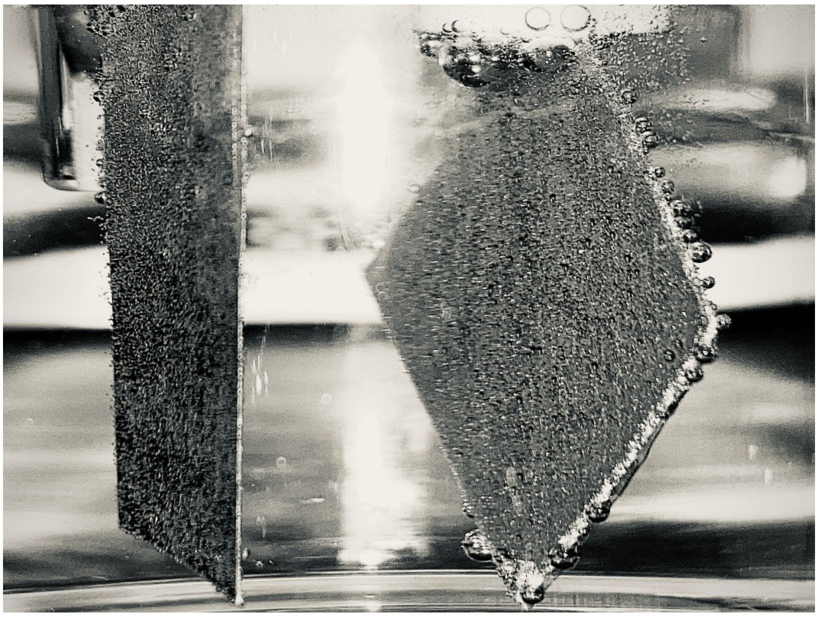

Prospects of Green Hydrogen as a Key Enabler for the Swedish Steel Industry

Bachelor Thesis in Industrial and Materials Science, B.Sc

Rebecka Berg
Lucas Bjugård
Filippa Forsman
Hugo Nilsson
Olle Söderberg
Axel Öskog

DEPARTMENT FOR INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg 2024
www.chalmers.se

BACHELOR THESIS 2024

Prospects of Green Hydrogen as a Key Enabler for the Swedish Steel Industry

Rebecka Berg
Lucas Bjugård
Filippa Forsman
Hugo Nilsson
Olle Söderberg
Axel Öskog

Department for Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg 2024

Prospects of Green Hydrogen as a Key Enabler for the Swedish Steel Industry

R.Berg, F.Forsman, L.Bjugård, H.Nilsson, O.Söderberg, A.Öskog

Supervisor: Zhenyuan Xia, Chalmers University of Technology
Co-Supervisor: Sankar Sasidharan, Smoltek
Examiner: Uta Klement, Chalmers University of Technology

Bachelor Thesis 2024
Department for Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Phone +46 31 772 1000

Cover picture: A proton exchange membrane electrolyser half-cell, used to demonstrate hydrogen production.

Gothenburg 2024

Abstract

This study investigates the potential of using hydrogen produced with renewable electricity to establish a new standardised pathway in the reduction of iron oxide in the process of steel making. By analysing current projects, the latest research as well as interviews with renowned professionals, this study offers insights into the green shift of the steel industry and offers a brief look into the future.

Besides this, the thesis also delves into the process of proton exchange membrane electrolyser, a promising method producing hydrogen with renewable energy. Discussion of a potential bottle neck using limited rare earth metals along with recent research proving the amount of catalyst used in the proton exchange membrane might be very little.

The study concludes that PEM is a promising method, however currently it is not economically profitable to utilise this electrolysis method because of the high investment cost. Furthermore, it is concluded that if it possible to reduce the iridium loading and replace expensive metals such as gold and titanium, PEM can potentially replace the more commercially available alkaline water electrolysis in the future.

Steel manufacturing contributes to a large part of the Swedish economy but also to the yearly carbon emissions. The method of reducing iron ore by hydrogen gas have shown promising results, however the questions remains if the incentive is big enough. To fundamentally change the industry would require contribution from both the industry itself but also from the state. It would be a hefty investment and presumably too expensive for the companies to handle without the help through loans and political regulations.

In Sweden there are two large projects that are planing to produce green steel by using hydrogen from water electrolysis in large scale. The thesis concluded that green steel has potential to be the future for the steel industry, however the industry will face challenges such as maintaining the supply of renewable electricity as well as the necessity to change established infrastructure.

Sammanfattning

Den här studien undersöker potentialen att använda vätgas producerad med förnybar elektricitet för att etablera en ny väg för reduktionen av järnmalm i processen för ståltillverkning. Genom att analysera nuvarande projekt, den senaste forskningen samt intervjuer med erkända professionella, ger denna studie insikter i den gröna omställningen av stålindustrin och en uppskattad framtidsutsikt.

Utöver det gröna stålet går arbetet även in på en elektrolysmetod som baseras på protonutbytesmembran. Detta har visat sig vara en lovande process för att producera väte med förnybar el. Diskussion om en potentiell flaskhals genom användningen av begränsade och sällsynta jordartsmetaller tillsammans med forskning som visar att mängden katalysator som används i protonutbytesmembranet kan göras mycket liten vilket då skulle öppna möjligheter. Studien drar slutsatsen att PEM elektrolys är lovande, däremot är metoden förnuvarande inte finansiellt gångbar. Om det i framtiden är möjligt att minska mängden iridium och att byta ut dyrbara metaller så som guld och titan kan PEM konkurrera med den mer kommersiellt tillgängliga alkanisk elektrolys.

Ståltillverkningen bidrar till en stor del av den svenska enonomin, men även till de årliga koldioxidutsläppen. Metoden att reducera järnmalm med vätgas som reduktionsmedel har visat potential, men frågan kvarstår om incitamentet är stort nog. För att ändra industrin krävs bidrag från industrierna själva men även från staten. Det skulle vara en stor investering vilken antagligen skulle vara för stor för industrin att hantera utan stöd i form av lån och regulationer.

I Sverige finns det två större projekt som planerar att producera grönt stål med hjälp av grön vätgas från storskalig elektrolys. Denna studie kommer fram till att grönt ståla har potential till att bli förtiden för stålindustrin, men att industrin kommer möta utmaningar så som att underhålla förnybara elbehovet och att förändra en etablerad infrastruktur.

Acronyms

AWE	Alkaline Water Electrolysis
BF-BOF	Blast Furnace - Basic Oxygen Furnace
DR	Direct Reduced
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
H-DRI	Hydrogen Direct Reduced Iron
HER	Hydrogen Evolution Reaction
MEA	Membrane Electrode Assemblies
OER	Oxygen Evolution Reaction
OCV	Open Circuit Voltage
PEM	Proton Exchange Membrane
PFAS	Per- and Polyfluoroalkyl Substances
PTL	Porous Transport Layer
VAT	Value Added Tax
SOEC	Solid Oxide Electrolysis Cell

Contents

List of Figures

1

Introduction

In 2015, 196 countries, including Sweden, entered into the Paris Agreement [1]. In doing so they committed to collectively limit global warming to two degrees above pre-industrialisation temperatures by reducing greenhouse gas emissions. The Paris Agreement states that “Developed countries should continue to take the lead by undertaking absolute economy-wide reduction targets”, and thus countries like Sweden do not only have a moral obligation but also a legal one to reduce greenhouse gas emissions in every part of the economy [1].

Over the last two decades, there has been a rapid increase in the commitment of developed countries to address climate change. Companies and industries have been needing to seek new solutions for established processes as well as products, disassemble to reassemble, to find new paths aligned with the goals set.

For the steel industry, the result of rethinking the processes ends up in a route that, in theory, appears ideal and somewhat self-evident. Instead of using expensive fossil fuels from far away, the process will utilise water from local sources and electricity produced with renewable resources. Theoretically, this sounds like a convenient path for the steel industry to pursue. Cutting carbon emissions significantly [2], being more self sufficient for resources as well as remaining competitive meeting the market’s demands for green alternatives.

1.1 Background

Iron was first extracted from ores around 4000 years ago, most likely as a side product from making copper [3]. This led to the earliest types of iron refining which was essentially a small hole in the ground with a charcoal bed and bellows to reach temperatures of around 1100 °C [3]. Using this method the iron is not heated past the melting point but is simply reduced using solid carbon to make lumps of more or less pure iron weighing around 5 kg each [3]. From that period, the major advancements were making the equipment larger and more efficient, but it was not until the 12th century that an entirely new process was invented [3][4]. This process involved using a blast furnace to reduce the iron ore and was able to reach high enough temperatures for the iron to melt and dissolve carbon [3]. This resulted in a product usually referred to as pig iron which is an iron alloy containing around 4 % carbon, making it too brittle to be effectively forged and used in tools [4]. At first this was solved by burning off most of the coal by forging it [5] and eventually by a process referred to as fining where coal was simply burned off in a finery hearth [3]. In the early 19th century, with the utilisation of coke rather than charcoal a blast furnace could produce around three to four tonnes of pig iron per day [4].

With the increased use of fossil coal rather than charcoal, the European steel market changed and “during the 19th century Europe’s iron production gradually switched to countries with ample resources of fossil coal” [5]. This has naturally had an impact on countries like Sweden which does not have significant resources of fossil coal.

1.1.1 Background of Hydrogen Production

Today, hydrogen gas is mostly used for chemical fertiliser production [6] which has been an important industry since it was invented in the early 1900s [7]. During this time, hydrogen was mostly produced using Alkaline Water Electrolysis (AWE) according to Björn Wickman, Associate Professor in chemical physics at Chalmers University of Technology, in a personal interview. For example, an entire hydroelectric power plant in Rjukan, Norway was used to power an AWE factory which supplied a chemical fertiliser factory with hydrogen. Later, in the 70’s steam reforming was invented and became much cheaper than electrolysis says Wickman, which has meant that for many years electrolyser technology has remained mostly undeveloped.

1.1.2 Background of Proton Exchange Membrane Electrolysis

The PEM technology began development in the 60’s by the company General Electric [8]. Before, AWE was the main electrolysis technology in the industry, but due to the possibilities with PEM electrolysers with a higher current density, highly dynamic operation as well as lower operating temperature, research began in the area [8]. PEM electrolysers consist of the expensive noble metals iridium and platinum for the catalyst, which gives it a higher cost than traditional AWE [8]. PEM electrolysers have similarities with the PEM fuel cell, such as using the same membrane. In a personal interview, Jan Froitzheim, professor at Energy and Materials at Chalmers University of Technology, said that there are companies that have recently converted their research from fuel cells to electrolysis due to the increased demand in green hydrogen.

1.2 Purpose of the Project

The aim of this project is to investigate the viability of green hydrogen as an alternative to fossil-based reductants of iron ore, used in the steel industry. Further, PEM electrolysis technology will be investigated as a key enabler for hydrogen production.

1.3 Limitations

The geographical boundary of this thesis will be the national borders of Sweden. This choice of boundary is applicable because of the fact that Sweden is a host for multiple companies that undergo projects that are engaged in the forefront globally. The abundance of green electricity from both hydro- and wind power in the northern part of the country, along with the presence of a well-established mining industry supports the choice of geographical boundary.

The evaluation of this thesis will mainly be based on comparing the current state of steelmaking with a future scenario, considering the best available technology for hydrogen production and direct reduction of iron ore, as of the year 2024. The in-depth technical part of this thesis will primarily revolve around the PEM method for hydrogen production. Further, a discussion will be carried out investigating the evolution of green hydrogen, trends over the years and future demands.

2

Method

This report is a study based on research from academic, governmental and industrial sources. As green hydrogen and green steel are areas that have been heavily researched recently, the companies developing the products are producing data that is constantly updated and somewhat withheld.

In this project, there were several important methods of information gathering. The main ones included a field study of research and an interview study involving academics and companies in the industry.

2.1 Field Study

The use of literature and reports from company research gives the project an important background to what research has already been done and what type of methods are already in use.

The collection of data in this report was gathered from a selection of published academic articles and reports from the industry found through digital searches from the databases found at Chalmers Library. Here, different search terms such as “Hydrogen Direct Reduction” and “Green Steel” gave us results that would be relevant to our field of study. Additionally, research from the companies in the industry and their websites has been used and reviewed.

The articles found through this method gave many results in the area, they were therefore sorted through to be able to filter away non-relevant articles and to use the relevant information to fit the purpose of the project.

2.2 Interviews with Academics and Industry Representatives

The project conducted interviews with academic institutions and companies in Sweden to get a larger perspective on the prospects of green steel and green hydrogen in the country. The choice of academic researchers to interview was made from relevant research of literature and their authors and through recommendations from earlier known contacts. The choice of companies to interview was made through research of which companies in Sweden are relevant in this area of business and through the first stage of the field study. Further, there were recommendations from the interviewees to interview other people that they knew to have competence in the field.

The interviews were conducted as face-to-face interviews, either in person or over a digital meeting platform with two or three interviewers where one took notes and the other conducted the questioning and discussion.

The questions were formulated individually for each recipient as the expertise can be different with each researcher or company representative. These questions were sent out in advance to provide the interviewees time to consider and formulate their answers. In Appendix 1, the questions asked from each interviewee are listed.

2.3 Experimental observation

To provide a deeper understanding of water electrolysis an experimental observation took place at IMS Chalmers 2D materials laboratory. The required preparatory work prior to the application of the catalyst on the substrate and the machines used in the process were shown. Later on, there was a demonstration on the assembling of the half cell as well as the half cell under operation. To further develop the understanding of PEM water electrolysis a study visit to Smoltek in Gothenburg took place where the full PEM cell was shown and explained.

