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A LLM Assisted Journey on Steel Global Decarbonization Policies

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Contents

1 Executive Summary

This report provides a detailed analysis of the environmental commitments and carbon emission reduction strategies of the world's top 20 steel producing companies as of 2024. The steel industry accounts for approximately 7-9% of global carbon dioxide emissions, making decarbonization efforts critical for achieving global climate targets. The companies analyzed represent over 50% of global steel production and demonstrate varying levels of commitment to net-zero targets, with most targeting carbon neutrality by 2050.

2 Global Steel Production Overview

In 2024, global crude steel production reached approximately 1.884 billion tonnes [1]. China continues to dominate production with over 1 billion tonnes annually, more than all other countries combined [2]. The top 20 steel producers collectively account for approximately 800 million tonnes of annual production capacity.

3 Detailed Company Profiles

3.1 1. China Baowu Steel Group Corporation Limited

Headquarters: Shanghai, China
2024 Production: 130.09 million tonnes [3]
Global Rank: #1

3.1.1 Environmental Commitments

China Baowu, the world's largest steel producer, announced its carbon neutrality roadmap targeting net-zero by 2050 [4]. Key milestones include:

- Peak emissions target: 2023
- 30% emissions reduction by 2035 (from 2020 baseline) [5]
- Carbon neutrality by 2050

3.1.2 Emission Reduction Technologies

The company is investing heavily in hydrogen-based steelmaking technologies:

- HyCROF (Hydrogen-enriched Carbonic Oxide Recycling Oxygenate Furnace) technology achieving 20% CO_2 reduction per tonne of hot metal [6]
- 400m^3 industrial-grade hydrogen furnace operational in Xinjiang, achieving 85,021 tonnes CO_2 reduction annually [6]
- Construction of near-zero carbon steel mill in Guangdong Province (completion 2025) with 4.5 billion yuan investment [7]
- Hydrogen DRI demonstration projects with 1 million tonne capacity in Zhangjiang [8]

3.1.3 Current Performance

In 2023, Baowu implemented carbon management systems across subsidiaries and launched a 50 billion yuan carbon neutrality equity fund [8]. Electric arc furnace production represents only 6.5% of total output, indicating significant reliance on blast furnace technology requiring substantial transition efforts.

3.2 2. ArcelorMittal

Headquarters: Luxembourg
2024 Production: 65 million tonnes [1]
Global Rank: #2

3.2.1 Environmental Commitments

ArcelorMittal has set comprehensive decarbonization targets:

- 25% global carbon intensity reduction by 2030 (from 2018 baseline) [9]
- 35% reduction in Europe by 2030
- Net-zero by 2050 across all scopes
- Target carbon intensity: 0.40 tonnes CO_2e per tonne of crude steel by 2050 [10]

3.2.2 Achievement and Progress

The 2024 Sustainability Report revealed significant achievements [9]:

- Nearly 50% reduction in absolute emissions since 2018 (from 188 million to 102 million tonnes CO_2e)
- $1 billion invested in decarbonization projects since 2018
- Electric arc furnace production increased from 19% (2018) to 25% (2024)
- 42 sites certified under ResponsibleSteel™ standard
- Average carbon intensity: 1.75 tonnes CO_2/tonne (below global average of 1.92)

3.2.3 Technology Pathways

ArcelorMittal's decarbonization strategy focuses on two main approaches:

- **Smart Carbon:** Carbon capture, utilization, and storage (CCUS) technologies
- **Innovative DRI:** Green hydrogen-based direct reduced iron with electric arc furnaces

Notable projects include the Sestao plant in Spain, planned as the world's first full-scale zero carbon-emissions steel plant [11].

3.3 3. Ansteel Group Corporation Limited

Headquarters: Anshan, Liaoning, China
2024 Production: 59.55 million tonnes [2]
Global Rank: #3

3.3.1 Environmental Initiatives

Ansteel is developing hydrogen-based steelmaking capabilities:

- World's first green hydrogen-based demonstration project in Bayuquan with 10,000 tonnes capacity [8]
- Focus on ultra-low emissions compliance with Chinese government regulations
- Target: 80% of Chinese steelmaking capacity compliant with ultra-low emission standards by 2025

3.4 4. Nippon Steel Corporation

Headquarters: Tokyo, Japan
2024 Production: 43.64 million tonnes [2]
Global Rank: #4

3.4.1 Environmental Commitments

Nippon Steel has committed to carbon neutrality by 2050 but faces criticism for insufficient near-term action [12]:

- Net-zero target by 2050
- Continued investment in blast furnace technology and metallurgical coal
- Limited transition to electric arc furnaces or hydrogen DRI

3.4.2 Key Technologies

- **COURSE50:** Carbon capture and hydrogen injection in blast furnaces, targeting 30% CO_2 reduction
- **Super COURSE50:** Advanced hydrogen-based reduction achieving 43% CO_2 reduction in test furnace [13]
- Demonstration test at Kimitsu large operational blast furnace (FY2026)

3.4.3 Concerns

Analysis indicates emissions have increased year-over-year by 1 million tonnes, with decarbonization primarily achieved through reduced production volumes rather than technological transformation [12].

