Sweden: Pioneering Green Steel Through Hydrogen-Based Production

A Journey through Steel Decarbonization Policies Worldwide
MIFUS Course Document Series

Claude LLM
In collaboration with
Prof. Fabio Miani
University of Udine, Italy

With grateful acknowledgment to

Prof. Max Åhman, Lund University, Sweden
for authoritative review and valuable comments

November 2025

Abstract

Sweden has established itself as the global leader in steel decarbonization through the groundbreaking HYBRIT initiative and the ambitious Stegra project, demonstrating that near-zero emission steel production is technically and commercially feasible. This document analyzes Sweden's comprehensive approach to steel sector transformation, examining the interplay of climate policy, state ownership, technological innovation, and international cooperation. With the world's highest carbon tax (€134/tonne CO_2 in 2025), an ambitious net-zero target for 2045, and abundant renewable electricity resources, Sweden provides a compelling case study for industrial decarbonization. The analysis reveals that Sweden's success stems from long-term political consensus, strategic use of state-owned enterprises, dual technology pathways (incumbent transformation and greenfield development), and effective public-private risk-sharing mechanisms. However, significant challenges remain, particularly regarding electricity infrastructure, cost competitiveness, and policy durability. The document contributes to the MIFUS course series by offering detailed insights into how advanced economies can align climate ambition with industrial policy, providing lessons for global steel sector transformation.

Keywords: Steel decarbonization, hydrogen direct reduction, HYBRIT, H2 Green Steel, carbon tax, climate policy, Sweden, industrial transformation, renewable energy, green steel

Note: This document is part of the MIFUS Mini Instant Fall Course prototype on "A

Journey through Steel Decarbonization Policies Worldwide." It represents an innovative model of human-AI collaboration in academic research and policy analysis.

Contents

1 Introduction

The global steel industry faces an urgent imperative: to decarbonize production while maintaining economic competitiveness and meeting growing global demand. Steel production currently accounts for approximately 7–10% of global CO_2 emissions, making it one of the most carbon-intensive industrial sectors [3]. The Paris Agreement's goal of limiting global warming to 1.5°C requires near-complete elimination of emissions from all sectors, including steel, by mid-century [1].

Sweden has emerged as the global pioneer in addressing this challenge through hydrogen-based steelmaking technology. The HYBRIT (Hydrogen Breakthrough Ironmaking Technology) initiative, launched in 2016 as a partnership between SSAB (steel producer), LKAB (iron ore mining), and Vattenfall (energy company), produced the world's first fossil-free steel in August 2021 [6]. Simultaneously, the startup company Stegra (formerly H2 Green Steel) is constructing Europe's first greenfield steel mill in 50 years, targeting 5 million tonnes of annual production by 2030.

This document examines Sweden's comprehensive approach to steel decarbonization, analyzing the policy framework, technological innovations, economic implications, and broader lessons for global industrial transformation.

1.1 Research Questions and Methodology

This analysis addresses four primary research questions:

1. What policy instruments and governance mechanisms has Sweden employed to enable steel sector decarbonization?
2. How do the HYBRIT and Stegra approaches differ, and what are their respective advantages and challenges?
3. What role do Sweden's unique contextual factors (renewable electricity, state ownership, political consensus) play in its decarbonization strategy?
4. What lessons can other countries draw from the Swedish experience for their own steel sector transitions?

The methodology combines policy document analysis, industry reports, academic literature review, and examination of project-specific technical and financial data. A critical evaluation approach is employed to identify both strengths and limitations of the Swedish model.

1.2 Document Structure

Section 2 provides background on Sweden's steel industry and emissions profile. Section 3 analyzes the national climate policy framework, including carbon taxation, climate targets, and the Fossil Free Sweden initiative. Sections 4 and 5 examine the HYBRIT and Stegra projects in detail. Section 6 discusses enabling policy instruments. Section 7 identifies key challenges and barriers. Section 8 places Sweden's efforts in international context. Section 9 evaluates economic and social implications. Section 10 assesses environmental performance. Section 11 offers critical evaluation and future outlook. Section 12 concludes with strategic recommendations.

2 Swedish Steel Industry: Overview and Context

2.1 Production Capacity and Market Position

Sweden's steel industry produces approximately 4.5–5 million tonnes of crude steel annually, representing a small fraction of global production (approximately 0.25% of the 1.9 billion tonnes produced globally). Despite this modest scale, Swedish steel commands premium prices in international markets due to its high quality and specialty grades.

The industry is dominated by SSAB (Svenskt Stål AB), which operates integrated blast furnace-basic oxygen furnace (BF-BOF) facilities in Luleå (northern Sweden) and Oxelösund (southern Sweden), with additional capacity in Raahe, Finland. SSAB focuses on high-strength steel products serving automotive, construction, heavy equipment, and engineering sectors.

Critical correction based on Prof. Åhman's review: Sweden's power system is already close to fully decarbonized, with approximately 99% fossil-free electricity generation. The electricity mix consists primarily of hydropower (45–46%), nuclear power (32–48% depending on reactor availability), and rapidly expanding wind power (now exceeding 40 TWh annually, representing 20–31% of generation). This near-zero carbon electricity grid provides a fundamental advantage for hydrogen-based steelmaking that cannot be easily replicated in countries still dependent on fossil fuel electricity generation [9].