3

Theory

3.1 Steel

Throughout the last century, global steel production has undergone a significant increase, starting from almost nothing in the early 1900s to becoming the cornerstone upon which modern society relies. According to the World Steel Association, the global steel production in January 2024 was 148 million tonnes of steel [9] which by approximation gives 1,8 billion tonnes over one year. This amount of steel produced annually, by weight, would roughly be similar to 180 thousand Eiffel towers a year [10]. Because of the large volume and the predicted increase of demand [11], the method of producing steel globally will have significant impact on the total emissions of green house gases.

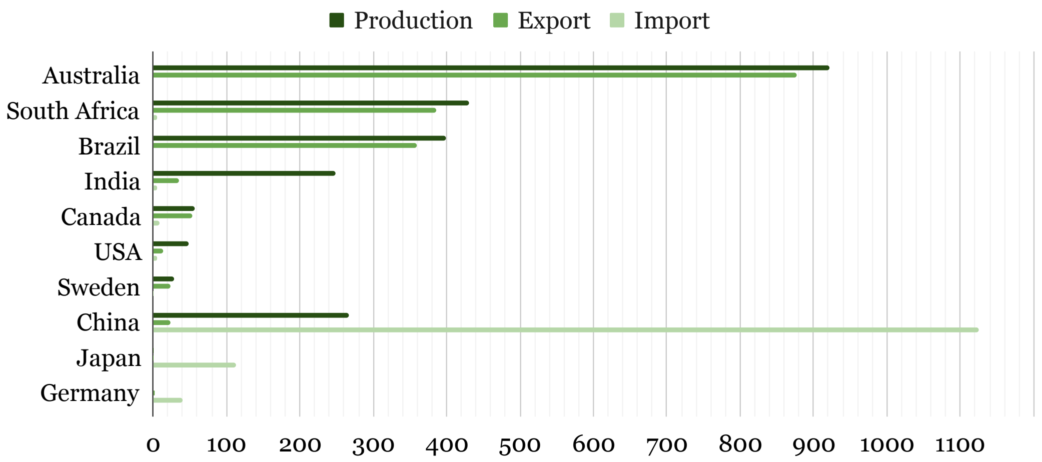

Figure 3.1: Weight per year presented in million tonnes of raw iron for ten countries. Figure by authors, data from [12].

What makes steel in such high demand globally is due to its versatility being formable as well as to keep a high strength and durability meeting ordinary and specific demands from different industry sectors such as vehicles, buildings and infrastructure for example.

As a material, steel is defined as an alloy of iron and carbon along with other additives. Depending on the proportions and the additives the steel has different names such as stainless steel for example. The chemistry of plain carbon steel is metallic iron atoms together with the smaller carbon atoms that find their place in the so-called interstitial spaces within the iron lattice [13].

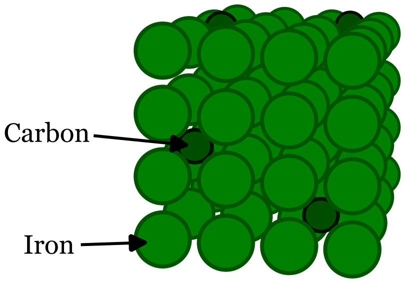

Figure 3.2: Carbon-steel, a solid solution of carbon and iron atoms.

The presence of carbon dissolved in the iron matrix affects properties such as strength because it interrupts the regular crystalline arrangement [13]. In the context of alloys, carbon is just one example of an additive used in ferro-steel making. Besides carbon, it is common to use chromium, nickel and manganese in steel making [13], all providing their unique characteristics contribute to a useful end product.

3.1.1 The Manufacturing of Steel

The process of steel manufacturing can be divided into two main parts; the refining of metallic iron and the production of the steel as the end product. In the first part iron ore is reduced resulting in metallic iron. In the second part, metallic iron reacts under high heat with carbon as well as additives to achieve the desired steel product [14].

To date, the main route for steel making has been through reducing pellets by burning relatively cheap solid coke [14]. Burning solid coke has been a suitable approach from a process technical aspect reaching high temperature and keeping a low intensive long and even temperature profile. In blast furnace steel making, high temperature and stability during combustion has been essential and because fossil fuels being the most established fuels and able to meet these demands for a relatively low price, this has been the choice for the industry historically.

The Electric Arc Furnace (EAF) is an oven operating at 1600°C melting the Direct Reduced Iron (DRI) together with recycled steel called scrap steel and calcium carbonate to reduce impurities [15]. Compared to a blast furnace, this electric arc furnace is using electrodes made out of carbon and operates by electricity. When an electric current is passed through the electrodes, intense heat is generated raising the temperature high above the melting point of the scrap steel enabling a quick melting process. Since scrap steel chemically already is the desired product, it does not need to be purified as the DRI would. Therefore, recycling of steel and using it in the process is beneficial for both the environment and the steelmakers [16].

According to the U.S. Geological Survey, the average global iron content in iron ore is 66 % [17]. The requirement of iron content in ore to be suitable for direct reduction is more than 66 % [15].

The carbon emissions throughout the whole steel-making process, are mostly linked to the reduction of iron ore whilst using coke or natural gas as reductant, or while burning fossil fuels in the traditional BF-BOF route.

3.2 Reduction of Iron Ore

The purpose of reducing iron ore is to remove oxygen to increase the portion of metallic iron in the compound. The reduced iron is called sponge iron due to its porous structure. To provide a picture of how porous the sponge iron is, it has less than half the density 3,5 g/cm^3 compared to pure iron at 7,8 g/cm^3 [18].

The term Direct Reduction (DR) is direct in the sense it bypasses the process of making pig iron by first melting the iron ore. In direct reduction, the iron ore is instead sintered into pellets and then reduced to a solid state.

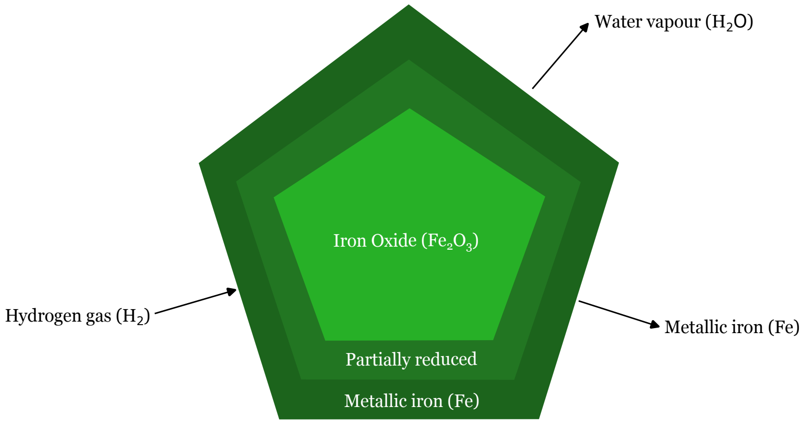

Figure 3.3: Gradual reduction of an iron oxide particle to metallic iron using hydrogen gas.

Historically, the concept of direct reduction was used as the main procedure because it being easier to handle the lower temperature then to actually melt the iron steel.

3.2.1 Reduction using Blast Furnace

The by far most common method of making steel is using the Blast Furnace - Basic Oxygen Furnace (BF-BOF) method. This method uses a blast furnace where solid coal in the form of coke is mixed with flux, such as limestone, and sintered iron ore. In the blast furnace, preheated air reacts with the coke to create the reducing gas carbon monoxide through the following reaction:

$$2\,\mathrm{C(s)} + \mathrm{O_2(g)} \longrightarrow 2\,\mathrm{CO(g)} \tag*{\{1\}}$$

This reaction is strongly exothermic releasing heat, melting the ore. As the ore is reduced and molten, some of the carbon is instead dissolved in the iron resulting in an iron alloy with a carbon content of around 4 % [3]. With a carbon content this high the alloy known as pig iron is brittle. The carbon content is reduced using a BOF where oxygen is pumped through the molten pig iron.

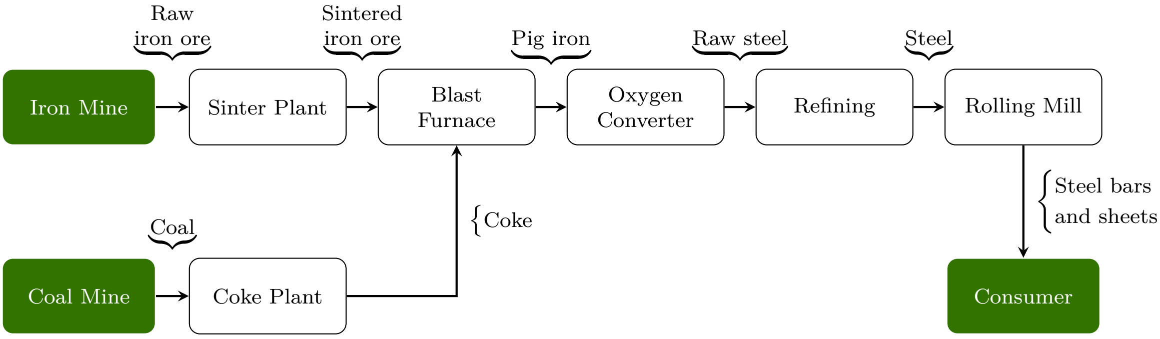

Figure 3.4: Production steps and material flows of steel production using BF-BOF.

3.2.2 Direct Reduction using Natural Gas

Direct reduction of iron ore using natural gas first has to be reformed to its two corresponding reducing agents: carbon monoxide and hydrogen gas [18]. One method of making this mixture of carbon monoxide and hydrogen gas would be through Steam Methane Reforming (SMR) [19].

$$\mathrm{CH_4} + \mathrm{H_2O} \longrightarrow 3\,\mathrm{H_2} + \mathrm{CO} \tag*{\{2\}}$$

In SMR, natural gas is reacting with water under a lot of heat and then forming a mixture of carbon monoxide and hydrogen gas as seen in equation (2) that then can be used for reduction of iron oxide.

The reactions below shows the overall reduction of iron oxide, assuming 100 % of hematite (Fe_2O_3) in the ore, using a mixture of carbon monoxide and hydrogen derived from natural gas [18].

$$2\,Fe_2O_3 + 6\,CO \longrightarrow 4\,Fe + 6\,CO_2 \qquad \{3\}$$

$$Fe_2O_3 + 3\,H_2 \longrightarrow 2\,Fe + 3\,H_2O \qquad \{4\}$$

The portion of reducing agents in the reducing gas mix differs between methods [18]. However, if taking into account the stoichiometry from SMR, per reformed methane molecule one gets three hydrogen gas molecules being able to each carry one oxygen molecule form the iron oxide. Also, per reformed methane molecule there is one carbon monoxide molecule being able to carry one oxygen atom. Ideally, this would result in the 75 % of all oxygen atoms leaving the DRI reactor having formed water while 25 % would be part of the carbon dioxide molecules.

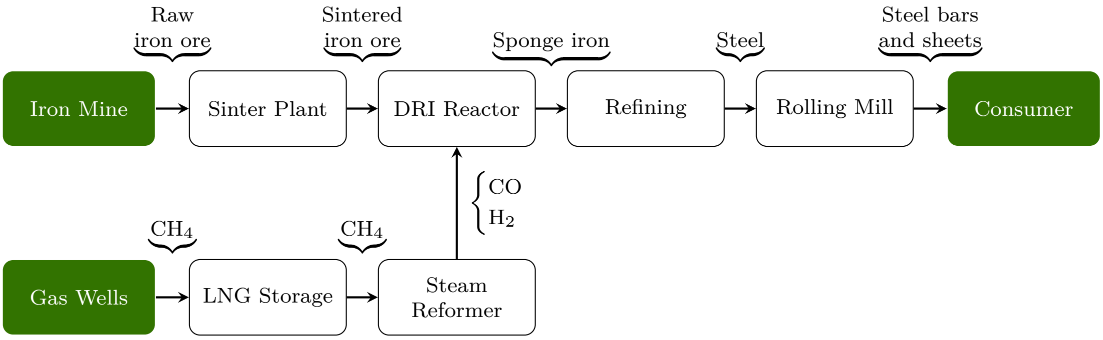

Figure 3.5: Production steps and material flows of steel production using methane DRI-EAF.

3.2.3 Direct Reduction using Hydrogen Gas

The process of using hydrogen as a reductant, according to the book Sponge Iron by Direct Reduction of Iron Ore, was first called the Circored method [18]. This was first investigated in 1995 through a research project by the European Coal and Steel Community to try to solve process technical problems that had appeared within the gas-based DR processes [18]. This method of reducing iron oxide was proven successful and under the years 1999 to 2005, a plant in Trinidad was producing 0,5 million tonnes per year of hot-briquette iron with hydrogen as the reducing agent [20]. The process using hydrogen gas as the reductant is described in figure 3.6. The process below using renewable energy for electricity production is referred to as green steel production.