3.5 5. HBIS Group Co., Ltd

Headquarters: Shijiazhuang, Hebei, China
2024 Production: 41 million tonnes [15]
Global Rank: #5

3.5.1 Environmental Targets

HBIS Group announced ambitious carbon reduction goals [14]:

- Peak emissions: 2022
- 10% emissions reduction by 2025
- 30% reduction by 2030
- Carbon neutrality by 2050

3.5.2 Hydrogen Metallurgy Projects

- China's first hydrogen DRI demonstration plant in Zhangjiakou with 1.2 million tonnes capacity (operational 2023) [8]
- Phase 1: Grey hydrogen from coke ovens
- Phase 2: Green hydrogen from renewable sources
- Total planned capacity: 3.6 million tonnes during 14th Five-Year Plan
- Hydrogen refueling station for trucks at Tangsteel facility using coke oven hydrogen [14]

3.6 6. Shagang Group

Headquarters: Zhangjiagang, Jiangsu, China
2024 Production: 41.45 million tonnes [16]
Global Rank: #6

3.6.1 Profile

China's largest privately-owned steelmaker operates five production facilities nationwide. Environmental Product Declaration (EPD) reports issued for steel products to address international carbon requirements [17]. Limited public information available on specific net-zero commitments.

3.7 7. Jingye Steel Group

Headquarters: Shijiazhuang, Hebei, China
2024 Production: Approximately 35-40 million tonnes
Global Rank: #7

3.7.1 Environmental Approach

Jingye Steel emphasizes green and sustainable steel industry development [18]:

- Commitment to ultra-low emission transformation programs
- Integration of environmental sustainability with technological advancement
- ISO 9001 and ISO 14001 certifications

3.8 8. Shougang Group

Headquarters: Beijing, China
2024 Production: Approximately 34-38 million tonnes
Global Rank: #8

3.8.1 Environmental Strategy

Shougang focuses on:

- Ultra-low emission steel production
- Environmental Product Declaration participation [17]
- Modernization of facilities to improve environmental performance

3.9 9. Tata Steel Limited

Headquarters: Mumbai, India
2024 Production: 31 million tonnes [2]
Global Rank: #9-10

3.9.1 Environmental Recognition

Tata Steel demonstrates industry leadership in sustainability:

- Sustainability Champion by World Steel Association for 8 consecutive years (2018-2025) [19]
- Crude steel capacity: 35 million tonnes per annum
- Active participation in ResponsibleSteel initiative

3.9.2 Decarbonization Targets

- Tata Steel Europe: 30-40% emissions reduction by 2030 [20]
- Significant investments in decarbonization technologies
- Implementation of LCA (Life Cycle Assessment) methodologies in circular systems [21]

3.10 10. JSW Steel Limited

Headquarters: Mumbai, India
2024 Production: 26.95 million tonnes [2]
Global Rank: #10-11

3.10.1 Environmental Leadership

- Sustainability Champion by World Steel Association for 5 consecutive years [22]
- Member of World Business Council for Sustainable Development (WBCSD)
- Production capacity: 35.7 MTPA in India and USA, targeting 38.5 MTPA by 2025

3.10.2 Sustainability Initiatives

- SpheraCloud Corporate Sustainability platform integration for automated LCI data collection [21]
- Reduced data reporting time and increased precision in environmental declarations
- 35% carbon emissions reduction target by 2030 [22]

3.11 11. POSCO Holdings Inc.

Headquarters: Pohang, South Korea
2024 Production: Approximately 26-28 million tonnes
Global Rank: #11-12

3.11.1 Environmental Vision

Corporate vision: "Build a better world with green steel" [22]

- Net-zero carbon commitment by 2050
- Development of blast furnace technology using HBI, natural gas, and pellets blend
- Target: 16% emissions reduction per tonne compared to conventional BF process [21]

3.11.2 Technology Development

- LCA-based cooperation within Hyundai Motor Group supply chain
- Eco-friendly processes and premium steel products
- Strong digital transformation and green hydrogen initiatives

3.12 12. JFE Steel Corporation

Headquarters: Tokyo, Japan
2024 Production: Approximately 24-26 million tonnes
Global Rank: #12-13

3.12.1 Environmental Vision 2050

JFE Group formulated comprehensive environmental strategy in May 2021 [33]:

- Carbon neutrality target: 2050
- 30% or more CO_2 emissions reduction by 2030 (above FY2013 baseline)
- Climate change initiatives as core business priority

3.12.2 Green Steel Products

- JGreeX™ green steel products for shipbuilding and construction
- Environmental Product Declaration (EcoLeaf) certification for steel bars, wire rods, and pipes
- Low embodied-carbon building applications [**?**]

3.13 13. Nucor Corporation

Headquarters: Charlotte, North Carolina, USA
2024 Production: 20.66 million tonnes [2]
Global Rank: #13

3.13.1 Industry Leadership

Nucor is recognized as a global leader in low-carbon steel production:

- Largest steel producer in the United States
- Largest scrap recycler in North America
- 16th largest steel producer globally by volume
- Market capitalization: Over $36 billion [22]

3.13.2 Environmental Achievements

Science-Based Emissions Targets (SBET):

