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Understanding the potential future capacity of distributing green steel solutions -
current knowledge and future challenges



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Abstract

Transitioning from the conventional steel process to a direct hydrogen reduction process in the steel industry is a significant step towards reducing CO₂ emissions and achieving greater sustainability. The process involves using hydrogen gas as a reducing agent instead of carbon to remove oxygen from the iron ore. This study aimed to investigate the future capacity of the hydrogen-based steelmaking process in Sweden by 2050 while also examining the pathway for transitioning to hydrogen-based steelmaking in other European countries in comparison to the Swedish case. To achieve this goal, a systematic literature search was conducted using Scopus and Web of Science databases to identify relevant case studies and reviews that focused on green steel solutions and that discussed associated challenges and barriers. A conceptual model was designed by simplifying the process into three production steps, hydrogen storage and hot briquette iron storage to calculate the energy consumption and material requirements for a hydrogen direct process in Sweden.

Additionally, a survey providing insights regarding current practices and perspectives was administered to seven companies in Sweden and two in other European countries, namely the Netherlands and Germany. Furthermore, a comparative analysis of the literature review on life cycle assessment (LCA) was conducted to compare the carbon emissions associated with two different steel production processes: the conventional methods using the basic oxygen furnace (BOF-BF) and the emerging hydrogen-based steel production process.

An analysis of the energy consumption within the hydrogen-based process reveals several components, including the electrolyze, direct reduction shaft furnace, electric arc furnace, and briquetted iron and hydrogen storage. The model results showed that electrolyzing alone accounts for 60% of the energy needed in the process. The model showed that hydrogen direct reduction steelmaking needs 3.66 MWh of electricity per ton of liquid steel produced in Sweden. Only a few of the Swedish companies have adopted innovative approaches while the remaining steel mills primarily rely on scrap-based methods. While they may obtain hydrogen-reduced iron as a raw material in the future, emission reduction is not their primary focus. These mills contribute to emissions through fuel usage, and efforts are underway to transition from fossil fuels to electricity, bio-based gas, or hydrogen. Hydrogen-based steel production produces significantly lower greenhouse gas emissions than conventional steel production, by up to 90 percent, depending on the specific process and energy used, as stated in the life cycle analysis literature reviews.

This thesis shows key factors for the success of H₂-based steel production methods; low-emission electricity and the flexibility to store hydrogen. All three countries have expressed interest in and invested in hydrogen-based steelmaking. The share of renewable energy produced and consumed in the H₂-based steel production in Sweden is expected to make up a share of 2.3% of the total renewable energy production in the country, while Germany and the Netherlands are projected to contribute a modest 1.5% and 1.3% respectively. However, the search for ways to lower carbon dioxide emissions is costly in terms of the amount of electricity required. There are practical reasons for the restricted usage of this steelmaking process in Europe, including the availability of scrap steel, electricity demand, and the low

likelihood of scrap generation and recycling scrap availability on the EU market. Because of this, it is challenging to predict capacity and CO₂ reduction by 2050.

Keywords

Carbon dioxide (CO₂), greenhouse gas (GHG) emissions, Steelmaking fossil-free, direct hydrogen reduction, Sustainability transitions.

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Abbreviations used

BF Blast furnace

BOF Basic oxygen furnace

H-DR Hydrogen direct reduction

CCS Carbon capture and storage

CCU Carbon capture and use

DRI Direct reduction iron

DRHI Direct reduction hydrogen iron

DR Direct reduction

CC Carbon capture

EAF Electric arc furnaces

GHG Greenhouse gas

CO₂ Carbon dioxide

GWP Global warming potential

LCA Life cycle assessment

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1 Introduction

The steel industry is one of the world's most Greenhouse Gas (GHG) intensive sectors, it is responsible for 7-9% of global GHG emissions [1]. To achieve the goal set by the Paris Agreement to limit global warming to below 2°C, the steel industry must embrace clean technologies, enhance energy efficiency, and invest in renewable energy sources. Previous advancements have primarily concentrated on improving productivity and efficiency. However, these gradual innovations have inserted only modest reductions in emissions, falling short of the targets outlined in the GHG Protocol. [2]

By combining the substitution of carbon-intensive inputs, renewable energy integration, and carbon capture, the steel industry can significantly reduce its environmental impact and contribute to a greener future. The substitution of coal, which is a major source of carbon emissions in traditional steelmaking with hydrogen is one of the key approaches to reducing carbon emissions in the steel sectors. Integrating carbon capture techniques to capture and store exhaust gases and incorporating renewable energy sources in steel manufacturing has a critical role in reducing carbon emissions. Additionally, Increasing the utilization of recyclable materials in the steelmaking process also effectively achieves more sustainable steel production. [3]

Understanding the historical development of steel demand is important as the global economy expands. The new technical strategies are supplemented by energy and material efficiency to reduce primary steel consumption and increase secondary production in steel making to achieve a more circular economy. They are especially difficult to provide without emitting carbon dioxide. Rapidly increasing demand for these services, combined with long lead times for technology development and long lifespans of energy infrastructure, makes the decarbonization of these services both necessary and urgent. [4]

1.1 Background

Currently, the industry is taking steps to mitigate GHG emissions to improve its environmental impact, as well as to obtain a competitive market advantage. According to the SSAB report 2021, several companies such as IKEA, Volvo Group, and Mercedes Benz announced partnerships with SSAB to set up a carbon-neutral value chain for their steel products. However, other businesses are also on the waiting list due to insufficient production quantities. Understanding the potential future capacity of distributing green steel can aid stakeholders in setting up long-term emission reduction goals. [5]

Typically, steel production involves several stages, including mining raw materials, the steel-making process, and the production of finished steel products. Two different production routes can be distinguished: the primary route, where steel is produced from iron ore, and the secondary route, where steel is produced from scrap melting. The primary routes include the integrated path as illustrated in Figure1:

- Blast furnace (BF) and basic oxygen furnace (BOF).
- Smelting reduction plant and direct reduction plant (DR).
- Direct reduction plant and an electric arc furnace (EAF).

On the other hand, the secondary paths produce steel by using steel scrap as raw material in the EAF. Due to different economies of scale, BF-BOF-based plants are typically much larger than EAF-based plants. [6]

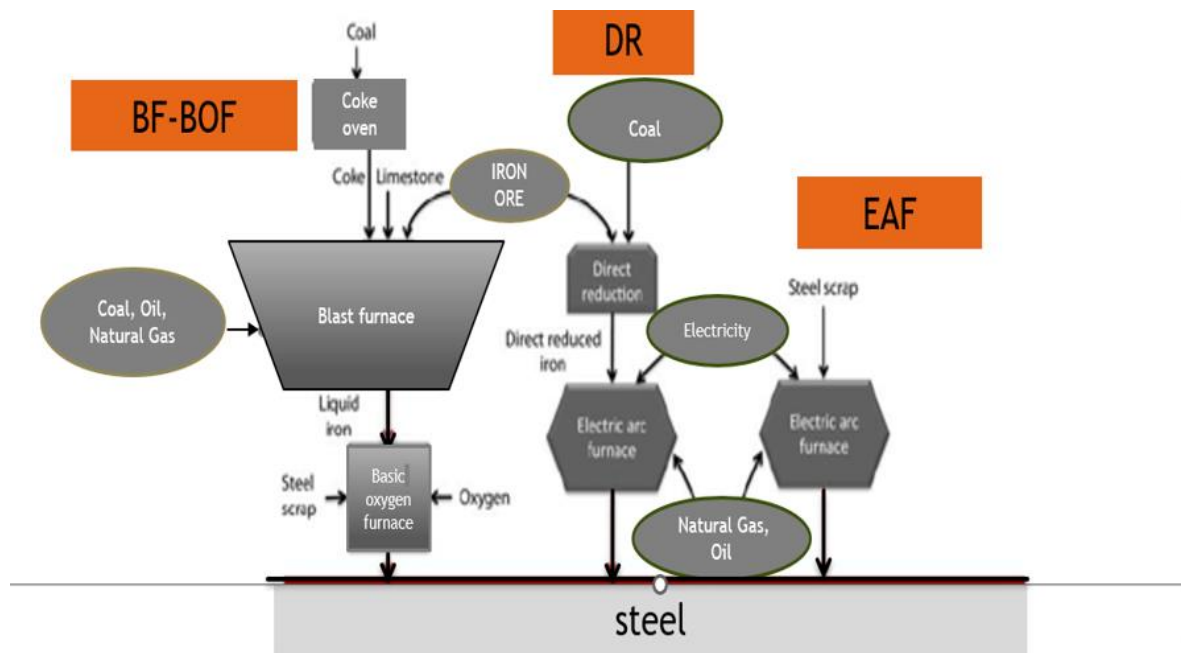


Figure 1. The main processes where steel can be produced from iron ore or scrap. The figure highlights the primary route, where steel is produced from iron ore, and the secondary route, where steel is produced from scrap melting. (BF) Blast furnace, (BOF) basic oxygen furnace, (DR) direct reduction plant, and (EAF) electric arc furnace route.