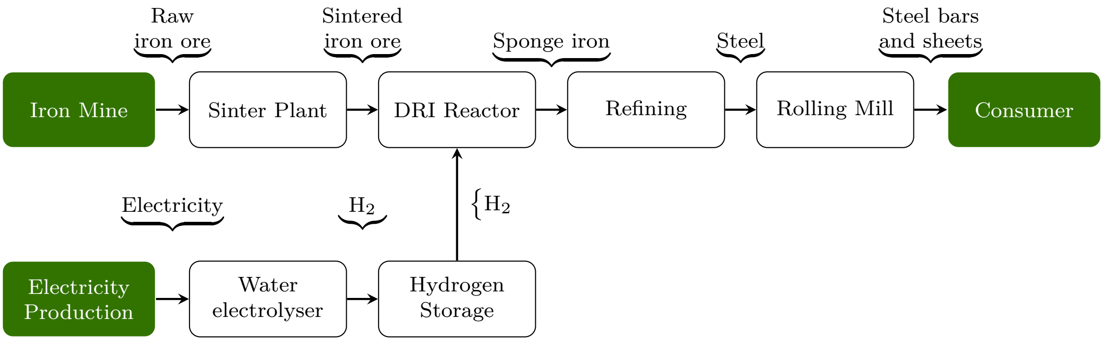

Figure 3.6: Production steps and material flows of steel production using H-DRI-EAF.

As described in section 3.2.2, hydrogen gas is a reducing agent forming water when reacted with iron oxide, leaving the iron oxide with less amount of oxygen in the lattice [21]. This process of using hydrogen gas produced with renewable electricity for reduction has proven successful in the Hybrit plant, producing green sponge iron [21]. Here follows the gradual reaction of the iron oxide hematite to metallic iron and water.

$$3\,Fe_2O_3 + H_2 \longrightarrow 2\,Fe_3O_4 + H_2O \tag{5}$$

$$Fe_3O_4 + H_2 \longrightarrow 3\,FeO + H_2O \tag{6}$$

$$FeO + H_2 \longrightarrow Fe + H_2O \tag{7}$$

3.3 Electricity

The Swedish electricity demand is a major topic of discussion as both the industry wants to develop and become more sustainable, while the electricity prices have never been as volatile [22].

3.3.1 Swedish energy market today

The energy market in Sweden is divided into four bidding zones. SE1 to SE4, going from north to south [22]. The two northern zones are producing electricity on a surplus of 51,5 TWh and the southern zones had a deficit of 26 TWh in 2021 [22]. Because of this, Sweden has a large transmission grid that can transport electricity from the north to the south when needed. Most of the electricity produced in Sweden is sold on the wholesale market Nord Pool Spot Power Exchange, where electricity retailers and industries with large electricity demand can buy electricity straight from producers [22].

In Sweden 2022 there was 179,3 TWh of electricity produced. Of the total produced, 69,8 TWh was produced from hydropower, 51,9 TWh from nuclear, and 33,2 TWh from windpower [23]. In total, there was 87,6 % from renewable and nuclear sources excluding imported electricity [23].

3.3.2 Industry demand

According to the Swedish multidisciplinary organisation of Forest, Mining, Chemistry and Steel (SKGS), the Swedish industry electricity demand is projected to increase by 72 TWh between 2023 and 2030 [24]. As the industries in Sweden are demanding more energy for the green transformation there is a considerable demand for reduced exports of the electricity from the northern regions to the south of Sweden [24]. The report from SKGS approximates the industries in the north will expand and switch to electricity as an energy source so that the production surplus of electricity in the electricity zones SE1 and SE2 will disappear [24].

As the statistics show from the Swedish Energy Agency, the use of electricity has decreased from 150,3 TWh in 2001 down to 136,8 TWh in 2022. This is the case as many industries and households have invested to more efficient systems to lower their energy use [25].

3.3.3 Price of Electricity

The state-owned energy company Vattenfall has their price for large customers in Sweden which can be assumed that the larger industries have in Sweden. The price of the transmission for the largest companies is 580 000 SEK in a yearly fee [26]. On top of that price for peak power transmission is 42 000 SEK MW/year in the northernmost region of Sweden where we have the largest mines and planned steel industries [26].

The electricity price depends if the company has a set price or if they pay the hourly price. The average electricity price for non-households in 2023 was 805,1 SEK/MWh [25]. This is just the average price for the year and differs depending on the energy supply and demand.

There is a tax reduction for large industries in sectors with high electricity demand which is set at 6,0 SEK/MWh [27]. The normal household in Sweden pays 428,0 SEK/MWh in tax for the electricity. Private households also pay value added tax (VAT) for the electricity consumed on the hourly price which is 25 % extra [27].

3.4 Current projects

There are several projects in the world that investigates the possibility to utilise hydrogen gas as a reductant in steel making. In this thesis, the focus will be on the two largest Swedish projects: Hybrit and H2 Green Steel, both based in the northern region and planning to be entirely green [28].

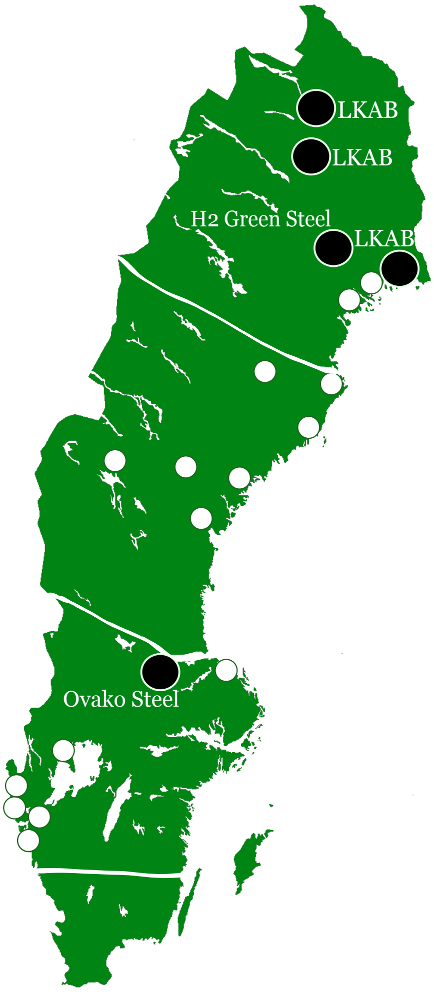

Figure 3.7: Planned electrolysers in Sweden where black indicates steel industries and white indicates other industries. Figure by authors, data from [29].

Hydrogen gas is a growing market and the gas may come to be vital for several industries in the future. In figure 3.7 one can see planned electrolysers. The black dots indicate planned electrolysers for companies within the steel industry.

3.4.1 HYBRIT

Hybrit is a cooperation between SSAB, LKAB and Vattenfall, which all contribute with vital parts for a fossil-free steel industry. Currently, a pilot facility is in use, it includes both direct reduction of iron ore as well as an electrolyser [30]. The direct reduction relies on old techniques which utilise natural gas. The facility has been able to produce one tonne of iron ore per hour under operating periods. Hydrogen storage has been built in connection with the pilot plant through pipelines [31], which enables fluctuating production. When the electricity is expensive, the stored hydrogen can be used and when the electricity is cheap one can maximise the hydrogen production.

Traditionally the iron ore pellets are made by using fossil fuels, in a straight-grate process [32]. However, when striving for a fossil-free process this was considered not sustainable. Hence, an alternative fuel had to be considered. LKAB with Hybrit created a pilot plant, where a few changes had been made from the original plant [32]. According to the company, several different fuels are investigated, but the biggest test currently uses bio oil [32]. Another fuel that is of interest is a combination of hydrogen and plasma, which would not generate carbon dioxide, though the testing of this is limited at the moment [32].

The pilot project has been considered successful so moving forward a demonstration facility will be built and it is expected to be in use in 2026 [33]. According to Hybrit the facility will include electrolysis as well as direct reduction. Hydrogen storage is not expected but can be of interest in the future. The demonstration plant is expected to demonstrate industry-scale production. LKAB has been accepted a loan for 3,7 billion SEK for the implement of green steel on an industry scale [34]. LKAB is supposed to produce the sponge iron, which is then transported to SSAB who produce the steel. Vattenfall provides the renewable electricity that is needed in both the electrolysis and the electric arc furnace. In 2026, SSAB's blast furnace in Oxelösund is expected to be converted to an electric arc furnace [35].

3.4.2 H2 Green Steel

H2 Green Steel is a Swedish company based in Stockholm that has projects worldwide acting at the forefront of making steel and hydrogen based on renewable energy. In a personal interview with H2 Green Steel, they explained about building a steelmaking facility where they are planning to begin their process by direct reduction of iron ore using hydrogen gas. The hydrogen gas for direct reduction will be produced on their site from renewable energy, mostly based on nearby hydro-power.

According to the European Investment Bank, H2 Green Steel's plan is to produce 2,5 million tonnes of steel through direct reduction per year along with recycling of steel using an EAF [36]. The electrolyser plant is planned to be around 700 MW [36], 740 MW according to H2 Green Steel. The environmental permit is given for production as well as for an expansion of the process in the near future for integrated production of 5 million tonnes of steel per year [36] which resonates with the aim of H2 Green Steel planning to produce 5 million tonnes of steel by 2030.

Further in the in the interview with H2 Green Steel, they said that the electrolysers planned for the production site in Boden mainly will be AWE because of it being the most cost-effective due to the conditions in Boden. Besides AWE, they are also planning for other electrolysis such as PEM electrolysis and high-temperature Solid Oxide Electrolysis Cell (SOEC) for their ability to efficiently balance the process due to more direct operational characteristics.

3.5 Green Hydrogen through Electrolysis

There are several methods of producing hydrogen gas available today, using different energy sources, renewable or not, and with variations in production performance. The overall most used method as of now is steam reforming of fossil methane gas, which is commonly used in industries such as the petrochemical industry, fertiliser production or fuel cell systems [8].

Another way of producing hydrogen without using fossil fuels is through water electrolysis. If using renewable electricity it would result in green hydrogen, and if using SMR it would result in grey hydrogen [37]. This may give a higher purity of the produced hydrogen gas and emit less environmentally harmful gases such as carbon dioxide from the production [8]. Other types of water electrolysis methods are for example AWE which occurs in an alkaline environment, SOEC that is distinguished by its high temperature between 500-700 °C and PEM electrolysis which has a highly acidic environment and a proton conducting membrane between the electrodes [8].

The water electrolysis technique is generally based on the splitting of water into oxygen and hydrogen gas using a direct current [8]. The overall reaction is,

$$\mathrm{H_2O\,(l)} \longrightarrow \mathrm{H_2\,(g)} + \frac{1}{2}\,\mathrm{O_2\,(g)} \tag*{\{8\}}$$

This reaction occurs in an electrolytic cell, which is an electrochemical cell where the half reactions do not occur spontaneously, but are driven by an external current [38]. This could be explained as the "opposite" of a galvanic cell, which is an electrochemical cell where an electric current is produced due to a spontaneous reaction occurring in the cell [38]. The cell consists of two electrodes, inert metallic conductors, that do not themselves take part in the reaction. However, they can act as catalysts [38]. The electrode where the reduction half-reaction occurs is called the anode. At the other electrode, the cathode, oxidation occurs [38].

There are different types of electrolysis methods to produce hydrogen, but the main idea is similar. There are two half reactions occurring in the cell that together result in the overall reaction. There is the hydrogen evolution reaction (HER) occurring at the cathode in either alkaline (reaction 9) or acidic (reaction 10) conditions [8].

$$2\,\mathrm{H_2O} + 2\,\mathrm{e^-} \longrightarrow \mathrm{H_2} + 2\,\mathrm{OH^-} \tag*{\{9\}}$$

$$2\,\mathrm{H^+} + 2\,\mathrm{e^-} \longrightarrow \mathrm{H_2} \tag*{\{10\}}$$

On the anode side, the Oxygen Evolution Reaction (OER) occurs, and for an alkaline (reaction 11) compared to an acidic (reaction 12) environment, the reaction looks like the following [8].

$$2\,OH^- \longrightarrow H_2O + \frac{1}{2}\,O_2 + 2\,e^- \qquad \{11\}$$

$$H_2O \longrightarrow 2\,H^+ + \frac{1}{2}\,O_2 + 2\,e^- \qquad \{12\}$$

3.5.1 Proton Exchange Membrane Electrolysis

The PEM electrolysis method for hydrogen production occurs by letting a flow of highly pure water enter the anode side of the cell, where it is split into oxygen gas and protons [8]. The protons travel over a solid polysulfonated membrane to the cathode side, where they acquire electrons and form hydrogen gas, and the hydrogen stream is passed on for either storage or direct use [8].

PEM electrolysis, compared to other water electrolysis methods has the advantage that it is dynamic in the sense that it is possible to turn the unit on and off quickly [8]. This might be favorable in areas where the price of electricity fluctuate since it is possible to pause production when prices are high. It also operates at lower temperatures ($<80°C$) and has the advantage of a high current density. However, PEM electrolysis also has some disadvantages such as the high cost of the anode electrocatalyst made out of iridium [8].

The reactions that occur in a PEM electrolysis cell are the following [8];
OER in acidic conditions,

$$H_2O \longrightarrow 2\,H^+ + \frac{1}{2}\,O_2 + 2\,e^- \qquad \{13\}$$

and HER in acidic conditions,

$$2\,H^+ + 2\,e^- \longrightarrow H_2 \qquad \{14\}$$

This means, that for PEM electrolysis, 1 mole of water gives 1 mole of hydrogen gas. With water having a molar mass of 18,015 g/mol and hydrogen gas having a molar mass of 2,016 g/mol, this would ideally result in 1 kg of hydrogen gas from 9 kg of water.