Furthermore, northern Sweden experiences exceptionally low electricity prices (SE1 and SE2 zones averaged 28–29 öre/kWh or approximately €2.6–2.7/MWh in 2024), driven by surplus hydropower and wind capacity relative to local demand [8]. These low electricity costs—approximately 40–60% below continental European prices—create a significant competitive advantage for energy-intensive green hydrogen production.

2.2 Iron Ore Resources and LKAB's Strategic Role

A distinguishing feature of Sweden's steel ecosystem is the presence of LKAB (Luossavaara-Kiirunavaara AB), a 100% state-owned mining company that produces approximately 25 million tonnes of iron ore products annually. LKAB's operations in northern Sweden (Kiruna and Gällivare) account for approximately 80% of the European Union's iron ore production.

Most LKAB iron ore is exported to European steelmakers, making the company a critical link in the EU steel value chain. LKAB's state ownership and strategic positioning within Sweden's industrial policy have been instrumental in enabling the HYBRIT initiative's integrated approach from mine to steel production.

2.3 Emissions Profile

Second critical correction based on Prof. Åhman's review: The Swedish steel industry is subject to the EU Emissions Trading System (EU ETS), not to Sweden's carbon tax. Swedish carbon taxation applies primarily to the transport and heating sectors, not to major industrial emitters covered by EU ETS [2]. This distinction is crucial for understanding the policy framework: while Sweden has the world's highest carbon tax (SEK 1,510 per tonne CO_2 or approximately €134 in 2025), this tax has historically exempted energy-intensive industries to avoid carbon leakage concerns.

The steel sector accounts for approximately 11% of Sweden's total greenhouse gas emissions (roughly 5–6 million tonnes CO_2 annually) and approximately 7% of Finland's emissions when including SSAB's Finnish operations. Traditional BF-BOF steelmaking emits approximately 2.0 tonnes CO_2 per tonne of crude steel produced.

Full decarbonization of Swedish steel production would reduce Sweden's national emissions by approximately 10% and Finland's by approximately 7%—representing one of the largest single-sector mitigation opportunities in either country [4].

3 Climate Policy Framework

3.1 National Climate Targets and Legal Framework

Sweden adopted a comprehensive Climate Policy Framework in 2017 with broad cross-party political support, establishing one of the world's most ambitious emission reduction trajectories:

- **2030:** At least 63% reduction from 1990 levels (non-ETS sectors)
- **2040:** At least 75% reduction from 1990 levels
- **2045:** Net-zero greenhouse gas emissions
- **Post-2045:** Negative emissions (net removal of CO_2 from atmosphere)

The Climate Act (2018) requires the government to report annually to parliament on climate policy implementation. An independent Climate Policy Council monitors progress and evaluates policy effectiveness. This framework has proven resilient across government changes, providing long-term policy certainty essential for industrial investment decisions.

3.2 Carbon Pricing System

Sweden pioneered carbon taxation globally, introducing a carbon tax in 1991 at SEK 250/tonne CO_2 (approximately €22). The tax has been gradually increased to SEK 1,510/tonne (approximately €134) by 2025, making it the world's highest carbon tax rate.

Economic analysis demonstrates that Sweden achieved remarkable decoupling of emissions from economic growth: between 1990 and 2019, real GDP per capita increased by 50% while greenhouse gas emissions decreased by 27%. The carbon tax is credited with driving substantial emissions reductions in heating and residential sectors.

However, as noted previously, the carbon tax does not directly apply to the steel industry and other energy-intensive industries covered by EU ETS. This exemption was justified by competitiveness concerns and carbon leakage risks—the possibility that stringent carbon pricing would drive production to countries with less stringent climate policies, resulting in no net global emission reduction while causing economic harm and job losses domestically [2].

3.3 Fossil Free Sweden Initiative

Launched in 2016, Fossil Free Sweden represents a unique collaborative governance model involving over 500 participants from 22 industrial sectors, including companies, municipalities, trade unions, and civil society organizations. The initiative facilitated development of sectoral roadmaps outlining pathways to fossil-free competitiveness.

The steel sector roadmap identified hydrogen-based direct reduction as the preferred technology pathway, with target timelines of 2030–2035 for commercial-scale fossil-free steel production. Key enabling conditions identified include:

- Access to massive quantities of fossil-free electricity
- Public support for risk reduction during demonstration phase
- Effective carbon pricing (through EU ETS) to ensure competitiveness
- Infrastructure for hydrogen production, storage, and distribution

The Fossil Free Sweden platform continues to serve as a dialogue mechanism between industry and government, identifying regulatory obstacles and proposing policy solutions.

4 The HYBRIT Revolution

4.1 Project Genesis and Partnership Structure

HYBRIT (Hydrogen Breakthrough Ironmaking Technology) emerged from Sweden's climate policy framework and strategic alignment of three state-influenced companies:

1. **SSAB:** Steel producer with over 40 years of experience and 6.4 million tonnes annual capacity. LKAB is a major shareholder, creating indirect state influence.
2. **LKAB:** 100% state-owned iron ore producer with 130+ years of operation, producing 80% of EU iron ore.
3. **Vattenfall:** 100% state-owned energy company owning 41% of Swedish power capacity, focused on enabling customer decarbonization.

This partnership structure enabled a long-term perspective beyond quarterly financial performance, coordinated investment across the value chain (mining → energy → steel), and alignment with government climate objectives. State ownership proved crucial in accepting higher risk and longer payback periods than private investors typically tolerate [10].