1.2 Sustainability Transitions in the Steel Industry

The steel industries face the challenge of reducing CO₂ emissions and achieving environmental sustainability while keeping profitability in compliance with climate change mitigation policies. This highlights the importance of exploring sustainability transitions within the steel industry. The sustainability transition field perceives the iron and steel industry as slow to embrace a large sustainable scale due to this sector's costly and risky technological improvements. This makes any transition a complex and lengthy process. [7]

Several ways can be used to significantly reduce emissions, as illustrated in Figure 2 below. The figure highlights both "bridging technology" used as a "transitional technology" and "low emission steelmaking," technologies that can achieve significant emission reductions in the future.

Current production → bridging technology → Emission steel making.

The blast furnace can be supplemented with carbon capture or converted into an EAF mill. Moving from current production to fossil-free steelmaking is not necessarily

a single large step but can be done gradually by introducing bridging technologies, such as switching, to electric arc furnaces, natural gas direct reduction, CCU, top as recovery, or injecting biomass into blast furnaces.

Current production → Bridging technology → Emission steel making.

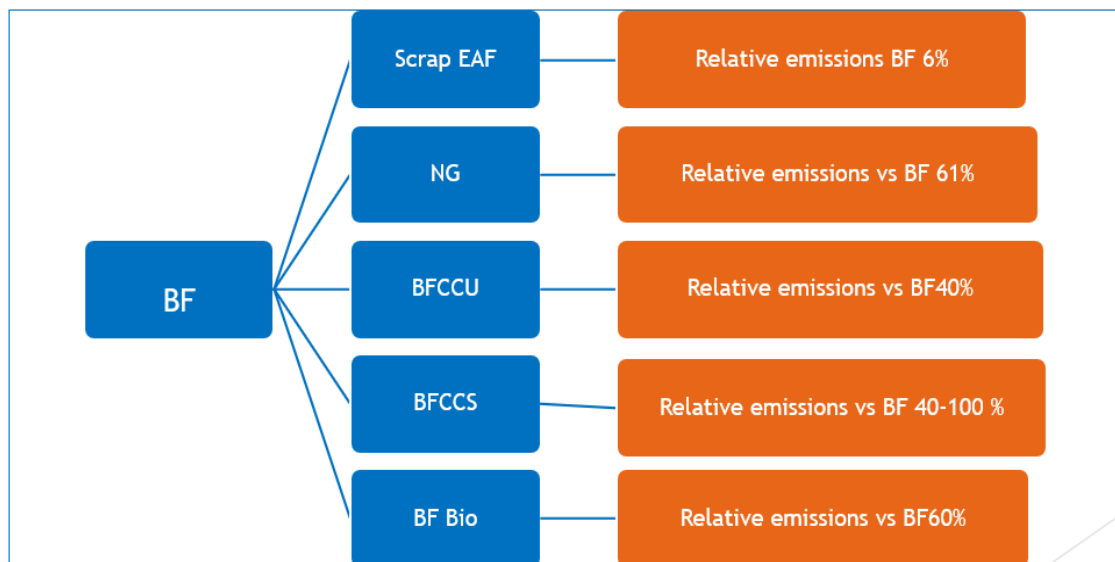


Figure 2. Technical emission reduction pathways for primary steelmaking. The figure highlights both "bridging technology" used as a "transitional technology" with a blue rectangle and "low emission steelmaking," technologies with an orange rectangle [8]. Abbreviations: BF: basic furnace, EAF: electric arc furnace, NG-DR: natural gas direct reduction, BFCCU: basic furnace carbon capture utilizing, BF CCS: basic furnace carbon capture saving, BF BIO: basic furnace with biofuel.

1.3 Selection

The selection of the countries the study compared was based on a low-emission projects map published by the European Steel Association. The focus was on comparing the steel companies listed on this map Germany, Sweden, and the Netherlands. Steel companies in the study have operations in several different countries and different parts of the world, but the study focused on the country where they have their headquarters. For example, ArcelorMittal has steel plants all over the world, but because the company is based in Luxembourg, which is a member of the EU, the study examined how ArcelorMittal's strategies could contribute to reducing emissions in the EU. In this essay, emission refers to the emission of CO₂ unless otherwise explicitly stated. The emission of CO₂ is the only greenhouse gas that will be investigated. [9]

As a reference, we compare the future green solution with the current steel process configuration in Sweden, for which 70 % of the steel is produced in the BOF process, and 30 % of the steel production is based on the secondary steelmaking process using EAF. The European steel industry is constantly evolving as it includes incorporating modern technologies to improve production efficiency, lower prices,

and improve product quality. The following are some of the important technologies that have recently gained popularity in Europe's steelmaking industry:

- EAF are becoming increasingly popular in Europe due to their energy efficiency, lower environmental impact, and versatility in producing a wide range of steel grades.
- DRI technology has grown due to its ability to create high-quality steel while using natural gas or hydrogen as a reducing agent, resulting in reduced CO₂ and other pollutant emissions.
- CC: This method is used to produce high-quality steel products while reducing waste and increasing efficiency. [8]

1.4 Overview of decarbonization strategy in the steel industry

Hybrit hydrogen-based steel

Sweden has begun a shift to hydrogen-based technology to reduce carbon dioxide emissions related to iron and steel manufacturing through collaborative initiatives involving the firms LKAB, SSAB, and Vattenfall. This initiative resulted in the construction of Hybrit in northern Sweden with the start of the first experimental phases concentrating on the manufacture of fossil-free iron ore pellets. Even though this technology is a promising shift towards sustainable ability transition in the steel sectors and has the potential to drive a change in basic assumptions in the steel industry, the technology still requires significant research about the available quantities and prices.

The initial strides towards achieving fossil-free steel were initiated with the inauguration of the pilot plant for direct reduction at SSAB's facility in Luleå in 2016. Notably, this plant marked a significant milestone by producing the first- fossil-free iron ore pellets. The pilot plant will continue to facilitate refining and optimizing the iron ore reduction process using fossil-free hydrogen between 2020 and 2024, encompassing both hydrogen-based direct reduction and smelting in steel works. Subsequently, efforts towards hydrogen storage from 2021 to 2024 culminated in large-scale demonstration projects by 2026. The final goal of this concerted endeavor is the full commercialization of hydrogen-based steel production, projected to occur between 2030 -2050. [10]

Zeremis Carbon Lite

Zeremis is an abbreviation for Zero-Emission. Since 2021 Tata Steel Nederland has introduced Zeremis Carbon Lite: steel with a reduced carbon footprint. In 2018, this investment in new technology to reduce its environmental impact by introducing concrete steps towards carbon neutrality was started. According to Tata Steel Sustainability Report 2019-2020, potential emerging technology options for decarbonization initiatives are represented in the following, focus on energy efficiency and maximizing the use of recycled content and re-use of materials. [11]

According to Tata Steel report, the 2021 green solution can introduce four stages down to a process with green hydrogen direct reduced iron technology, which will make a giant leap towards CO₂-neutral steelmaking in a clean environment at Ijmuiden by:

- Certified CO₂ savings
- Carbon neutral downstream operation
- Recycled content
- Zero carbon planning

ArcelorMittal X_Carb® Towards carbon neutral steel

In terms of total crude steel production as well as primary steel, Germany is the largest steel producer in Europe; according to the Steel World Association Report 2021, it produced approximately 4024 million tons. ThyssenKrupp, ArcelorMittal, and Salzgitter dominate the primary steel market in Germany. The sustainability agenda started with Arcelor Mittal in 2021 launching the X_Carb certification based on the BF-BOF process.

X-Carb- green steel certificates: Specifically designed for ArcelorMittal's flat steel products manufactured in a blast furnace from iron ore, 100% renewable energy is available in specific HRC also by:

- Certificates enable customers to benefit from absolute CO₂.
- Reductions realized by ArcelorMittal without being geographic.
- connected to the supply site. The CO₂ reductions and the physical product are decoupled, allowing the CO₂ reduction to be transferred directly to the customer via a dedicated registry.
- A similar approach has already been successfully implemented in the renewable energy sector.

The CO₂ reductions are generated by reducing the fossil coal consumption of the BF and by CCU.

1.5 Market and Energy Assessment

Steel demand is projected to increase by 30% by 2050. However, the market for low-carbon steel technologies has not yet experienced significant growth for achieving the climate targets set for 2050. Electricity is a crucial factor in the development of a sustainable transition in the steel sector. The demand for electricity in the industry can be met by two types of electricity generation technologies: renewable and non-renewable. [12 ,13]

Given the significant negative externalities associated with non-renewable energy-generated electricity, renewable sources are becoming increasingly important in power production, especially in the transition towards fossil-free steel sectors. In countries or regions that have already started moving away from fossil fuels, their electricity generation capabilities are better equipped to meet the growing demand from low-carbon sources compared to countries where electricity supply still heavily relies on fossil fuels.

