explore novel approaches that could transform industry post-2040.

8.2 Investment and Deployment Priorities

8.2.1 Immediate Actions (2024-2030)

1. Maximize scrap-based EAF production with renewable electricity
2. Deploy energy efficiency measures in existing BF-BOF facilities
3. Construct first commercial-scale H-DRI-EAF integrated facilities
4. Develop green hydrogen production and distribution infrastructure
5. Implement advanced process control and optimization systems

8.2.2 Medium-Term Development (2030-2040)

1. Scale H-DRI technology globally to multi-hundred Mt/year capacity
2. Retrofit existing natural gas DRI plants to hydrogen
3. Deploy CCS at remaining BF-BOF facilities in transition
4. Commercialize advanced technologies (MOE, advanced DRI variants)
5. Build out renewable electricity generation capacity for steel sector

8.2.3 Long-Term Transformation (2040-2050)

1. Complete transition to near-zero emission steelmaking
2. Phase out remaining fossil-based production capacity
3. Optimize circular economy with maximum scrap utilization
4. Deploy next-generation technologies from current TRL 1-4 pipeline
5. Achieve <0.2 t CO_2/t steel global average emissions intensity

8.3 Key Enabling Factors

Successful steel decarbonization requires coordinated development across multiple domains:

- **Renewable electricity:** 3000-5000 TWh additional renewable generation needed globally for complete steel sector decarbonization
- **Hydrogen infrastructure:** Production, storage, and distribution networks requiring $500B-1T investment

- **Carbon pricing:** Economic drivers (\$50-100/t CO_2) making green steel cost-competitive
- **Technology development:** Sustained R&D funding (\$5-10B annually) accelerating TRL advancement
- **Policy frameworks:** Regulations, standards, and incentives supporting transition
- **Finance mechanisms:** Green bonds, public-private partnerships, development banks funding capital-intensive transformation
- **International cooperation:** Technology transfer, trade policies, and coordinated emission reduction commitments

8.4 Regional Considerations

Steel decarbonization pathways vary by region based on resource endowments, existing infrastructure, and economic conditions:

- **Europe:** Leading H-DRI deployment with strong policy support and renewable electricity. Target 30-50 Mt/year green steel capacity by 2030.
- **China:** Dominant producer (1000+ Mt/year) focused on efficiency improvements, increased EAF deployment, and CCS trials. Hydrogen transition beginning post-2030.
- **Middle East/North Africa:** Natural gas-based DRI transitioning to hydrogen utilizing excellent solar resources.
- **North America:** High scrap availability favoring EAF expansion. Selective H-DRI development in regions with renewable electricity and hydrogen access.
- **India:** Mix of efficiency improvements, increased DRI (natural gas and hydrogen), and EAF growth. Coal-based production gradually phasing out.

8.5 Research Gaps and Priorities

Continued technology development should focus on:

1. Cost reduction for green hydrogen production (target $<$\$1.5/kg)
2. Scale-up of emerging TRL 3-5 technologies to demonstration phase
3. Integration of intermittent renewable electricity with continuous steelmaking
4. Advanced materials for high-temperature hydrogen environments
5. Tramp element removal enabling higher scrap utilization
6. Process intensification for capital cost reduction
7. Carbon capture improvements reducing energy penalties
8. Digital technologies for real-time optimization
9. Life cycle assessment and techno-economic analysis frameworks
10. Workforce training and transition management

8.6 Conclusions

The steel industry possesses a credible portfolio of decarbonization technologies spanning early research through commercial deployment. The H-DRI-EAF pathway, complemented by maximum scrap utilization, provides a proven route to near-zero emissions steel production. This technology is transitioning from TRL 7-8 to commercial deployment (TRL 9) during 2024-2030.

Success requires unprecedented investment (\$2-3 trillion globally by 2050), supportive policy frameworks, and coordinated development of enabling infrastructure (renewable electricity, hydrogen). While challenges remain substantial, the technical pathways are clear, and early movers are demonstrating commercial viability.

Emerging technologies at lower TRLs provide insurance against technical or economic challenges with leading approaches and may offer superior long-term solutions. Sustained R&D investment across the complete TRL spectrum is essential.