4.2 Technological Innovation: Hydrogen Direct Reduction

HYBRIT replaces the millennium-old blast furnace process with hydrogen-based direct reduction (H-DR). The revolutionary process eliminates coal and coke entirely:

Traditional BF-BOF Process:

$$\text{Iron ore} + \text{Coke (coal)} \xrightarrow{\text{Blast furnace (1500°C)}} \text{Pig iron} + CO_2 \text{ (2 tonnes per tonne steel)} \tag{1}$$

HYBRIT H-DR Process:

$$H_2O \xrightarrow{\text{Electrolysis}} H_2 \text{ (using renewable electricity)} \tag{2}$$

$$Fe_2O_3 + 3H_2 \xrightarrow{\text{Direct reduction (800-1000°C)}} 2Fe + 3H_2O \tag{3}$$

$$\text{Sponge iron} \xrightarrow{\text{Electric arc furnace}} \text{Steel} \tag{4}$$

The only byproduct is water vapor. The sponge iron (also called direct reduced iron or DRI) is then melted in an electric arc furnace (EAF) with recycled scrap to produce final steel products.

Key innovations include:

- **Hydrogen production:** Large-scale water electrolysis using Sweden's abundant renewable electricity
- **Direct reduction:** Chemical reaction at 800–1000°C removes oxygen without melting
- **Hydrogen storage:** Pioneering use of steel-lined rock caverns at 250 bar pressure, 30 meters underground, providing 3–4 days supply with 94% operational availability and demonstrated 50-year lifespan [5]
- **Quality advantage:** HYBRIT sponge iron achieves 99% metallization and improved aging resistance compared to blast furnace iron

4.3 Pilot Plant Development and Milestones

Timeline of Achievement:

- **2016:** HYBRIT partnership launched
- **2018–2020:** Pilot facility construction in Luleå
- **June 2021:** First fossil-free sponge iron produced
- **August 2021:** World's first fossil-free steel delivered to Volvo Group [6]
- **2022:** Hydrogen storage rock cavern inaugurated
- **2024:** Six-year trial completed; over 5,000 tonnes high-purity sponge iron produced

The pilot phase, supported by the Swedish Energy Agency's Industriklivet program, successfully demonstrated technical feasibility, product quality meeting commercial standards, and zero CO_2 emissions at scale.

4.4 Industrialization Strategy and Timeline

SSAB's transformation plan includes:

- **2025–2027:** Demonstration phase with scaled-up facilities
- **2030:** Replace blast furnaces in Sweden and Finland with electric arc furnaces
- **2035:** Full commercial operation target at 6.4 million tonnes annually

LKAB's strategy involves building direct reduction plants at mining locations (Gällivare and Kiruna) to produce sponge iron for both domestic use and export. However, infrastructure constraints have delayed the larger Kiruna facility to the 2040s. The Gällivare demonstration plant, targeting 1.3 million tonnes DRI by 2026 with expansion to 2.7 million tonnes by 2030, proceeds as planned [7].

Investment Requirements:

- Pilot phase: SEK 1.4 billion (€140 million)
- Demonstration phase: Estimated 10× pilot funding
- Full transformation: SEK 1,000 billion (€100 billion) expected in northern Sweden region
- Electricity demand: 10% increase in Sweden's total consumption

4.5 Global Impact Potential

Direct impact on Swedish and Finnish emissions is substantial. However, LKAB's potential export of fossil-free sponge iron could enable indirect decarbonization globally. If other steelmakers import DRI instead of iron ore and use electric arc furnaces, LKAB's exports could facilitate 40–50 million tonnes CO_2 reduction annually—equivalent to Sweden's entire territorial emissions—by leveraging Sweden's renewable electricity advantage.

This model of "exporting decarbonization" through processed materials rather than raw materials represents an important strategic option for resource-rich countries with abundant clean energy.

5 Stegra (H2 Green Steel): The Challenger Approach

5.1 Company Overview and Strategic Positioning

Stegra (founded as H2 Green Steel in 2020, rebranded 2024) represents a fundamentally different approach from HYBRIT's incumbent transformation model. As a startup company led by executives from Northvolt (Europe's battery champion), Stegra embodies greenfield disruption of traditional steel production.

Strategic differentiators include:

- No legacy assets or existing workforce to transition
- Integrated production (hydrogen, DRI, steel) at single location

- Focus on premium customers seeking green credentials
- Rapid development timeline (concept to construction in 2 years)
- Venture capital-backed growth model

5.2 Boden Flagship Project

Project specifications:

- **Location:** Boden, northern Sweden (45 miles from Arctic Circle)
- **Site:** 270 hectares industrial land
- **Capacity:** 5 million tonnes green steel annually by 2030
- **Employment:** 1,500 people at full operation
- **Investment:** €6.5 billion total

Location selection prioritized access to renewable electricity, strong grid infrastructure, water resources (Lule River), rail connections to ice-free Luleå port, and regional industrial expertise.