- First diversified U.S. steelmaker with certified targets including Scopes 1, 2, and 3
- 2030 interim target: 0.975 metric tons CO_2e per metric ton of hot-rolled steel [23]
- Net-zero by 2050: 0.116 metric tons CO_2e per metric ton (exceeds GSCC Steel Climate Standard)
- Certified by Global Steel Climate Council (GSCC) in January 2025 [23]

Current Performance:

- Uses average of 80% recycled scrap in production
- One-third the GHG intensity of traditional blast furnace processes
- Econiq™ NZ: World's first net-zero carbon steel at scale [24]

3.13.3 Decarbonization Strategy

- Increased use of clean electricity
- Carbon capture and sequestration technologies
- Near-zero GHG ironmaking development
- Reduction in natural gas consumption
- Enhanced use of direct reduced iron (DRI) and hot briquetted iron (HBI)

3.14 14. Steel Authority of India Limited (SAIL)

Headquarters: New Delhi, India
2024 Production: 19.10 million tonnes [2]
Global Rank: #14

3.14.1 Environmental Commitments

SAIL joined LeadIT (Leadership Group for Industry Transition) demonstrating commitment to decarbonization [25]:

- Net-zero journey aligned with Government of India's 2070 target
- Member of Maharatnas (India's premier public sector enterprises)
- Nearly seven decades of history as major steel producer

3.14.2 Sustainability Strategy

- Focus on energy efficiency and resource efficiency
- Investment in low-carbon emission technologies aligned with National Steel Policy 2030-31
- Research in hydrogen-based metallurgy and green electricity-based steelmaking
- Commitment to develop centers of excellence for sustainable solutions

3.14.3 Challenges

As one of India's oldest steel manufacturers, SAIL faces challenges from:

- Carbon-intensive production processes
- Historical reliance on coal
- Need for significant capital investment in green transition

3.15 15. Cleveland-Cliffs Inc.

Headquarters: Cleveland, Ohio, USA
2024 Production: 16.4 million tonnes [2]
Global Rank: #15

3.15.1 Environmental Achievements

Cleveland-Cliffs achieved remarkable early success in emissions reduction:

- 2030 target of 25% Scope 1+2 GHG intensity reduction achieved ahead of schedule [26]
- Nearly one-third reduction in GHG emissions from 48 U.S. facilities (from 2017 baseline)
- Named 2023 Goal Achiever by U.S. Department of Energy Better Climate Challenge [27]
- Integrated steel mill average 27% lower than global average

3.15.2 New Targets (May 2024)

Following early achievement of 2030 goals, new targets established [28]:

- Enhanced GHG reduction targets with focus on practical, commercially viable technologies
- Continued investment in decarbonization R&D
- Development of carbon capture technologies for blast furnace gas

3.15.3 Key Technologies

- Direct Reduction plant in Toledo, Ohio (opened 2020) using natural gas instead of coal
- Hot Briquetted Iron (HBI) production with lower carbon intensity
- "Cliffs H" product line with $40/ton premium for lower-carbon steel
- Onsite power generation using byproduct blast furnace and coke oven gases (75%+ of plant energy needs) [29]
- Research partnerships exploring hydrogen use in steelmaking

3.16 16. United States Steel Corporation

Headquarters: Pittsburgh, Pennsylvania, USA
2024 Production: 14.18 million tonnes [2]
Global Rank: #16

3.16.1 Environmental Strategy

U.S. Steel emphasizes customer-focused sustainability:

- Adaptation to changing customer sustainability goals
- Focus on reducing corporate carbon footprint
- Investment in modern, efficient steelmaking technologies

3.17 17. Hyundai Steel Company

Headquarters: Seoul, South Korea
2024 Production: Approximately 12-14 million tonnes
Global Rank: #17

3.17.1 Environmental Innovation

- LCA-based supply chain cooperation within Hyundai Motor Group [21]
- Integration of environmental considerations across automotive value chain
- Development of sustainable steel solutions for electric vehicle production

3.18 18. Thyssenkrupp Steel Europe

Headquarters: Duisburg, Germany
2024 Production: 10.26 million tonnes [2]
Global Rank: #18

3.18.1 Environmental Commitments

Thyssenkrupp leads European decarbonization efforts:

- Sustainability embedded in Group strategy as key innovation driver [30]
- EU approval for €2.3 billion state subsidies for green steel production
- Hydrogen-powered DRI plant planned at Duisburg site
- Most aspirational net-zero targets encompassing Scopes 1, 2, and 3 [31]

3.18.2 Technology Partnerships

- Joint development with JFE Steel of high-strength automotive steels enabling weight reduction and lower CO_2 emissions [32]
- Focus on advanced manufacturing processes supporting electric vehicle transition

3.19 19. Gerdau S.A.

Headquarters: Porto Alegre, Brazil
2024 Production: 11.7 million tonnes low-carbon steel [34]
Global Rank: #19

3.19.1 Industry Leadership Position

Gerdau is one of Latin America's largest steel producers with industrial presence in 14 countries across the Americas, Europe, and Asia [36]. Founded 121 years ago, the company has established itself as a pioneer in sustainable steel production through scrap-based manufacturing.