System description

The PEM electrolysis cell has two electrodes, often coated on each side of a proton exchange membrane, where the anode is usually made of platinum with carbon and the cathode of iridium oxide [8]. The water enters on the cathode side where it is distributed by a porous transport layer and onto the anode material. There, the OER occurs. The protons from the OER travel through the proton-conducting membrane to the cathode side where the HER occurs. The hydrogen gas is then purged out with nitrogen gas to keep balance in the cell, this according to representatives from Smoltek. The external current that is needed to initiate the OER reaction is distributed through the bipolar plates [39].

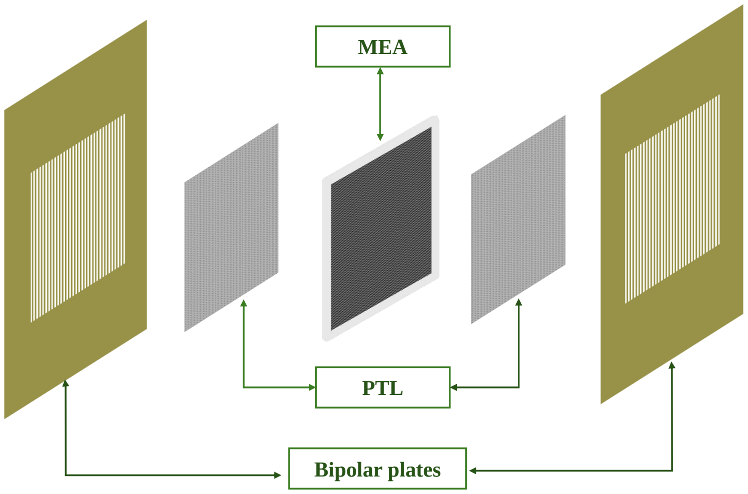

Figure 3.8: Schematic picture of main components in a PEM electrolysis cell.

The main parts that distinguish the PEM electrolysis cell are the Membrane Electrode Assemblies (MEA), the Porous Transport Layer (PTL), and the bipolar plates [8]. These are tightly pressed together using bolts to form a single cell. The MEA's consist of the proton exchange membrane and the electrocatalysts with the cathode and anode material often directly attached on each side of the membrane [8]. The membrane is where the protons formed in the OER travel to the cathode side where they combine to form hydrogen gas through the HER. Therefore, the membrane needs a high proton conductivity, as well as a high durability to handle high current densities. The anode side is often a coating of the membrane with around 2 mg/cm^2 IrO_2 whereas the cathode side is a coating of 0,5-1 mg/cm^2 Pt/C. The membrane is a type of polymer that fulfills these demands [8]. The PTL is responsible for better use of the catalyst layer and distributes the gases that are formed to avoid bubbles that can lead to further mass-transport over potentials [8]. The bipolar plates acts as separators of single cells in a stack and conducts the heat and current between the cells in the stack [40]. They are often made out of titanium [40].

Operating conditions

One of the main issues with PEM electrolysis is the demand for the OER to occur. According to Björn Wickman, Associate Professor at Chemical Physics at Chalmers University of Technology, in a personal interview, there are requirements on the electrocatalyst material to sustain the highly acidic environment, as well as a need for a high voltage for the OER, leading to high costs on both aspects. Therefore, the importance of optimising both the catalyst material and the operating conditions to keep the over potentials as low as possible becomes apparent.

For water to split electrochemically (i.e. inducing the OER), an activation energy is required since the reaction is not spontaneous. The Gibbs free energy of the OER reaction is 237,22 kJ/mol [8]. The equation that describes the Open Circuit Voltage (OCV) for the cell, meaning the maximum voltage through the cell with no load, is given by [41],

$$E_{ocv} = \frac{-\Delta G}{n \cdot F} \tag{3.1}$$

with n being the number of electrons involved in the OER, which from reaction 12 is given as $2e^{-}$, and F is Faradays constant. Which gives a OCV of approximately 1,23 V. However, this is not the minimum voltage that needs to be supplied to the cell for the OER to occur. It turns out there are several losses in voltage throughout the cell [41].

Activation losses

The exchange current density for the anode and cathode respectively play a part in the overall activation voltage, so does the temperature [39]. The activation over potential can be seen as the potential from the equilibrium potential, needed to overcome the activation energy for the reaction. In the following equation, j denotes either cathode or anode. $i_{0,j}$ is the exchange current density for either the anode or the cathode side, which determines the electrochemical rate at equilibrium. The exchange current density is greater for the cathode compared to the anode [39]. i is the current density, which often lies around 1 A/cm^2 however this does vary [39]. R is the ideal gas constant, F is Faradays constant and T is the cell temperature.

$$V_{act,j} = \frac{R \cdot T}{F} \cdot \sinh^{-1} \cdot \frac{i}{2 \cdot i_{0,j}} \tag{3.2}$$

Ohmic losses

PEM electrolysers are sometimes demanded to run at higher current densities, as much as 2-6 A/cm^2, which leads to high ohmic losses due to proton transport over the membrane [41]. There is a linear dependence of ohmic losses over the membrane and current density. This loss can be described by Ohms law, where R_{cell} is the overall resistance of the whole cell (anode, cathode and membrane resistance), I is the current and V_{ohm} is the over potential due to ohmic losses [41].

$$V_{ohm} = I \cdot R_{cell} \tag{3.3}$$

Mass transport losses

Losses due to mass transport mainly occur due to small pore sizes in the diffusion layers, which can be described using Fick's law of diffusion [41]. The voltage drop from mass transport losses can be estimated from the Nernst equation (equation 3.4), individually on the anode vs cathode side [41]. In equation 3.4, $C_{X,mem}$ denotes either the oxygen or hydrogen concentration at the membrane-electrode area. $C_{X,mem,0}$ denotes these concentrations at standard conditions [41].

$$V_{tran} = \frac{R \cdot T}{2 \cdot F} \cdot \ln \frac{C_{X,mem}}{C_{X,mem,0}} \tag{3.4}$$

Other operating conditions that can be modified are temperature, pressures, membrane thickness and proton conductivity through the membrane [39].

Open Circuit Voltage

As shown by equation 3.1, the OCV for the OER is 1,23V. However, when accounting for the overpotentials (η) in the cell, the total cell voltage is described by equation 3.5 [41],

$$V_{total} = E_{ocv} + V_{act} + V_{ohm} + V_{trans} \tag{3.5}$$

As a way to show how the cell voltage varies with the current density for the PEM cell, a polarisation curve was made. From figure 3.9, it can be seen that when the applied voltage were increased, the current density also were increased. This polarisation curve were inspired by the results of an experiment using a Smoltek anode and the process of this is described in section 4.1.

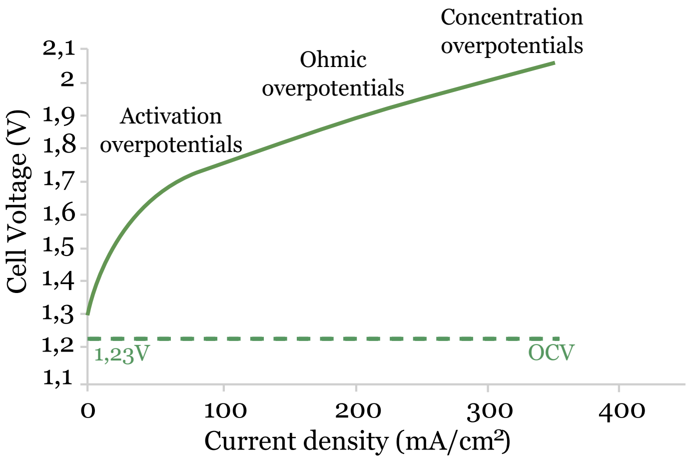

Figure 3.9: Typical polarisation curve for a PEM electrolysis cell.

Materials

In the PEM electrolysis, a solid electrolyte separates the cathode and the anode, currently the technique uses a membrane that consists of Nafion™ [42]. The membrane has a thickness of about 0,2 mm [43]. Nafion™ has proven to be an effective conductor of protons and at the same time being able to block out any anions to pass through [44]. Nafion™ is a perfluorinated sulfonic acid ionomer [45] and is therefore classified as a Per- and Polyfluoroalkyl Substance (PFAS) [46]. In the PEM water electrolysis, ultrapure water is required. In the interview with Björn Wickman, he explained that the reason for that is because the membrane is sensitive to compounds of metal ions. The ions can get lodged in the channels in the membrane, which would decrease the lifetime.

The anode is made of iridium oxide whereas the cathode consists of particles of platinum coated on carbon black [43]. Currently, the iridium loading varies between 1-2,5 g/kW [43]. In connection to each electrode there is a PTL consisting of sintered porous titanium, on the PTL on the anode side a layer of platinum is also required [43]. On the bipolar plates, the inflows and outflows are regulated in different pathways and these have a base of titanium [43]. However, the anode side has a platinum coating whereas the cathode side has a gold coating. Overall the PEM cell requires about 0,3 g/kW of gold [42] and 1 g/kW of platinum [43]. The framework and the sealing consists of different plastics that can manage the working conditions. Examples of these are polytetrafluoroethylene, polysulfone and ethylene tetrafluoroethylene [43].

The combination of a highly acidic environment and high current densities sets high demands on the catalyst. Wickamn mentioned that iridium is an effective catalyst and has a high resistance against corrosion. Furthermore, Björn Wickman explained that platinum may seem as an alternative catalyst but trouble arises in its oxidised state, where the activity is decreased. Gold has good resistance against corrosion, however low activity and hence is not an effective catalyst.

4

Results & Discussion

4.1 Proton Exchange Membrane electrolyser assembly with Smoltek

The authors of this thesis got the opportunity to observe a half-cell demonstration at Chalmers IMS-Chalmers 2D materials laboratory. In a addition to a study visit to Smoltek Hydrogen where the authors observed a full PEM cell in use.

4.1.1 Half-cell test of electrode developed at Smoltek for Oxygen Evolution Reaction

The catalysts developed for electrolysers are usually tested in laboratories as half-cell reactions in various types of electrolytes. Together with Smoltek personnel, a technical observation was conducted for one of their already prepared catalyst materials seen in figure 4.1.

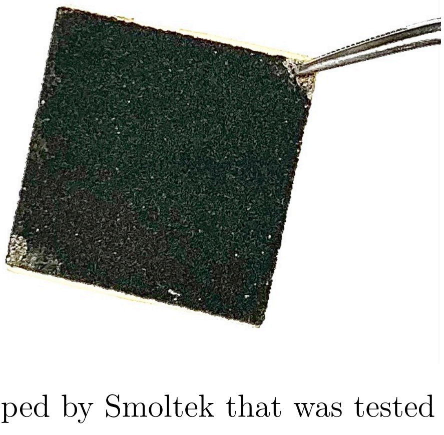

Figure 4.1: Electrode developed by Smoltek that was tested for oxygen evolution reaction.

A powerful and common electrochemical technique used to investigate the reduction and oxidation processes of molecular species is Cyclic Voltammetry (CV). A type of OER catalyst developed as a Porous Transport Electrode (PTE) by Smoltek Hydrogen was demonstrated in the half-cell reaction in 0,5 M of sulfuric acid, shown in figure 4.2.

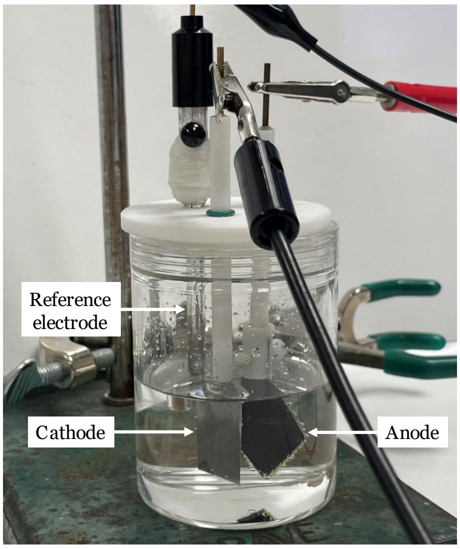

Figure 4.2: Half-cell test of the electrode at IMS-Chalmers 2D materials laboratory.

The measurement was performed at the 2D materials lab in IMS-Chalmers, using a three-electrode setup involving platinum as the counter electrode, PTE with iridium as the working electrode, and an Ag/AgCl reference electrode. During the electrolysis of water, oxygen bubbles were seen evolving on the PTE and hydrogen bubbles were observed on the counter electrode, figure 4.3

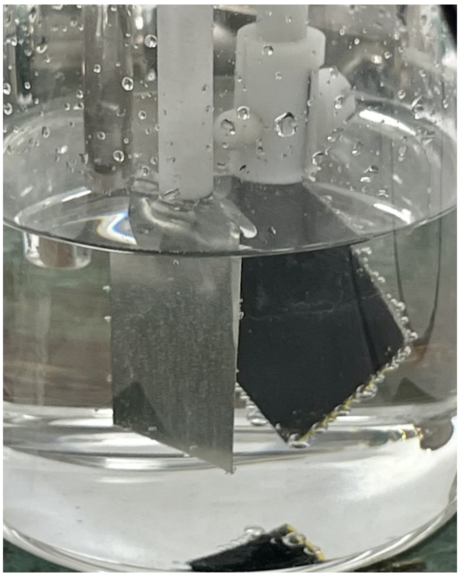

Figure 4.3: Produced hydrogen on the left electrode and oxygen on the right electrode

The catalytic performance of IrOx coated anode (0,2 mg/cm^2) was estimated by a linear scan voltammetry test, seen in figure 4.4. The iridium-based catalyst made by Smoltek exhibited stable OER performance with relatively low over potential of $\eta_{OER} = 260\,\text{mV}$ at the current density of 10 mA/cm^2. The OER behaviour is comparable with other commercial IrOx anode with higher iridium loading (1-2 mg/cm^2).