According to the Energy Information Administration, a transition toward renewables is already underway in the EU. Renewable energy sources made up 22% of the EU's energy consumption in 2021. This shows a notable growth in the utilization of renewable energy sources for generating electricity within the EU region. According to the International Energy Agency EIA, renewables will exceed coal as the leading

source of electricity generation by 2025, and renewable electricity production will account for half of global electricity generation by 2050. [14 ,15]

The recent energy crisis prompted by the war between Russia and Ukraine has highlighted the importance of the transition to renewable energy. While the renewable energy community offers a promising solution, it faces various technical, financial, and regulatory challenges to ensure a sustainable and secure energy future for the region.

1.6 Swedish case compared with other countries.

Sweden's electricity generation stands out for its low carbon emissions. Hydroelectric power contributes 43% of the country's electricity production, while wind power plays a significant role, accounting for approximately 12% of the country's total electricity production. Currently, Sweden operates six nuclear reactors across three nuclear power plants. This diverse mix of low-emission power sources positions Sweden as a sustainable and environmentally friendly electricity generation leader. In 2021, around 60 percent of Sweden's energy production came from renewable sources. However, the recent energy crisis is expected to increase the use of renewable energy in Sweden. [15]

Germany is one of the countries focusing on scaling up solar and wind energy to transform its power sector and achieve national climate protection goals. Since 2000, Germany has had an ambitious policy to increase the share of renewable energy in the electricity mix to around 43% by 2021. According to Renewable Energy Sources, 2021 as well as the federal government, renewable energy will account for 80% of Germany's total annual electricity consumption by 2030 from renewable energy [16].

In the year 2022, the carbon intensity of German electricity was approximately 553 grams of CO₂ per kilowatt-hour. Due to its recent high dependence on Russia, notably for natural gas, Germany is under intense pressure to build new gas import infrastructure and change its energy sources to ensure its economy receives ample energy. This carbon intensity is attributed to the composition of the electricity generation mix, which includes a 34.1% share of coal, a 14.9% share of natural gas, a 5.71% share of nuclear power, and a significant 45% share of renewable power sources. [17]

The Netherlands produced around 118 billion kWh of electricity in 2021. This is a reduction of more than 2 billion kWh from 2020. The output of fossil fuels fell by 33%, while renewable energy output increased by 22%. Natural gas (47%), wind (15%), coal (14%), solar (10%), and biomass (8%) were the top five energy sources in the Netherlands. Other energy sources included nuclear, petroleum, and hydropower. There is one nuclear power plant and one liquefied natural gas terminal in the nation. [18]

1.7 Scrap route in the European market

Iron ore accounts for approximately 70 % of worldwide steelmaking, while scrap accounts for 30% of global steel production. Depending on many factors, such as scrap purity, scrap availability, access to resources, and industry structure, the

relative share of primary and secondary steelmaking varies around the world. The national production of main types of steel production in Germany is 25%, the Netherlands 4%, and Sweden with 2% ranks the lowest, as illustrated in Table 1 below. [19]

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Sweden (tons)	2804	4846	4867	4326	4404	4539	4557	4817	4926	4654
Germany (tons)	32670	43830	44284	44284	42661	42645	42943	42676	42080	43287
The Netherlands (tons)	5194	6651	6937	6879	6713	6964	6993	6917	6781	6813

Table 1 shows the national production of the main types of steel production in Sweden, Germany, and the Netherlands. Data are expressed in thousand metric tons for the year between 2009-2018.[19]

Further, compared to the carbon-intensive between secondary and primary steelmaking, it is much less energy and CO₂-intensive with secondary steelmaking than primary as the iron in the recycled steel scrap has already been reduced. Thus, increased steel scrap recycling would help reduce steelmaking climate impact. Due to the expected increase in demand for steel and the known limitations of the recycling process, the availability of abrasives in the European market for secondary steelmaking in electric arc furnaces is expected to reach only 46-70% of the total steel production by 2050, leaving a huge continuous demand for primary steelmaking.

Today the electric arc furnace represents about 30% of steel production in the European market while 60 % is produced using BF- BOF. However, the share between the two routes is different in the different countries, such clearly in Figure 3. In any case, the limited utilization of such steelmaking process in Europe has a practical justification based, among other things, on the high cost of steel scrap and electricity and the low scrap generation and recycling potential. However, due to the importance of reducing greenhouse gas emissions, some scientists are calling for the replacement of the blast furnace converter with a scrap electric arc furnace in the European steel industry. [20]

	BOF	EAF	The total production	%BOF of the production	%EF of the production
Germany	29732	12703	42435	70%	30%
The Netherlands	6813	3120	6813	100%	0.0%
Sweden	2829	1824	4654	61%	39%
European Union	98057	69587	167644	59%	40%

Table 2. The share of the EAF process and BOF; Data are expressed in thousand metric tons for the year 2018. [20]

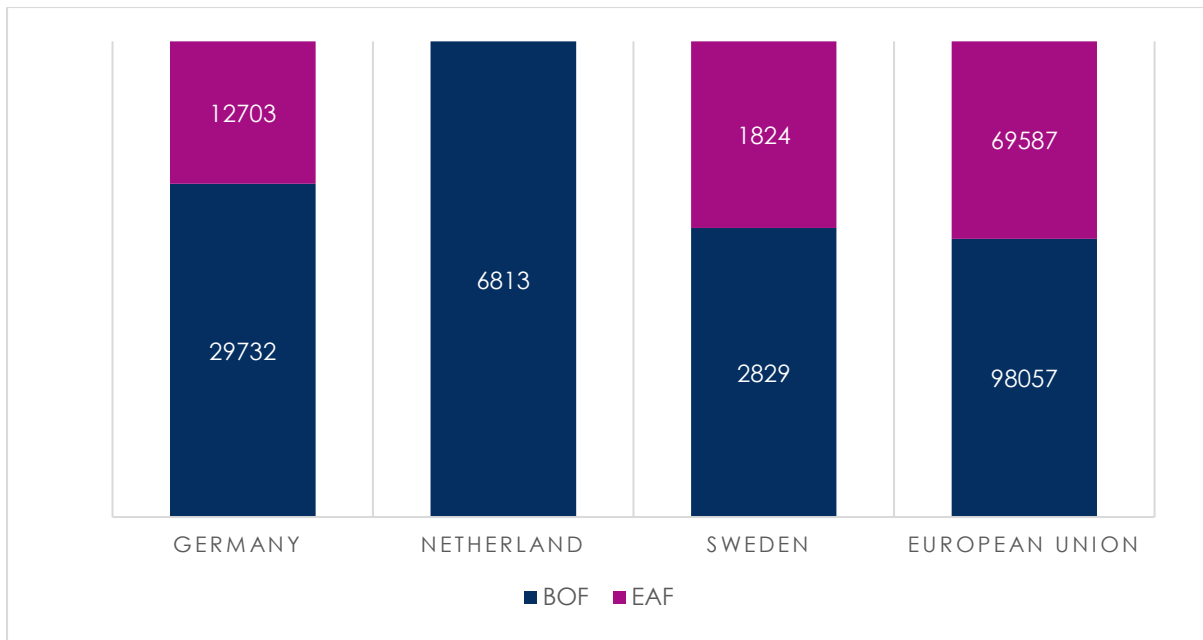


Figure 3. The production of BOF, EAF, and total production of steel making in Germany, Sweden, and the Netherlands for the year 2018. The production between the two routes is presented in the figure which the blue area is the production for the BOF route, and the pink area is for the EAF. [20]

2 Aim and questions

Understanding the future demand for green steel is significant due to the direct correlation between carbon dioxide emissions and the steel production process, which is known for its intensive energy consumption. Key aspects such as renewable energy sources, sufficient production capacity, and hydrogen storage play roles in enabling the hydrogen-based steel process. *This study aimed to investigate the reality of the future distribution of hydrogen-based steelmaking technology in the European market. Also, it aimed to identify the technologies available by 2050 and explore the conditions necessary for the successful implementation of hydrogen-based technology with a focus on energy considerations.*

To achieve this goal, the research question guiding this study was formulated as follows: *In terms of electricity generation and integrated hydrogen storage, what are the prospects for the transfer and adoption of hydrogen-based iron and steel production technology in Sweden by 2050, and what are the possible pathways for sustainability transitions in the iron and steel industry in other countries in Europe: namely Germany and the Netherlands.* Given the complexity of the research topic, a case study approach was adopted, allowing for an in-depth analysis of both qualitative and quantitative data. [21]

To address the main question, three sub-questions have been formulated:

1. *What are the enabling factors associated with hydrogen-based H-EAF steel production in Sweden compared to other European countries in terms of electricity generation, hydrogen storage, and energy consumption?*

2. *What are the estimated strategies and techniques that Swedish steel industries and other countries plan to implement to reduce GHG?*
3. *What is the difference in carbon emissions between hydrogen-based steel production and the traditional basic oxygen furnace process?*

3 Method

In the first step to answering the first question about the enabling factors associated with the H-EAF-based steel production in Sweden compared with other European countries related to electricity generation and hydrogen storage, a [Conceptual Model](#) is developed in section 3.1. This model was developed to figure out the yearly energy consumption, emission, and material need for a steel factory in Sweden with a liquid steel output capacity of one-ton liquid steel as the main product, as well as slag and oxygen, representing outputs. [22]

To answer the second question a survey of the key questions was sent to find the case of transaction compared with the Swedish case. This survey is presented in section 3.2. [23]

A literature review of LCA inventory by ISO14040:2006 and ISO 14044:2006 is performed in section 3.3 to investigate and compare the carbon emissions associated with two steel production methods: the conventional process BOF-BF and the emerging hydrogen-based steel production process. This review examined the environmental impact of these two processes by exploring relevant scholarly articles, reports, and industry publications. [24]

3.1 Conceptual Model

The conceptual model was created to answer the first question *What are the enabling factors associated with hydrogen-based H-EAF steel production in Sweden compared to other European countries in terms of electricity generation, hydrogen storage, and energy consumption?*

The calculations were based on the production of one ton of liquid steel by using hydrogen as a reduction agent in Sweden.