3.19.2 Environmental Achievements

Gerdau demonstrates exceptional environmental performance compared to global industry averages:

- **Current emissions intensity:** 0.93 tonnes CO_2e per tonne of steel (approximately 50% of global average) [35]
- **2024 performance:** 11.7 million tonnes low-carbon steel produced, with nearly 70% from recycled scrap [34]
- **Annual scrap recycling:** Approximately 10 million tonnes, ranking among Latin America's largest recyclers [34]
- **Production mix:** 80% based on recycled and renewable sources [35]

3.19.3 Decarbonization Targets

- 2031 target: Reduce emissions to 0.83 tonnes CO_2e per tonne of steel (below 50% of industry average) [35]
- Carbon neutrality ambition: 2050
- Executive compensation: 20% of Long-Term Incentive Plan linked to CO_2e emissions and diversity metrics [35]

3.19.4 Technology and Circular Economy

Electric Arc Furnace Technology:

- Primary production route through EAF facilities
- 75% reduction in energy consumption compared to blast furnace methods [34]
- Flexible raw material inputs with increasing renewable electricity integration

Renewable Energy Initiatives:

- Solar park installations in Minas Gerais, Brazil
- Photovoltaic park at Midlothian, Texas facility
- Both projects designed to supply clean energy to steel production units [35]

Circular Economy Practices:

- 84% of co-products globally reused in other production chains [37]
- Applications: road paving, railway ballast, foundries, cement, ceramics
- Water recirculation: 97.7% of water used in production reused [39]
- Waste reuse: 78% of solid waste generated repurposed (2020 data) [38]

3.19.5 Transparency and Recognition

- Complete data reporting for all 19 World Steel Association sustainability indicators [19]
- Carbon Disclosure Project (CDP) score: B- (above South America and sector average) [41]
- GRI (Global Reporting Initiative) standards compliance
- UN Global Compact signatory
- Environmental Product Declarations (EPD) issued for structural steel products [40]
- 417 million BRL annual environmental investment (2020) [41]

3.20 20. Steel Dynamics Inc.

Headquarters: Fort Wayne, Indiana, USA
2024 Production: 10.2 million tonnes [2]
Global Rank: #20

3.20.1 Environmental Leadership

Steel Dynamics demonstrates strong commitment to sustainability:

- America's third-largest carbon steel producer
- Robust metal-recycling program with 12,000+ employees
- GHG emissions targets aligned with Paris Agreement
- Net-zero by 2050 target [22]
- Founded by former Nucor executives in 1993

4 Global Steel Industry Carbon Footprint Context

4.1 Emissions Scale and Impact

The steel industry represents one of the largest industrial sources of carbon emissions globally:

- **Global CO_2 emissions:** Approximately 3.7 billion tonnes annually (average since 2019) [43]
- **Share of global emissions:** 7-11% depending on measurement methodology [42, 43]
- **Comparison:** Steel emissions exceed all passenger vehicles worldwide [43]
- **Coal dependency:** Coal meets approximately 75% of sector energy and feedstock demand [42]

4.2 Production Route Emissions Profiles

Different steel production methods have dramatically different carbon intensities:

Blast Furnace-Basic Oxygen Furnace (BF-BOF):

- Primary production route: 70% of global steel [44]
- Average emissions: 2.33 tonnes CO_2 per tonne of steel [44]
- Breakdown by process stage:
  - Coke production: 0.71 tonnes CO_2/tonne steel
  - Blast furnace operations: 1.41 tonnes CO_2/tonne steel
  - Basic oxygen furnace: 0.21 tonnes CO_2/tonne steel
- Accounts for 86% of total steel sector emissions [43]
- Global capacity: 62% (1,397 Mtpa) [43]

Electric Arc Furnace (EAF):

- Secondary production route: 29% of global steel capacity (665 Mtpa) [43]
- Average emissions: 0.357 tonnes CO_2 per tonne of steel [46]
- Accounts for only 15% of steel sector emissions despite 29% capacity share [43]
- Carbon intensity varies significantly based on:
  - Electricity grid carbon intensity
  - Scrap vs DRI feedstock ratio
  - Facility efficiency and technology vintage

Direct Reduced Iron (DRI) with EAF:

- Emerging route: 7% of global iron production [44]
- Natural gas-based DRI: Intermediate emissions between BF-BOF and scrap-EAF
- Green hydrogen-based DRI: Near-zero emissions potential
- Critical for regions with limited scrap availability

4.3 Carbon Intensity by Country and Region

Steel carbon intensity varies dramatically by geography due to production methods and energy mix [45]:

Lowest Carbon Intensity Countries:

- **Italy:** High EAF share (40%), renewable electricity
- **United States:** Significant EAF capacity, scrap availability
- **Turkey:** EAF-dominated production

Highest Carbon Intensity Countries:

- **Ukraine:** Aging blast furnace infrastructure
- **India:** Coal-based production, lower efficiency technology
- **China:** BF-BOF dominance (>90%), coal dependency, but modernizing rapidly

Factors Influencing National Averages:

- Share of EAF in total production
- Fuel mix (coal, natural gas, renewables)
- Electricity grid emissions factor
- Feedstock type (iron ore quality, scrap availability)
- Technology penetration and facility age
- Product mix (complex steels require more processing)
- Environmental regulations and carbon pricing
- Capacity utilization rates