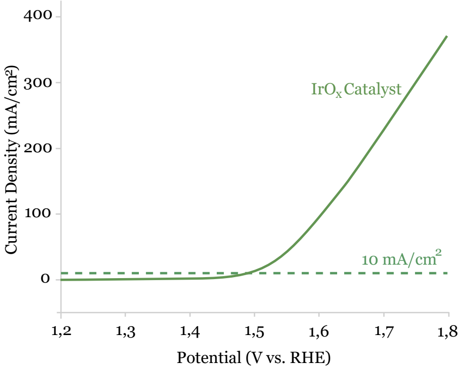

Figure 4.4: Oxygen evolution reaction catalytic activity of IrOx.

4.1.2 PEM electrolyser demonstration at Smoltek Hydrogen

OER and HER individual reactions in water electrolysis, a demonstration of the of the full cell was enabled by Smoltek Hydrogen at their H2LAB. With an understanding of earlier mentioned OER and HER, the technical observation proceeded with investigation of the full electrolyser cell at Smoltek Hydrogen in Gothenburg. The components that form part of assembling a single cell PEM electrolyser can be seen in figure 4.5. This includes bipolar plates, gaskets, water flow channels, and bolts.

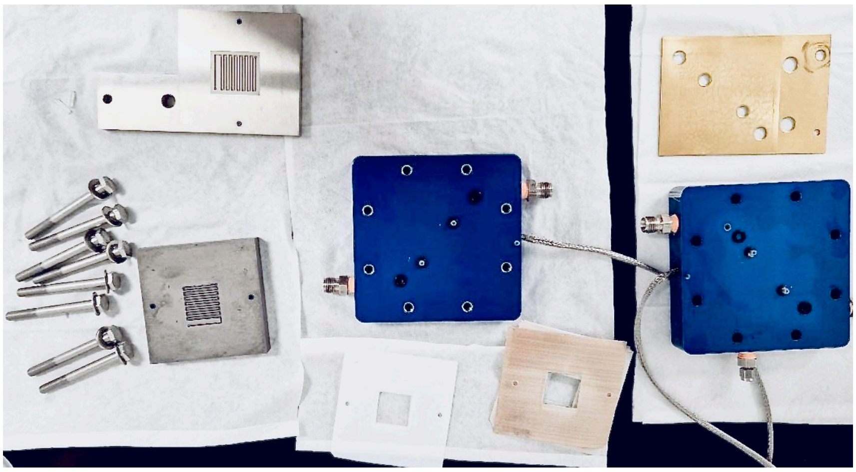

Figure 4.5: Components of a PEM water electrolyser single cell. Photo: Smoltek.

After preparing the MEA with the anode electrode, the ion exchange membrane and the cathode electrode, the PEM cell can be assembled as shown in figure 4.6.

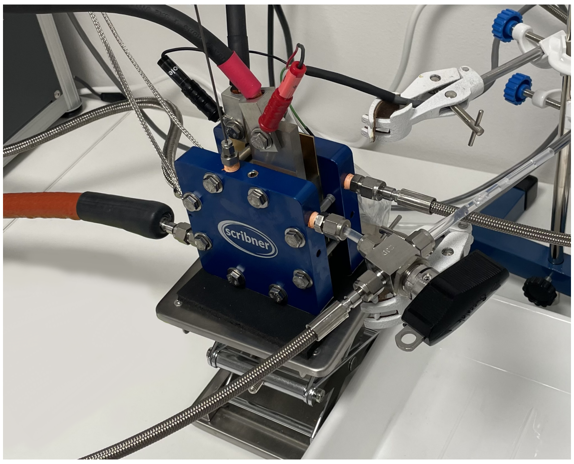

Figure 4.6: Proton exchange membrane water electrolyser under operation at Smoltek.

The membrane used for the PEM water electrolysis at Smoltek is Nafion™ because they offer high conductivity, reliability, and performance that current and future water electrolysis applications need. The ultra pure water was connected to the anode, while nitrogen gas was linked to the cathode for the cell testing.

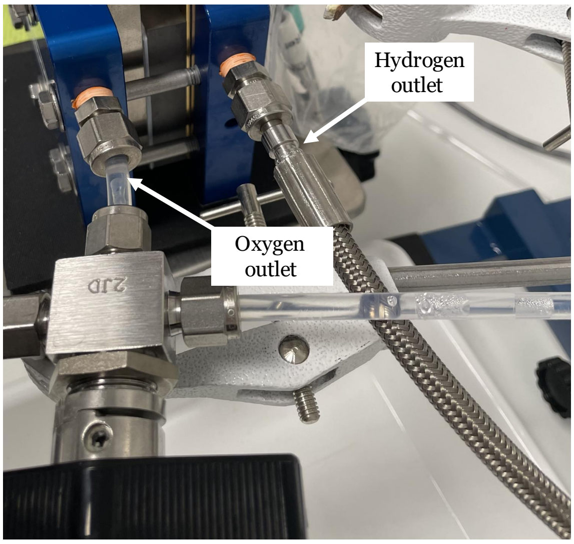

Figure 4.7: Produced hydrogen gas outlet and oxygen gas outlet.

The bubbles seen on the tubes connected to the anode show the result of oxygen evolution from the water splitting using the iridium-based anode catalyst, figure 4.7. The operation of the electrolyser along with testing conditions and parameters were explained by personnel from Smoltek.

4.2 Environmental Impact of Direct Reduction in Steel Making

As presented in section 3.2, the currently established way of making steel is through reduction using steam-reformed methane. In order for it to be worthwhile to research and implement a new technique and replace a method that is already working well, there has to be a cause. The cause for implementing green hydrogen in the steel industry is the environmental benefits, namely the reduction of CO_2 emissions.

Looking at reactions 3 and 4 in section 3.2.2, it is apparent that 1 mole of CH_4 steam reformed into 3 moles of H_2 and 1 mole CO gives 2,67 moles of Fe in total. In the ideal case, that is. Looking at reaction 3, it is also apparent that for every 1 mole of CO and therefore for every 1 mole of CH_4 there will be produced 1 mole of CO_2 assuming a 100 percent. Converting this to a mass basis, 0,01604 kg CH_4 per mole and 0,04401 kg CO_2 per mole, the value for kg CO_2 per kg becomes 2,744 kg CO_2/kg CH_4 used.

$$240\,\text{kg CH}_4/\text{tonne DRI} \cdot 2{,}744\,\text{kg CO}_2/\text{kg CH}_4 = 0{,}66\,\text{tonne CO}_2/\text{tonne DRI}$$

If instead looking at DRI using only H_2 for reduction, no CO_2 is produced in the reduction step according to reactions 5-7. And by the definition of "Green Hydrogen", the hydrogen gas is produced using renewable, non-fossil, energies which results in green steel, with substantially lower CO_2 emissions. Since the steel industry accounts for approximately 8 % of the global CO_2 emissions [47], this decrease in CO_2 emission by using green hydrogen would have a large impact on the global environment goals.

According to SSAB, the company reduces around 3,8 million tonnes of iron ore per year [48]. This is reduced using a blast furnace and according to section 4.3, 1,87 tonnes of CO_2 is released per tonne of steel produced. This means that over the span of a year, an estimate of 7,11 million tonnes of CO_2 is released from SSAB's reduction process. If the same amount would have been reduced using natural gas (which is not the case in Sweden), 2,51 million tonnes of CO_2 would be released per year, assuming the emissions are 0,66 CO_2 per tonne of DRI for natural gas. If reducing iron ore using green hydrogen, no CO_2 would be released during the reduction reaction if looking at the reactions 5-7.

4.3 Economy of Green Steel Production

To attain a comprehensive understanding of the viability of green steel and PEM as an electrolysis method it is important to analyse from an economical perspective.

For the currency conversion the following data have been used:

$$1\,\text{USD} = 10,88\,\text{SEK}$$

$$1\,\text{CNY} = 1,50\,\text{SEK}$$

$$1\,\text{EUR} = 11,65\,\text{SEK}$$

4.3.1 Electricity cost

To approximate an electricity price, a company that needs a peak power rating of 100 MW and uses an average of about 60 % of that peak power during the year can be considered. This gives us the possibility to calculate an average cost per MWh from the information found in section 3.3.3.

$$100\text{ MW} \cdot 24\text{ h} \cdot 365\text{ days} \cdot 0.6 = 525\,600\text{ MWh}$$

$$100\text{ MW} \cdot 42\,000\text{ SEK/MWh} = 4\,200\,000\text{ SEK}$$

$$\frac{(526\text{ GWh} \cdot (6 + 805)\text{ SEK/MWh}) + 0,58\text{ MSEK} + 4,2\text{ MSEK}}{525\,600\text{ MWh}} = 820,2\text{ SEK/MWh}$$

This is an approximation of the average price of electricity where Sweden has 58,6 percent renewable energy and to have green hydrogen the electricity would have to be 100 percent renewable. The calculations above have not taken in account the price for having only renewable electricity for the production of the hydrogen, as it would have to be for green hydrogen. Also the companies negotiate their own energy prices with the producers and this price is not made available to the public.

4.3.2 Price of Green Hydrogen gas produced with Proton Exchange Membrane electrolyser

The cost of the membrane with a thickness of 0,18 mm can be estimated to 2959,39 SEK/kW under the presumption that at least 50 000 membranes are produced yearly [49]. PTLs consisting of titanium cost about 3551,23 SEK/kW [49]. The prices for the noble metals fluctuate, however, the price for gold, iridium and platinum was 830,25 SEK/gram [50], 1693,04 SEK/gram [51] and 338,37 SEK/gram [52] for respective metal on the sixteenth of April in 2024 . Overall the PEM cell requires about 0,3 g/kW of gold [42] and 1 g/kW of platinum [43]. Currently, the iridium loading varies between 1-2,5 g/kW [43]. The price in SEK per kW then equals 249,08 for gold, 1693,04 for iridium and 338,37 for platinum. On the bipolar plate the the weight of titanium per active area is 0,99 g/cm^2 [53]. The price for raw titanium stands on 79 SEK/kg [54].

The following calculations provides an estimation of the price of hydrogen produced by a 100 MW facility.

The weight per active area can be used to calculate the price per kW for the titanium on the bipolar plates. On a active area of 0,1 m^2, PEM have a capacity of 0,67MW [42]

$$\frac{0,99\text{g/cm}^2}{0,67\text{kW/cm}^2} = 1,48\ \text{g/kW}$$

The price for the titanium on the two bipolar plates then equals:

$$1,48\text{g/kW} \cdot 0,079\ \text{SEK/g} \cdot 2 = 0,23\ \text{SEK/kW}$$

The price for the raw materials can be estimated in SEK per kW.

$$2959,39 + 3551,23 + 249,08 + 1693,04 + 0,23 = 8791,34\ \text{SEK/kW}$$

Which leads to the total capital costs for a 100 MW facility,

$$8791,34\ \text{SEK/kW} \cdot 100000\ \text{kW}\cdot = 879\,134\,000\ \text{SEK}$$

The PEM cells have reported lifetimes between 50 000 hours and 80 000 hours [43]. The following calculation has an optimistic approach in the sense that 80 000 hours were used.

$$\frac{879\,134\,000\ \text{SEK}}{80\,000\ \text{h}} = 10\,989,18\ \text{SEK/h}$$

The electrical efficiency for a PEM stack varies between 47 and 66 kWh/kgH$_2$ [43]. To get a estimation of the about of hydrogen that is possible to produce under one hour, 47 kWh/kgH$_2$ have been used.

$$\frac{100\,000\ \text{kW}}{47\ \text{kWh/kgH}_2} = 2127,66\ \text{kgH}_2\text{/h}$$

Stoichiometrically, one kilogram of produced hydrogen requires nine kilograms of water feed. The following calculation is regarding the price for the needed water per hour [43]. The operating cost of our PEM electrolysis includes both the price for the ultra-pure water and for the renewable electricity. The price of the ultra-pure water can be assumed to be 2,72 SEK/liter [55].

$$2127,66\ \mathrm{kgH_2/h} \cdot 9\ \mathrm{liter/kgH_2} \cdot 2,72\ \mathrm{SEK/liter} = 52\,085,11\ \mathrm{SEK/h}$$

$$820,2\ \mathrm{SEK/MWh} \cdot 100\ \mathrm{MW} = 82\,020\ \mathrm{SEK/h}$$

The total price for running the facility per hour then becomes:

$$52\,085,11 + 3174,53 + 82\,020,00 = 145\,094,29\ \mathrm{SEK/h}$$

Which leads to the price of hydrogen gas per kilogram:

$$\frac{145\,094,29\ \mathrm{SEK/h}}{2127,66\ \mathrm{kgH_2/h}} = 68,19\ \mathrm{SEK/kgH_2}$$

The reality differs from the theoretic value of nine kilograms of water for one kilogram of hydrogen gas since in reality an abundance of water is needed to maximise the efficiency of the cell. If one has the possibility to have a water purification service, the water price would presumably be lower. When calculating the hydrogen price, an optimistic approach has been chosen where a range of data could be chosen from.

The price of the bipolar plates differs a lot from reality since the price used is based on crude titanium and processed titanium more expensive. The bipolar plates is responsible for 53 % of the stack investment [43]. However, this also includes the gold and the platinum coating on the bipolar plate on the cathode side respectively on the anode side. The costs of the labour as well as the cheaper materials have been neglected in this analysis and they would presumably affect the results a little. Though one can get a hint of what the price would be if a facility as built now.