Energy balance and material calculations were performed across the control volumes of the proposed system's major components. The conceptual process flow diagram for the iron and steel production process using a shaft furnace and an EAF is like one that has been proposed previously. [25]

The energy needs that cause CO₂ mitigation are divided into three different subprocesses:

- *Preparation of hydrogen* through electrolysis of water with energy that can be renewable or Swedish average electricity or marginal.
- *Energy to melt* the iron pellets in the shaft furnace.
- *Energy to convert* the hot metal to steel in the EAF.

Figure 4 shows a schematic of the hydrogen-direct reduction process, which is divided into hydrogen production, ironmaking process, and steel making. Only the

main reactions in the process have been considered to keep a model simple. The system boundaries were defined as well and the material and energy balance were set up for the system between the inputs (Iron ore or pellets, lime, alloys) and the outputs (liquid steel, slag, oxygen). [26]

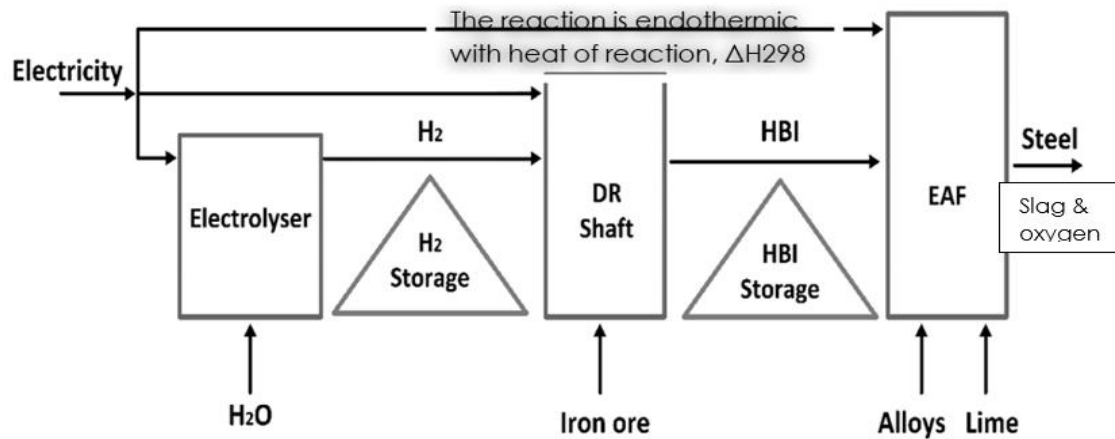


Figure 4. Schematic of a grid-connected H₂-SF-EAF-based steel production system. [26]

Alkaline electrolyze systems were previously used on an industrial scale and are now available in megawatt module sizes with lower cost compared with other electrolysis systems technologies such as platinum or iridium electrolyzes. The process of splitting water into hydrogen and oxygen in the electrolyze requires energy supplied by the electric current. Overall, the process of water splitting is energy-intensive, as it requires a significant amount of electrical energy to break the strong bonds between hydrogen and oxygen atoms in water molecules. The enthalpy value for the reaction is + 244 kJ/mol. [26]

Iron melts at 1500 °C in the DR shaft furnace, from where Hematite transforms to metallic iron. First, Hematite (Fe₂O₃) is converted to Magnetite (Fe₃O₄), which is converted to Wurtzite (FeO), and finally, metallic iron. Reactions absorb energy, and the three steps are represented in the equation:



The enthalpies of all modeled reactions were found to be +99.5 kJ/mol. This means that these reactions absorb energy. [27]

The rest of the energy needs come from reactions, C to CO₂ and Si to SiO₂, which generate remarkably high heat. About 20 percent of the contents of the converter are steel scrap that is added to cooling. Several chemical reactions occur in addition to material balance in the process, carrying EAF through the slag. [28]

3.2 Survey

The target respondents for this survey were companies involved in steel industries in Sweden with relevant expertise in the focus on manufacturing steel with H₂ methods or have oriented their efforts towards mitigating GHG emissions, including SSAB, Ovako, Höganäs, Allemia, Uddeholm, Outokumpu and H2GS.

To be able to answer the question about comparing modern technologies in more detail, the method was supplemented by sending out another survey holding simple questions to companies in three countries Germany, the Netherlands, and Sweden (choice criteria are detailed in section 1.3 above).

This was to learn about the strategies and techniques used in Swedish steel industries and other countries. The survey was designed at a specific point in time using a Google form; invitations to participants in the survey were sent to potential participants via mail, along with a brief explanation of the study's purpose and a link to access the questionnaire. The structured online questionnaire consisted of multiple themes, including scrap availability, hydrogen storage renewable energy, and barriers to adopting innovative technologies.

To cover various aspects of the hydrogen-based production process in several steel sectors in Sweden and other countries in Europe, perception-based questions were asked to provide background information and attitudes towards embracing challenges as well as enablers associated with HDR technologies. Perception-based questions were also asked to supply background information and attitudes towards embracing challenges and to assess respondent knowledge about mitigating GHG emissions in steel sectors.

Questionnaires were sent in April 2023 to seven companies in Sweden, one in the Netherlands, and one in Germany. Totally six companies responded to the questionnaire, while two companies in Sweden and one in Germany did not respond to this survey.

(See Appendix 1 which shows results from European companies in Germany and the Netherlands) (See Appendix 2 which shows results from Swedish companies)

3.3 Comparative analysis of LCA

A literature study on LCA was the method used in this section to gain insights about the climate impact of the conventional steel-making process and the modern technologies with the hydrogen-based process to answer the question "*What is the difference in carbon emissions when utilizing hydrogen-based steel versus BOF process?*". The method was to conduct a review, a literature search of scientific publications through the Linnaeus University Library webpage (One Search and Libris). The review was based on articles from studies conducted on topics such as comparing carbon emissions between (BOF-BF) and hydrogen-based steel production processes, LCA of hydrogen-based steel processes, and conventional processes. The total number of articles between 2019-2023 was 20 reviews with the keywords "carbon footprint of hydrogen-based steel ", and " LCA hydrogen-based steel ". A total of 3 case studies were considered to fulfill the purpose of this thesis and were studied in detail. Studies were screened based on the title and abstract for relevant research questions. The search was conducted in July 2023.

4. Results

The results of specific energy consumption are presented in section 4.1 to answer the question *about the contributing factors for H₂-EAF steel production in Sweden*

compared to other European countries. The results from the survey sent to the companies are presented in section 4.2 to answer the second sub-question about *the estimated strategies and techniques that Swedish steel industries and other countries plan to use to reduce GHG.* Finally, in Section 4.3, a result of the literature review is given *to find the difference in carbon emissions when using hydrogen-based steel versus it with a basic oxygen furnace process.*

4.1 Specific energy consumption

This section evaluates the hydrogen direct reduction process and proposes a potential process design for H-DR as the foundation for the model evaluation. The material and energy flows through the various components were calculated to produce one ton of liquid steel in Sweden via the DRHI process. To figure out the energy demand, the system boundaries were defined in Figure 3 above, which showed the structure of the hydrogen direct reduction process. Hydrogen is produced in electrolysis and then stored in the hydrogen storage before being fed into the shaft furnace, where it is used as a reduction agent. Iron ore is converted into directly reduced iron and then compacted into hot briquetted storage to avoid reoxidation. To melt and create liquid steel, HBI is fed into an EAF. The model was designed based on existing technologies. The model has been simplified, only major reactions in the process have been considered.