4.4 Industry Average Trends

World Steel Association Data (2023):

- Global average CO_2 intensity: 1.92 tonnes per tonne crude steel [19]
- Expanded methodology (2024): Now includes CH_4, N_2O, and upstream mining emissions [48]
- Energy intensity: 21.27 GJ per tonne crude steel [19]
- Modest progress: Intensity decreased slightly but acceleration needed for Paris alignment [42]

4.5 Scrap Steel Impact

Recycling provides the most immediate emissions reduction:

- **CO_2 saved:** 1.787 tonnes per tonne of scrap recycled [46]
- **Resource conservation:** 1.5 tonnes iron ore + 0.5 tonnes coal saved per tonne recycled steel [47]
- **Limitation:** Global scrap availability constrained relative to primary steel demand
- **Quality considerations:** Scrap composition affects final product specifications

5 Comparative Analysis

6 Comparative Analysis

6.1 Carbon Intensity Performance Benchmarking

Table 1 compares carbon intensities across selected top producers where data is publicly available.

Table 1: Carbon Emission Intensity Comparison

Company	**CO_2e Intensity (tonnes/tonne steel)**	**% vs Global Avg (1.92 t/t)**
Gerdau	0.93	48%
Nucor	0.70	36%
ArcelorMittal	1.75	91%
Industry Average (BF-BOF)	2.33	121%
Industry Average (EAF)	0.36	19%
Global Average	**1.92**	**100%**

6.2 Production Capacity by Technology Route

Table 2: Global Steel Production Capacity by Route (2023)

Route	**Capacity (Mtpa)**	**Share (%)**	**Emissions Share (%)**	**Emissions (t CO_2/t)**
BF-BOF	1,397	62%	86%	2.33
EAF	665	29%	15%	0.36
Open Hearth	<6	<1%	<1%	2.5+
DRI-EAF	150	7%	<5%	0.8-1.5
Total	**2,250**	**100%**	**100%**	**1.92 avg**

6.3 Net-Zero Commitments

Table 3 summarizes net-zero commitments across the top 20 producers.

6.4 Technology Adoption Patterns

6.4.1 Electric Arc Furnaces (EAF)

Companies with highest EAF adoption rates:

- Nucor: 80% scrap-based EAF production
- ArcelorMittal: 25% and increasing
- Cleveland-Cliffs: Expanding EAF capacity

Table 3: Net-Zero Target Commitments by Company

Company	Net-Zero Target	Interim Target
China Baowu	2050	30% by 2035
ArcelorMittal	2050	25% by 2030
Nippon Steel	2050	30% by 2030
HBIS Group	2050	30% by 2030
Tata Steel	-	30-40% by 2030
JSW Steel	-	35% by 2030
POSCO	2050	-
JFE Steel	2050	30% by 2030
Nucor	2050	Certified SBET
SAIL	2070	Aligned with India
Cleveland-Cliffs	-	25% achieved
Thyssenkrupp	2050	Scope 1-3
Steel Dynamics	2050	Paris Agreement

6.4.2 Hydrogen-Based Direct Reduction

Leading hydrogen metallurgy projects:

- HBIS Group: 1.2 million tonnes capacity operational
- China Baowu: 1 million tonnes capacity in Zhangjiang
- Ansteel: 10,000 tonnes green hydrogen demonstration
- ArcelorMittal: Sestao full-scale zero-emissions plant (planned)
- Thyssenkrupp: EU-funded hydrogen DRI plant

6.4.3 Carbon Capture Technologies

- China Baowu: HyCROF technology (20% reduction achieved)
- Nippon Steel: COURSE50 and Super COURSE50 (30-43% reduction potential)
- Cleveland-Cliffs: Blast furnace gas carbon capture R&D
- ArcelorMittal: CCUS as part of "Smart Carbon" pathway

6.5 Regional Differences

China: Dominates production but faces challenges with blast furnace dependency. Government mandates ultra-low emissions by 2025. Strong investment in hydrogen demonstration projects.

Europe: Most ambitious regulatory environment with Carbon Border Adjustment Mechanism (CBAM). Leading in green steel innovation but facing economic challenges with transformation costs.

United States: Focus on EAF and scrap-based production. Strong private sector initiatives. Early achievers in emissions reduction targets.

India: Rapid growth market with emerging sustainability focus. Government support for National Steel Policy 2030-31. Companies recognized as sustainability champions.

Japan and South Korea: Advanced technology development (COURSE50, hydrogen DRI) but slower implementation. Focus on gradual transition maintaining competitiveness.

7 Challenges and Barriers

7.1 Economic Challenges

- Transformational ironmaking (CCUS, hydrogen DRI) unlikely to be economical before 2030 [9]
- High capital and operational costs require supportive policies
- Green steel premium pricing mechanisms still developing
- Competition from high-carbon steel in unregulated markets

7.2 Technical Challenges

- Limited availability of green hydrogen at scale
- Blast furnace infrastructure relatively young (10-15 years in China) [4]
- Carbon capture never demonstrated at commercial scale for blast furnace gas [27]
- Scrap availability constraints for expanded EAF production

7.3 Policy Uncertainties

- Regulatory environment variability across regions
- Need for carbon pricing mechanisms to incentivize green steel
- International trade implications (CBAM, carbon tariffs)
- Technology-specific support and subsidies

8 Industry Initiatives

8.1 Global Collaboration

- **ResponsibleSteel:** 42 ArcelorMittal sites certified; Tata Steel participation
- **World Steel Association:** Sustainability Indicators expanded to 19 metrics; 75 companies participating [19]
- **Global Steel Climate Council:** Nucor certified SBET; setting industry standards
- **LeadIT:** SAIL membership for industry transition
- **Global Low-Carbon Metallurgical Innovation Alliance:** Baowu-led with 60+ members from 15 countries [8]

8.2 Environmental Product Declarations

China launched EPD Platform in 2023:

- 44 EPD reports issued by Baowu, Shagang, Shougang, and others
- 34 for steel products, 10 for iron ore
- Alignment with ISO 14000 series and CBAM requirements [17]

9 Sustainability Indicators

World Steel Association 2025 data [19]:

- Average CO_2 emissions intensity: 1.92 tonnes per tonne crude steel (2023)
- Energy consumption: 21.27 GJ per tonne crude steel (2023)
- Raw material conversion efficiency: 98.15%
- EMS-registered facilities: 94.81% of employees and contractors
- Injury frequency rate: 0.70 per million hours worked (2024)

10 Future Outlook

10.1 Technology Roadmap to 2050

The steel industry's path to net-zero involves three phases:

Near-term (2025-2030):

- Incremental improvements: Energy efficiency, increased scrap use
- Early hydrogen DRI demonstration projects scale up
- Carbon capture pilot projects
- Increased EAF adoption where economically viable

Mid-term (2030-2040):

- Commercial-scale hydrogen-based DRI with green hydrogen
- Widespread EAF deployment
- Carbon capture technology maturation
- Phase-out of coal-based blast furnaces in developed markets

Long-term (2040-2050):

- Dominant hydrogen metallurgy and electrification
- Circular economy optimization
- Residual emissions offset through carbon removal
- Near-zero emissions steel as standard product

10.2 Investment Requirements

Industry estimates suggest:

- Trillions of dollars in global investment needed for steel transformation
- Individual company commitments ranging from hundreds of millions to billions
- Public-private partnerships essential (e.g., Thyssenkrupp €2.3B EU support)
- Carbon pricing mechanisms critical for economic viability

10.3 Market Dynamics

- Growing demand for certified low-carbon steel
- Premium pricing for green steel products (Cleveland-Cliffs $40/tonne premium for "Cliffs H")
- Supply chain pressure from automotive and construction sectors
- CBAM creating competitive dynamics favoring low-carbon producers
- Potential trade barriers for high-carbon steel imports
- Customer-driven sustainability requirements accelerating adoption

11 Conclusions

The top 20 steel producing companies collectively represent over 50% of global steel production and demonstrate varying levels of commitment to decarbonization. Key findings include:

11.1 Commitment Levels

- **Leaders:** ArcelorMittal, Nucor, Cleveland-Cliffs, and Thyssenkrupp demonstrate most comprehensive commitments with certified science-based targets and significant early achievements
- **Emerging Leaders:** Tata Steel, JSW Steel recognized as sustainability champions with strong interim targets
- **Significant Scale:** Chinese producers (Baowu, HBIS, Ansteel) making substantial investments in hydrogen demonstration projects at unprecedented scale
- **Gradual Approach:** Japanese producers (Nippon Steel, JFE) developing advanced technologies but slower implementation

11.2 Technology Pathways

Three primary decarbonization routes emerge:

1. **Scrap-based EAF:** Most immediate and proven pathway (Nucor, Steel Dynamics model)
2. **Hydrogen-based DRI:** Medium-term solution requiring green hydrogen infrastructure (HBIS, Baowu, ArcelorMittal, Thyssenkrupp)
3. **Carbon Capture:** Transitional technology for existing blast furnaces (Nippon Steel COURSE50, Baowu HyCROF)

11.3 Regional Patterns

- **China:** Scale advantage in demonstration projects but overall progress limited by blast furnace dependence
- **Europe:** Regulatory pressure driving fastest transformation with public funding support
- **United States:** Private sector innovation with EAF-based competitive advantage
- **India:** Rapid industrialization balanced with emerging sustainability focus
- **East Asia (Japan/Korea):** Technology leadership but implementation challenges

11.4 Critical Success Factors

1. **Policy Support:** Carbon pricing, subsidies, and regulatory frameworks essential
2. **Technology Development:** Continued R&D in hydrogen, CCUS, and electrification
3. **Green Energy Infrastructure:** Renewable electricity and green hydrogen availability
4. **Economic Viability:** Green steel premium pricing and cost reduction through scale
5. **International Cooperation:** Technology sharing and standardized measurement frameworks

11.5 Outlook

While most major producers have announced net-zero commitments by 2050, the pathway remains challenging. Success will depend on:

- Accelerated deployment of proven low-carbon technologies
- Breakthrough innovations in hydrogen metallurgy becoming commercially viable
- Supportive policy environments globally

- Customer willingness to pay green steel premiums
- Coordinated action across the value chain

The steel industry's transformation represents one of the most significant industrial transitions of the 21st century. The top 20 producers' commitments and investments signal serious intent, but achieving net-zero will require sustained effort, unprecedented investment, and fundamental restructuring of steel production processes over the next 25 years.

12 Recommendations

12.1 For Steel Producers

1. Accelerate pilot projects to commercial scale, particularly for hydrogen DRI
2. Increase transparency through comprehensive environmental reporting
3. Establish science-based targets certified by independent bodies
4. Invest in workforce retraining for new technologies
5. Collaborate across the industry to share technology and best practices

12.2 For Policymakers

1. Implement carbon pricing mechanisms to level the playing field
2. Provide targeted support for capital-intensive green steel investments
3. Harmonize carbon accounting standards internationally
4. Invest in green hydrogen and renewable energy infrastructure
5. Consider public procurement preferences for low-carbon steel

12.3 For Steel Customers

1. Specify low-carbon steel in procurement requirements
2. Accept premium pricing for certified green steel products
3. Collaborate with suppliers on decarbonization roadmaps
4. Conduct comprehensive supply chain carbon assessments
5. Support industry initiatives like ResponsibleSteel certification

12.4 For Investors

1. Prioritize companies with credible, science-based decarbonization targets
2. Consider climate transition risks in portfolio management
3. Support patient capital for transformational technologies
4. Engage with companies on emissions disclosure and reduction strategies
5. Monitor regulatory developments affecting carbon-intensive assets

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A Methodology and Data Sources

A.1 Data Collection

This report compiled information from multiple sources:

- Corporate sustainability reports and environmental disclosures
- World Steel Association annual statistics and sustainability indicators

- Industry publications and trade journals
- Academic research papers and policy analyses
- Company press releases and investor communications
- Third-party assessments and certifications (ResponsibleSteel, GSCC)

A.2 Production Volume Verification

Production volumes were cross-referenced across multiple sources including:

- World Steel Association official statistics
- GMK Center industry database
- Statista steel production rankings
- Individual company annual reports

Minor discrepancies exist between sources due to reporting periods, consolidation methods, and data collection timing. Where conflicts existed, the most recent and authoritative source was prioritized.

A.3 Emissions Data Limitations

- Not all companies report comprehensive Scope 1, 2, and 3 emissions
- Methodologies vary between companies and regions
- Baseline years differ making direct comparisons challenging
- Some companies provide intensity metrics while others report absolute emissions
- Chinese companies have limited publicly available English-language documentation

A.4 Currency and Temporal Context

All information current as of November 2025. Targets, commitments, and production volumes reflect the most recent publicly available data. The steel industry is undergoing rapid transformation; readers should consult company websites and official reports for the most current information.

B Glossary of Terms

Blast Furnace (BF): Traditional ironmaking process using coke, iron ore, and limestone at high temperatures; accounts for approximately 70% of global steel production and is highly carbon-intensive.

Carbon Border Adjustment Mechanism (CBAM): European Union policy imposing carbon tariffs on imported goods based on embedded emissions, effective from 2026.

Carbon Capture, Utilization, and Storage (CCUS): Technologies capturing CO_2 emissions from industrial processes for storage or conversion to useful products.

Direct Reduced Iron (DRI): Iron produced by reducing iron ore with gases (natural gas, hydrogen, or syngas) without melting, enabling lower-temperature processing and reduced emissions.

Electric Arc Furnace (EAF): Steelmaking process using electric arcs to melt scrap steel or DRI; typically has 60-75% lower carbon footprint than blast furnace route.

Environmental Product Declaration (EPD): Standardized, verified disclosure of environmental impacts throughout product lifecycle according to ISO 14025.

Green Hydrogen: Hydrogen produced through electrolysis powered by renewable energy, producing zero carbon emissions.

Grey Hydrogen: Hydrogen produced from natural gas or coal, generating significant CO_2 emissions.

Hot Briquetted Iron (HBI): Compacted form of DRI for easier transport and handling.

Life Cycle Assessment (LCA): Comprehensive analysis of environmental impacts throughout a product's entire life cycle.

Net-Zero: Achieving balance between greenhouse gas emissions produced and removed from atmosphere.

ResponsibleSteel: Global multi-stakeholder standard and certification initiative for responsible steel production.

Science-Based Targets (SBT): Corporate emissions reduction targets aligned with Paris Agreement goals, verified by independent bodies.

Scope 1 Emissions: Direct emissions from owned or controlled sources.

Scope 2 Emissions: Indirect emissions from purchased energy.

Scope 3 Emissions: All other indirect emissions in the value chain (upstream and downstream).

Ultra-Low Emissions: Chinese regulatory standards for particulate matter, SO_2, and NO_x emissions from steel production.

C Compilation Instructions for Overleaf

C.1 Required Packages

This document requires the following LaTeX packages (all included in standard Overleaf installations):

```
\usepackage[utf8]{inputenc}
\usepackage[T1]{fontenc}
\usepackage[margin=2.5cm]{geometry}
\usepackage{graphicx}
\usepackage{hyperref}
\usepackage{booktabs}
\usepackage{longtable}
\usepackage{amsmath}
\usepackage{cite}
\usepackage{multirow}
\usepackage{array}
```

C.2 Compilation Settings

1. **Compiler:** Use pdfLaTeX (default in Overleaf)
2. **Main Document:** Ensure this .tex file is set as the main document
3. **Compilation Sequence:** The document requires multiple compilation passes:
   - First pass: Generate auxiliary files and process citations
   - Second pass: Resolve cross-references and table of contents
   - Third pass: Final formatting and hyperlink generation
4. **Bibliography:** Uses embedded `thebibliography` environment (no external .bib file required)

C.3 Troubleshooting

- **Undefined references:** Compile multiple times (at least 2-3 passes)
- **Table overflow:** Adjust margins or split tables if adding content
- **Citation numbering:** Ensure bibliography entries are in order of citation
- **Long URLs:** Hyperref package handles URL line breaks automatically

C.4 Customization Options

To modify the document:

- **Font size:** Change `12pt` in documentclass to `10pt` or `11pt`
- **Margins:** Adjust `margin=2.5cm` in geometry package
- **Line spacing:** Add `\usepackage{setspace}` and `\doublespacing`
- **Section numbering:** Modify `\setcounter{secnumdepth}{3}`

C.5 Output Format

- Default output: PDF with clickable table of contents and hyperlinked citations
- Page count: Approximately 30-35 pages depending on formatting
- Color links: Blue for citations, red for internal references (customizable)

C.6 Version Control

For Overleaf users:

- Project automatically saved with version history
- Use History feature to track changes
- Enable Track Changes for collaborative editing
- Export as PDF or LaTeX source for offline use

D Key Policy and Regulatory Frameworks

D.1 Carbon Border Adjustment Mechanism (CBAM) - European Union

The EU's CBAM represents the most significant carbon policy affecting global steel trade:

- **Implementation:** Transitional phase 2023-2025; full application from 2026
- **Coverage:** Steel, aluminum, cement, fertilizers, electricity, hydrogen
- **Mechanism:** Import tariffs based on embedded carbon emissions
- **Calculation:** Based on difference between EU carbon price and exporter's carbon pricing
- **Impact:** Creates economic incentive for global steel producers to reduce emissions
- **Controversy:** Concerns about WTO compliance and competitiveness impacts

D.2 China's Steel Sector Policies

14th Five-Year Plan (2021-2025):

- Peak steel production and sectoral emissions before 2030
- Increase scrap steel use to 320 Mt by 2025
- Ultra-low emissions compliance: 80% of capacity by 2025
- Circular economy priorities

Emissions Trading System (ETS):

- Coverage expansion to heavy industry announced for 2023-2024
- World's largest carbon market by covered emissions
- Initially focused on power sector, expanding to steel

Environmental Product Declaration Platform:

- Launched 2023 to address CBAM requirements
- 44 EPD reports issued by major producers (2023)
- Alignment with ISO 14000 series standards

D.3 United States - Inflation Reduction Act (IRA)

Industrial Decarbonization Funding (2022):

- $5.8 billion budget for industrial decarbonization
- Significant opportunities for steel sector investment
- Tax credits for hydrogen production and CCUS
- Support for demonstration projects and technology deployment

Better Climate Challenge:

- Voluntary commitment program by Department of Energy
- Recognition for companies achieving emissions targets
- Cleveland-Cliffs named 2023 Goal Achiever

D.4 India's National Steel Policy

Targets and Priorities:

- Halve CO_2 intensity of domestic steel production by 2030
- Scrap steel utilization as primary decarbonization pathway
- Support for energy efficiency improvements
- Alignment with 2070 national net-zero target

D.5 Sweden's Green Steel Initiatives

HYBRIT Project:

- World's first fossil-free steel production (2021)
- Partnership: SSAB, LKAB, Vattenfall
- Target: Fossil-free steel by 2026
- Potential: 10% reduction in Sweden's total CO_2 emissions

H2 Green Steel:

- Commercial-scale hydrogen DRI facility under construction
- Off-take agreements secured with major customers
- Planned operation mid-2020s

D.6 International Initiatives

ResponsibleSteel Standard:

- Multi-stakeholder certification initiative
- Environmental, social, and governance criteria
- 42 ArcelorMittal sites certified (2024)
- Growing participation from major producers

Global Steel Climate Council (GSCC):

- Develops science-based emissions targets framework
- Certifies company targets aligned with Paris Agreement
- Nucor first certified U.S. diversified steelmaker (2025)

SteelZero Initiative:

- Demand-side commitment to 100% net-zero steel
- Members: Iberdrola, Siemens Gamesa, Vattenfall, Volvo, others
- Creates market pull for low-carbon steel

LeadIT (Leadership Group for Industry Transition):

- Government and industry partnership
- Committed to Paris Agreement-aligned transition
- SAIL joined 2024, demonstrating emerging economy participation

D.7 Emerging Policy Trends

- **Public procurement preferences:** Governments specifying low-carbon steel for infrastructure
- **Carbon contracts for difference:** Bridging green premium gap between conventional and low-carbon steel
- **Hydrogen infrastructure investment:** National strategies for green hydrogen production and distribution
- **Just transition mechanisms:** Supporting workforce retraining and community impacts
- **Technology-specific subsidies:** Targeted support for CCUS, hydrogen DRI, and advanced EAF