In large-scale PEM electrolysis units, the single cells described above are combined into stacks of cells. When upscaling the PEM units to the gigawatt scale that would be needed to cover the hydrogen demand for large industries, a few issues may occur. In smaller cells, the voltage losses due to mass transport are not big [41]. However, when a larger cell is to be built, the effects of mass transport becomes more relevant to study in terms of optimising the contact area with the catalyst. Since the price of iridium is high, the coating needs to be optimised for the large-scale units to be feasible [41].

4.3.3 Price Comparison of different Reduction Methods

The energy density of natural gas is 55 MJ/kg [56].

$$\frac{55\,\text{MJ/kg}}{3600\,\text{s}\cdot 1000} = 15{,}28\,\text{kWh/kg}$$

To reduce one tonne of iron it is needed approximately 300 Nm^3 of natural gas [18], and the density of natural gas is approximately 0,8 kg/Nm^3 [57]. This provides an equation for the mass needed for direct reduction of a tonne of iron:

$$300\,\text{Nm}^3 \cdot 0{,}8\,\text{kg/Nm}^3 = 240\,\text{kg/tonne DRI}$$

240 kg of natural gas is required to reduce one tonne of DRI. This times the energy density in kWh per kg of natural gas gives:

$$240\,\text{kg/tonne DRI} \cdot 15{,}28\,\text{kWh/kg} = 3667\,\text{kWh/tonne DRI}$$

Given that the price of natural gas being 1,1413 SEK/kWh [58], the cost of the natural gas needed to reduce one tonne of DRI is approximately 4185 SEK.

$$3667\,\text{kWh/tonne DRI} \cdot 1{,}1413\,\text{SEK/kWh} = 4185\,\text{SEK/tonne DRI}$$

Larger Swedish industries are part of the European Union Emissions Trading Scheme (EU-ETS) and are therefore not regulated by the Swedish carbon tax [59]. As of may 2024, the price for an EU-ETS credit is 72,01 EUR which is around 838,9 SEK [60].

Considering the cost of the amount of hydrogen needed for reduction of one tonne of DRI being 50 kgH_2/tonneDRI [61], along with the price of hydrogen produced through alkaline electrolysis being 43,7 SEK/kgH_2 [62] gives the price per tonne DRI as:

$$43{,}7\,\text{SEK/kg} \cdot 50\,\text{kg/tonne DRI} = 2185\,\text{SEK/tonne DRI}$$

According to the calculations in section 4.3.2 and the amount of hydrogen needed for the reduction of one tonne of DRI being 50 kgH_2/tonneDRI [61], the price of DRI using hydrogen produced by PEM elctrolysis is presented to be:

$$68{,}2\,\mathrm{SEK/kg} \cdot 50\,\mathrm{kg/tonne\ DRI} = 3410\,\mathrm{SEK/tonne\ DRI}$$

Table 4.1: Cost comparison of different DR methods.

	Cost of DR [SEK/tonne DRI]	Emissions [tonne CO2/tonne DRI]	Carbon tax [SEK/tonne]	Total [SEK/tonne DRI]
Natural gas	4185	0,66	838,9	4739
H_2 (AWE)	2185	0	0	2185
H_2 (PEM)	3410	0	0	3410

As shown in the table above, the hydrogen DRI solution seems to be the most viable solution compared to DRI utilizing natural gas in Sweden.

The price of green steel as a product of direct reduction by hydrogen gas and the operation of electric arc furnaces which are both reliant on renewable energy, will be highly dependent on the cost of the electricity. This will also be the case for DRI with the use of natural gas where the final price will be very dependent on the price of the natural gas.

An estimation of carbon emissions per tonne of steel produced by the most common blast furnace route is 1,87 tonnes of CO_2 per tonne of steel [62]. Multiplying this value by the price of the EU-ETS gives 1567 SEK per tonne of steel produced. Production of one mega-tonne of steel on yearly basis would, given these assumptions, lead to a cost of 1,57 billion SEK per year only in carbon taxes.

4.4 Benefits for Sweden using Green Hydrogen for Steel Production

Today 83 % of the iron ore produced in Sweden is exported [12]. According to LKAB 67 % of their iron ore is exported to Europe, 23 % to northern Africa and the Middle East, along with 10 % to the rest of the world including Turkey [2]. For Sweden this means a considerable amount of potential wealth is exported since the refining is done elsewhere. According to LKAB's annual sustainability report for 2021 [2], if LKAB began to produce reduced iron ore in the form of sponge iron, instead of selling iron ore pellets, their sales would "more than double". Additionally, LKAB states that this would decrease carbon emissions for them and their customers by roughly 35 million tons per year, around two-thirds of Sweden's entire carbon emissions.

4.5 Advantages of Location in Northern Sweden

When fossil coal is no longer required to make steel, there are once again new conditions for finding a good location for steel production. First and foremost very significant infrastructure is required to handle the huge amounts of iron ore and finished steel, and even better if the supply is local which makes supply chains more robust and transports cheaper. Furthermore, to supply with the reducing agent there either has to be a reliable supply of water and green electricity or green hydrogen where once again the better alternative would be if the hydrogen could be produced locally. In northern Sweden there is both a large supply of high purity iron that, as mentioned in section 4.4, is currently almost entirely exported, the purity is also important since DR requires a iron purity of around 67 % or higher [15]. Also northern Sweden produces large amounts of green electricity through hydro power which is mostly exported, as discussed in section 3.3. Since hydro power is stable and predictable it is also possible to produce hydrogen using AWE. This means that there is good access to both iron ore and green energy to produced hydrogen, making it a suitable location for this type of industry.

4.6 Current Production of Steel

With the imminent threat of global warming, an industry with as high carbon emissions as the steel industry will have alot of pressure to change it's methods reducing it's carbon emissions . So it is crucial for the industry's survival to change the processes that cause the most emissions. Hybrits demo facility, where the iron ore has been reduced by hydrogen, has been deemed successful enough for the company to commit to a bigger plant which will supposedly be able to produce sponge iron on an industrial scale. This being said the method of reducing iron ore by hydrogen is working. However one can argue that the steel that is produced is not entirely green, since the fuels that are used in the making of the iron ore pellets, causes carbon emissions [32].

In a personal interview with Björn Wickman he mentioned that both Hybrit and H2 Green Steel will utilise AWE. In an interview with a representative from H2 Green Steel, they said that PEM is interesting for them in other regions with different energy supplies than northern Sweden. However, they also mentioned that PEM electrolysis will be limited and will not be existing on the largest scales due to the necessity of iridium.

In the interview with H2 Green Steel, it was also said that the competition for iron ore is tough. According to H2 Green Steel, they have to ship iron ore from Brazil and the USA since they have yet to come up with an agreement with LKAB. The whole idea with green steel revolves around zero carbon emissions and if long transportation is needed, then one get large carbon emissions as a result. The electricity supply is of greatest importance in the regard of electrolysis and with Hybrit already secured a deal with Vattenfall, there is not much room for H2 Green Steel.

4.7 Politics and Regulations

The political spectrum varies around the world with countries having diverse governments, which makes it difficult globally to unite and develop common plans to tackle large problems such as climate change. Despite the differences in government types, the Paris Agreement was developed in 2016 and has provided the world with a common goal to achieve [1].

The development of a green hydrogen economy is seen as a significant contributor to achieving the climate goals set by the Paris Agreement [63]. This green hydrogen will need a shift in the energy system that we have in the world today, from a fossil fuel dependent to a renewable source system.

In Sweden, there is already a large part of renewable electricity produced but the demand will rise in the coming years. In 2022 wind power accounted for 18,5 % of the total electricity produced and is increasing every year [25]. The use of more volatile electricity production methods such as wind or solar could work well with PEM technology according to Jan Froitzheim professor at Chalmers in the interview with him. Because of this, there is a possibility to produce hydrogen when the electricity supply is high and the prices are low. This would need a possibility to store the hydrogen or use it in the industry at the time of production. Right now Sweden does not have any new large off-shore wind power, as the wind farm Lillgrund built in 2007 still is the largest farm with a capacity of 110 MW [64]. But the political landscape has changed and the government has now approved three larger farms and is now trying to approve more than ten other larger farms in the near future [65].

A possibility for green steel produced with H-DRI to be a viable solution compared to steel produced with fossil fuels is the carbon tax that we have implemented in Sweden today [59]. If the politicians decide to increase the tax to a level that would make the carbon emissions too expensive to release, the price of the fossil steel would likely surpass the price of the green steel. The problem as of now is that most of the larger industries are part of the European Union Emissions Trading Scheme (EU-ETS) market and are not subject to Swedish Carbon Tax [66]. As the price for an EU-ETS today is around 839,1 SEK/tonne [60], it is a lot lower than the price for the Swedish Carbon Tax credit which is 1326 [59]. In the case that either the price of the EU-ETS increases or the companies are made to pay the Swedish Carbon tax, green steel will probably be a viable solution to fossil-based steel. As mentioned in section 4.3.3 the BF-BOF reduction carbon emissions are high and could lead to even higher prices if the tax is increased to even higher levels.

Political support from governments in the form of subsidies could be a positive momentum for the green hydrogen industry. Such as the state aid project from the European Commission that will give subsidies to hydrogen development in member states of the project. In this case, Sweden was not one of them [67].

4.8 Market Analysis of Green Steel

Central to the transition to green industry in a world dominated by market economies is how new technologies fit into existing markets and the burgeoning markets that arise from a changing world. The market for steel is potentially one of the most mature markets in the world, existing since the Industrial Revolution began but with the advent of greater efforts to reduce carbon emissions it stands to change radically in the long term. Specifically, the decoupling of steel production from the market forces of fossil fuels changes both the underlying costs that define the break-even price of steel and the geographical incentives that have shaped it since its inception. Where the initial geographical incentives for steel production where in the vicinity of fuel/reducing agents and iron ore, the new incentives are instead in the vicinity of large-scale renewable energy for hydrogen production.

Sweden's place in the global steel market currently is that of a purveyor of low volume and high-quality product. This is a result of generally high quality of Swedish ore [17] and will not be affected by the transition to hydrogen reduction but it could still stand to affect the viability of Swedish-produced green steel. Because of the prevailing idea of Swedish steel as of high quality and exclusive in nature, Swedish companies may find it easier to market the green steel during the market juvenile stage where it will likely be used in high-end products. This combined with the previously stated fact that northern Sweden has access to large amounts of hydro power [68], means that the Swedish green steel industry stands to potentially benefit both from the motion of a realigning market and the shifting geographical incentives of new technologies.

An example of the potential of market realignment is that according to a representative of H2 Green Steel, companies have been willing to pay an extra cost of 20-30 percent for the fact the product is be produced using renewable energy and hydrogen gas as reductant. Among the companies listed was the Volvo group and during an interview with a representative from Volvo Construction Equipment it was made clear that the Volvo group aims to be a "technology leader" in regards to various renewable transitions, thereby motivating a higher value for green steel. Critically the representative from Volvo was clear that they did not believe that this kind of price increase was not a sustainable business model as fast adopters will almost certainly drive prices down to levels much closer to pre-transition values. This seems even more likely considering that innovations in hydrogen production like the reduction of iridium loaded on the PEM anode that are already on the cusp of lowering hydrogen cost considerably. In the end remains to be seen who will be the ultimate beneficiary of the volatility of this specific emerging market.

4.9 Societal Aspects

This project is fundamentally about making a change in society, electrifying the entire steel industry will consume very large amounts of electricity which at the moment is in high demand. This will lead to notably higher energy prices in all of Sweden, but particularly in areas close to the new industries. This is problematic because there is already a significant inequality when it comes to energy production in Sweden, where a disproportionately large part of the country's electricity is produced in the northern part, where only about a tenth of the population resides.

Expanding energy production might also cause problems since renewable energy sources such as wind turbines and solar parks take up large parcels of land. This could harm biodiversity and affect local communities primarily in northern Sweden.

Concerning Sweden, new industries also have the positive effect of creating new jobs and wealth for the local northern areas. However, with remote work being more socially acceptable, there could be some concern about a large fraction of the workforce not living in the specific region because of established convenience in the south.

Most climate initiatives that result in a higher cost seem to be of an increased risk with the fact that other things, more urgent might appear to change the game plan making countries, politicians and the general opinion change away from the longer sustainable perspective.

5

Future Outlook

One of the biggest challenges going forward for PEM electrolysis is becoming more economically profitable. To become a real competitor to the more commercially available alkaline electrolysis, the technique has to reduce the investment cost in several aspects. There are existing hopes for that in the future to make the expensive membrane thinner. Though this can make the cell less sturdy against the pressure and this could increase the gas permeability. If the hydrogen mixes with oxygen a lot of energy is released, so it is of greatest importance that the membrane can endure. There are concerns regarding the membrane because of its PFAS classification. However, in the interview with Björn Wickman, he said that a hydrocarbon based membrane is in testing and that it has shown promising results.

The most challenging material to replace is the iridium on the anode. Currently there is no other material that can handle the tough environment. One solution can be to instead of replacing the noble metal is to reduce the iridium load. This is something that is being tested at Smoltek. In an interview with representatives from the company we learned that they are testing the possibility to load the catalyst on a nano carbon fibre on the PTL. In contrast to the traditional way of applying the catalyst directly on the membrane. With the catalyst on an uneven surface might enable higher efficiency. If the project is later on deemed successful it would be a big breakthrough for PEM.