The results acquired from the conceptual model are presented in Table 3, where the model results show that the energy consumption in the DRH process was estimated to be 3.66 MWh per ton of liquid steel. The material and energy balance were set up for the system between the inputs (Iron ore or pellets, lime, alloys) and the outputs (liquid steel, slag, oxygen). The enthalpy of the reduction reactions in the process directly influences energy consumption. Higher enthalpy values signify greater energy requirements for the reduction of iron oxide, which affects the overall energy efficiency. Minimizing energy consumption while maintaining process efficiency is a key consideration in optimizing hydrogen-based steelmaking in EAF. In light of the recent research a 2.5 MWh alkaline electrolyze system is needed to produce hydrogen for the H-SF demonstration plant in Sweden (In this analysis, alkaline electrolyzes for hydrogen production are considered with an efficiency of 53 MWh/ton H₂. [29])

The specific energy consumption to convert iron ore to hot metal at 700 °C in the shaft furnace, based on the literature data was 0.5 MWh [29]. Combined with a sub-model, the specific energy consumption for the conversion of the hot iron to steel in the EAF was 0.66 MWh per ton of liquid steel for the operation of one pure scrap feed [30]. The difference in the specific energy consumption originates from the use of different electrolyze types, values of electrolyze efficiency, use of scrap in the EAF, and thermal energy requirements of the shaft furnace.

Energy consumed to split water into hydrogen and oxygen in the electrolysis is two-thirds of the energy needed in the process, i.e. 2.5 MWh. This highlights the importance of using renewable energy sources for electrolysis to achieve emission reduction. The result showed that the hydrogen-based process offered flexibility in

the process through storage of the hydrogen and HBI. The electric arc was 0.66 MWh, while the ore heating processes consumed 0.5 MWh.

The conceptual model described a breakdown of the unit's operations. The shaft's energy consumption was low, which could be explained using recovered heat from the condenser. The electrolyze consumed 60% of the energy with the ore heating processes, and the electric arc furnace was a further large energy user, in total 2.5 MWh. Only when replicated to replace today's BF/BOF path this would lead to a significant rise in electricity consumption. If HDR technologies expand to replace the current BF / BOF path, it will lead to a significant increase in electricity consumption.

Electricity consumption of production of hot iron	0.5 MWh
Electricity consumption of conventional hot iron in the EAF	0.66 MWh
Electricity consumption of electrolyze.	2.5 MWh
The total energy consumption of the H-DR process	3.66 MWh

Table 3. The total energy consumption results according to the conceptual model calculation.[29]

4.2 Survey result

The total number of respondents to the survey was six companies. Two companies in Sweden and one in Germany did not respond to the questionnaire.

Regarding the first theme about scrap availability, the first question read "**1- Which processes do you use to produce your steel?**" received the following responses 60 % of the Swedish companies still use the conventional methods with BF-BOF, and 40% of the steel companies use open Hydrogen based process while SSAB started HDR and focus on fossil-free steel, Tata steel efforts in the Netherlands oriented towards HDR technologies.

On the second question, "**2- if you produce your steel with a hydrogen-based - process- how much scrap is needed to produce one ton of steel?**" An answer for both companies that focus on HDR technologies was that 20-30% scrap was needed to produce one ton of steel. For Swedish companies, the answers varied between the significance of the availability of scrap or not needed depending on the methods used to produce the steel today.

Another question was about the current trend about scrap availability: Both the Netherlands and Sweden's steel sectors looking towards a more sustainable future as well as a growing trend to replace natural resources with scrap steel.

Netherlands Steel answered that steel sectors can increasingly expect that natural resources can be replaced with scrap. According to SSAB's answer, there will be more scrap steel available in the future, but the problem is the prices will increase in Europe.

86% of the Swedish companies expect the steel industry to increasingly replace natural resources with steel scrap, but this depends on the scrap prices.

When we come to the theme of hydrogen storage: **hydrogen is needed to produce one ton of steel**, and the respondents answered it is about 50 kg of hydrogen in the hydrogen-based steel process.

As for the question, "**What are the enabling factors associated with the H₂-EAF-based steel production in your country compared with other European countries?**" The companies answered that green electricity is the main factor in reducing the CO₂ emission associated with H-EAF. Decarbonization within the steel industry will also require enormous amounts of electricity generated from renewable energy. The process requires more than 5 MWh to produce one ton of steel using the HDR process. The current direction about electricity requirements for industry decarbonization in Sweden and the Netherlands is climate neutrality by 2050 as well and the estimated CO₂ emissions for fossil-free steel are in zero emissions or below 1 ton CO₂ eq, according to SSAB and TATA steel answers.

In terms of theme challenges: Political decisions and the availability generate green electricity are the big challenges for both TATA Steel and SSAB.

In response to the question, "**How does your process differ from other low-emission methods?**" SSAB ensures that the full process is fossil-free, from mining to final product transport, with no allocation of emissions or offsetting. TATA Steel combines a green hydrogen route with an intelligent carbon pathway. 29% of Swedish companies are heading to improve GHG emissions by focusing on the increase in the share of recycled content as well as no mass allocation of emissions or no offsetting. 15% focus on CCS technologies and technologies, and another 15 % combine green hydrogen routes with smart carbon pathways.

"**What are the main barriers/challenges to decarbonization within the steel industry in your country?**" SSAB's response to this question: green power and CCS are available. According to SSAB, hydrogen storage is one of the technical hurdles of fossil-free infrastructure, although there are no issues of fossil infrastructure from the TATA steel side. According to SSAB, a production capacity of green steel that matches the needs of stakeholders might be realized by 2050. 17 % of Swedish companies consider that the challenges should be dealt with by the state and economic factors.

4.3 Comparative analysis of carbon emissions this section

A review of the studies identified several key factors that make the hydrogen-based steel process have the potential to reduce CO₂ emissions from steel production. Suer et al. [31] compared the carbon emissions of hydrogen-based steel production with conventional steelmaking methods. The study conducted a LCA for both processes considering all stages from raw material extraction to end-of-life. The study found that hydrogen-based steel production has significantly lower carbon emissions compared to conventional steelmaking methods, due to utilize hydrogen as a reducing agent. Thus, an integrated steel site has a demand of 4.9 MWh of electric energy per ton of steel. Based on the study, steel production via the

HDRI-EAF route is expected to have a low carbon footprint of approximately 0.75 tons CO₂ equivalent per ton of steel by 2040. Suer et al. [31] highlighted that steel-based hydrogen processes can play a crucial role in achieving Europe's ambitious climate goals. However, it is important to note that the study primarily focused on the effects of climate change, without investigations of other environmental aspects such as those related to nuclear-based electricity production.

Suer et al. [32] compared the environmental impact of hydrogen-based steel production, including carbon emissions, and performed a life cycle assessment of the two processes, considering factors such as energy consumption, emissions, and resource consumption. The study found that hydrogen-based steel production has lower carbon emissions compared to conventional processes, due to the use of hydrogen as a carbon-cleaning reduction agent and the avoidance of carbon-intensive fuels. In addition, the literature reviewed that the use of breakthrough technologies such as hydrogen injection and pre-reduced iron ores in blast furnaces can already result in significant reductions in GHG emissions, up to 0,200 tons of CO₂ per ton of hot metal. However, the increasing steel demand cannot be filled by scrap recycling alone even until the year 2050 and beyond. [32]

Chen et al. [33] compared the environmental performance of HDRI with BFI. A life cycle assessment was conducted for both processes, considering factors such as energy consumption, material use, and emissions. The study concluded that HDRI had significantly lower carbon emissions compared to BFI, due to the removal of carbon-intensive coke during the reduction process. LCA was used to assess the environmental impact of these two processes, especially greenhouse gas emissions. Hydrogen-based steel production produces significantly lower greenhouse gas emissions than conventional steel production, by up to 90 percent, depending on the specific process and energy used, as stated in the LCA. The reduction of emissions resulting from the hydrogen-based steel process was estimated to be around 90 %. This estimate is based on a comparison of carbon emissions from various sources examined within the literature reviewed in this study. The transition toward this technology offers a substantial emission reduction, primarily when powered by renewable energy. [33]

5 Discussion

In this study, mixed methods; conceptual model, survey, and literature review of LCA have been used to estimate the future capacity of hydrogen-based steelmaking by 2050 as well as to find a pathway transition to a hydrogen-based reduction process in other countries in the EU compared with Sweden's case.

Direct reduction process with integrated electric arc furnaces enables steel production, which is exclusively based on electricity if hydrogen stems from electrolysis. Thus, an integrated steel site has a demand of 3.66 MWh of electric energy to produce one ton of liquid steel.

If the current German, Swedish, and Dutch primary steel production would be operated on the H-DR process 43.3;4.5; and 6.8 million metric tons respectively,

according to the conceptual model results, it would require 158.5 TWh, 16.5 TWh, and 24.8 TWh of electricity. At the same time, fuel use would be reduced intensively if electricity was generated from renewable sources.

According to the data compiled by the International Energy Agency for 2022, energy production from renewable sources is 233.9 TWh in Germany. This reveals that hydrogen-based steel production is expected to form a significant part of Germany's renewable energy, contributing around 1.5 % of the country's total renewable energy production. Significant changes have occurred in Germany's energy sector because of Russia's invasion of Ukraine. Germany expanded its coal use to make up for the decrease in natural gas imports, which raised environmental worries. Natural gas prices doubled by September 2022 despite efforts to lower gas use and diversify energy sources, creating economic difficulties and causing a review of energy regulations.

According to the International Energy Agency data for 2022, the total energy production in Sweden from renewable sources accounted for 63% of the total energy consumed in 38 TWh. This reveals that hydrogen-based steel production is expected to form a part of Sweden's renewable energy, contributing around 2.3% of the country's total renewable energy production. This process's energy requirements must be carefully balanced with energy availability and environmental considerations.

According to the data compiled by the International Energy Agency for 2022, the Netherlands had a renewable energy capacity of some 47 TWh. This reveals that hydrogen-based steel production is expected to form a part of the Dutch's renewable energy, contributing around 1.3% of the country's total renewable energy production.

The share of H₂-based steel production of the total renewable energy production in Germany and the Netherlands will be 1.5%, and 1.3% respectively, signifying substantial challenges in balancing renewable energy demands and the energy required for H₂-based steel production. In contrast, Sweden will be a stronger commitment, with a share of the H₂-based production of 2.3% of the total renewable energy production.

The availability of green electricity is one of the biggest barriers to reducing the GHG in the steel industry, and it might be a crucial factor in whether an emission reduction pathway appears in the steel sector. The condition of the energy sector and the amount to which it is decarbonized differ significantly among countries in the EU, even though the electrification pathway is shared by many sectors across the EU. To electrify these areas, the power sector should produce enough electricity from renewable sectors. As a result, it is critical that in nations with large emissions from power generation, carbon reduction of energy and other sectors occur concurrently.

Sweden is a country with particularly reliable results due to exceptionally low CO₂ emissions from the power sector. Hence, there are good conditions for producing electricity from renewable resources. Additionally, strategic policy decisions and investments may be needed to optimize the energy infrastructure to support a sustainable steel industry.

Germany is making significant efforts toward an energy transition, and the country has set itself up as a leader in renewable electricity. However, the shutdown of nuclear facilities has resulted in a protracted reliance on fossil coal for electricity generation, making reducing GHG emissions in the power sector more difficult. Furthermore, the Ukraine war has made Germany's situation much worse, when the Germans cannot rely on Russian natural gas anymore.

Even though the Netherlands is the country with the highest share of domestic renewable generation, the country is highly dependent on natural gas for electricity generation. There is a large focus on increasing renewable power production and integrating it with the grid. However, there is not a large focus on the electrification of the steel industry.

From a system standpoint, it will make no sense to begin using electricity in industrial processes if it results in a continued or increased reliance on fossil-based electricity. Compared with the respondent's answer the process requires more than 5 MWh to produce one ton of steel by using the HDR process technology.

Even though there are uncertainties and different opinions about the right way forward to reduce emissions related to steelmaking, there is unanimity about the significance of not only a technological process solution but also an increased focus on materials efficiency and circularity with green scrap availability. This is something stressed by the research results as well as the result of energy generated.

A weakness I discovered while I was going through the survey answers is that it is optional for the respondents, how much they wanted to answer as well as I needed more respondents who could answer. This makes it difficult to make a comparison where only the survey responses are used. The information often must be supplemented from other sources for comparison.

It is increasingly expected that natural resources can be replaced with scrap, which is confirmed by the theoretical knowledge in this field. As the survey result, many companies consider that the current trend about scrap availability will be expected to increase in the future, but the problem is the prices will also increase in the European market. Natural resources can be replaced by scrap in the future, but the main question here is *the availability of green scrap in the future*.

There was no direct access to external sources or the ability to borrow articles, reports, or industry publications concerning the role of scrap in decreasing direct GHG emissions in the steel sectors. However, a general overview supplies consider that the use of steel scrap in steel production offers several environmental benefits, including energy saving, conservation of resources, and waste reduction, as well as the industry can reduce its carbon footprint compared to using virgin iron ore.

On the other hand, one factor that may figure out which way the steel industry adopts to reduce GHG emissions and one of the biggest challenges facing the steel industry is access to electricity generated from renewable sources. To be able to electrify these sectors, the power sector needs to be able to supply enough green electricity. Therefore, the best environment for the introduction of hydrogen-based technology for iron steelmaking is an area where the energy sector has embarked on

decarbonization. Only when replicated to replace today's BF/BOF path would this lead to a significant rise in electricity consumption. If HDR technologies expanded to replace the current BF / BOF path, it would lead to a significant increase in electricity consumption as well and if electricity is generated with renewable resources, it would lead to a 90% improvement in GHG emissions.

6 Conclusion

What are the enabling factors associated with the hydrogen-based process in Sweden in terms of electricity generated and hydrogen storage?

The enabling factor associated with hydrogen-based steel production in Sweden was the availability of low-emission electricity in Sweden compared with other countries.

Steel manufacturing with a hydrogen direct reduction process is seen as a vital technical possibility for lowering emissions from steel production, while the energy consumption and electricity generated from renewable energy are recognized as crucial factors for a competition of hydrogen-based process steel making.

The conceptual model was applied in Sweden to analyze the energy consumption in the hydrogen-based process, including electrolyze, direct reduction shaft furnace, electric arc furnace, and storage of briquetted iron and hydrogen. Based on the model result, the electrolyze consumed 60% of the energy needed in the process. Only when replicated to replace today's conventional process, would this lead to a significant rise in electricity consumption and lower carbon emissions. However, the total energy demand is like a blast basic oxygen furnace, but instead of coal and coke, the process runs on low-emissions electricity. Through the storage of hydrogen and hot briquetted iron or changes in the percentage of scrap used, the process can be more flexible in terms of production and electricity demand. The competitiveness of the HDR process depends on technological advancements in the areas of hydrogen storage and electrolysis.

What are the strategies that the Swedish steel industry and other countries use to reduce GHG emissions?

This study demonstrated that some of the investigated steel companies have invested in modern technologies to reduce their emissions. The level of ambition differs between the surveyed companies. Based on the result of the survey and since the questions are about steel production with hydrogen-reduced ore process, it is only SSAB and H2GS that today have that orientation in Sweden. Höganäs, which also starts from ore, has a different process, and plans to replace fossil coal and gas with biochar and bio-based gas. The other steel mills in Sweden are scrap-based, and even in the future, they may also buy hydrogen-reduced iron as a raw material, which is not their focus when it comes to reducing emissions. Their emissions come from fuel use, and work is underway to replace fossil fuels with electricity, bio-based gas, or hydrogen.

The ambitious steel companies in other countries intend to use H-DRI with green electricity. The technology theoretically could be emission-free, but then decision-makers must make large investments in renewable energy supply and transmission

infrastructure. There is currently no plant with H-DRI that is ready to be commercialized in other countries in the European market.

What is the difference in carbon emissions when using hydrogen-based steel technology versus with basic oxygen furnace process in Sweden?

A literature review of life cycle analysis was used to figure out the difference in carbon emissions when using hydrogen-based steel versus the BOF process. The result showed that the reduction was estimated by 90%, which means it still emits CO₂.

Energy requirements and emissions related to hydrogen-based processes can vary depending on the energy used for production. The electrolysis process can be practically emission-free if the electricity used for it originates from renewable resources like solar, wind, or hydroelectric power. Using electricity from other non-renewable sources can lead to emissions of greenhouse gases and pollutants. It is important to consider the entire life cycle of steel produced by the hydrogen process, from the energy source to end use, when evaluating its environmental impact. LCA utilizes the cradle-to-gate system, which includes all operations from raw material mining to the finished steel slab. Due to the increasing role of scrap in the EU, not all of today's primary steel processes will be needed in the future, but the capacity is difficult to estimate.

Finding measures to reduce carbon dioxide emissions in the steel industry is very intensive in terms of measures of the need for electricity. However, the limited use of this process of steelmaking in Europe has a practical justification that depends, among other things, on the availability of scrap steel and electricity, and the low possibility of scrap generation and recycling scrap availability, in the EU market.

In light of these factors, accurately predicting production capacity and CO₂ reductions in 2050 is a complex task. Predicting how quickly these technologies will progress and be adopted on a large scale is difficult. To ensure the effective implementation of hydrogen steel production technologies into the global energy landscape while achieving significant carbon reductions, both the steel industry and stakeholders need to continuously monitor these factors.

Stakeholders who focus on and use products that contain steel have the right to review the facts behind the supplier's environmental promises. It is not enough to talk green; the responsibility of the steel industry is not only to eliminate the carbon footprint but also to show exactly how it is done. The successful shift of the EU steel industry to carbon neutrality by 2050 depends on the availability of low-cost, low-carbon energy sources, especially electricity and hydrogen.

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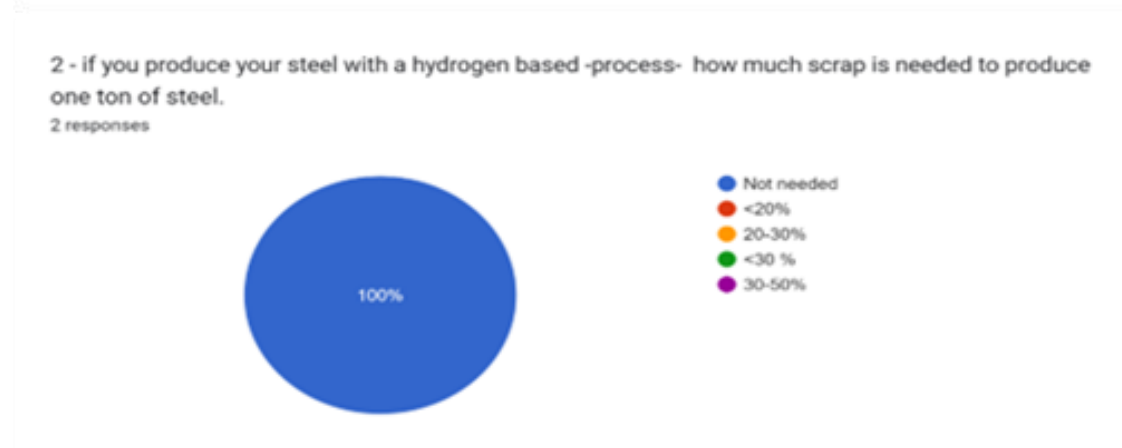
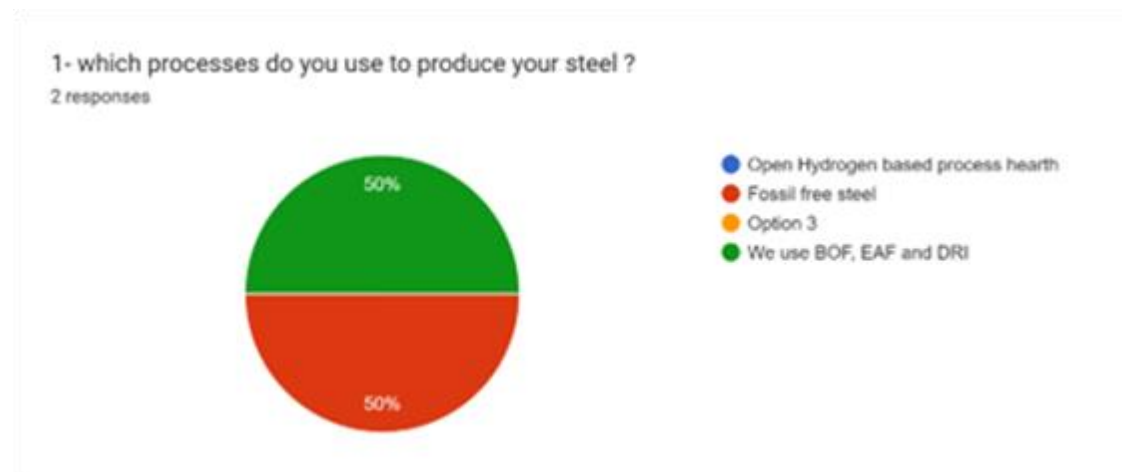
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Appendixes

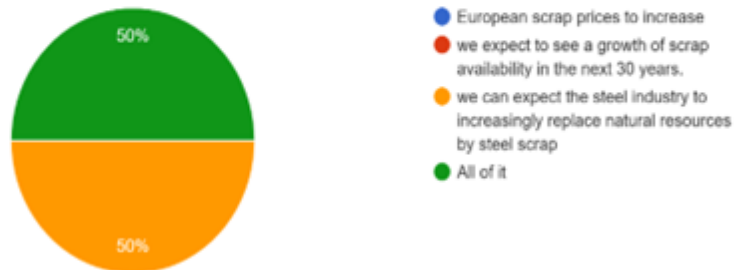
Appendix 1 Survey Eu companies

Theme: scrap availability



3- What is the current trend about scrap availability in EU?

2 responses



Theme: Hydrogen storage

1. How much hydrogen capacity is required to produce one ton steel by HD process per year in Europa ?

2 responses



5- An output capacity of green steel that meets the stakeholders requirements could be achieved by:

1 response



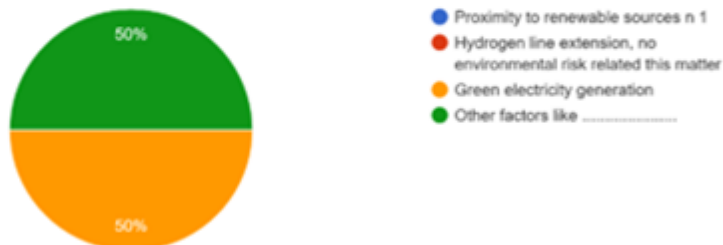
2. How much electrolyze capacity for hydrogen production will be needed If the hydrogen is produced by renewable electricity ?

2 responses



3. What are the enabling factors associated with the H2-EAF based steel production in your country compared with other European countries ?

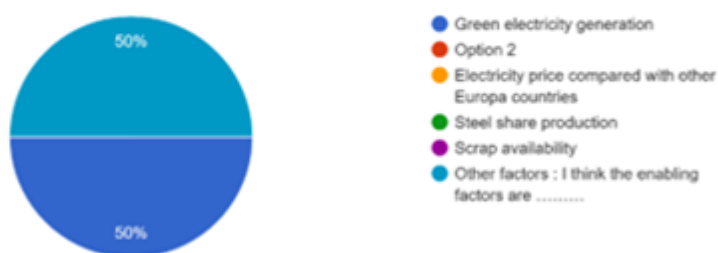
2 responses



Theme: renewable energy

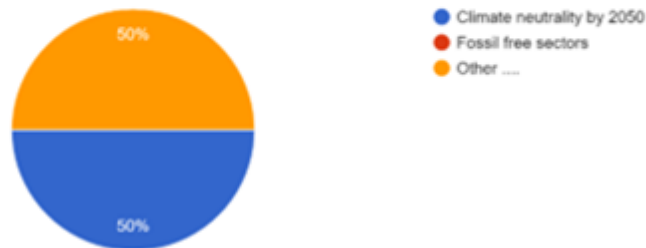
1- What are the enabling factors associated with the H2-EAF based steel production in your country compared with other European countries ?

2 responses



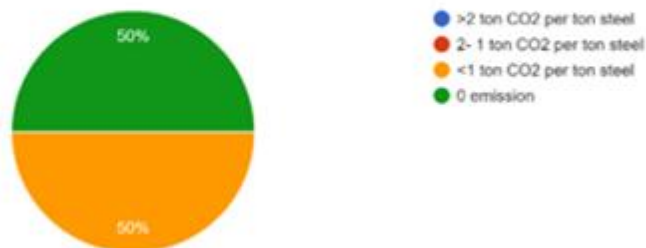
2- Decarbonization within the steel industry will also require large amounts of electricity. What is the current direction regarding electricity requirements for industry decarbonization in your country?

2 responses



3- What is the estimated CO2 emissions for your fossil free steel ?

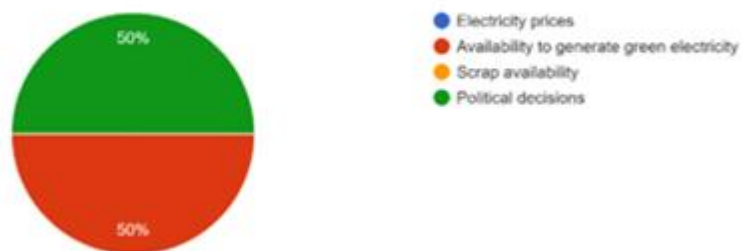
2 responses



Theme Challenges

1- Which is the biggest challenge with your process, except access to hydrogen available?

2 responses



4- Which are the technical challenges of fossil-free infrastructure?

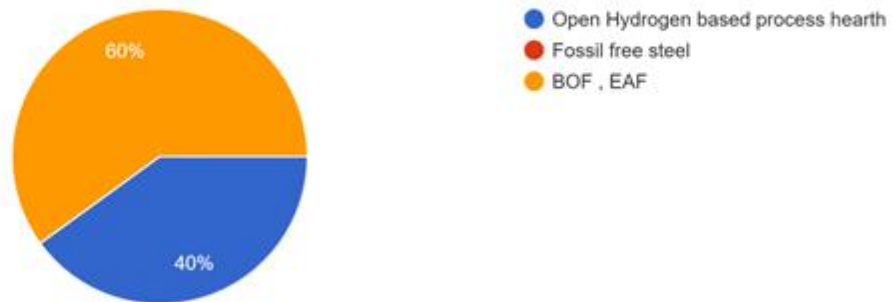
2 responses



Appendix 2 survey Sweden Companies

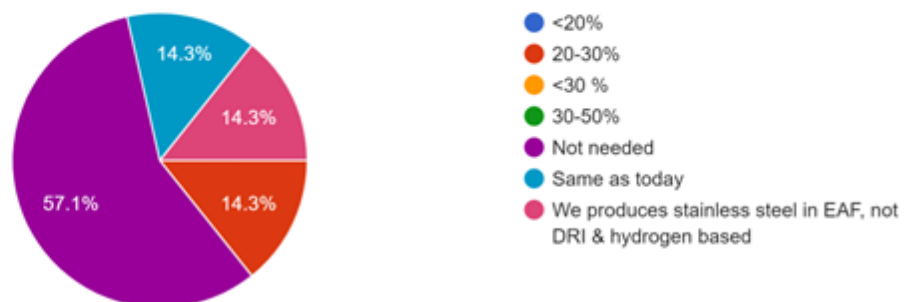
1- which processes do you use to produce your steel ?

5 responses



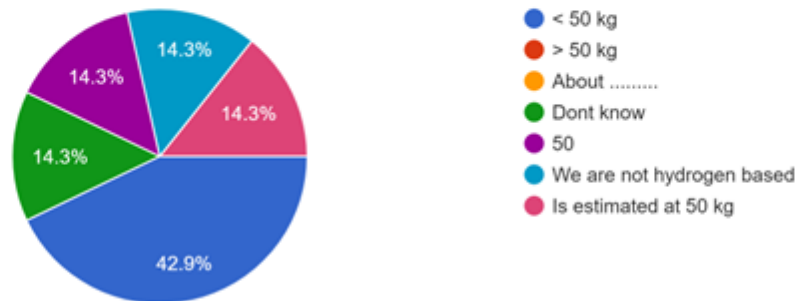
2 - if you produce your steel with a hydrogen based -process- how much scrap is needed to produce one ton of steel.

7 responses



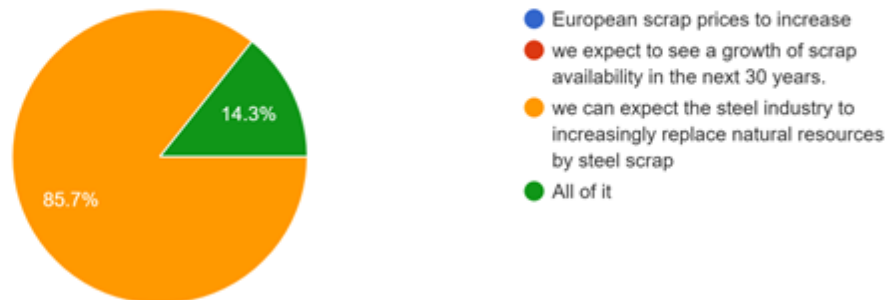
1. How much hydrogen capacity is required to produce one ton steel by HD process per year in Europa ?

7 responses



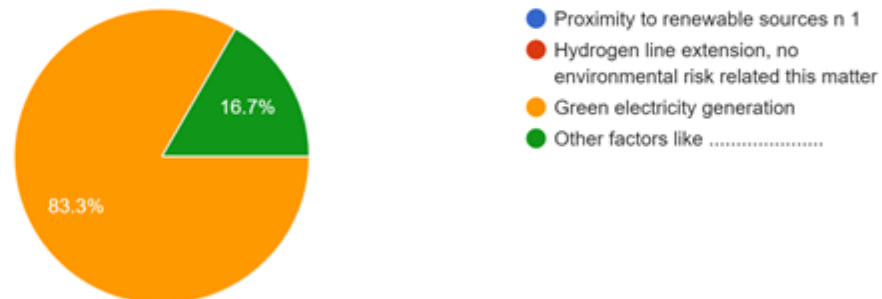
3- What is the current trend about scrap availability in EU?

7 responses



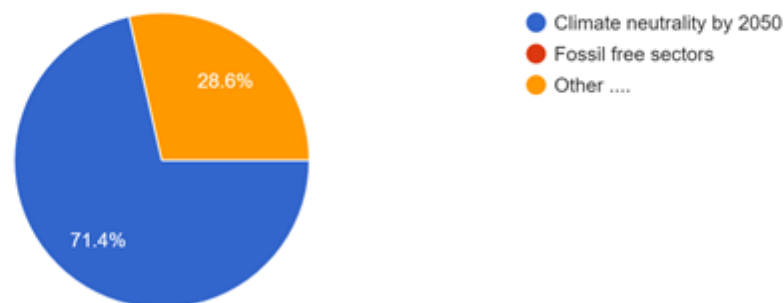
3. What are the enabling factors associated with the H2-EAF based steel production in your country compared with other European countries ?

6 responses



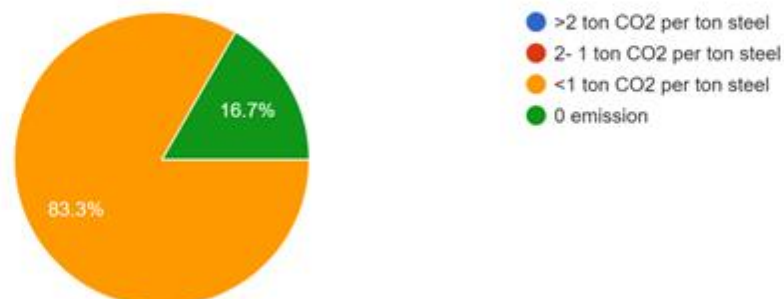
2- Decarbonization within the steel industry will also require large amounts of electricity. What is the current direction regarding electricity requirements for industry decarbonization in your country?

7 responses



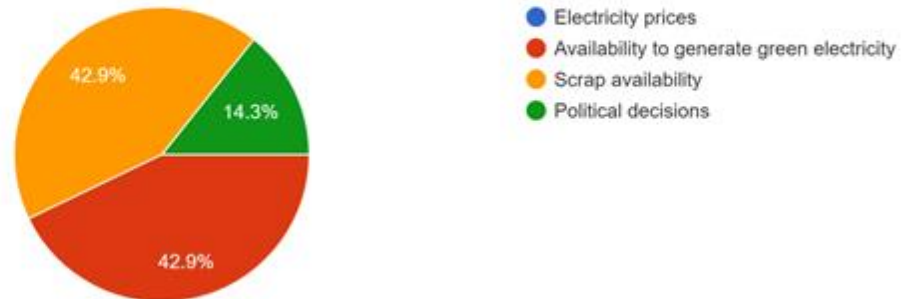
3- What is the estimated CO2 emissions for your fossil free steel ?

6 responses



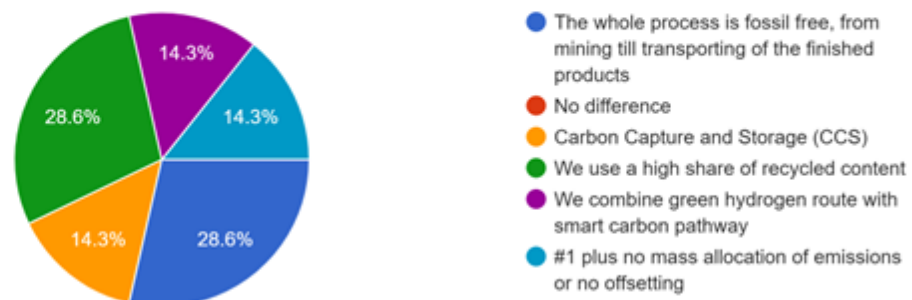
1- Which is the biggest challenge with your process, except access to hydrogen available?

7 responses



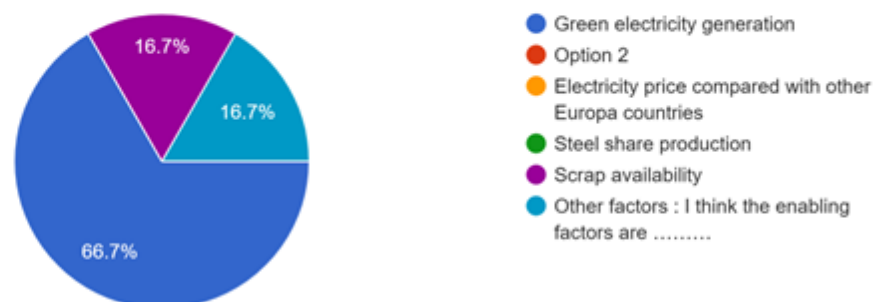
2- In what way does your process differ from other methods for low emission?

7 responses



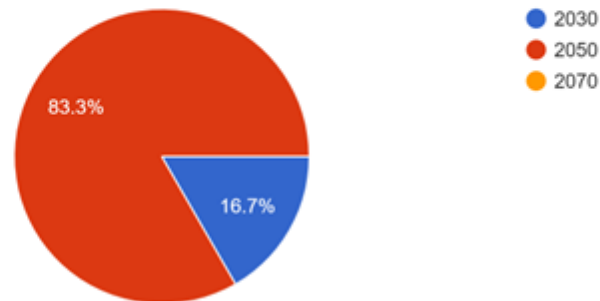
1- What are the enabling factors associated with the H2-EAF based steel production in your country compared with other European countries ?

6 responses



5- An output capacity of green steel that meets the stakeholders requirements could be achieved by:

6 responses



4- Which are the technical challenges of fossil-free infrastructure?

6 responses