The steel industry's decarbonization is technically feasible and economically viable given appropriate policy support. Successful transformation will produce a sustainable, circular, low-carbon steel industry by mid-century, eliminating one of the largest industrial sources of greenhouse gas emissions.

9 References

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9.3 Key Organizations and Resources

- **World Steel Association:** https://www.worldsteel.org/
  Industry statistics, sustainability reports, technology assessments
- **International Energy Agency (IEA):** https://www.iea.org/
  Technology roadmaps, energy statistics, policy recommendations
- **HYBRIT Development:** https://www.hybritdevelopment.se/
  Leading hydrogen-based steelmaking demonstration project
- **H2 Green Steel:** https://www.h2greensteel.com/
  First large-scale commercial green steel production
- **Mission Possible Partnership:** https://missionpossiblepartnership.org/
  Industry decarbonization initiatives and roadmaps
- **Global CCS Institute:** https://www.globalccsinstitute.com/
  Carbon capture and storage project database and resources
- **Hydrogen Council:** https://hydrogencouncil.com/
  Hydrogen economy development and industrial applications
- **ResponsibleSteel:** https://www.responsiblesteel.org/
  Steel sustainability certification and standards
- **SteelZero:** https://www.theclimategroup.org/steelzero
  Corporate commitment platform for net-zero steel procurement
- **Breakthrough Energy:** https://breakthroughenergy.org/
  Clean energy technology investment and development

9.4 Standards and Assessment Methodologies

- ISO 14404:2013 - Calculation method of carbon dioxide emission intensity from iron and steel production
- ISO 14067:2018 - Greenhouse gases — Carbon footprint of products — Requirements and guidelines
- ResponsibleSteel Standard v2.0 - Certification framework for sustainable steel production
- Green Steel Standard (under development) - EU taxonomy-aligned green steel definition
- TRL Assessment Framework - NASA and EU Horizon 2020 methodology adapted for industrial processes

10 Appendix: Abbreviations and Glossary

10.1 Abbreviations

- **BF-BOF:** Blast Furnace - Basic Oxygen Furnace
- **CCS:** Carbon Capture and Storage
- **CCU:** Carbon Capture and Utilization
- **CDQ:** Coke Dry Quenching
- **DRI:** Direct Reduced Iron
- **EAF:** Electric Arc Furnace
- **FID:** Final Investment Decision
- **HBI:** Hot Briquetted Iron
- **HDRI:** Hot Direct Reduced Iron
- **H-DRI:** Hydrogen-based Direct Reduced Iron
- **HYBRIT:** Hydrogen Breakthrough Ironmaking Technology
- **MOE:** Molten Oxide Electrolysis
- **Mt:** Million tonnes
- **PCI:** Pulverized Coal Injection
- **PPA:** Power Purchase Agreement
- **REC:** Renewable Energy Certificate
- **SOEC:** Solid Oxide Electrolysis Cell
- **TGR-BF:** Top Gas Recycling Blast Furnace
- **TRL:** Technology Readiness Level
- **TRT:** Top pressure Recovery Turbine
- **TWh:** Terawatt-hours
- **UHP:** Ultra-High Power

10.2 Key Terms

- **Decarbonization:** Reduction or elimination of carbon dioxide emissions from industrial processes
- **Direct Reduction:** Process of reducing iron ore to metallic iron without melting, typically using reducing gases
- **Green Hydrogen:** Hydrogen produced via electrolysis using renewable electricity
- **Green Steel:** Steel produced with near-zero greenhouse gas emissions across the production lifecycle
- **Metallization:** Degree of reduction of iron ore to metallic iron, expressed as percentage
- **Primary Steel:** Steel produced from virgin iron ore (as opposed to recycled scrap)
- **Scrap:** Recycled steel from post-consumer products or manufacturing waste
- **Smelting Reduction:** High-temperature process combining ore reduction and metal melting in single stage
- **Tramp Elements:** Undesirable metallic elements (Cu, Sn, Ni) accumulated in recycled steel
- **Transition Technology:** Intermediate solution providing emission reductions while enabling path to zero-carbon production

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The information presented represents the state of technology development at the time of writing. The steel decarbonization field is rapidly evolving, and readers are encouraged to consult primary sources and recent publications for the latest developments.

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