Currently PEM electrolysis uses several noble metals, which is also reflected in the price. In the future there is hope to replace the titanium with stainless steel and replace the gold with niobium [42]. The more economically profitable the method becomes the more attractive it will become to the market.

Iridium is one of the most scarce metals in the world and at the moment there is no recycling of the metal. Iridium is used in spark plugs in petrol driven cars. Under the assumption that the iridium in the spark plugs is intact enough to be recycled, this could possibly solve a part of the iridium problem. In the interview with Smoltek, they mentioned that 1 ton/year of iridium from spark plugs is thrown away.

Due to PEM electrolysis only existing as small scale electrolysers, the materials that are produced specifically for PEM are more expensive then they would be if larger volumes were produced. That is a problem for the market since the companies do not want to invest in something that is not profitable, but at the same time the producers can not lower the price if they can not sell it.

In Sweden, large investments have already been made which enables an outlook in an ideal case that this will be a successful shift towards a more environmental friendly industry sector.

Sweden has the benefits of a large amount of hydro-power in the energy mix already as well as locally produced high grade ore in the northern region. However the amount of this ore compared to the largest producers are limited and the energy market is an open system where participants affect each other. Taking into account the industry sector is a large contributor both to nations economy and the green house gases, a shift in this sector will have a significant impact on the nations total carbon emissions. The pressure the industry would put on the politics, enabling more renewable resources could lead to reduction in carbon emissions.

However, Sweden is a small country and regarding the iron ore reserves along with the steel production and the emissions of these on a global scale, it constitutes a mere faction. Taking this into account, the process of using renewable electricity and locally produced iron ore might be seen as an ideal situation. Sweden along with Australia that has an abundance of solar energy is said to have some of the most promising locations of utilising renewable energy in hydrogen production for the steel industry.

Because of the iron ore is transported far by sea, the constituents of iron ore is of importance in a future scenario where carbon taxes and carbon fuels might be more expensive. Iron ore constitutes of iron along with oxygen that is most just released taking up a large amount of the actual weight and space in the transports. Regarding this, the location of hydrogen based reduction plants close to the iron mine would be ideal whilst there is a lot of factors that would have to align for establishing this.

The technology of producing hydrogen gas by electrolyser is considered a mature while the main challenge as of date is the scale of things. Considering the characteristics of hydrogen being the smallest and most volatile of gases, there might be technical challenges considering dynamics while increasing the size of process equipment. With large scale electrolysers being established and the hydrogen more widely used in the market, both investment and operating cost are forecasted to decrease.

A key take away for the industry is the importance of making the move from the blast furnace route towards direct reduction of iron ore along with electric arc furnace. Using natural gas inhibits companies to provide the designation of “green steel” and maybe inhibits investors and initiatives to support the project. However, operating in a country with a large portion of renewable energy in the energy mix significantly reduces carbon emissions when using natural gas based DR along with EAF compared to the traditional BF-BOF method.

6

Conclusion

As a result of this study, it is shown that green hydrogen as a reductant for iron ore could be the future of the Swedish steel industry. There are companies that are already investing in the technologies to supply the growing market demand for green steel, as well as companies investing in researching and improving production methods. As renewable energy sources become more prevalent in the energy mix of steel-producing countries, along with supportive political regulations and having large scale electrolysers, producing green hydrogen for use in the steel industry might be a viable method.

The price of the reduction of steel in Sweden using the different methods is dependent on many factors including the price of the reducing agent, and the carbon taxation system in Sweden. In the case that the carbon tax is increased, hydrogen could have the economic potential to be the main reducing agent in the steel industry.

There is enough environmental cause to act as a driving force for the future development of the steel industry toward a more sustainable production. Since green steel saves approximately 0,66 tonne CO_2 per tonne DRI if hydrogen is used instead of natural gas and 1,87 tonne CO_2 per tonne DRI compared to blast furnace reduced steel, there is a large environmental benefit of the technology.

The PEM electrolyser technology is being researched and could become a future contender of green hydrogen production, if the coating of the iridium is reduced, as well as other expensive materials such as gold and titanium is replaced. The benefits of the dynamic PEM electrolyser can fit into a fluctuating electrical grid, optimising the hydrogen production.

Bibliography

[1] "The Paris Agreement | UNFCCC." [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement

[2] "LKAB Annual and Sustainability Report 2021 - LKAB." [Online]. Available: https://arsredovisning.lkab.com/2021-english/

[3] "Iron processing | Definition, History, Steps, Uses, & Facts | Britannica." [Online]. Available: https://www.britannica.com/technology/iron-processing

[4] "Blast furnace in earlier times - Jernkontoret." [Online]. Available: https://www.jernkontoret.se/en/the-steel-industry/the-history-of-swedish-steel-industry/blast-furnace-in-earlier-times/

[5] "The history of Swedish steel industry - Jernkontoret." [Online]. Available: https://www.jernkontoret.se/en/the-steel-industry/the-history-of-swedish-steel-industry/

[6] "hydrogen – Britannica Academic." [Online]. Available: https://academic.eb.com/levels/collegiate/article/hydrogen/110604

[7] "Fritz Haber – Britannica Academic." [Online]. Available: https://academic.eb.com/levels/collegiate/article/Fritz-Haber/38696

[8] S. Shiva Kumar and V. Himabindu, "Hydrogen production by PEM water electrolysis – A review," pp. 442–454, 12 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2589299119300035?fr=RR-2&ref=pdf_download&rr=872bb4654eaa92d3

[9] World Steel Association, "Crude steel production January 2024," 2024. [Online]. Available: https://worldsteel.org/media/press-releases/2024/january-2024-crude-steel-production/

[10] "Eiffel Tower | History, Height, & Facts | Britannica." [Online]. Available: https://www.britannica.com/topic/Eiffel-Tower-Paris-France

[11] I. Energy Agency, "Iron and Steel Technology Roadmap Towards more sustainable steelmaking Part of the Energy Technology Perspectives series," Tech. Rep. [Online]. Available: www.iea.org/t&c/

[12] "World Steel in Figures 2023 - worldsteel.org." [Online]. Available: https://worldsteel.org/data/world-steel-in-figures-2023/

[13] Donald R. Askeland and Wendelin J. Wright, *The science and engineering of materials si edition*, 7th ed. Boston: Cengage Learning, 2020.

[14] Jernkontoret, *Järn- och stålframställning*, Stockholm, 2004.

[15] A. Devlin, J. Kossen, H. Goldie-Jones, and A. Yang, "Global green hydrogen-based steel opportunities surrounding high quality renewable energy and iron ore deposits," *Nature Communications 2023 14:1*, vol. 14, no. 1, pp. 1–14, 5 2023. [Online]. Available: https://www.nature.com/articles/s41467-023-38123-2

[16] "Climate change policy paper - worldsteel.org." [Online]. Available: https://worldsteel.org/publications/policy-papers/climate-change-policy-paper/

[17] U. Geological Survey, "Mineral Commodity Summaries 2024," Tech. Rep., 2024. [Online]. Available: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024.pdf

[18] Amit Chatterjee, *Sponge Iron Production by Direct Reduction of Iron Oxide*, second edition ed. Delhi: PHI Learning Private Limited, 2012.

[19] "Hydrogen Production: Natural Gas Reforming | Department of Energy." [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

[20] "Relaunching a process that uses 100% H2 for the direct reduction of iron ore - Chemical Engineering | Page 1." [Online]. Available: https://www.chemengonline.com/direct-reduction-of-iron-ore/

[21] A. Zakeri, K. S. Coley, and L. Tafaghodi, "Hydrogen-Based Direct Reduction of Iron Oxides: A Review on the Influence of Impurities," *Sustainability 2023, Vol. 15, Page 13047*, vol. 15, no. 17, p. 13047, 8 2023. [Online]. Available: https://www.mdpi.com/2071-1050/15/17/13047/htmhttps://www.mdpi.com/2071-1050/15/17/13047

[22] P. Holmberg and T. P. Tangerås, "The Swedish electricity market – today and in the future," Riksbanken, Tech. Rep., 2023. [Online]. Available: https://www.riksbank.se/globalassets/media/rapporter/pov/artiklar/engelska/2023/230512/2023_1-the-swedish-electricity-market--today-and-in-the-future.pdf

[23] "Bruttotillförsel av el-energi, GWh efter produktionsslag och år. PxWeb," 2024. [Online]. Available: https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__EN__EN0105__EN0105A/ElProdAr/table/tableViewLayout1/

[24] "Industrins elbehov till 2030-en kartläggning," Profu, Tech. Rep., 4 2023. [Online]. Available: https://www.ikem.se/globalassets/media-ikem/bilder/rappotermaterial-120x170/industrins-elbehov-till-2030---en-kartlaggning.pdf

[25] "Tillförsel och användning av el 2001–2022 (GWh)," 2024. [Online]. Available: https://www.scb.se/hitta-statistik/statistik-efter-amne/energi/tillforsel-och-anvandning-av-energi/arlig-energistatistik-el-gas-och-fjarrvarme/pong/tabell-och-diagram/tillforsel-och-anvandning-av-el-20012022-gwh/

[26] "Regionnätstariffer 2024," Tech. Rep., 2024. [Online]. Available: https://www.vattenfalleldistribution.se/globalassets/vattenfalleldistribution/kund-i-elnatet/elnatspriser/elnatspriser-och-avtalsvillkor-foretag/regionnatstariffer-2024.pdf

[27] "Återbetalning av skatt på el och bränsle," 2024. [Online]. Available: https://skatteverket.se/foretag/skatterochavdrag/punktskatter/energiskatter/aterbetalningavskattpaelochbransle.4.109dcbe71721adafd252816.html

[28] "Hydrogen unleashed: Opportunities and challenges in the evolving H2-DRI-EAF pathway beyond 2024 | IEEFA." [Online]. Available: https://ieefa.org/resources/hydrogen-unleashed-opportunities-and-challenges-evolving-h2-dri-eaf-pathway-beyond-2024

[29] "Vätgasledningar en ny infrastruktur på framväxt | Luleå tekniska universitet." [Online]. Available: https://www.ltu.se/forskning/centrumbildningar-och-samarbeten/centre-for-hydrogen-energy-systems-sweden/vatgasledningar-en-ny-infrastruktur-pa-framvaxt

[30] "Direktreduktion med vätgas i pilotskala - HYBRIT." [Online]. Available: https://www.hybritdevelopment.se/en-fossilfri-utveckling/direktreduktion-med-vatgas-i-pilotskala/

[31] "Vätgaslagring - HYBRIT." [Online]. Available: https://www.hybritdevelopment.se/en-fossilfri-utveckling/vatgaslagring/

[32] "Fossilfri pelletsproduktion - HYBRIT." [Online]. Available: https://www.hybritdevelopment.se/en-fossilfri-utveckling/fossilfri-pelletsproduktion/

[33] "Direktreduktion med vätgas i demonstrationsskala - HYBRIT." [Online]. Available: https://www.hybritdevelopment.se/en-fossilfri-utveckling/direktreduktion-med-vatgas-i-demonstrationsskala/

[34] “HYBRIT: LKAB bygger demonstrationsanläggningen i Gällivare.” [Online]. Available: https://lkab.com/press/hybrit-lkab-blir-ansvarigt-for-bygget-av-demonstrationsanlaggningen-i-gallivare/

[35] “SSAB Time line for fossil-free steel production - SSAB.” [Online]. Available: https://www.ssab.com/en/company/sustainability/first-in-fossil-free-steel/timeline

[36] “Environmental and Social Data Sheet 1,” European Investment Bank, Tech. Rep., 2020. [Online]. Available: https://www.eib.org/attachments/registers/133208080.pdf

[37] National grid, “The hydrogen colour spectrum,” 2 2023. [Online]. Available: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum#:~:text=Green%20hydrogen%2C%20blue%20hydrogen%2C%20brown,between%20the%20types%20of%20hydrogen.

[38] P. Atkins, J. de Paula, and R. Friedman, *Physical Chemistry - Quanta, Matter and Change*, 2nd ed. Oxford University Press, 2014, vol. 1.