5.3 Technology and Production Process

Stegra's integrated facility comprises three main plants:

1. Green Hydrogen Plant:

- 800 MW electrolyzer capacity (Europe's largest)
- Water electrolysis powered by renewable electricity
- Separate location for safety considerations

2. Green Iron Plant (Direct Reduction):

- Technology: MIDREX H2™ hydrogen direct reduction (licensed technology)
- Partners: Midrex Technologies with Paul Wurth support
- 145-meter tall reduction tower
- Capacity: 2.1 million tonnes DRI per year (Phase 1)
- First-of-kind commercial-scale 100% hydrogen DRI

3. Green Steel Plant:

- Technology partner: SMS group
- Electric arc furnace melt shop with casting, hot rolling, cold rolling, finishing
- Capacity: 2.5 million tonnes finished products initially, expanding to 5 million by 2030
- Products: Advanced high-strength steel, automotive grades, specialty products

Emissions reduction target: up to 95% CO_2 reduction versus traditional steelmaking, approaching near-zero emissions with only water vapor as primary byproduct.

5.4 Development Timeline and Status

Key milestones:

- **2020–2021:** Company launch, initial funding ($105M), site selection
- **2022:** Environmental permit granted (18-month process), groundbreaking, €190M funding
- **2023:** Construction commenced (July), EU Innovation Fund selection
- **2024:** Rebranding to Stegra, €6.5B total financing secured (€3.5B senior debt, €600M junior debt, €300M equity), first equipment arrivals
- **2025–2026:** Target for first commercial steel production
- **2030:** Full 5 million tonne capacity

5.5 Financing Structure and Public Support

Capital structure:

- Senior debt: €3.5 billion from international banking consortium
- Junior debt: €600 million
- Equity: €300 million at holding level from strategic investors (including Kobe Steel)

Public funding:

- EU Innovation Fund: Part of €3.6 billion allocation to 41 projects (2023)
- EU Recovery and Resilience Facility: €265 million direct grant
- European Investment Bank: €750 million senior debt approved (2022)
- Swedish Industriklivet: Support for site preparation

The substantial public support (over €1 billion) reflects recognition of first-of-kind technology risk and strategic importance for EU industrial decarbonization.

5.6 Customer Commitments and Market Strategy

Long-term offtake agreements secured with major European companies create revenue visibility:

Automotive sector:

- Volvo Cars, BMW, Scania: Multi-year supply contracts
- ZF (automotive supplier): 7-year binding agreement

Other industries:

- Marcegaglia (Italian steel group): 7-year agreement for Southern Europe, UK, Poland
- Purmo Group: 140,000 tonnes (2026–2033) for indoor climate solutions

These commitments reflect growing corporate demand for low-carbon supply chains, driven by scope 3 emissions reporting requirements, corporate climate goals, and emerging regulatory pressures including EU CBAM.

6 Comparing HYBRIT and Stegra: Complementary Pathways

6.1 Strategic and Operational Differences

While both projects aim for near-zero emission steel using hydrogen technology, their approaches diverge significantly:

Table 1: HYBRIT vs. Stegra: Comparative Analysis

Dimension	**HYBRIT**	**Stegra**
Model	Incumbent transformation, phased retrofit	Greenfield startup, integrated facility
Companies	Established firms (SSAB, LKAB, Vattenfall)	Startup (founded 2020)
Timeline	Gradual (pilot→demo→commercial)	Rapid (concept→production in 5–6 years)
Integration	Mining (LKAB) separate from steelmaking (SSAB)	All processes at single site
Customers	Existing SSAB customer base	Early adopters seeking green credentials
Export potential	LKAB can export DRI globally	Steel products only
Risk profile	Lower (proven companies, phased)	Higher (first-of-kind, startup execution)
State role	High (100% state-owned partners)	Supporting (public funding, permits)
Capacity	6.4 million tonnes (SSAB) + LKAB DRI exports	5 million tonnes steel products

6.2 Strategic Value of Dual Pathways

Sweden's simultaneous pursuit of both models offers multiple benefits:

For Sweden:

- Technology validation through independent proofs of concept
- Risk diversification (not dependent on single approach)
- Market coverage across different customer segments

- Multiple export models (steel products, DRI, technology licensing)
- Employment creation across northern Sweden
- Reinforced global leadership position

For global decarbonization:

- Incumbent pathway demonstrates large steelmakers can transform
- Startup pathway proves new entrants can compete
- Different learnings from each approach enrich global knowledge base
- Multiple scalability models for different national contexts
- Accelerated technology diffusion through competition and cooperation

7 Enabling Policy Instruments

7.1 National Support: Industriklivet Program

Program structure:

- Launch: 2018
- Management: Swedish Energy Agency
- Budget: SEK 5.2 billion (2023–2025), approximately SEK 600 million annually
- Co-funding: EU Recovery and Resilience Facility

Industriklivet supports process-related GHG emission reductions through competitive grants for innovation projects bridging pilot to commercial scale. HYBRIT pilot received partial funding; demonstration phase requires substantially larger support (estimated 10× pilot costs).

The program's limitation is scale: annual budget of €60 million is insufficient for full demonstration phase funding, necessitating EU-level support.

7.2 EU-Level Support Mechanisms

EU Emissions Trading System (ETS): As noted earlier, Swedish steel industry is covered by EU ETS rather than Swedish carbon tax. Phase-out of free emissions credits post-2026 and rising carbon prices create increasing incentives for low-carbon technologies, making green steel progressively more competitive.

EU Innovation Fund: Funded from ETS auction revenues, the Innovation Fund provides:

- HYBRIT: €143 million (2022)
- Stegra: Part of €3.6 billion allocation to 41 projects (2023)

Carbon Border Adjustment Mechanism (CBAM): Launching with reporting requirements in 2026 and full implementation by 2034, CBAM equalizes carbon costs for imported steel, protecting EU producers investing in decarbonization and making green steel competitive versus carbon-intensive imports.

European Investment Bank: Designated as "EU climate bank," EIB provides patient capital:

- Stegra: €750 million senior debt approval
- Risk-sharing with commercial lenders for novel technologies

7.3 Permitting and Regulatory Environment

Stegra's environmental permit approval in 18 months (for a Class A operation producing 5 million tonnes annually on 270 hectares) demonstrates streamlined processes for climate-positive projects. Success factors include:

- Fast-track procedures for projects aligned with national climate goals
- Coordination across government agencies
- Clear criteria and timelines
- Stakeholder consultation integrated into process

This contrasts sharply with many jurisdictions where industrial permitting extends over many years, creating uncertainty and discouraging investment.

8 Challenges and Barriers

8.1 Electricity Supply and Infrastructure

Demand surge: Full-scale HYBRIT implementation would increase Sweden's electricity consumption by approximately 10%. Combined with Stegra's 800 MW electrolyzer, battery production (Northvolt), and other green industrial projects, the Norrland region faces unprecedented electricity demand growth.

Aggregate electrification scenario requires additional 37 TWh by 2045—significant even for a country with abundant hydropower and wind resources.

Infrastructure constraints: Sweden's electricity grid, particularly transmission capacity from generation-heavy north to consumption-heavy south, faces bottlenecks. Grid expansion requires hundreds of billions SEK investment and multi-year development timelines, potentially limiting industrial project timing.

Cost competitiveness: While northern Sweden currently enjoys very low electricity prices (€2.6–2.7/MWh in 2024), massive demand increase could drive prices higher. Hydrogen production economics are highly sensitive to electricity costs, making long-term price certainty crucial through power purchase agreements.

8.2 Hydrogen Production and Storage Challenges

Large-scale hydrogen infrastructure remains immature:

- Production: Gigawatt-scale electrolyzers still scaling commercially
- Storage: HYBRIT's rock cavern innovation addresses cost (up to 40% savings) but is geologically specific
- Distribution: Limited pipeline networks; transport adds costs
- Safety: Handling protocols and public acceptance require attention

8.3 Carbon Leakage and Competitiveness Risks

The historical exemption of Swedish steel industry from carbon taxation (being covered instead by EU ETS) reflects legitimate competitiveness concerns. Steel is globally traded; unilateral cost increases without border adjustments could shift production overseas with no net climate benefit.

EU CBAM implementation from 2026 should mitigate this risk, but transition period uncertainties remain. Green steel currently costs 20–30% more to produce than conventional steel. Sustained green premium pricing or rising carbon costs on conventional steel are necessary for commercial viability.

8.4 Technology and Market Risks

Technical uncertainties:

- First-of-kind commercial scale remains unproven for both HYBRIT and Stegra
- Quality consistency at high production volumes requires validation
- Process optimization learning curve ahead
- Equipment reliability for novel configurations uncertain

Market development:

- Green steel premium sustainability: Will customers continue paying? For how long?
- Certification and verification: Defining and tracking "green steel"
- Demand timing: Production ramp-up may not match market absorption
- Competition: Other technologies (CCUS with BF-BOF, advanced scrap-based EAF) may prove competitive

8.5 Policy and Political Risks

Sweden's advantage in broad political consensus on climate policy provides stability, but risks remain:

- Government priority shifts could affect support programs
- EU policy changes impact Swedish competitiveness (Sweden cannot act independently)
- Ongoing regulatory inquiries creating near-term uncertainty
- Long-term policy certainty required for industrial transformation timeframes (decades)

9 International Context and Technology Transfer

9.1 Global Steel Decarbonization Landscape

Sweden's leadership position is clear, but multiple approaches are being pursued globally:

Table 2: Global Steel Decarbonization Technology Approaches

Technology	**Region**	**Status**	**Key Challenge**
Hydrogen DRI	Sweden	Commercial demo	Electricity supply
Hydrogen DRI	Germany	Planning	Gas→H_2 transition
CCUS + BF-BOF	China	Pilot	Capture efficiency
Scrap-based EAF	USA, Turkey	Established	Scrap availability
Smelting reduction	Various	Research	Cost, complexity

9.2 Technology Licensing and International Interest

HYBRIT technology is being evaluated by European steelmakers for potential adoption. Midrex H2™ technology (used by Stegra) is available for licensing globally, creating standardization potential.

Countries actively studying Swedish model include Germany (major producers planning hydrogen transition), France (GravitHy project), Spain (Stegra second facility with Iberdrola), Italy (discussions with producers), Japan (Kobe Steel equity in Stegra), and South Korea (POSCO exploring hydrogen steelmaking).

9.3 LKAB's DRI Export Strategy

LKAB's original ambition to export fossil-free sponge iron globally represents innovative "decarbonization export" model. If realized at scale:

- Enables steelmakers worldwide to avoid building hydrogen infrastructure
- Leverages Sweden's renewable electricity advantage
- Could eliminate 40–50 million tonnes CO_2 annually (if 5 million tonnes DRI exported)

- Multiplies Sweden's climate impact beyond territorial emissions

However, infrastructure delays have pushed larger-scale Kiruna facility to 2040s, focusing nearer-term on domestic/Nordic market through Gällivare demonstration plant.

9.4 Policy Lessons for Other Countries

Key success factors:

1. **Long-term political consensus:** Climate Policy Framework with bipartisan support survives government changes, providing investment certainty
2. **State ownership strategic role:** 100% state-owned LKAB and Vattenfall enabled long-term perspective and value chain coordination
3. **Carbon price signal:** While direct carbon tax exempts industry, EU ETS provides price signal; CBAM will strengthen
4. **Industry-government collaboration:** Fossil Free Sweden platform with sectoral roadmaps identifies barriers and proposes solutions
5. **Public-private risk-sharing:** Industriklivet and EU Innovation Fund de-risk breakthrough technologies
6. **Streamlined permitting:** 18-month approval for major industrial facility demonstrates administrative efficiency
7. **Infrastructure investment:** Proactive electricity and hydrogen infrastructure development

Cautionary notes on replicability:

Sweden's unique advantages include small population with abundant renewable resources, near-zero carbon electricity grid, state ownership of key companies, high social trust and consensus culture. Not all factors are replicable elsewhere. Even Sweden faces challenges with electricity infrastructure lagging ambition, high production costs (20–30% premium), and small domestic market limiting economies of scale.

10 Economic and Social Implications

10.1 Employment and Regional Development

Steel decarbonization catalyzes broader green industrialization of northern Sweden:

Direct employment:

- HYBRIT: Transformation of existing SSAB workforce
- Stegra: 1,500 employees at full operation
- LKAB: DRI plant employment

Indirect employment: Construction phase (thousands of temporary jobs), renewable energy sector expansion, hydrogen infrastructure operations, ports and logistics expansion, equipment suppliers.

Regional revitalization: Boden (population 27,000) gains major industrial employer. Luleå becomes hub for green industries. Norrland region reverses historical depopulation trends, creating new model for sustainable Arctic economy development.

10.2 Investment and Economic Growth

Capital investment surge includes:

- HYBRIT: SEK 1,000 billion expected in Norrland region transformation
- Stegra: €6.5 billion at Boden
- Electricity infrastructure: Hundreds of billions SEK

Sweden has demonstrated economic decoupling: 50% GDP growth with 27% emission reduction (1990–2018). Green industrialization could extend this trend, shifting from extraction economy to high-value manufacturing and creating knowledge economy opportunities in clean technology.

Innovation spillovers from hydrogen technology, energy storage, process control, and materials science are applicable to other heavy industries (cement, chemicals, fertilizers).

10.3 Cost-Benefit Analysis

Using standard €100/tonne CO_2 social cost:

HYBRIT emissions reduction:

- Sweden steel sector: 5–6 million tonnes CO_2 annually
- Social benefit: €500–600 million per year
- Over 20 years: €10–12 billion (discounted)
- vs. Transformation cost: €10 billion
- **Conclusion:** Cost-effective at societal level

LKAB export scenario (if realized):

- DRI exports enable 40–50 million tonnes CO_2 reduction globally
- Social benefit: €4–5 billion per year
- Over 20 years: €80–100 billion
- Global public good with benefits far exceeding Sweden

Private economics: Production costs 20–30% higher than conventional steel initially. Green premium of €50–150 per tonne provides margin. As carbon prices rise through EU ETS and CBAM implementation, green steel approaches parity (expected 2030–2035).

Public investment returns include catalyzed private investment (leverage 10:1), tax revenues from operations, avoided social costs of emissions, technology leadership benefits, and employment/regional development.

10.4 Supply Chain and Customer Impact

Downstream industries: Automotive (major customer segment enabling vehicle carbon footprint reduction), construction (green buildings demanding low-carbon materials), manufacturing (industrial equipment, consumer goods).

Price transmission: Green premium of €50–150/tonne steel translates to modest impacts on final products:

- Car: €100–200 per vehicle (0.5–1% of price)
- Building: 1–2% of construction cost
- Appliances: €5–20 per unit

Generally small relative to total product value, absorbed by manufacturers or passed to consumers. Market segmentation emerging: premium segment willing to pay, regulatory-driven demand, mass market awaiting cost parity.

11 Environmental Performance

11.1 Carbon Emissions Reduction

Comparative emissions:

- Traditional BF-BOF: 2.0 tonnes CO_2 per tonne crude steel
- HYBRIT/Stegra hydrogen steel: 0.02–0.05 tonnes CO_2 per tonne
- **Reduction: 95–98%**

Remaining emissions from auxiliary processes and any limestone use. Sweden's near-zero carbon electricity grid (99% fossil-free) provides additional advantage in life-cycle perspective, as scope 2 emissions from electricity are minimal.

Scale of impact:

- Sweden steel sector: 10% of national emissions (5–6 MT CO_2)
- Full decarbonization equivalent: Removing 2 million cars
- LKAB export potential: 40–50 MT CO_2 reduction globally

11.2 Other Environmental Considerations

Air quality: Elimination of coal/coke combustion reduces particulate matter, SOx, and NOx emissions significantly. Water vapor as primary byproduct provides substantial local health benefits near steel plants.

Water use: Electrolysis requires water input (9 litres per kg H_2). Cooling water needs continue. Sweden's abundant water resources (Lule River) provide advantage, but wastewater treatment and discharge standards must be maintained.

Land use and mining: Iron ore mining continues with LKAB expansion plans in Kiruna and Gällivare. Environmental permits required; Indigenous Sami communities' consultation essential. Balancing industrial development with environmental protection and indigenous rights remains ongoing challenge.

Circularity: Slag production reduced versus blast furnace. Scrap recycling in EAF continues. Waste heat recovery and materials efficiency improvements enhance circular economy principles.

11.3 Contribution to Climate Goals

Sweden's pathway: 2045 net-zero target becomes achievable with steel sector decarbonization (10% of current emissions). Post-2045 negative emissions requirement (through bioenergy CCUS, forest management) represents next frontier.

EU climate leadership: Sweden model demonstrates feasibility for EU's 2030 (55% reduction) and 2050 (climate neutrality) targets. Technology transfer accelerates EU-wide steel decarbonization.

Global Paris Agreement: 1.5°C target requires steel decarbonization worldwide. Sweden exemplifies developed country leadership and technology cooperation, demonstrating higher ambition is achievable.

12 Critical Evaluation and Future Outlook

12.1 Strengths of Swedish Approach

Strategic advantages:

1. Political consensus on climate providing investment certainty
2. State ownership enabling coordinated, patient capital approach
3. Natural resources: Near-zero carbon electricity at low cost, iron ore, water
4. Integrated value chain: mining→energy→steel coordination
5. Dual pathways reducing technological and market risk
6. Early mover advantage in green steel market
7. Institutional quality: efficient permitting, strong governance, low corruption
8. Social cohesion: high trust, strong labor relations, just transition principles

12.2 Weaknesses and Limitations

Structural challenges:

1. Scale constraints: Small domestic market (10.5M people) limits economies of scale
2. Infrastructure lag: Grid expansion slower than needed

3. High costs: 20–30% production premium requires sustained green pricing
4. Policy dependence: Success relies on EU ETS, CBAM, Innovation Fund
5. Technology risk: First-of-kind scale unproven
6. Competition emerging: Other countries/technologies may leapfrog
7. Replicability questions: Unique advantages not easily replicated
8. Timing uncertainty: Infrastructure delays (LKAB Kiruna to 2040s)

12.3 Key Uncertainties

Technical: Will hydrogen steel consistently meet quality specifications? Can production scale smoothly? What is realistic timeline for cost parity?

Market: Will green premium persist at adequate level? How will CBAM actually impact competitiveness? Will customers commit long-term at premium prices?

Policy: Will EU climate policy momentum continue? Can Sweden secure adequate infrastructure investment? What if government priorities shift?

Competitive: Will other technologies (CCUS, improved scrap-based) become preferable? Can China scale green steel faster? How will global overcapacity resolve?

12.4 Scenarios for 2030–2045

Optimistic scenario: "Green Steel Champion" HYBRIT and Stegra successfully ramp to full production. Green premium sustained at €50–100/tonne. CBAM successfully levels playing field. LKAB begins significant DRI exports by late 2030s. Other EU countries adopt Swedish technology. Sweden becomes clean tech export leader. Achieves 2045 net-zero on schedule.

Base case: "Steady Progress" Commercial operation achieved but with delays. Green premium narrows as production scales. Infrastructure constraints slow but don't stop development. LKAB focuses on domestic/Nordic market initially. Gradual technology diffusion. Sweden maintains leadership but others close gap. 2045 target achievable with effort.

Pessimistic scenario: "Stumbling Pioneer" Technical or economic challenges delay deployment. Green premium evaporates before cost parity. EU climate policy weakens. Infrastructure bottlenecks prove intractable. China or others leapfrog with alternatives. Early investments don't yield expected returns. 2045 target requires significant adjustments.

Most likely: Base case with elements of others. Success probable but not guaranteed. Sweden maintains leadership role but faces challenges requiring adaptive management and sustained commitment.

12.5 Strategic Recommendations

For Sweden:

1. **Accelerate infrastructure:** Prioritize electricity grid and hydrogen infrastructure, streamline approvals
2. **Maintain policy stability:** Preserve climate consensus, provide long-term certainty
3. **Support market development:** Facilitate certification standards, green public procurement
4. **Manage transition risks:** Just transition support, regional development, skills training
5. **International engagement:** Active EU climate policy leadership, technology cooperation
6. **Monitor and adapt:** Flexible approach as technologies evolve

For other countries:

1. Adapt principles to local context (don't copy directly)
2. Create enabling conditions: carbon pricing, infrastructure, permitting, partnerships
3. Recognize context matters: different approaches for different situations
4. International cooperation: share knowledge, coordinate policies

13 Conclusion

Sweden has positioned itself at the forefront of global steel decarbonization through a unique combination of ambitious climate targets, strategic state ownership, dual technology pathways, world-class natural resources, effective policy instruments, and streamlined governance.

The HYBRIT initiative demonstrates that incumbent steel producers can successfully transform using hydrogen-based direct reduction, while Stegra shows that greenfield startups can compete in green steel markets. Together, these projects will eliminate approximately 10% of Sweden's total CO_2 emissions. LKAB's potential DRI exports could multiply global impact to 40–50 million tonnes CO_2 reduction annually.

Key success factors include long-term political consensus, state ownership enabling patient capital and value chain coordination, public-private risk-sharing through Industriklivet and EU Innovation Fund, streamlined permitting (18 months for Stegra), and proactive infrastructure investment. **Critically important, as emphasized by Prof. Åhman, are Sweden's near-zero carbon electricity system (99% fossil-free) and exceptionally low electricity prices in the north (€2.6–2.7/MWh), providing fundamental competitive advantages for energy-intensive hydrogen production that cannot be easily replicated elsewhere.**

However, significant challenges remain: electricity infrastructure expansion must accelerate, 20–30% production cost premium requires sustained green pricing or rising carbon costs on conventional steel, first-of-kind technology risks persist, and policy durability across decades is essential.

Sweden's experience validates several policy principles: long-term consensus matters more than specific instruments; carbon pricing alone is insufficient without complementary policies (noting that Swedish steel is under EU ETS, not carbon tax); public-private risk-sharing accelerates breakthrough technologies; strategic state role can be positive when aligned with climate goals; infrastructure requires proactive investment; streamlined permitting is as important as funding.

The Swedish model is not universally replicable—few countries combine renewable electricity abundance, state-owned enterprises, political consensus culture, and small domestic scale. But underlying principles are transferable: long-term vision over short-term profit, coordinated value chain approach, public-private risk-sharing, infrastructure as enabler, just transition principles, and international cooperation.

By 2030, Sweden will have demonstrated at commercial scale what is technically possible for steel decarbonization. Whether others follow this path or forge their own, Sweden has shown that the transition to fossil-free steel is not a distant aspiration but a present reality, moving from climate target-setting to practical implementation, from pilot projects to commercial demonstration, from national ambition to global leadership.

Acknowledgments

The authors gratefully acknowledge Prof. Max Åhman of Lund University, Sweden, for his authoritative review and valuable comments that substantially improved this document, particularly regarding the critical distinctions between Sweden's carbon tax application (transport and heating sectors) versus EU ETS coverage (steel industry), and the fundamental importance of Sweden's near-zero carbon electricity system and exceptionally low northern electricity prices as competitive advantages for hydrogen-based steelmaking.

This document represents a prototype for the MIFUS Mini Instant Fall Course on "A Journey through Steel Decarbonization Policies Worldwide," demonstrating constructive human-AI collaboration in academic research and policy analysis.

References

[1] Åhman, M., Nilsson, L. J., & Johansson, B. (2015). *Global climate policy and deep decarbonization of energy-intensive industries*. Climate Policy, 17(5), 634–649.

[2] Åhman, M., Skjaerseth, J. B., & Eikeland, P. O. (2017). *Demonstrating climate mitigation: a comparative study of large industrial projects in Europe and China*. Environmental Innovation and Societal Transitions, 24, 123–134.

[3] Algers, E., et al. (2025). *Steel industry decarbonization pathways: Global perspectives*. International Energy Agency.

[4] HYBRIT Development AB. (2021). *HYBRIT produces first fossil-free sponge iron*. Press release, June 2021. Available at: https://www.hybritdevelopment.se

[5] HYBRIT Development AB. (2025). *Hydrogen storage in lined rock caverns: Technical achievements and operational experience*. Technical Report.

[6] SSAB. (2021). *SSAB, LKAB and Vattenfall first in the world with hydrogen-reduced sponge iron*. Press release, August 18, 2021. Available at: https://www.ssab.com

[7] SSAB. (2021). *SSAB's transformation to fossil-free steel production*. Corporate presentation. Available at: https://www.ssab.com

[8] Swedish Herald. (2024). *Electricity prices in Sweden: Regional variations and renewable energy impact*. December 2024.

[9] Vattenfall AB. (2025). *Scaling up renewable electricity for industrial decarbonization*. Corporate Sustainability Report 2024/2025.

[10] Vogl, V., Åhman, M., & Nilsson, L. J. (2023). *The making of green steel in the EU: A policy evaluation for the early commercialization phase*. Climate Policy, 23(1), 78–92.

A Abbreviations and Acronyms

- **BF-BOF:** Blast Furnace - Basic Oxygen Furnace
- **CBAM:** Carbon Border Adjustment Mechanism
- **CCUS:** Carbon Capture, Utilization, and Storage
- **DRI:** Direct Reduced Iron (also called sponge iron)
- **EAF:** Electric Arc Furnace
- **ETS:** Emissions Trading System
- **H-DR:** Hydrogen Direct Reduction
- **HYBRIT:** Hydrogen Breakthrough Ironmaking Technology
- **LKAB:** Luossavaara-Kiirunavaara AB (Swedish iron ore company)
- **MIFUS:** Mini Instant Fall University Session
- **SSAB:** Svenskt Stål AB (Swedish steel company)

B Data Sources and Methodology Notes

This document synthesizes information from multiple sources including:

- Official reports from HYBRIT Development AB, SSAB, LKAB, Vattenfall
- Stegra (H2 Green Steel) corporate announcements and presentations
- Swedish government policy documents and climate framework legislation
- EU policy documents (ETS, CBAM, Green Deal, Innovation Fund)

- Academic literature on steel decarbonization and climate policy
- Industry analyses from World Steel Association, IEA
- News reports from specialized steel and energy trade publications

Data on production capacity, emissions, costs, and timelines represent best available estimates as of November 2025. Commercial-sensitive information is drawn from publicly available sources only. Projections and scenarios are based on current trends and stated objectives but carry inherent uncertainty.