[39] S. Toghyani, S. Fakhradini, E. Afshari, E. Baniasadi, M. Y. Abdollahzadeh Jamalabadi, and M. Safdari Shadloo, “Optimization of operating parameters of a polymer exchange membrane electrolyzer,” *International Journal of Hydrogen Energy*, vol. 44, no. 13, pp. 6403–6414, 3 2019. [Online]. Available: https://www.researchgate.net/publication/331094885_Optimization_of_operating_parameters_of_a_polymer_exchange_membrane_electrolyzer

[40] S. Lædre, O. E. Kongstein, A. Oedegaard, H. Karoliussen, and F. Seland, “Materials for Proton Exchange Membrane water electrolyzer bipolar plates,” *International Journal of Hydrogen Energy*, vol. 42, no. 5, pp. 2713–2723, 2 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319916307613

[41] D. L. Fritz, J. Mergel, and D. Stolten, “PEM Electrolysis Simulation and Validation,” *ECS Transactions*, vol. 58, no. 19, pp. 1–9, 2 2014. [Online]. Available: https://iopscience.iop.org/article/10.1149/05819.0001ecst

[42] S. Krishnan, V. Koning, M. Theodorus de Groot, A. de Groot, P. G. Mendoza, M. Junginger, and G. J. Kramer, “Present and future cost of alkaline and PEM electrolyser stacks,” *International Journal of Hydrogen Energy*, vol. 48, no. 83, pp. 32 313–32 330, 10 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319923022590

[43] “GREEN HYDROGEN COST REDUCTION SCALING UP ELECTROLYSERS TO MEET THE 1.5°C CLIMATE GOAL H 2 O 2,”

2020. [Online]. Available: https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

[44] N. Yusoff, "Graphene–Polymer Modified Electrochemical Sensors," *Graphene-Based Electrochemical Sensors for Biomolecules*, pp. 155–186, 1 2019. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/B9780128153949000078

[45] Y. S. Kim and B. S. Pivovar, "Polymer Electrolyte Membranes for Direct Methanol Fuel Cells," *Advances in Fuel Cells*, vol. 1, pp. 187–234, 1 2007. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S1752301X07800093

[46] "PRIO - Kemikalieinspektionen." [Online]. Available: https://www.kemi.se/prioguiden/sok?hitsPerPage=20&UseAndOrOr=0&SortDirection=0&lastSearchType=advanced&tab=advancedSearch&SubstanceGroupIDs=%5B867%5D&PriorityLevelIds=%5B%5D&CriteriaIDs=%5B%5D&MatchCriteria=1&MatchSubstanceGroups=1&ProductTypeIDs=%5B%5D&MatchProductTypes=1&ReferenceIDs=%5B%5D&MatchReferences=1&MaterialIDs=%5B%5D&MatchMaterials=1&OrderBy=PriorityLevel_Id&Size=20&Paged=true&NameCASEg=nafion

[47] I. International Energy Agency, "CO 2 Emissions in 2023," Tech. Rep., 2023. [Online]. Available: https://www.iea.org/reports/co2-emissions-in-2023

[48] SSAB, "Sites all over the world," 2024. [Online]. Available: https://www.ssab.com/en/company/about-ssab/our-business/sites-all-over-the-world

[49] A. Mayyas, M. Ruth, B. Pivovar, G. Bender, and K. Wipke, "Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers," 2019. [Online]. Available: https://www.nrel.gov/docs/fy10osti/72740.pdf.

[50] "Live Gold Spot Price Chart | BullionVault." [Online]. Available: https://www.bullionvault.com/gold-price-chart.do

[51] "Iridiumpris just nu - Grundämnen.com." [Online]. Available: https://xn--grundmnen-z2a.com/metallpris/iridium

[52] "Platinum Spot Price Live Chart & Trends | BullionVault." [Online]. Available: https://www.bullionvault.com/platinum-price-chart.do

[53] S. Celik, B. Timurkutluk, U. Aydin, and M. Yagiz, "Development of titanium bipolar plates fabricated by additive manufacturing for PEM fuel cells in electric vehicles," *International Journal of Hydrogen Energy*, vol. 47, no. 89, pp. 37 956–37 966, 11 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319922039994

[54] “Titanium - Price - Chart - Historical Data - News.” [Online]. Available: https://tradingeconomics.com/commodity/titanium

[55] “Freshly prepared lab water or commercially bottled pure water? Part 4 | ELGA LabWater.” [Online]. Available: https://www.elgalabwater.com/blog/freshly-prepared-lab-water-or-commercially-bottled-pure-water-part-4

[56] “Energy density - Energy Education.” [Online]. Available: https://energyeducation.ca/encyclopedia/Energy_density

[57] “Gases - Densities.” [Online]. Available: https://www.engineeringtoolbox.com/gas-density-d_158.html

[58] “Handelspris, öre/kWh efter årlig konsumtion (MWh) och halvår. PxWeb.” [Online]. Available: https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START___EN___EN0302/SSDHalvarGasIckehus/table/tableViewLayout1/

[59] “Carbon Taxation in Sweden Ministry of Finance,” 2023. [Online]. Available: https://www.government.se/contentassets/419eb2cafa93423c891c09cb9914801b/230323-carbon-tax-sweden---general-info.pdf

[60] “Carbon Price Tracker | Ember.” [Online]. Available: https://ember-climate.org/data/data-tools/carbon-price-viewer/

[61] K. Christian, “The potential of hydrogen for decarbonising steel production,” European Parliment, Tech. Rep., 2020. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf

[62] V. Vogl, M. Åhman, and L. J. Nilsson, “Assessment of hydrogen direct reduction for fossil-free steelmaking,” *Journal of Cleaner Production*, vol. 203, pp. 736–745, 12 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652618326301

[63] M. Wappler, D. Unguder, X. Lu, H. Ohlmeyer, H. Teschke, and W. Lueke, “Building the green hydrogen market e Current state and outlook on green hydrogen demand and electrolyzer manufacturing,” 2022. [Online]. Available: https://doi.org/10.1016/j.ijhydene.2022.07.253

[64] “Power plants: Lillgrund – the largest offshore wind farm in Sweden - Vattenfall.” [Online]. Available: https://powerplants.vattenfall.com/lillgrund/

[65] “Havsbaserad vindkraft - Regeringen.se,” 2024. [Online]. Available: https://www.regeringen.se/regeringens-politik/miljo-och-klimat/havsbaserad-vindkraft/

[66] “Koldioxidskatt | Svebio,” 2024. [Online]. Available: https://www.svebio.se/vi-verkar-for/koldioxidskatt/

[67] “State Aid,” 2022. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_4544

[68] “Vattenkraftproduktion.” [Online]. Available: https://www.energiforetagen.se/energifakta/elsystemet/produktion/vattenkraft/

A

Appendix 1 - Interviews

Between the 15th of February and the 18th of March in 2024, interviews where held with these prominent people of academia and industry discussing the prospects of green hydrogen enabling a shift in steel production. Discussions ranged from specific questions in their own domain towards the bigger picture sharing thoughts about societal aspects and the future outlook.

A.1 Björn Wickman - Associate Professor in Chemical Physics at Chalmers University of Technology

- Vilken metod tror du är framtiden för storskalig vätgasproduktion via elektrolys?

- Vi kommer mest att se över möjligheterna med PEM. Vad ser du för fördelar och nackdelar med PEM elektrolys?

- Hur ser framtiden ut för PEM? Pågående forskning, utvecklingsmöjligheter?

- Vad för material tror du kommer spela stor roll för dessa elektrolysörer? Finns det begränsningar med dessa material (alltså material på elektroderna)? (Slitage med tiden, upplösning i mediet, dyra att få tag i, begränsade naturresurser återvinning efter det dyra metallernas livstid osv)

- Hur stor kapacitet tror du att man kan uppnå i elektrolysörer? Låg strömförbrukning med hög verkningsgrad.

- Parameteroptimering?

- Han har projekt inom vattenrening. Hur viktigt är det med vattnets renhet för PEM cell? Vad blir konsekvenserna annars? Varför?

- Slutligen: Har du några tips eller rekommendationer på texter/ källor/ personer inom dessa områden? Eller idéer på vad som skulle vara intressant att kolla på.

A.2 Jan Froitzheim - Professor at Energy and Material at Chalmers University of Technology

- Vilken metod tror du är framtiden för storskalig vätgasproduktion via elektrolys? (GW skala, vilket vi tror behövs för stålindustrin)
- PEM: Iridium-oxid (anod) och platina (katod) som elektroder/katalysatorer. Tror du att dessa är framtidens material för storskalig PEM, eller finns andra möjliga material?
- Hur stor kapacitet tror du att man kan uppnå i elektrolysörer? Låg strömförbrukning med hög verkningsgrad och renhet.
- Parameteroptimering?
- Hans artiklar om SOEC.

A.3 Centre for Hydrogen Energy Systems Sweden

- Vad anser du är de två största tekniska utmaningarna som företag eller forskare står inför just nu kopplat till vätgas inom stålindustrin?
- Kan du ge exempel på ett tekniskt framsteg som industrin gjort under det senaste som du vill dela till oss?
- Vad anser du är den största nyckeln för att omställningen till grön stålproduktion ska gå vägen och vara långsiktigt hållbar?
- Enligt dig, hur är utsikterna för de olika elektrolysörerna kopplat till stålföretagen? Kommer PEM kunna konkurrera mot AWE i stor skala?
- Vad anser du om ett ökat elbehov i norra Sverige kopplat till vätgasetablering? Har du några konkreta metoder eller satsningar som du tror på?
- Hur ser du på vattenbehovet kopplat till vätgasproduktion?
- Kopplat till materialkrav för lagring och transport, hur svårt är det att hantera vätgas som fluid?

- Hur ser du på hur företag möter kunskapsförsörjning och arbetskraft inom ex. vätgasområdet?

- Ser du några sociala eller etiska risker som skulle kunna stå i politisk konflikt med etablering och utveckling av vätgas infrastruktur? Ex. vindkraftsparker eller gasledningar.

- Har du någon rekommenderad läsning eller kontakter du vill dela med oss?

A.4 H2 Green Steel

- Hur har ni resonerat kring PEM jämfört med mer etablerade AWE i erat fall?

- Kan du ge exempel på ett tekniskt framsteg som ni eller industrin gjort under det senaste som du vill dela till oss?

- Vad är de två största tekniska utmaningarna som ni står inför just nu?

- Enligt era prognoser, vad är nyckeln för att H2 Green Steel i synnerhet och omställning till grön stålproduktion i allmänhet ska gå fungera?

- Hur ser ni på era elektrolyser ur ett livscykelperspektiv? Några särskilda flaskhalsar eller osäkra kort?

- Hur ser eran infrastruktur för vatten ut? Tillgång, rening etc.? Vi är nyfikna på data, gärna flöden och kostnader om ni har möjlighet att dela något även om hypotetiskt.

- Hur ser ni på H2 Green Steel och Hybrit som två olika aktörer kopplade till stålindustin som hanterar vätgas? Största tekniska skillnaderna?

- Hur ser ni på arbetskraft i Boden nu närmast men även på längre sikt?

- Rekommenderad läsning eller kontakter?

A.5 Simon Harvey - Professor in Energy Technology at Chalmers University of Technology

- Enligt dig, vad är de senaste två till tre största stegen i utvecklingen av vätgasanvändning vid stålproduktionen under det senaste som kanske inte nått ut till den breda allmänheten?

- Utifrån ditt perspektiv, vad är de två till tre största utmaningarna företagen och samhället står inför med utvecklingen, etableringen och användandet för vätgas inom stålproduktion i Sverige?

- Spontant, har du något tips på vad vi som analyserar vätgasens utsikter i grön stålproduktion i stora lag borde hålla ett extra öga på utifrån ditt perspektiv?

- Kanske svårt att säga för industrier överlag, men hur är din bild av vätgasens kretslopp inom industrin? Sker recirkulation? Finns etablerad design/princip?

- Finns ett enkelt svar på hur företag vågar ta första steget in i utvecklingen? Främst ”morot” i frågan om CO_2 reduktion eller ”piska” i frågan om höjda CO_2 skatter.

A.6 Fredrik Normann - Professor at Energy Technology at Chalmers University of Technology

- Enligt dig, vad är de senaste två till tre största stegen i utvecklingen av vätgasanvändning vid stålproduktionen under det senaste som kanske inte nåt ut till den breda allmänheten?

- Utifrån ditt perspektiv, vad är de två till tre största utmaningarna företagen och samhället står inför med utvecklingen, etableringen och användandet för vätgas inom stålproduktion i Sverige?

- Vätgaseldning i roterugn för järnmalmsbearbetning (publikation 09/2023). Intressant. Hittills inte hittat mycket om användning av vätgas vid eldning. Hur ser utsikterna ut här enligt dig?

- Spontant, har du något tips på vad vi som analyserar vätgasens utsikter i grön stålproduktion i stora lag borde hålla ett extra öga på utifrån ditt perspektiv?

- Kanske svårt att säga för industrier överlag, men hur är din bild av vätgasens kretslopp inom industrin? Sker recirkulation? Finns etablerad design/princip?

- Utan att nödvändigtvis gå in i detalj, hur ser du från ditt perspektiv på behovet av förnyelsebar energi kontra de möjligheter som finns för utbyggnad.

- Finns ett enkelt svar på hur företag vågar ta första steget in i utvecklingen? Främst ”morot” i frågan om CO_2 reduktion eller ”piska” i frågan om höjda CO_2 skatter.

A.7 Interview with Volvo Group Trucks Operations

- Vad har Volvo för plan för omställning till grönt stål?

- Så Volvo har bestämt sig för att bli net zero 2040, kommer det vara lönsamt?
- Vad är den drivande faktorn till omställningen?

A.8 Interview with Volvo Construction Equipment

- Vad har Volvo för plan för omställning till grönt stål?
- Varför eller varför inte tror Volvo att omställningen kommer bli lönsam?

A.9 Interview with Smoltek

- Enligt dig, vad är de senaste två största stegen i utvecklingen av PEM som metod för vätgastillverkning?
- Vad är den största utmaningen ni står inför inom utveckling av PEM?
- Vad är den största utmaningen ni står inför inom utveckling av PEM?
- Kan ni beskriva vad som gör eran PEM unik jämfört med andra?
- För er som företag som utvecklar metoder för vätgastillverkning, hur ser det ut med konkurrens och patent?
- Vad tror ni är största nyckeln för att storskalig grön stålproduktion ska bli den nya standarden för ståltillverkning?
- Vätgasproduktion med elektrolysör kräver mycket ström, hur ser ni på detta på nationell och global skala?
- Vi har förstått att det både etablerade och andra lovande elektrolysörer. Hur ser ni på valet av elektrolys för storskalig ståltillverkning?
- Hur ser ni på den begränsade tillgången till irridium och användning i PEM?

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS