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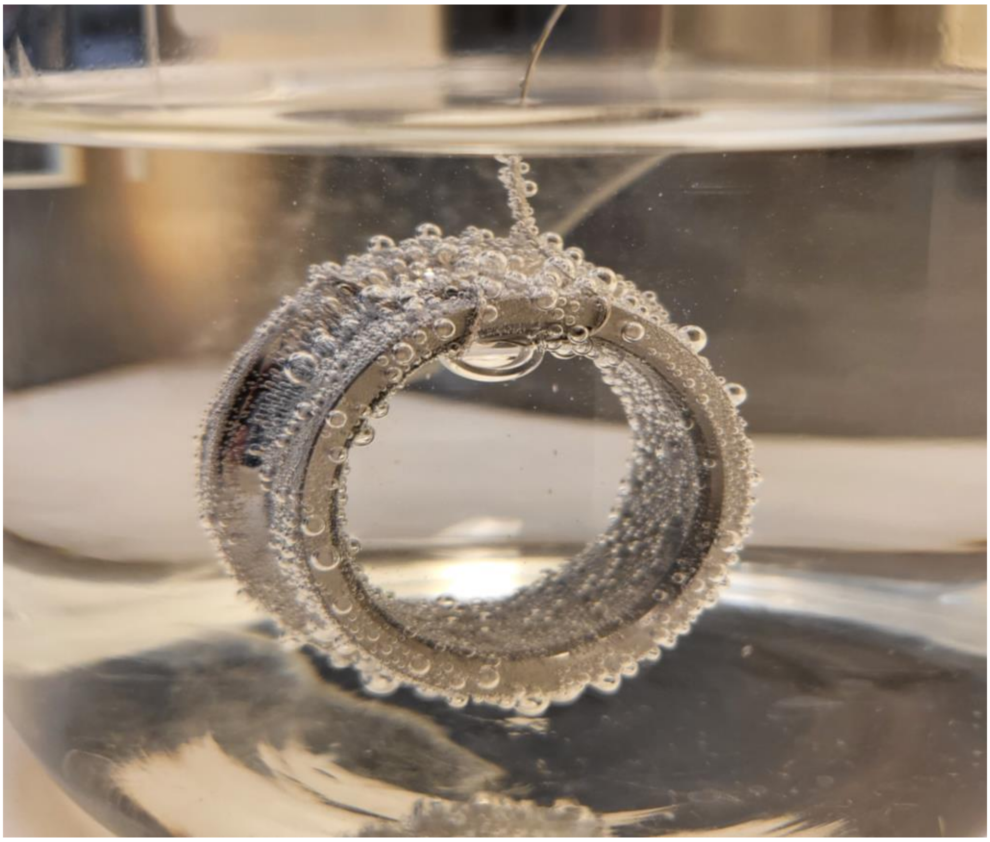

The Role of Hydrogen and its Effects on Bearings in Compressor applications

Master's thesis in Sustainable Energy Systems

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Abstract

The hydrogen market is growing and becoming more and more relevant for future energy systems. It is, therefore, necessary to know what role hydrogen will play in the energy system, and for what applications it will be used. Most hydrogen applications utilize compressed hydrogen which makes this relevant for SKF, as hydrogen compressors contain bearings. The bearing material is likely to be exposed to hydrogen in these applications, making it necessary to know how susceptible the bearings are to hydrogen embrittlement. To answer these questions were a literature study of the future of hydrogen and a market study of the compressor market done. A lab trial was also performed, where bearings made of 100Cr6 grade steel were cathodically charged with hydrogen before being tested in a test rig. It was found that hydrogen is likely to play a significant role in the future energy system, as a potential fossil-free energy carrier. Both the demand for hydrogen and the number of applications are growing. Infrastructural applications will probably be widely used as they are a key part of hydrogen becoming a part of the energy system. To compress hydrogen a wide variety of compressors will be used as different applications use different amounts of hydrogen at different pressures, where mainly reciprocating and centrifugal compressors are highlighted as the most promising alternatives. The lab tests showed that the charging was detrimental to the material, which broke after only a short time in the test rig. With the equipment available could it however not be proven that this is due to hydrogen embrittlement, although that is the most likely cause. The 100Cr6 EN ISO 683-17 grade steel is thus not suitable for hydrogen applications.

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Abbreviations

BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CHP	Combined Heat and Power
DLC	Diamond Like Carbon
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HB	Hydrogen Blistering
HE	Hydrogen Embrittlement
HEDE	Hydrogen-Enhanced Decohesion
HELP	Hydrogen-Enhanced Localized Plasticity
HESIV	Hydrogen-Enhanced Strain-Induced Vacancies
HIC	Hydrogen Induced Cracking
HID	Hydrogen Induced Disbondment
HIPT	Hydrogen Induced Phase Transformation
HTHIC	High Temperature Hydrogen Indcude Cracking
ICE	Internal Combustion Engine
IEA	International Energy Agency
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membran Fuel Cell
PPM	Parts Per Million

PV	Photovoltaic
PVD	Physical Vapor Deposition
RPM	Revolutions Per Minute
SOEC	Solid Oxide Electrolysis Cells
SMR	Steam Methane Reforming
SSC	Sulfide Stress Cracking

1

Introduction

Fossil based fuels supply around 80% of the world's energy and are essential for the functions of today's society [1]. Future energy systems must become less dependent on fossil based fuels, and there are two main factors which contribute towards this statement.

The first factor that supports the replacement of fossil fuels are the effects that they have on climate change. The release of greenhouse gases (GHGs) during the combustion of fossil fuels contribute significantly towards global warming. There is an uncertainty on how large the impact of emissions of GHGs are, since the amount is varying over time and is difficult to estimate. Scientists usually try to quantify this by looking at how much doubling the amount of CO_2 in the atmosphere compared to the pre-industrial era would increase global temperature. This is commonly referred to as climate sensitivity and the accepted range is between 1.5 to 4.5^oC. It is therefore highly uncertain how large and what effects emissions of CO_2 will have on the environment, but it is likely that the effects will have a negative outcome. Those who will be affected the most by climate change will be the ones living in poorer conditions. From an ethical perspective it is therefore important to make an effort against climate change to prevent exacerbating the living standard for these people [2].

The second factor is that fossil fuels are finite. The current reserves-to-production ratio of oil, natural gas, and coal is 53.5, 48.8, and 139 years respectively [3]. This means that if no changes are made to lower the consumption of fossil fuels, all fossil fuel reserves will be depleted in 139 years. With the prices of these fuels increasing, larger environmental awareness and discovery of new reserves, they are expected to last longer, but a switch to renewable energy sources will eventually be necessary.

These factors make it necessary to use alternative renewable fuels in the future energy system. There are currently multiple promising alternative fuels under development and one of these fuels is hydrogen. Hydrogen is a versatile fuel that can be used in many applications, such as vehicles, gas turbines, energy storage, etc., and can supply the need for heat and power. It can be produced through renewable means with the only byproducts being heat and water. Hydrogen is therefore an auspicious fuel that can contribute towards the use of more renewable energy sources, though there are some problems related to its use. Many applications require compressed hydrogen due to its low density at ambient conditions and there are many challenges related to its handling [4]. One such challenge is hydrogen embrittlement, which occurs in the presence of hydrogen during diffusion of atomic hydrogen to a susceptible material during stress. This can lead to fractures in products and materials, and due to the importance of some of these hydrogen applications, it is highly undesirable to have these products malfunction [5]. Rolling bearings are found in the compressors used for the compression of hydrogen and these might experience hydrogen embrittlement depending on their environment.

SKF is a company whose expertise is built upon development, design, and manufacture of bearings, seals, and lubrication systems [6]. SKF are interested in what effects hydrogen has on rolling bearings in different environments to guarantee the function of hydrogen applications in the energy system. They are also interested in the hydrogen compressor market. Compressors need bearings to function and if bearings are used that SKF are currently not producing, they might consider to adapt the types of bearings that are commonly used, or try to promote a type of bearing which they manufacture for these compressors. This master's thesis project will be conducted by Chalmers students on request from SKF Technology, to evaluate the effects of hydrogen on rolling bearings in different environments to ensure the function of hydrogen applications in the energy system, and further consolidate its role in the energy system. To accentuate the importance of hydrogen will the role of hydrogen and its most common applications be mapped, which indicates the future of the hydrogen compressor market and thus which bearings that will be used in these compressors.

1.1 Aim

The aim of this thesis is to, through a literature study, explore the role of hydrogen in the energy system, map out the hydrogen conditions of different applications, evaluate both the hydrogen compressor and bearing markets, and then perform tests on rolling bearings to examine the effect of hydrogen on the material.

1.2 Delimitations

- Other hydrogen carriers, such as ammonia or toluene, will not be evaluated and tested in this report, since this would be too extensive.
- The hydrogen applications mentioned in this report are for the most common and well developed applications, and similarly, the most common compressors for hydrogen compression are listed. Analysis of niche markets could be promising for the future, but it is difficult and time consuming to assess which markets have the largest potential and will therefore not be evaluated for this

report.

- While making evaluations and finding information on energy systems, the focus has been put towards industrialized countries, since this is where hydrogen implementation is the most relevant.

1.3 Hypothesis

To fulfill the aim of the thesis, the role of hydrogen in future energy systems and its common applications have to be investigated. The most common transportation, storage processes and distribution at point of use for hydrogen in the applications will be explored. This will include the processes for how hydrogen is compressed and at what operating conditions this is done. An evaluation of the most common compressor types that are used for the investigated applications will be made. From this evaluation it will be possible to determine what type of bearings that are most commonly used. For the lab tests, the temperature suitable to charge in has to be decided as it is a variable that influences hydrogen diffusion. A high temperature increases the diffusion constant and thus it is necessary to determine which temperature that would allow for the most hydrogen to enter the material. After the charging, the effect that hydrogen has on the bearings will be determined and it is expected to have a negative influence on the material properties, leading to early failure.

2

Methodology

Multiple different steps were taken during the course of the thesis, beginning with a literature study of the role that hydrogen will have in the future energy system and what its potential applications are. The compressor market was then investigated, both through accessing the websites of company websites and through interviews. Lastly was a lab trial done where bearings were charged cathodically before being run in a test rig and then investigated using a microscope.

2.1 Literature study and market survey

The literature study began with conveying both quantitative and qualitative gathering of information from scientific reports, and articles that gave information and views on the role in the future energy system, applications, and material properties of hydrogen. Each piece of literature was read thoroughly and information that was seen as valuable was documented. The gathering of information to the study stopped once the literature began to repeatedly give similar information and was therefore seen as sufficient. For the role of hydrogen and the applications, there was much literature with differing views and in the final survey the information and views that could be seen in multiple sources was presented.

The following keywords were used to find information to the literature study: Hydrogen role, hydrogen applications, hydrogen energy system, hydrogen embrittlement, hydrogen diffusion, future energy system, low-carbon technologies, and corrosion. Search engines used were Google Scholar and Chalmers lib, as well as company and authority websites.

For the market survey for hydrogen compressors and the bearings used, information was gathered by visiting the websites of companies that had stated publicly that they were either already supplying compressors for hydrogen or that they were planning to supply. Finding companies was done internally through SKF Technology and by browsing company websites. To find information about hydrogen compressors the product catalogs of the companies were inspected and which compressors they recommended for hydrogen. The recommended compressors were then documented by looking through brochures and online company articles. If essential information, such as discharge pressure or bearings were missing, interviews were conducted to complement the information.

The interviews were either conducted through video calls, phone calls, and email. The interview methodology was shaped after [7], where there were initially pre-studies conducted to guide the interview towards the study and to know what questions to ask. The interviews had a semi-structured setup, since this gives the interviewee the possibility to answer more honestly [7]. The interviews were not recorded, but one person was in charge of the interview while another person took notes on what was said and noted important pieces of information. People interviewed were either discovered through company websites, where contact information regarding the specific compressors were posted and often were conducted by phone for an interview, or by sending in a contact form where a person would agree either to answer questions.

2.2 Hydrogen charging

The lab tests were performed with the purpose of investigating the effects of hydrogen on the SKF grade 3 bearings. To do this, 7205 BEP single row angular contact ball bearings, made of 100Cr6 EN ISO 683-17 grade steel, were charged with hydrogen cathodically under extreme conditions. This was done by placing the bearing under cathodic protection at a potential below the hydrogen evolution potential, thus increasing the amount of atomic hydrogen generated on the surface of the bearing, which can diffuse into the material leading to hydrogen embrittlement. To confirm that the hydrogen has an impact on the material were the bearing mounted into a test rig, in which an axial load of 13 kN was placed on the bearing where it ran at 2000 rpm for 20 hours or until failure. The bearing was then sent to the metallurgy lab at SKF, where the bearing was analyzed to confirm the cause of the wear and potential failure.

The test process consisted of cathodically charging an inner ring of a bearing with hydrogen before the bearing was reassembled and mounted in a test rig. After the test was finished, either after 20 hours or after failure, the inner ring was checked for potential damages caused by the influence of hydrogen on the material. To find the method used pre-trials were made, which can be read about in Appendix A.

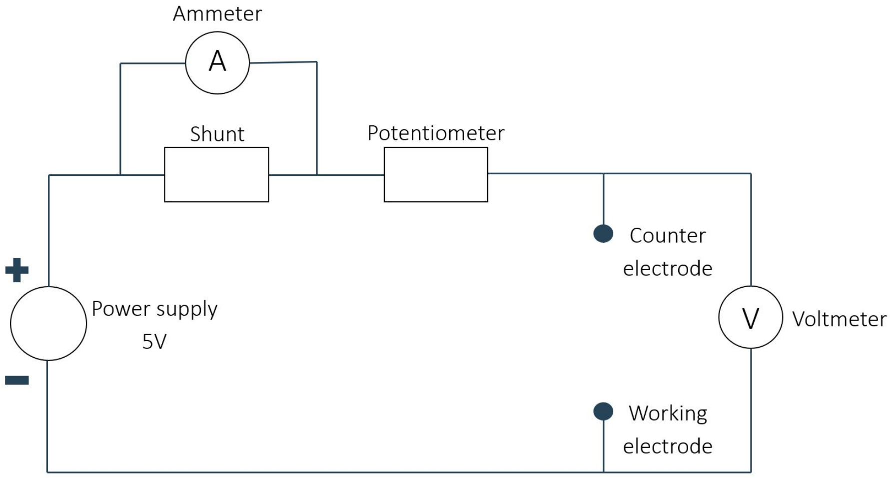

Figure 2.1: The circuit used for cathodic hydrogen charging

The circuit used for charging is shown in figure 2.1. The circuit consists of a $5V$ power supply where the plus side is connected to a shunt resistor, followed by a potentiometer, and then a platinum wire which is used as the anode in the electrolyte. The shunt resistor has a low and precise resistance and it is over this component that the current of the circuit was measured. The potentiometer was used to ensure that the voltage was at $3V$ between the electrodes for all tests. The cathode, consisting of an inner ring enveloped in platinum wire, was directly connected to ground.

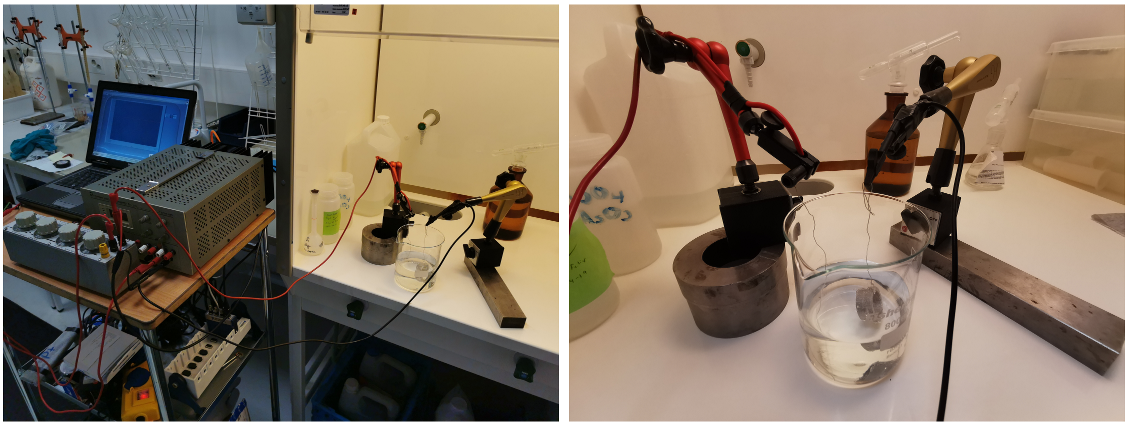

Figure 2.2: The setup used when charging

Before the charging the inner ring was cleaned by wiping it with a cloth and ethanol. Figure 2.2 shows the setup used when charging. The inner ring hanging in the platinum electrode was fully submerged in the electrolyte as shown in figure 2.3.The electrolyte consisted of a solution of 0.2 M/liter H_2SO_4 and 1 g/liter Na_2HAsSO_4, in which the inner ring was charged at room temperature for 35 minutes.

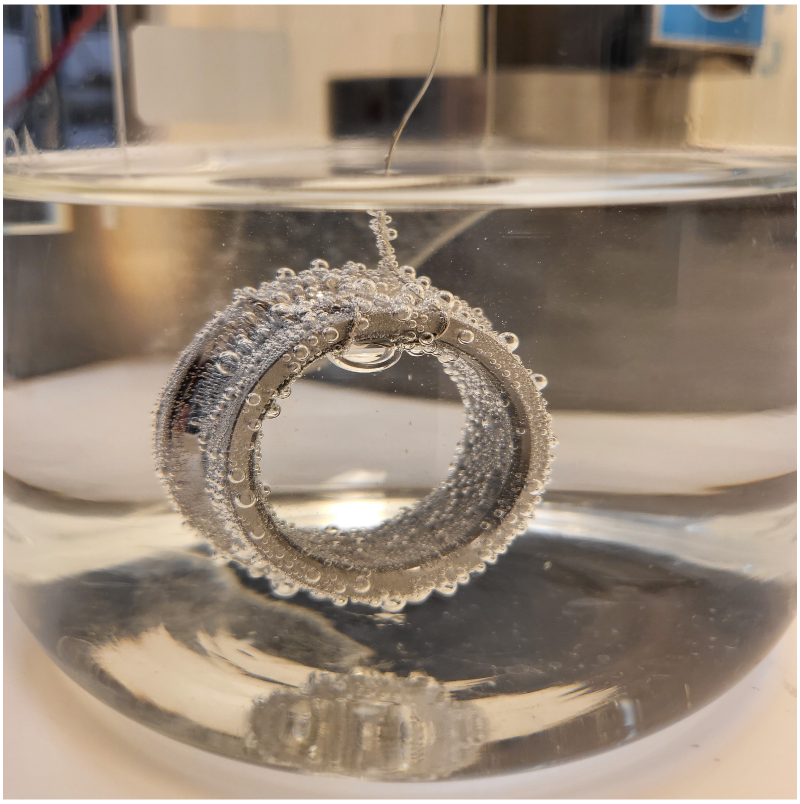

Figure 2.3: The inner ring during the cathodic hydrogen charging. The bubbles shown on the sample consists of hydrogen gas, which come from atomic hydrogen combining into molecular hydrogen on the surface, meaning that it cannot diffuse into the material.

After charging, the sample was rinsed using distilled water, after which the inner ring was dipped in oil and sent to the test rig for reassembly and testing.

Figure 2.4: The test rig used during testing

The test rig is shown in figure 2.4, where the bearing received an axial load of 13 kN and was run at a speed of 2000 rpm. The allowed temperature for the inner ring was set to 45°C and the outer ring to 40°C. For the three charged samples the break level of the vibrations was lowered every sample in an attempt to stop the machine as soon as any damage occurred. After the test run was finished was the bearing sent to the metallurgy lab, where the wear and cause of failure was investigated.

A microscope was used to check the inner rings for signs of corrosion and damages visible on the surface. To check for effects of hydrogen in the sub-surface material, the ring was sectioned, where a piece of it was cut off for a cross section, as seen in figure 2.5. The cut off piece was polished to mirror finish and then etched in 1.5 % Nital before inspection using a microscope.

Figure 2.5: Inner ring with a piece cut off

To see the if the bearings are sensitive to hydrogen-induced cracking, was another test attempted. An outer ring was charged for four hours at an even higher voltage of $4.1V$ and an elevated temperature of 80°C with the purpose of getting as much hydrogen into the bearing as possible. This sample was then taken directly to the metallurgy lab, where it was sectioned and polished to mirror finish before being examined using a microscope.

3

Role of hydrogen

Hydrogen will likely have a major role in the global future energy system. This is due to the flexibility of hydrogen as an energy carrier, which allows it to be used in many different areas and applications. The main uses of hydrogen in a future energy system are as follows:

- Hydrogen will be used to support renewable energy sources, which have issues related to intermittency and variability, and will help with integrating them into the energy system while providing energy security.
- Electricity demand will increase in the future as energy demand increases and fewer fossil-based fuels are used. However, the energy system can not solely rely on electricity due to some of its downsides and hydrogen can then act as a complement to provide a more flexible energy system.
- Hydrogen is also a zero-emission energy carrier that has the potential to decarbonize sectors that heavily rely on fossil-based fuels.

The infrastructure required to make hydrogen a large part of the energy system will be both complex and expensive to implement, and a major part that will have to be implemented is its storage and distribution. It is still uncertain how hydrogen will be produced in the long term since there are multiple production paths available, but the most economic production methods have major greenhouse gas emissions related to them while the production of low-carbon hydrogen is exceedingly more expensive.

There are still significant uncertainties related to the predictions of hydrogen deployment. Technological, social, economic, and political factors will all continue to affect the prospects for hydrogen as an energy carrier. It is however likely that the global energy systems will move towards the use of electricity and hydrogen as the world's dominant energy carriers [8].

3.1 Supporting renewable energy sources

Renewable energy sources, such as solar power, and wind power will be required to decarbonize the future energy system [4]. However, the flexibility in power production that fossil-based electricity production provides will decrease [8], due to the intermittency and variability of solar and wind power, leading to an unpredictable energy supply [4, 8–10]. During some hours, the electricity production from renewable energy sources will therefore not meet the electricity demand, and at other times it might be necessary to curtail electricity [4, 8–10]. Hydrogen technologies provide a solution to counter these issues and also contribute toward achieving higher energy security [4, 9].

A key aspect to keep in mind regarding the production of hydrogen from renewable sources is whether it is feasible or not to produce enough hydrogen through renewable energy sources alone. This affects the feasibility of a hydrogen-based sustainable energy strategy. The amount of evidence that proves the possibility that the world can rely on energy efficiency and renewable energy sources to meet its energy demand is increasing, where politics and economics instead are the limiting factors [11].

3.1.1 Integrating renewable energy sources

One of the drivers behind the deployment of a hydrogen economy is supporting the integration of renewable energy sources [9]. During hours of curtailment, the excess electricity can be used to power an electrolyzer producing hydrogen which is then stored in hydrogen storage facilities [4, 8, 9, 11]. The stored hydrogen can be used later during hours when the renewable energy sources are unable to meet the electricity demand and therefore provide more flexibility to the energy system [9]. Hydrogen can be stored for both long and short periods of time, which adds to the flexibility of hydrogen storage. Hydrogen storage can also be used to handle seasonal variations in large-scale geological storage [11]. The hydrogen can be used for re-electrification in gas turbines, gas engines, or stationary fuel cells and be fed back to the electricity grid [9]. The hydrogen can also be used for other applications such as fuel for fuel cell electric vehicles (FCEVs), feedstock for the heating fuel industry, mixing of hydrogen into the natural gas grid, etc [4, 9, 12].

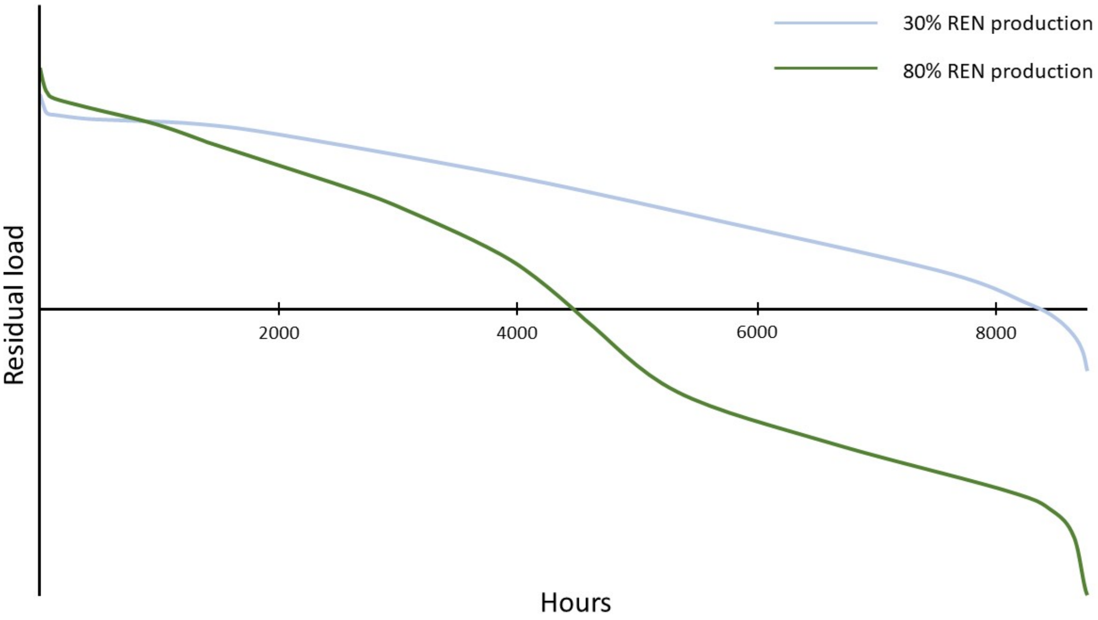

Figure 3.1: Residual load curves for different shares of renewables. Inspiration from [9]

Figure 3.1 shows two typical residual load duration curves for a 30% and 80% share of generation from intermittent renewable energy sources. The part of the curves below the x-axis is the residual load and a measure for the amount of surplus electricity that is produced, but for which there is no immediate demand, i.e. when generation exceeds the load. The part above the x-axis is a measure of the deficit which has to be covered by either flexible conventional generation or storage. Clearly, with a low (<30%) share of fluctuating renewable electricity generation, the amount of surplus electricity is very limited, occurring in the order of 500-1000 hours per year. With an intermittent renewable energy source share of 80% or more, substantial amounts of surplus electricity may occur during a total of 3000-4000 hours during a year. It is important to note, though, that these scenarios do not take into account the deployment of other storage technologies over time, such as batteries, that would reduce any surplus available for conversion to hydrogen [9].

Electrolysis of hydrogen is expensive and the main contributor to the high hydrogen price is the production cost and is today mainly used where hydrogen with high purity is required [8, 9]. Electrolyzers that use electricity from renewable energy sources can help reduce the life cycle emissions in different sectors. An example is the deployment of fuel cell vehicles and cogeneration fuel-cell plants, especially in densely populated regions. It is also estimated that renewable energy-based electrolysis using alkaline and polymer electrolyte membrane electrolyzers will become cost-competitive with steam methane reformation (SMR) by 2040 if continued investment in research and development leads to further cost reductions, high load factors, and low electricity prices [12]. Electrolysis is critical for a future energy system and requires more investments to become cost-competitive with other technologies [4, 12, 13].

3.1.2 Energy security

The IEA defines energy security as "The uninterrupted availability of energy sources at an affordable price" [14]. As described in the previous section, renewable energy sources have problems in achieving energy security, due to the intermittency, variability, and high cost of the technologies involved in the hydrogen value chain. Hydrogen storage can support energy security if converted back to electricity and also by converting it to other fuels which make end users less dependent on specific energy resources and increase the resilience of energy supplies. The same can be said about hydrogen produced from fossil fuels with carbon capture, utilisation, and storage (CCUS) or from biomass. Countries with suitable sources for hydrogen production are widely dispersed and a lot of the countries that export energy have renewable resources that could produce hydrogen. Hydrogen trade could enable the supply and storage of renewable energy across different regions to overcome geographical and seasonal variations[4].

3.2 Emission reduction

The future energy system will heavily depend on electricity, but there are some areas in the energy system in which electricity needs complementing technologies and hydrogen can be one of these complements. Hydrogen is not an energy source, but an energy carrier with a role similar to that of electricity. There are no harmful emissions related to the use of hydrogen and only water and heat is emitted when used in a fuel cell [4]. Hydrogen can help to decarbonize sectors that heavily rely on fossil fuels and mitigate climate change [4, 15].

3.2.1 Complement electricity

A mix of electricity and hydrogen will be needed in the future energy system since they can not meet all energy service demands on their own [8]. A system purely based on electricity suggests that electricity will be stored in storage batteries, supercapacitors, and superconductors. Both the electricity and hydrogen economies combine well with nuclear energy and renewable energy sources and provide flexible energy supply, a high level of security, reliability of the energy systems, and the possibility of unifying the technologies in the final energy consumption [16]. A significant difference between electricity and hydrogen is that hydrogen is a chemical energy carrier and is the reason why hydrogen might out-compete electricity in some areas [4, 8]. The flexibility of a chemical energy carrier is its multitude of application areas; it can be [8]:

- Stored and transported in a relatively stable way across the sea in ships

- Burned to produce high temperatures
- Be used in existing infrastructure and business models designed for fossil fuels

For energy storage, it is generally more cost-effective to have hydrogen storage when it has to be stored for longer periods and batteries for shorter periods [4, 16]. Hydrogen is less cost-effective than electricity for short-term power supply periods. When hydrogen is produced from electrolysis, hydrogen becomes more cost-effective when the storage time is longer than 100 to 110 hours. This is explained by the fact that when the storage time increases, the costs of accumulators in the electricity-based system increase much faster than the costs of hydrogen tanks [16]. Thus both batteries and hydrogen storage should be used in the future energy system since they complement each other.

FCEVs and battery electric vehicles (BEVs) will compete with each other in the future, thus making the overall costs important. Even though FCEVs have a high potential to lower emissions, there are several regional factors that their effectiveness depends on, such as the source of the hydrogen, its transport, population density, and average distance traveled each day. Hydrogen may prove to be a less efficient option in some regions but might have an advantage in being better suited for more heavy-duty, long-range, and mass transit applications [12].

3.2.2 Zero-emission energy carrier

With the increasing scarcity of fossil fuels and growing environmental concerns, it is likely that hydrogen will become an increasingly important energy carrier for the energy system and may become the main chemical energy carrier. Today's societies are dependent on chemical fuels and feedstocks. Many researchers agree that hydrogen will be the best chemical fuel in the future for many decades. Hydrogen will be produced from low-cost renewable energy sources and then used as an energy carrier to take advantage of its unique properties. With fewer fossil-based energy sources used, there will be a growth in electricity and hydrogen demand which will be the dominant energy carriers for the provision of the end-user services [8].

The increased demand for hydrogen is not enough for it to be deemed a key pillar of decarbonization, hydrogen production must also become cleaner than today. Of the approximately 90 Mt of hydrogen used in 2020, about 80% was produced using fossil fuels, mostly unabated, and practically all the remainder came from residual gases produced in refineries and the petrochemical industry [10, 13]. This resulted in almost 900 Mt of CO_2 emitted in hydrogen production, equivalent to the emissions of the United Kingdom and Indonesia combined [10].

3.2.3 Replace fossil fuels

Hydrogen will have a major part in the energy system once fossil fuels become too expensive and/or have caused too much environmental damage. By then, the infrastructure will hopefully be well-established to support the deployment of the hydrogen economy, and final use technologies will be widely spread to support the transition from fossil-based fuels [8]. Hydrogen also comes as a byproduct of the chemical industry and could represent a cheap supply source where it can replace natural gas and could be good for use during the expansion of hydrogen. The most widespread production methods of hydrogen are today fossil-based and it is expected that they will remain the most common production paths in the coming years since they are the cheapest alternatives, capable of using existing infrastructure [9].

Hydrogen has a similar performance to fossil-based technologies, which makes the transition easier, and companies and countries have put forward hydrogen as a key solution to the energy transition [4, 10, 11]. Hydrogen can also be produced anywhere which makes it attractive to oil-deficient countries as one of the alternative fuels with a considerable potential for long-term substitution of oil and natural gas [11].

When the transition to hydrogen occurs, it will be used as an industrial feedstock and as chemical fuel [8]. Hydrogen has a critical role as a fuel for reducing emissions in sectors that are hard to decarbonize and will find uses in transportation, commercial and residential sectors, and industry [10]. Since electrolyzers are scalable and modular they are good for hydrogen expansion. By-product hydrogen will be the first supply of hydrogen and also existing fossil production pathways. With increasing demand, it will be possible to gradually increase the capacity at a reasonable cost. The hydrogen production mix will be region-dependent and will be influenced by feedstock prices and CO_2 regulations, such as availability and policy support when it comes to green hydrogen. Green hydrogen is therefore not what will introduce hydrogen on the market [9].

3.3 Infrastructure

Hydrogen technologies are currently being put forward as a promising solution to the climate change crisis by politics and industry, where several political programs have been put forward to advance them. This does however require new infrastructure as well as modifications to the existing energy system [17]. There are a few barriers identified that hold hydrogen technologies back, and to shift away from fossil fuels in the transport sector to hydrogen fuel cells, radical changes are required, both for the resource base and the technological routes used in supply and distribution. The radical changes are required since the fuels primarily used today differ vastly from the primary sources used for hydrogen, thus requiring new infrastructure and technologies [15].

Some difficulties may be encountered in this transition due to the resistance towards change caused by the present well-to-wheel infrastructure being deeply embedded not only into our physical capital but also the human capital in terms of knowledge and expertise. To overcome this it is necessary for governments and international agencies, such as the IEA, to shift their support currently provided to fossil fuels and nuclear fission technologies toward the newer renewable hydrogen technologies [15].

There are issues related to the complexity of the value chain and infrastructure needs, where the most viable solution will be different for different regions and applications. For each value chain, the investments and policies have to be synchronized in both scale and time if hydrogen is to be produced and delivered to the end-users[4]. In the case of hydrogen refueling stations, there will be a period of low utilization, around 10 to 15 years long, before it can transition towards a mass market. It is difficult to avoid this situation since the initial network coverage must be large enough to provide everyone with access to a hydrogen station, and thus both meet customer demand and get acceptance for fuel cell electric vehicles. For this reason, station deployment has to proceed with the vehicles and once demand grows, it will be necessary to build even larger stations which will then be underutilized. To have an incentive framework to have hydrogen at a competitive price is therefore important, but due to the difficult business case, one company alone can not take the risk of an initial investment [9].

Another hydrogen barrier is that the industrial base backing the use and development of hydrogen technologies still is relatively small and unorganized. This lacking community support may be rooted in that those advocating for a hydrogen economy consider it to be an essential good rather than arguing for hydrogen from an environmental and sustainability perspective [15].

The development of hydrogen infrastructure and technologies, in the context of energy transitions, is often considered for broader economic development. Hydrogen value chains touch upon many different technology and manufacturing sectors, and both new technology and knowledge will be necessary. There are plans to develop leadership, technical expertise, and new jobs in these areas, particularly in the sectors where they reinforce existing skills and capacities [4]. Green hydrogen in industrial applications needs a carbon tax of 100-200 euros per tonne to become an economically viable mitigation option. This also applies for large-scale electricity time shifts using hydrogen and to make re-electrification viable it is necessary to have this combined with a suitable cavern reservoir and an appropriate electricity market with a high share of intermittent renewable energy sources [9].

3.3.1 Production

The methods of producing hydrogen require a lot of development since some of the largest technological problems associated with hydrogen lie in production. If the troubles with production are not solved, the storage, distribution, and conversion technologies will not be used, since the production is economically non-viable. The processes involved in hydrogen production are processes for generating and purifying hydrogen as well as compression and/or liquefaction [8]. There are multiple production paths for hydrogen, the conventional path utilizes pyrolysis and hydrocarbon reforming to produce hydrogen while the alternative sources use renewable electricity to produce hydrogen either from water or biomass which is described in figure 3.2 [18]. The most common methods are partial oxidation, steam reforming, catalytic decomposition of natural gas, coal gasification, electrolysis of water, thermochemical water decomposition, as well as electrochemical and biological processes [8, 18]. It is also likely that fossil-based fuels will see continued use in the future to produce hydrogen even though more sustainable alternatives exist [8].

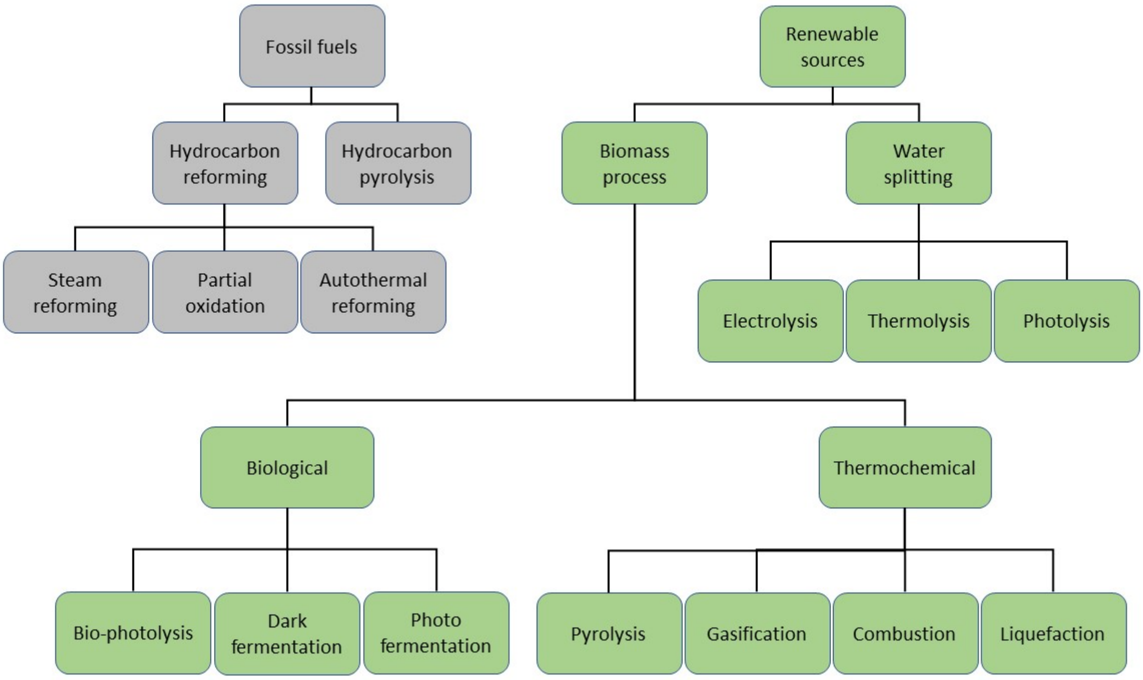

Figure 3.2: The production pathways to producing hydrogen. In gray are the production methods based on fossil fuels and in green the production methods based on renewable energy sources. Descriptions on the production paths are given later in this section. With inspiration from [18]

The production of hydrogen from non-carbon energy sources is expected to increase even if the fossil-based methods still are used. The increase is expected to occur for the following processes [8]:

- Water electrolysis using electricity from energy sources such as solar, nuclear, wind, or hydro.
- Photochemical and photobiological processes
- Thermochemical hydrogen production using high-temperature heat produced in concentrating solar devices

Hydrogen is often looked at as green hydrogen, overlooking other hydrogen production paths. Hydrogen produced from fossil fuels is termed gray hydrogen, but when utilizing carbon capture and storage technologies for carbon dioxide is it commonly referred to as blue hydrogen. Attention should however be paid to the green hydrogen market. Countries with cheap and abundant energy, low personnel costs, land, and raw material will have an advantage over the EU member states. This is especially important since the main challenge for green hydrogen is becoming cost-competitive compared to gray and blue hydrogen, as well as hydrogen produced through electrolysis powered by nuclear energy [19], which is expected to be a common route of hydrogen production in the future [8]. To achieve the global carbon emission goals, the production source of hydrogen is an important issue. The offshore hydrogen production using fossil fuels without CCS that is currently occurring is essentially offshoring the CO_2 production, which is undesirable, and recognizing this is important to provide an incentive for even more ambitious targets [12].

The hydrogen production paths that receive a lot of focus today are methane reforming, electrolysis, coal gasification, and biomass gasification. These processes have widely different efficiencies and energy requirements, and increased energy requirement leads to lower efficiency. Methane reforming has the lowest energy requirement per kilogram of hydrogen gas, and thus it also has the highest efficiency, followed by electrolysis, then coal gasification, and finally biomass gasification, which has the lowest efficiency and highest energy requirement [11].

There is a multitude of trade-offs to keep in mind for the different production paths, namely between the scale of production, cost, and greenhouse gas emissions. The fossil-based paths are the cheapest at large-scale production but come with the downside of having the highest environmentally damaging emissions. This can be countered using CCS or CCUS, where the emissions are lowered but at an increased price. Biomass can also provide a path for large-scale production, with significantly lower emissions than fossil-based alternatives but is also more expensive. Producing hydrogen through electrolysis is the most expensive option but is the most suitable for small-scale production due to the inherent modularity of electrolyzers. The costs do however increase even further when the electricity is sourced from low-carbon energy sources, even more, if the energy sources are renewable [11].

Splitting water into hydrogen and oxygen can be done with processes such as electrolysis, photo-electrolysis, and thermolysis where electrolysis is the most established and effective method today. Electrolysis has no emissions when paired with renewable energy sources while being a proven technology. The reaction is endothermic and thus requires energy input in the form of electricity where the most developed and widespread electrolysis technologies are solid oxide electrolysis cells (SOEC), alkaline, and proton exchange membranes (PEM). The PEM electrolyzer splits water into hydrogen and oxygen ions at the anode which then goes through the membrane to the cathode where it forms hydrogen and oxygen gas. In the alkaline and SOEC electrolyzer, the water is split at the cathode and the protons, originating from the hydrogen molecules, are separated from the water in external separation units. The hydroxide ions travel through the electrolyte to the anode where it forms oxygen gas. The SOEC technology differs from the other in that it replaces the electricity with thermal energy and as a result, the temperature increases, which makes hydrogen gas remain in the unreacted steam stream. Through electrolysis high purity hydrogen can be produced but the high energy consumption limits the technology by making them less cost-competitive against other large-scale technologies [18].

When nuclear provides the power, the price is typically lower, since nuclear is relatively widespread and typically have large production rates of electricity. Solar thermal and solar PV usually has higher hydrogen costs, while wind, both on- and offshore have lower costs, but usually not as low costs as for nuclear. The differences in wind and their hydrogen costs are based on the photovoltaic costs varying and if there is a co-production of electricity and hydrogen or if the costs are focused on only hydrogen production. The downsides of producing hydrogen through electrolysis are found in the low efficiency of the process and the high capital cost. [18]. The costs of production are influenced by not only the capital cost but also the degree of utilization and the average electricity purchase price during operation. A high degree of utilization leads to a decrease in the share of the total cost that the investment cost has while the share of the electricity cost increases. The balancing of these costs leads to an optimal utilization of 3000-6000 hours [9].

Thermochemical splitting of water, or thermolysis, is the process at which water is heated to a high temperature and then split into hydrogen and oxygen. The high temperature can be supplied by both solar and nuclear but the focus has been on solar. During photo-electrolysis, the energy of visible light is absorbed using photo-catalysts and then utilized to split water into hydrogen and oxygen gas with a process similar to electrolysis. This process has a very low conversion efficiency and requires sunlight to function [18].

Biomass originates from plants, which consist of biomass in which energy from the sun is stored in chemical bonds through photosynthesis. When biomass is used for energy production CO_2 is emitted, but plants regrow and absorb the amount of CO_2 released, thus closing the carbon loop. There are multiple ways to produce hydrogen from biomass which can be categorized into thermochemical and biological processes. The biological processes are less energy-intensive and more environmentally friendly than the thermochemical alternatives but they also have lower production rates of hydrogen. Thermochemical processes have much higher production rates, whereas gasification is a promising option due to its good economic and environmental properties [18].

Most biological processes operate under ambient conditions and are therefore less energy-intensive than thermochemical processes. The main feedstocks are water, where hydrogen is produced by bacteria or algae through their hydrogenase or nitrogenase enzyme system. Biomass goes through a fermentative process where carbohydrates are converted into organic acids and then hydrogen. Bio-photolysis, dark fermentation, and photo fermentation are the most common biological processes used to produce hydrogen [18].

Hydrogen production through hydrocarbon reforming can use steam or oxygen as a reactant, in which the endothermic reaction is known as steam reforming or partial oxidation respectively. Steam reforming, which involves a catalytic conversion of the hydrocarbon and steam to hydrogen and carbon dioxide, and consists of the reforming of syngas, followed by water-gas shift and gas purification or methanation. The most developed technology with infrastructure to support it is SMR, which has a relatively high conversion efficiency [18]. The amount of carbon dioxide formed during this process is not larger than the amount produced during the direct burning of the methane gas [8] but the amount of CO_2 generated will still be a major byproduct since the technology is dependent on fossil fuels. Utilizing carbon capture and storage is therefore important for SMR and the process with CCS is shown in figure 3.3. From the figure, there are three locations where CO_2 can be captured, either after the water-gas shift reaction, after the pressure swing adsorption, or from the SMR flue gas. Fuel and natural gas feedstock is fed into a reformer where the steam reforming takes place and produces CO and hydrogen gas. In the water-gas shift reaction step, more hydrogen is released where the carbon monoxide reacts with water to form hydrogen gas and CO_2. After this step, about 60% of total CO_2 can be captured by using a methyl diethanolamine solvent. Then the pressure swing adsorption is used to separate the hydrogen gas from the gas stream. It is then possible to capture CO_2 from the tail gas by once again using a methyl diethanolamine solvent to achieve a 55% capture rate of total emitted CO_2. The final option is to capture the CO_2 from the flue gases from the steam reforming. where the CO_2 is captured by using a ethanolamine solvent and achieves a 90% capture rate. The tail gas leaving the pressure swing adsorption unit is sent to the primary reformer as fuel [4]. Implementing CCS significantly reduces the amount of CO_2 emitted but leads to an increase in the production costs [18].

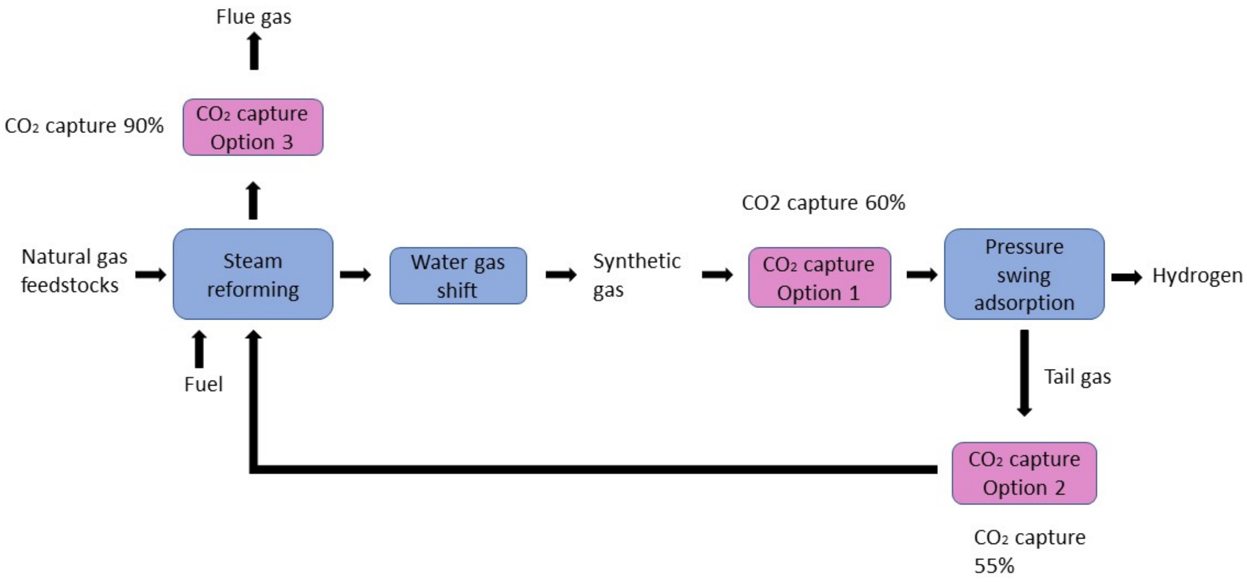

Figure 3.3: Production of hydrogen from natural gas with CCUS. With inspiration from [4]

Partial oxidation is also a proven technology and takes place when steam, oxygen, and hydrocarbons are converted into hydrogen and carbon dioxide. The plant requires a lot of capital due to the costs of the oxygen plant and the costs associated with desulphurization. Partial oxidation is the best option when heavier feedstocks are used, such as heavy oil residues and coal, and for hydrogen production. Coal gasification, which is a form of partial oxidation, is one of the primary ways to produce hydrogen from coal. Combining partial oxidation and steam reforming results in the autothermal reforming process, which supplies heat through the exothermic partial oxidation which is used for the endothermic steam reforming to increase hydrogen production [18].

Hydrocarbon pyrolysis is a CO_2 neutral technology still dependent on fossil fuels, with carbon as a byproduct. During pyrolysis, the hydrocarbon undergoes thermocatalytic decomposition where liquid hydrocarbons are converted into carbon and hydrogen. Heavy residual fractions require that the process is converted to a two-step process, consisting of hydrogasification and the cracking of methane. Pyrolysis does not include any CO_2 removal steps, replacing the energy-intensive stage of CCS from carbon management, which could be used in various industries or stored for future use [18].

3.3.2 Production centers

The hydrogen production hierarchy is expected to depend on local conditions and thus vary accordingly. The following principal types of centers are examples of how this could be done [15].

- Off-shore hydrogen centers produce hydrogen using wave, tidal stream, and/or wind power at very large scales through electrolysis of seawater, with local bulk storage in the subsea or nearby on-shore storages.
- Coastal hydrogen centers, which are located close to major cities or energy-intensive areas, produce hydrogen from wave, tidal stream, and/or wind power at very large scale through electrolysis of either fresh or seawater, and/or through SMR if necessary with bulk storages in land-based storage facilities nearby.
- Inland hydrogen centers are distributed throughout populated regions, particularly near large inland cities, regional towns, and industrial facilities. The hydrogen is produced by electrolysis, photolysis (if proven viable), or local biomass using solar and wind power, with storage in local small-capacity facilities.
- Autonomous hydrogen centers, distributed throughout remote, low population density areas, or new development sites located far from the centralized electricity grid, produce hydrogen from solar and wind power through electrolysis

or photolysis (if proven viable) of freshwater, or from local biomass resources. The produced hydrogen is stored in local small-capacity facilities.

3.3.3 Distribution

Hydrogen has been compared to electricity as a long-distance energy carrier in a nationwide distribution network [4, 15] but its low energy density means that the transportation can be expensive[4]. To overcome the high cost, compression and liquefaction are two options to be considered, and blending hydrogen into the natural gas grid or modifying the grid for hydrogen could also be an option. It is also possible to build new pipelines and shipping networks dedicated to hydrogen but this would be expensive [4]. When producing hydrogen using renewable energy stations, the production is more localized, which allows for more local production and consumption of hydrogen, thus reducing the need for long-distance energy transportation [15].

There are however some difficulties encountered with hydrogen energy transmissions. Hydrogen is typically produced at 15-80 bars by high-pressure electrolyzers and the pipelines thus most often operate at these pressure levels, using compressors to maintain the pressure [11]. In high-pressure hydrogen pipes, some of the difficulties that may be encountered are hydrogen leakage and hydrogen pipe embrittlement; when transferred in liquid form there is also a risk of hydrogen boil off [15]. If transferred in a liquefied state, the hydrogen has to be cooled to $-253°\text{C}$, which represents about 25-35% of its energy content. Pipelines have lifetimes spanning from 40 to 80 years and low operational costs but the main challenges to overcome are the high capital cost and acquiring rights to build new pipelines, making it crucial to have governmental support [4].

Hydrogen is commonly transported by gas trailer trucks with compressed hydrogen when the transport distance is less than 300 kilometers. Liquid tankers are used when there is a reliable demand and the liquefaction cost can be offset by lower transport costs, and it is generally cheaper to transport hydrogen in a liquid tanker. If it is possible to install high capacity pipeline, this will be the cheapest alternative, but the high capital costs often lead to reluctance of building out pipeline [4].

Produced hydrogen can be compressed and stored in geological storage, to be distributed when needed. It either goes directly from production or storage by truck or pipeline, as compressed gas or liquefied in cryogenic tankers, to the point of use. Depending on the pressure of the hydrogen gas or if it is liquefied, there are energy penalties and electricity requirements involved. [11]

3.3.4 Hydrogen storage

Utilizing hydrogen storage provides new opportunities for energy storage. Other forms of energy storage, such as batteries and pumped hydro, can fulfill the same energy needs but come with other limitations that hydrogen energy storage does not have. Batteries encounter storage degradation and a limited amount of energy that can be stored at the same time, unlike hydrogen which can be stored indefinitely with a capacity only limited by the size of the storage facilities. Batteries are best suited for shorter discharge times due to the limited capacity while hydrogen energy storage can be expanded to discharge energy for days to weeks. Pumped hydro does not suffer from the capacity and duration limitations of chemical batteries, but can instead only be used in geographic areas with hills or mountains, using large amounts of land, and are expensive to build [20]. By combining hydrogen storage with electrolyzers fueled through renewable energy sources, such as wind power, allows a significant share of curtailed energy to be stored are reutilized. A study in Japan found that this would allow 57.5% of all curtailed renewable energy to be stored, thus resulting in a higher efficiency of the gross renewable production [12].

3.4 Policies that facilitate hydrogen technologies and public perception

When new technologies are initially adopted, there are concerns regarding that technology, some justified, others irrational. This is true for hydrogen technologies as well, where some concerns regarding safety and feasibility have been raised throughout the years. For a breakthrough to happen, it is therefore imperative that public acceptance of hydrogen technologies is built, and for this purpose, it is key to implement policies supporting hydrogen development.

The public perception of a technology, commonly concerning benefits and costs, affects market and behavioral patterns for new technologies. Having an understanding of the public perception of the technology is therefore important and analysis is required to manage the transition for hydrogen technologies. Policymakers should engage citizens in effective, easy, and appreciated supporting actions to receive support. It is also important to keep the trust of the users to minimize opposition against hydrogen technologies [8].

There has been an ongoing debate regarding how safely hydrogen can be used for several decades. This is due to the "Hindenburg Syndrome" which is characterized by the fear of anything related to hydrogen and the consequences which may occur when hydrogen is used. Hydrogen comes with safety issues, but other fuels also have these issues. The results of many studies on hydrogen's safety show that it is not more dangerous than gasoline, natural gas, or any other fuel. Explosion energy, flame emissivity, and flame temperature of hydrogen suggest that it is safer than methane and gasoline. Since hydrogen is non-toxic, it means that leakages do not lead to environmental damage. Hydrogen also dissipates rapidly due to its low density which reduces the risk of fire or explosion, unless trapped inside a container [8]. However, hydrogen has a higher flammability range and therefore is a higher flammability hazard, since it is more likely for an explosion to occur [21].

As of today, the "Hindenburg Syndrome" from the public seems to be low and it is rather the fear of not knowing what the technologies are that the public is hesitant towards. There have been funded research studies in Europe to examine the social acceptance of hydrogen. From these studies, it can be seen that the views from a demographic with low education were mostly positive or neutral towards hydrogen, while well-educated people were more positive[8]. However, when it comes to implementing hydrogen infrastructures, such as pipelines and refueling stations, in the nearby area, they were more hesitant [17].

Climate change ambition is one of the most important drivers for use of clean hydrogen. Even though policy frameworks exist, they are not fully developed in most countries and regions. Most applications for low-carbon hydrogen are reliant on government support and are otherwise not cost-competitive. Certain regulations are unclear and are in some cases not written with new uses of hydrogen and therefore do not have the benefits of hydrogen in mind [4].

An example of countries that are implementing policies to support hydrogen development is Japan. They are a signatory to the Paris Agreement and have shown interest in establishing a hydrogen economy as a part of their overall climate change and energy transition strategy and they have shown this through their early and significant investment into hydrogen research and development. There are three stimulatory policy types to realize a hydrogen economy in Japan. The first promising type is the ambitious reduction targets, such as the 80% emission cuts. The second policy instrument that facilitates a hydrogen economy is putting a price on carbon, or carbon taxes. Carbon taxes and subsidies are considered essential to achieve carbon reductions but to reach the goal for 2050, these prices have to be significantly higher than what they currently are [12].

4

Applications

In this section, the most relevant hydrogen applications will be listed. This includes both current and future applications that have reached different levels of maturity and adoption. The current applications include chemical processes such as ammonia and methanol production. Applications that will likely see adoption rather soon are some FCEVs, such as personal cars and buses. Future applications are hydrogen blending and heat provision together with FCEVs such as ships and aircrafts. It is however more uncertain that the less mature applications will see widespread use, since low-carbon options need to be adopted soon due to the urgency of handling climate change.

4.1 Chemical processes

Currently, hydrogen is mostly used in the chemical sector for the production of other chemicals and to remove impurities of oil. For chemical uses, the main uses are; ammonia production, methanol production, and oil refining, which account for around 27%, 11%, and 33% respectively, and therefore constitute around 71% of global hydrogen use. The future growth of hydrogen use depends largely on downstream applications and demand. The hydrogen demand will probably be larger in other applications than the chemical sector, but they will most likely be important for the deployment of hydrogen in the future [4]. Most of this hydrogen has been produced from fossil fuels and it is most common to use hydrogen produced from natural gas, and some from coal [4, 22, 23]. The hydrogen can either be produced on-site, which is most common, or be purchased from merchant suppliers. There is, however, a possibility to establish low-carbon hydrogen technologies instead and pave the way for more environmentally friendly hydrogen applications. Energy efficiency and fuel switching are some options that have been adopted in refineries, which limits further emissions increase [4].

The demand for hydrogen in the chemical sector is expected to increase and will continue to increase. The increase in demand can vary, since there are uncertainties around the efficiency of chemicals produced from hydrogen-derived products and demand might not increase as much as expected. Demand for ammonia and methanol could increase if these chemicals were to become established energy carriers for the transmission, distribution, and storage of hydrogen, but also if they found new uses in applications, or if they were used as fuel. The demand could therefore rise even more. These uncertainties make it difficult to predict the future demand for hydrogen for the chemical sector [4].

4.1.1 Ammonia and methanol production

In chemical production, hydrogen is mostly used to produce ammonia and methanol but is also used in small-scale chemical processes. In the long term, the demand will continue to grow. The use of chemicals will be more efficient, but with the growing demand for clean chemicals, there will likely be a large growth in demand [4]. Ammonia can be obtained from hydrogen and nitrogen and has the potential to see quite a lot of use in the future since it also has low carbon emissions and is easier to transport than hydrogen. Higher ammonia demand will then in turn increase the demand for hydrogen and might be a viable way of hydrogen transport, or ammonia might be used in other end-use applications [22].

Ammonia is produced from the Haber-Bosch process, which is energy- and capital-intensive, and requires high pressure and temperature [22]. The production of ammonia has become one of the most vital industries in the world and is commonly used as a fertilizer and it would not have been possible to reach the current world population without it. Ammonia production typically occurs at pressures above 150 bar, and with higher pressure, less catalyst is needed for the reaction to occur at the same rates. In recent years, there has been a shift from reciprocating compressors to centrifugal compressors when it comes to processing equipment [23].

Methanol is usually not the final product, but it typically undergoes one further chemical transformation and is one of the major building blocks for a large number of synthetic materials. Methanol is commonly used to produce synthetic fuels and is one of the sectors that affect methanol demand [24].

4.1.2 Oil refining

In oil refining, hydrogen is primarily used to remove impurities from crude oil and to upgrade heavier crude [4, 25]. More specifically, the petroleum industries use hydrogen for hydroprocessing and hydrocracking of crude oil and its derivatives. Hydrocracking is used to produce lighter fuels with a high hydrogen/carbon ratio, which is the ratio of water vapor in the products of combustion, and refers to the simultaneous cracking and hydrogenation of heavy hydrocarbons. Hydroprocessing is used to remove heteroatoms, which are atoms that are neither carbon nor hydrogen, such as sulfur, oxygen, nitrogen, and heavy metals [26]. One challenge is related to hydrogen production and use is integrated within refining operations, which makes it tough to replace existing capacity. Another challenge is that the hydrogen costs influence the refining margins. It is expected that the demand for hydrogen will increase in the short term, but since oil will be used less, the demand will increase by a small amount [4]. In oil refineries, hydrogen is used as feedstock, reagent, and energy source [4, 25]. The hydrogen use of today is responsible for around 20% of the total refinery emissions and produces 230 Mt of CO_2 annually. Large-scale demand for hydrogen will increase as regulations for sulfur content will increase. The refining capacity to fulfill the expected demand for oil products is sufficient and together with the long lifetime of refineries, this limits the addition of new refining capacity. In 2030, most hydrogen supply would come from refineries that already exist [4].

As of today, economical incentives for refineries to retrofit their hydrogen production facilities with CCUS are low. This is because they would rather pay the carbon tax instead of having to make capital costs for the required retrofit. It would therefore be necessary to have a higher CO_2 tax before it would be economically feasible. The introduction of CCUS is also dependent on the costs of the storage of CO_2. Several refineries have implemented CCUS to their facilities, but with higher capture rates, the price significantly increases. There are currently few refineries that use electrolysis to produce hydrogen, but policy support is needed to increase the wide use of electrolysis [4].

4.2 Natural gas network modification and applications

Current natural gas networks provide gas to consumers and can be distributed over large distances and for multiple applications. Hydrogen infrastructure is, as previously stated, underdeveloped and could use a gas network such as the one which natural gas is currently using. One option to support the deployment of hydrogen gas and decarbonize the already existing natural gas network is to retrofit and modify the gas network to use hydrogen. The current gas network can not support pure hydrogen and needs to see large modifications. A possibility is to blend hydrogen into the gas network and therefore have a blend of hydrogen and natural gas. For lower volumetric hydrogen concentrations, there are little effects on the supplied gas and infrastructure, but when the concentration increases, problems progressively arise [27].

The gas network could be used as a form of storage of hydrogen produced and could therefore help with the integration of renewable energy sources and would help with curtailment issues. This is therefore a power-to-gas solution where the gas afterward could be used in different applications, such as heating and other gas-related applications. Figure 4.1 shows how a power-to-gas network could be utilized for different applications [27].

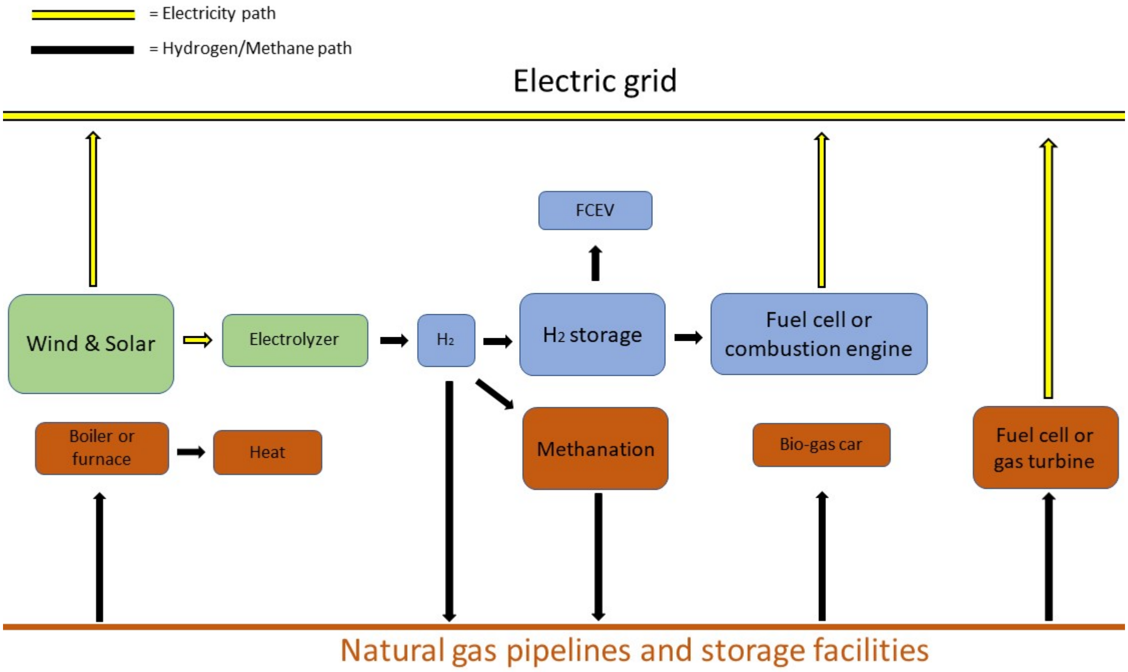

Figure 4.1: Example schematic Power-to-gas network. The generated hydrogen could be stored, blended into the natural gas pipelines, or methanized to create synthetic natural gas. The gas can then be used in applications such as heat, fuel for vehicles, or be converted back into electricity for the grid. Made with inspiration from [27]

4.2.1 Hydrogen blending and network conversion

If hydrogen is produced from low-carbon energy sources, such as steam methane reforming with CCUS or through electrolysis powered by electricity from renewable energy sources, it can significantly reduce greenhouse gas emissions [4, 27–30]. In a system that uses a considerable amount of renewable energy sources, a lot of the electricity will be curtailed, but if more hydrogen is allowed to be injected into the gas network, this could instead be used and lower the natural gas demand [30]. Hydrogen produced from curtailed electricity can be stored in the pipeline gas network as linepack, which is when the pressure is increased or reduced in the transmissions pipeline to release or store additional gas [29]. It is possible to store hydrogen of up to 50% volume concentration, with some technical adjustments [27]. In a future with a lot of hydrogen production, large-scale storage will also be necessary and these two storage options will work in tandem [4]. The blending of hydrogen into the natural gas network links the electric and gas systems by storing otherwise curtailed electricity in the form of hydrogen or synthetic natural gas. Power-to-gas processes are expensive and have low efficiencies. Overall power-to-gas efficiency is around 56%, which includes the process of methanation. If the methanation part is excluded, the efficiency is around 70% and it is therefore desirable to use hydrogen directly [27].

There is always resistance towards rapid change, and it is therefore likely that hydrogen blending would begin at low levels and increase when modifications are made to the natural gas system. End-use requirements are often the limiting factor when it comes to the concentration of hydrogen in natural gas blends [28]. With relatively low concentrations of 5 to 15% of hydrogen blend, the strategy of storing and delivering hydrogen through the gas network seems to be viable without significantly increasing risks related to hydrogen, such as utilization in end-use applications, public safety, and the function of the existing natural gas pipeline network, but appropriate blends will differ between systems [27].

It is difficult to make an assessment of hydrogen blends into the network, due to multiple factors that are involved. Hydrogen has a broad range of conditions where it will ignite and the main concern is the increased likeliness of ignition which it entails [27, 28]. The compressors of the system are often the limiting factor of the hydrogen blend where they typically have a limit of around 10% concentration, while the distribution network and storage allow for higher hydrogen blends. The material can handle mixtures of up to 30% hydrogen without seeing any significant effects, but after an increase of 50% of hydrogen, there is a risk of material failure of the pipeline [27]. Technical issues related to the injection of hydrogen into the existing natural gas network are hydrogen embrittlement, the low energy content of the hydrogen that might lead to linepack swings, and safety issues [30]. For turbines and gas compression, the operation remains non-critical for concentrations of 10% and 20% respectively. For gas turbines, the recommended hydrogen concentration is in the range of 1 to 5%, but with moderate retrofitting, it is possible to increase it to 10%. Gas turbines are being developed which can handle higher mixes of hydrogen [27]. Some projects focus on the blending of hydrogen into the natural gas network and studies have shown that it is possible to use existing pipelines for natural gas to retrofit them to operate with pure hydrogen [4]. It not possible to directly use hydrogen in units designed for natural gas due to the higher combustion velocity of hydrogen, thus making specialized hydrogen burners required [26].

The blending of hydrogen also affects the calorific value of the natural gas [27, 30]. It will be necessary to adjust the gas flow rate when hydrogen is injected into the network to satisfy gas network operating constraints. This has to be based on the amount which is injected and also that it can be injected at different points of the gas network [30]. A 2% blend of hydrogen into the gas network has a negligible effect on the gas quality, but a 10 to 20% concentration affects the calorific value of the gas mixture below desired levels [4, 27]. It will be necessary to increase the flow rates of mixtures according to the demand. An example for a 15% hydrogen and 85% natural gas mixture would require a flow rate increase of 1.7 to maintain the energy supply and it might be necessary to replace existing compressors and valves. A consequence of high flow rates is a pressure drop within the pipeline, and hence a pressure drop in the pipeline transmission and distribution network is affected [27].

High levels of hydrogen when in contact with steel can lead to hydrogen embrittlement, which is troublesome for end-use applications. Other applications also have to be tested to ensure that the hydrogen does not have large negative effects, and there are also potential leakages in the gas network [27, 28]. Hydrogen has higher mobility than methane in a lot of polymer materials, such as the elastomeric seals and plastic pipes used in natural gas distribution systems and the permeation rate is about four to five times greater than for methane. There is generally leakage through the threads or mechanical joints in steel and ductile iron systems and measurements, it has been concluded that the volume leakage rate for hydrogen is about a factor of 3 higher than for natural gas. An estimate has been made that in a network with a 20% hydrogen blend, 60% of total losses would be of hydrogen and 40% natural gas. Even though the leakage is considerably higher for hydrogen, the total gas volumetric losses are 0.0002% of the total delivered natural gas mix. This was however seen as an overestimation and in a test made with a 17% hydrogen blend, the gas leakage was 0.00005%, but further investigation is needed to have a clear view of total gas leakage, which will probably differ from system to system anyway. Even though the overall leakage is negligible, there is a risk that gas might leak into confined spaces and might pose a safety risk. Leakage from elastomeric seals at joints might increase this risk and monitoring and further analysis might be required [28].

The blending of hydrogen has also been proposed as a means of distribution of hydrogen to markets, where the hydrogen will be separated and purified downstream to extract the hydrogen from the blend. Since there is little delivery infrastructure of hydrogen, this would help in the deployment of the early hydrogen market development. This strategy leads to costs related to the blending, extraction, and modification of existing pipelines. Pressure swing adsorption , membrane separation, and electrochemical hydrogen separation are three gas-separation technologies that may be used for downstream separation of hydrogen from natural gas. It might be hard to acquire high purity hydrogen, especially for lower hydrogen concentrations [28].

There are different hydrogen pipeline transmission pressures that can be utilized for a hydrogen gas network. For the National Transmission System is the pressure range 45 to 85 bar, the Local Transmission System range is between 7 to 70 bar, and for the distribution system, it is up to 7 bar. In the distribution system, the pressure is divided into intermediate pressure between 2 to 7 bar, medium pressure of 0.075 to 2 bar, and low pressure under 0.075 bar [29].

4.2.2 Heat

Heat generation in households and industry is responsible for about half of the global energy consumption and over a third of all CO_2 emissions [26]. About 30% of global final energy use goes to the buildings sector, where around 75% is used for space heating, cooking, and hot water production. About half of the heat is produced from fossil-based fuels, where most comes from natural gas [26, 29]. Most of the rest comes from electric equipment, for example, cookstoves and electric resistance radiators, and commercial heat, where around 85% of which was produced from fossil fuels. Almost 28% of global energy-related CO_2 emissions come from the energy required for buildings [4]. Electricity for heating would require an entirely new system in some parts of the world. This would require a lot of time and effort and with the existing natural gas networks, it would be easier to replace this with hydrogen and would be faster [29].

It is challenging to replace the heat provision with low-carbon alternatives and the reduction of heat demand. To make decisions for energy use in buildings there are multiple factors to take into account, like building type, ownership, location, equipment costs, customer preferences, energy prices, and overall convenience, which makes it complex. Due to the many factors to have in mind, it will be necessary to have many different options that co-exist and complement each other, like heat pumps, boilers, district heating, and solar thermal heating. Hydrogen can be blended into the existing natural gas network to make the natural gas stream less carbon-intensive and it can be used to produce methane. It can therefore make use of existing building and energy network infrastructure and provide flexibility and continuity [4].

Hydrogen has seen little use in the global buildings sector, but there are some areas where it has the potential to see use. Some projects have focused on micro co-generation and fuel cell hydrogen [4]. Several hydrogen to fuel cell technologies to deliver heating exist. This includes hydrogen boilers, fuel cell combined heat and power (CHP), and residential fuel cells. Residential fuel cells have seen significant adoption, especially in Japan with them having adopted 223 000 micro-CHP systems. Fuel cell CHPs are quiet and have low emissions which make them very good for use in urban areas [11]. There have been several homes that have a stationary fuel cell system connected to their home for heating, but which uses natural gas or liquefied petroleum gas. The two main uses are hydrogen blending and direct use of hydrogen for heat production in buildings. These potential applications can see use in countries where heat provision has to be provided to existing buildings. Buildings that are more than 25 years old, and which typically require energy-intensive heating loads, will represent a sizable share of the overall building stock for a long time, and heat demand is therefore certain in the future. A major advantage for the use in the building sector is the potential to find synergies with the energy system that provides advantages in terms of the overall system cost of low-carbon transitions [4].

To only use hydrogen in buildings is attractive for large commercial buildings or buildings complexes, and district energy networks. In cases with possibilities of hydrogen storage, fuel cells, co-generation units, or other hybrid systems could be used to meet electricity, heating, and cooling demand, while taking advantage of low electricity prices and on-site renewable energy sources. Fuel cells and co-generation technologies could also be used in district heating networks with storage and could improve power system balancing during the year, help avoid large seasonal peaks, and provide more flexibility to the grid. Together with large-scale heat pumps, these solutions could increase the overall efficiency of heat production for buildings. For broader buildings markets, hydrogen conversion in the longer term will depend on hydrogen price and technology cost. Hydrogen prices would have to be in the range of 1.5 to 3 \$/kgH$_2$ in a lot of major heating markets to be able to compete with natural gas boilers and electric heat pumps. In countries with low gas prices, it will be harder for hydrogen to become cost-competitive. More weight is typically put on high upfront costs than on overall lifetime costs. The cost of heating equipment varies with unit capacity, consumer preference, brand, availability in local markets, and overall size of the product demand. Ease of installation and safety are also factors that have to be considered. If hydrogen as the sole heating gas can be cost-competitive in the capital- and operational costs, in some markets, the market potential in buildings is massive. Heat will remain central in the energy consumption of buildings. Achieving high levels of hydrogen use in buildings, and higher levels in the long term sees several barriers. High upfront capital costs, higher energy demand prices for consumers, and also safety concerns pose difficult problems to overcome [4].

4.3 Fuel cell electric vehicles

Fuel cell electric vehicles are some of the most covered applications for hydrogen in literature, especially in automobile applications. The main reason for this is because hydrogen vehicles can decarbonize the transport industry, and therefore improve local- and global air quality, and these are urgent priorities since, climate change is a threat that requires immediate action, and over half a million premature deaths occur in Europe per year due to particulates and NOx emissions [11].

The competitors to the FCEVs are the power trains of internal combustion engines (ICE), BEVs, and hybrid vehicles. The ICEs are currently the cheapest option and FCEVs are the most expensive, FCEVs have the potential to drop in price when manufacturing volumes increase. Several analyses see that mass production could see its total cost of ownership converge with other principal powertrains by 2030 [11]. FCEVs usually have a similar travel range to an ICE, while BEVs usually have a shorter range [9, 11, 31], and this is due to the high energy density of of the hydrogen [31]. The refueling time for ICEs and FCEVs are quite similar, while it takes much longer to charge a BEV and if faster charging of the batteries is employed, then the lifetime of the batteries will decrease, since the fast-charging degrades the battery faster. If a BEV wants to extend its range, it means that the vehicle will become much heavier [11]. For an FCEV the tank might require more space, but the added weight is insignificant, and the volume requirements are more problematic [32].

There are a few identifiable barriers for FCEVs, and to shift the use of fossil fuels in the transportation sectors to hydrogen fuel cells, a radical change is required in both resource base and technological routes used in supply, distribution, and on-vehicle consumption. The primary sources used are completely different from the fuels mainly used today, and as such, a lot of new infrastructure and technologies are necessary [15, 33]. The industrial base backing the use of hydrogen technologies is still relatively small and unorganized politically. The lacking community support regarding hydrogen may have its roots in that those who are advocating for a hydrogen economy consider hydrogen to be an essential good in itself rather than arguing for hydrogen in terms of sustainability and environmental benefits [15]. Production and transportation of hydrogen to the refueling stations are unproblematic, but the number of stations is. FCEVs have been proven to be a feasible concept and their availability and reliability are high enough for commercialization [33].

4.3.1 Automobiles

Almost half of the global energy demand from the transport sector comes from light-duty vehicles and the number of passenger cars is expected to increase from 1 billion to 2.5 billion by 2050. Due to the bad air quality which comes from ICEs a lot of cities and countries are trying to ban ICEs, or at least promote vehicles with lower emissions [11, 31]. BEVs and FCEVs are the two zero-emission tailpipe vehicle options available today, and when it comes to the fuel cell system, the efficiency is twice as good as that of the ICE drivetrain [9, 11]. Currently, BEVs are several years ahead of FCEVs in terms of maturity, and this can be seen in car prices and the infrastructure that supports BEVs [11, 31]. Due to the inefficiency of hydrogen from well-to-wheel, there are opinions against hydrogen in the energy system. When hydrogen is produced from renewable energy sources by electrolysis and is used as a fuel in FCEVs the efficiency is 19-23%, whereas the efficiency of electric vehicles using renewable energy sources and charging of battery has an efficiency of 69%. It is however necessary to have economic estimates. These efficiencies do also not consider energy storage [16]. The expected lifetime of a battery is 10-15 years, but the fuel cell stack of the FCEV is expected to outlive other drivetrain components. Both FCEVs and BEVs offer quieter cars and therefore lower noise pollution. However, hydrogen tanks are rather large and inconveniently shaped, which means that a lot of space is taken up, and therefore there is less space for other necessities, such as luggage space [11]. Other issues include hydrogen handling, battery costs, fuel cell component costs, water management, etc [31].

The fuel cell system is the main power source in FCEV automobiles. The most common solution to store hydrogen is to use a composite material, which is made out of carbon fiber wrapped metal or plastic cylinder, with a storage pressure of 700 bar to provide sufficient driving range. The storage system consists of valves, pressure cylinders, sensors, and piping. A small battery is also onboard the fuel cell automobile to recover braking energy and to have an optimized operation of the fuel cell system. The overall tank-to-wheel efficiency of an FCEV is very high and is twice as high as compared to an ICE. The well-to-wheel efficiency of the FCEV is, however, lower than that of an ICE. FCEV costs are still significantly higher than costs for ICEs which are the most common on the market [33].

Proton exchange membrane fuel cells (PEMFCs) are the most commonly used fuel cell in automobile fuel cell applications, due to the high energy intensity and relatively low complexity of the PEMFC. Since hydrogen is highly volatile and explosive storage and handling are difficult [31, 33].

It is still expected that the ICEs will have a dominant role in the transport sector for the coming decades, due to their low price, easy to handle, and infrastructure which is already in place [8]. However, due to the recent success of hybrid and plug-in electric cars, the expectations for fuel-cell cars powered by hydrogen have lowered. There has been hope in the industry that the costs of the fuel cell would follow that of the batteries, where the costs have sunk by a considerable amount during recent years. This has however not happened and is a reason that the fuel cell electric car has started to fall off. This is mainly due to the high cost of fuel cells and the need to develop refueling infrastructure which brings the fuel cell vehicles down. Honda decided to move out of the automobile market for hydrogen in April of 2019 and in March of 2020 Volkswagen, Daimler, and General Motors did the same [32].

4.3.2 Heavy-duty road vehicles

Most heavy vehicles are not dependent on a spread-out network of refueling stations, since they can follow a predetermined route of the central hub, and therefore fleets can be refueled from one refueling station[32]. There is little use of hydrogen in road freight transport, but Honda, Volkswagen, Daimler, and General Motors have begun looking at heavy commercial and military vehicles, where refueling can take place at centralized locations. The fuel cell has a constant power output and if excess electricity is produced it is used to charge a battery when extra power is needed, the battery can supplement the fuel cell [32]. Trucks also show considerable potential for fuel cell adoption as high energy requirements mean few low emissions alternatives exist. Long haul heavy vehicles which require high utilization are likely to require hydrogen. This is due to the long-range which hydrogen can provide and also fast refueling times compared to batteries [11].

Several countries have also started to use hydrogen buses for their public transport. In China, they had around 300 buses in operation in 2019 [11]. For bus yards, it is easier to refuel them compared to using electricity, where it takes much longer to charge them, but it is also cheaper to recharge with electricity [32].

Hydrogen buses have reached a rather high level of maturity, but they are currently not in large-scale production and therefore mean that they are substantially more expensive than conventional buses. Hydrogen buses can see gradual implementation, just a few can be used for a start, and then more and more can be purchased and be put into operation as older buses are replaced. Since fuel cell buses will lead to higher costs, it might lead to higher fares for passengers, unless some policies or incentives support the implementation of the buses. Higher fares will lead to fewer passengers, and they might switch to unsustainable options [34].

Even if there would be enough hydrogen production from renewable energy sources, there are still not sufficient storage options that can supply enough hydrogen for a large fleet of hydrogen buses [34].

4.3.3 Forklifts

Other promising applications include forklift trucks, with around 12 000 fuel cell units deployed in the US and a handful elsewhere. The zero emissions from fuel cell forklifts allow them to operate indoors and their faster refueling can lead to total consumption cost savings of up to 24% in a typical throughput warehouse [11]. Fuel cell forklifts refuel in approximately 3 minutes, which is very fast compared to an electric truck which can take around an hour to recharge. Hydrogen refueling dispensers also only take up a small portion of space inside the facility, compared to the battery equipment. The refueling equipment can be located outside of the facility where space is less precious. The capital cost is however higher than for electric trucks. The upsides of using fuel cells for industrial trucks are improved operational performance, more reliability, less maintenance overhead, and faster refueling compared to batteries [33].

Industrial trucks give fuel cell manufacturers a market on which they have the opportunity to build economies of scale by developing small modular fuel cells that can later be scaled up for other transportation markets. The market for trucks is substantially smaller than that of the automotive market and it should be easier to penetrate these markets [33].

4.3.4 Trains

Plans exist to convert electric trains to hydrogen trains to negate the need for rail electrification and meeting goals of eliminating diesel trains. Once again, this is due to the longer range hydrogen can provide and also the shorter refueling times [11]. Hydrogen trains can offer higher efficiencies, and lower energy demands, and can act as a complement to electric trains on long trips on rail without overhead charging. A 350 bar hydrogen tank is usually located on the roof of the train, and will therefore not take up space inside of the train and can guarantee a suitable hydrogen amount for required operations. Similarly to other FCEVs, the hydrogen train infrastructure must be built out and hydrogen refueling stations are essential [35].

Hydrogen trains have the highest potential in rail freight, since there is usually regional lines with low network utilization and cross border freight. Hydrogen trains are good options in non-electrified regions, which are quite large in most countries. With optimistic assumptions, there is a possibility that trains with fuel cells could become cost competitive on passenger services with low frequency of utilization [4].

4.3.5 Ships

The maritime shipping sector, which has been growing in recent years, has seen an increase in trading and transportation of cargo ship and thus a following increase in the consumption of maritime fuels. The implications from this are caused by the increased emissions from consuming an increasing amount of fossil fuels [26]. Maritime freight vessels usually use heavy oils as fuel, which leads to detrimental effects on air quality, especially near ports [4]. Other feasible fuels are necessary to address the challenge of ever-increasing fuel prices, and both liquid and gaseous fuels (such as hydrogen) have been investigated [26]. Hydrogen can help reducing both the global and local emissions and also synergize with forklifts, trucks, and goods movement in connection to the port. There is a possibility to co-fire hydrogen together with diesel to lower total emissions, and a possibility exists to use ammonia as fuel [4].

International shipping volumes are expected to increase by a substantial amount in the future, and will lead to higher demand for oil products. It is however more likely that hydrogen will be used for oil refining, rather than fuel, at least on the short term. Large freight vessels require large power demands, and have high per-kilometer energy intensity, and therefore have high fuel requirements. Infrastructural and ships costs will be rather small compared to the fuel costs during the lifetime of a ship. This is especially true for long-distance maritime trade routes, since hydrogen storage and fuel cells costs will be much lower compared to fuel costs. Space requirements could pose a rather large problem, especially for smaller ships. Storage of liquid requires around five times more volume than oil-based fuels, and ammonia requires around three times the volume. To use these fuels, long term redesign of maritime freight vessels will be necessary. It might be necessary to have more frequent refueling and/or reduced cargo volumes to make it possible to use hydrogen or ammonia as a fuel [4].

An average vessel will be operated on a worldwide basis. For special applications like ferries, it might only be necessary with a single point of hydrogen infrastructure. The high energy demand will however lead to a large hydrogen storage capacity. Storage tanks will require large amounts of space and also be heavy. It will therefore be necessary to store hydrogen with as little space as possible. It could be viable to have the reformer system onboard and instead store fossil fuels. It is unclear how much space this would require and the costs related to implementing it on the ship [33].

The fuel cell system weight is also around 7 to 19 times higher than for a diesel generator and the weight per kilowatt must decrease. The volume uptake is around 10 to 15 times larger than for a diesel generator and the volume per kilowatt must therefore also decrease. The lifetime of a fuel cell system of this kind would be between 10 000 to 40 000 hours and it has to be comparable to that of a diesel generator which has a lifetime of about 25 000 to 30 000 hours. It will be a challenge for the fuel cell system to enter the market and the reliability and availability will be a problem [33].

4.3.6 Aviation

The most popular fuel in the aviation sector is kerosene, where most other fuels used also originate from petroleum resources [26, 33]. There is a growing interest in the use of alternative fuels to minimize the environmental impacts and facilitate energy security, and liquid hydrogen is one of these alternatives. Liquid hydrogen emits fewer greenhouse gases than kerosene and can be produced from renewable lifestock, while also coming with the benefits of low maintenance costs, long engine life, high energy content, and improved combustion mechanics [26]. The more efficient energy to power transformation which fuel cells offer could be an advantage over fossil fuels, together with the environmental benefits [33]. It does however come with some difficulties, where its low ignition energy and high flame velocity puts up a barrier during combustion, and there is a risk that traces of unburnt hydrogen will cause hydrogen embrittlement. The cost of using hydrogen is also higher than that of conventional jet fuel [26]. The gravimetric energy density of hydrogen is about four times higher than kerosene, but the volume requirements are still higher for gaseous hydrogen. Liquid hydrogen requires less space, the liquefying process requires about one-third of the energy content of the hydrogen is stored. The tanks must be kept in a cryogenic state to avoid heat going into the storage system, which would lead to boil-off of hydrogen. Making a transition towards turbo engines that uses hydrogen would require new aircraft designs. The high volume requirements would result in higher drag forces on the plane, more weight and an efficient insulation system would be needed to counter boil-off. Similar to other applications, the infrastructure to support hydrogen in aircraft applications is underdeveloped. Another problem is that the water vapor coming from the combustion is 2.5 times higher than that of kerosene and at high altitudes, the water acts as a strong greenhouse gas [33].

In military use on a small scale, hydrogen offers two advantages. Firstly, the high energy content by weight and secondly the ability to convert hydrogen at a low temperature into electricity. This makes it difficult to detect the aircraft by usual means. Hydrogen is good for long endurance flights since the weight of the propulsion system remains nearly the same[33].

Usage of pure hydrogen in aviation applications still requires significant research and development, since the volatility of hydrogen and need for cryogenic hydrogen would require large changes in aircraft design. Using hydrogen as fuel in commercial aviation applications will be much more expensive, and since fuel costs represents a large share of total operation costs for aircrafts, the ticket prices would increase by a lot. This might lead to customers choosing cheaper traveling options that are less expensive and more carbon-intensive [4].

4.4 Hydrogen in metallurgical industries

In the metallurgical industry there are two main technological areas for the utilization of hydrogen:

- Burning hydrogen at a high temperature produces oxy-hydrogen flames through the reaction between hydrogen and oxygen, capable of reaching temperatures above 3000°C. These are used for welding, oxy-hydrogen cutting, or in the metallurgy of non-ferrous metals when processing elements with a high melting point [26, 36].
- Elemental hydrogen has an inherent reducing ability to precipitate metal powders from aqueous solutions of the metal's salts. Hydrogen reduction is viewed as one of the most reliable production methods for metal recovery and is thus widely used in metal processing. [26]. The hydrogen contained in the gases obtained from burning alternative fuels cooperates as a deoxidizing agent, significantly influencing the course of combustion and improving the kinetics of reducing reactions. The reduction reaction of hydrogen is less endothermic than the direct reduction by carbon, thus leading to a better heat balance in the furnace [36].

Metals, rarely encountered in their pure form besides noble metals, copper, and mercury, are commonly found as compounds with oxygen, sulfur, and halogens. To extract the metals from these compounds, the process of reduction is used, utilizing natural gas, methane, hydrogen, aluminum, magnesium, calcium, silicon, etc as a reducing agent. One of the most frequently used reducers is carbon due to its high efficiency with relatively low costs and wide availability. Tackling the large carbon footprint of the metallurgical industry is a great challenge that has lead to alternative reducers being investigated. Hydrogen is one of the most promising reducers that is already used in the industry to achieve the required emissions reductions without the quality of the product deteriorating [37]. Hydrogen is a cleaner, efficient, and very energy-dense from an energy and environmental perspective due to its ability to participate in metal interactions with elements from different groups of the periodic table. It is also able to attract free electrons and do self-trapping in metals, thus creating a state of electrostatic shielding. Hydrogen can be used in aqueous solutions to reduce nickel, which currently is a common production path for nickel. The rate of production depends on a multitude of factors, such as particle size, the pH of the solution, metal concentration, and the types of additives [26]. Hydrogen can replace carbon containing reducers both for producing non-ferrous metals and producing steel. In powder metallurgy it is also used for sintering and treating various metals, not only as hydrogen but also in mixtures of other gasses [37]. The reaction kinetics of pig iron production are improved when using hydrogen, mainly due to the endothermic reaction being smaller than that of direct carbon combustion, thus improving the blast furnace's heat balance [26].

4.5 Hydrogen storage

Hydrogen storage is an important technology that is the key to advancing the application of hydrogen technologies. Hydrogen, which has the highest energy per mass of any fuel, has a low density at ambient temperatures and thus low energy per unit volume. This means that developing advanced storage methods is important to improve the energy density [38]. The most common way to store hydrogen is as a pressurized gas which, due to the low density, requires either high pressures or extremely low temperatures. Hydrogen is however, a volatile substance and there is a risk of leakage from the high-pressure vessels. The materials used for the pressure vessels are commonly steel and aluminum but another option is to use carbon fiber reinforced plastic composite vessels. This alternative is adequately strong and has an impact resistance high enough for safe storage with a low weight compared to steel and aluminum but this comes at the expense of increasing costs, which is undesirable for hydrogen deployment [39]

Geological storage is most likely the most optimal solution for large-scale and long-term storage which can utilize salt caverns or depleted reservoirs of gas or oil [4]. The hydrogen can be stored at higher pressures and discharged at a relatively high rate with a low degree of hydrogen leakage, making this a desirable storage alternative [39]. The geological storage today is mostly used for natural gas with high efficiencies, low operational costs, and low land costs, and they can potentially be converted to store hydrogen [39]. The hydrogen storages in use have an efficiency of around 98% and a low contamination risk while hydrogen stored in tanks, either as liquefied or compressed hydrogen, have similar benefits with a high discharge rate and efficiencies of around 99% [4, 39]. These storages are attractive in industrial and power appliances, since a high pressure can be maintained, but the technology is still unproven with uncertain costs and no proven feasibility [4]. The geological storage of hydrogen can be used to complement renewable energy sources through discharging hydrogen during times of low wind and solar power production and used to generate electricity [39].

Cryogenic storage provides a higher density, 1.8 times more dense when at its boiling point of 20 K than hydrogen compressed to 700 bar at 278 K. To maintain the low temperature, about 30% of the hydrogen's total energy content is needed, making it essential to develop special double-walled vessels with good insulation systems to reduce the heat leakage. The more compact and lighter cryogenic vessels provide more safety than the storage vessels for compressed hydrogen. The problems that restrict cryogenic storage are the boil-off of hydrogen and the high energy requirements to maintain the low temperature [39].

An issue encountered with the utilization of hydrogen is the large volume requirements of hydrogen storage in applications where space is limited, such as for fuel cell electric vehicles. Storing hydrogen in solid-state materials could provide a solution to this since solid-state materials can reversibly release and absorb hydrogen [39]. It is a promising storage method, capable of guaranteeing compact, stationary, and long-term storage of hydrogen in hydrides with a high level of safety and capacity [37]. This storage technique is limited due to the low hydrogen storage capacity at ambient temperatures, thus requiring lower temperatures for a high storage capacity. There have been several prototypes created of complex hydride vessels that have confirmed high energy densities but they are limited by the complexity of the hydrogenation and dehydrogenation reactions. Metal hydrides has been recognized as the alternative with the highest potential for a high gravimetric capacity for hydrogen storage. The hydrides are formed through chemical reactions, acting as a physical storage method, where the hydrogen molecules bind with metal under relatively low temperature and pressure. One issue encountered with this technology is the weight, where metal hydride tanks are heavier than compressed hydrogen tanks, but this issue should be irrelevant for stationary use and other niche applications. The weight issue might even be solved through the discovery of lighter novel materials that can be used for mobile applications. Storing hydrogen in this manner is significantly denser than both liquid and compressed hydrogen, where magnesium hydrides has an atom density of 6.5 hydrogen atoms/cm^3. In comparison, liquid hydrogen has 4.2 atoms/cm^3 and hydrogen gas 0.99 atoms/cm^3 [39].

5

Compressors and bearings

SKF have previously determined that compressors will be important in the supply chain of hydrogen. Bearings are usually necessary for the function of compressors and by determining what compressors it is that will be used, it is also possible to determine what bearings it is that will be needed in the supply chain of hydrogen. This section will therefore try to map out the possible compressors that will be used for the mentioned applications in the hydrogen supply chain and explain the working principles of some of the most common compressors for hydrogen. Bearings that are used for some of the compressors will also be presented.

5.1 Compressor requirements and types

Hydrogen compressors have requirements that have to be met to have smooth operation and to avoid early failure of the turbomachines. Firstly, the compressors should be non-lubricated, since lubrication oil can lead to contamination and therefore all of the compressor suggestions do not have any oil for lubrication [40]. The required discharge pressure of the compressors varies between applications and can reach pressure levels of up to 900 bar. For example, FCEV automobiles require compressed hydrogen at 700 bar and to achieve these high pressure levels a pressure of 900 has to be achieved to have a smooth flow of hydrogen into the vehicle [41]. Flow rate also varies between applications and is determined by the amount of hydrogen that requires compression, and is specified as the volume velocity. Discharge pressure together with the flow rate determines the required speed of the compressor, where speed is the revolutions per minute (RPM), where high discharge pressure and flow rate lead to high speed, but the flow rate has a larger effect on the required speed [42]. The duty cycle of the compressor has to be determined for the application and is the percentage of time while it is in use that it is running fully loaded and the other percentage is when it is running unloaded or needs to be off [43]. The amount of required stages for the compressor is determined by the discharge pressure and the compressor type. A centrifugal compressor typically has a lower compression ratio per stage and therefore requires more compression stages compared to a reciprocating compressor for example [44]. The size of the compressor is determined by the flow rate, the discharge pressure, and the duty cycle [45].

Compressors are machines that are designed to increase the pressure of gases. Classification and differentiation are based on the pressure increase, working pressure, specific speed, and mechanical design. These machines can be categorized into positive displacement and dynamic compressors [46, 47]. There are different working principles to achieve compression [46];

- One is to trap gas into some type of enclosure, then reduce the volume to increase the pressure, and then push the compressed gas out of the enclosure [46].
- Another similarly traps the gas in an enclosure and then carries it without changing the volume to the discharge opening, and the gas is compressed by overcoming backflow from the discharge system and also pushing the gas out of the enclosure [46].
- The gas can also be compressed by the mechanical action of rotating bladed rotors, or impellers that impart pressure and velocity to the gas. In an adjacent stationary diffuser, additional velocity energy is converted to pressure [46].
- Finally, the gas can be put into a high-velocity jet of another gas and the high velocity of the mixture can be converted into pressure with the help of a diffuser [46].

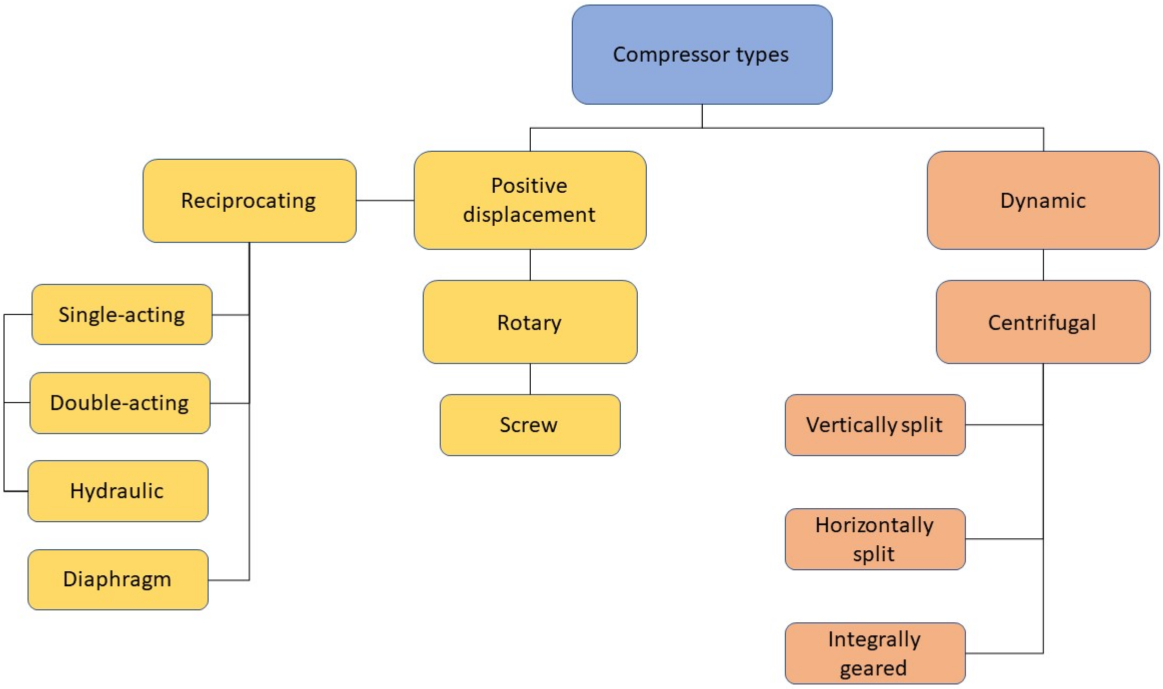

Figure 5.1: Compressor types commonly used for hydrogen applications

Figure 5.1 shows the compressor types and the subcategories of the compressors that are commonly used for hydrogen applications.

The most common compressor types and their classifications for hydrogen applications are:

- **Positive displacement**: The positive displacement compressors trap gas in a compression chamber and mechanically change the volume of the working fluid and increase the pressure of the gas before discharging it [46, 47].
  - **Reciprocating**: A subcategory of the positive displacement machines is the reciprocating compressors. The compressing and displacing element of this compressor is supplied by having a piston in a reciprocating motion within a cylinder [46, 48].
    - **Single-acting**: Single-acting reciprocating compressors use one cylinder to compress the gas on one side [48].
    - **Double-acting**: Double-acting reciprocating compressors compress the gas on both sides, and therefore use two cylinders. The double-acting variant is more common than the single-acting [48].
    - **Hydraulic**: Can be either single- or double-acting and is a type of compressor that converts hydraulic power to pneumatic power [49].
    - **Diaphragm**: The diaphragm compressor, also called a membrane compressor, is a reciprocating compressor that uses a rotary diaphragm to compress the gas. The rotating diaphragm delivers the gas into the compression chamber and applies the required pressure [50].
  - **Rotary**: Rotary screw compressors have seen much use and market share in the compressor market, where the most common type is the helical twin compressor [47]
    - **Screw**: Helical screw compressors have two intermeshing rotors that compress and displace the gas. Gas is trapped in the rotor pockets at one part and the other end, it is compressed between the rotors [46, 47]. Some of the helical screw compressors operate with fluids and are called flooded screw compressors [46].
- **Dynamic**: Dynamic machines mechanically change the velocity of the fluid [46]. Bladed impellers are used to apply inertial forces to the gas and velocity energy is added to the gas and resulting in a static pressure rise of the gas [51].
  - **Centrifugal**: A subcategory of the dynamic compressors is centrifugal compressors, which use a rapidly rotating impeller that increases the velocity of the gas. The process flow propagates from axial to radial and goes into a stationary diffuser that converts velocity into pressure. Single-stage centrifugal compressors can operate at very high RPMs [46]
    - **Horizontally split**: Consists of half casing that are joined along the horizontal center-line. This compressor type supplies gas at high flow rates, but at low pressure [52].

- **Vertically split**: Consists of a cylinder closed by two end covers and are used for high pressure services, but can not achieve as high flow rates as the horizontally split type [52].
- **Integrally geared**: These compressors have semi-open impellers that are overhung mounted directly onto the shaft of the gearbox. They are typically used when high flow rates and low pressure is required [53].

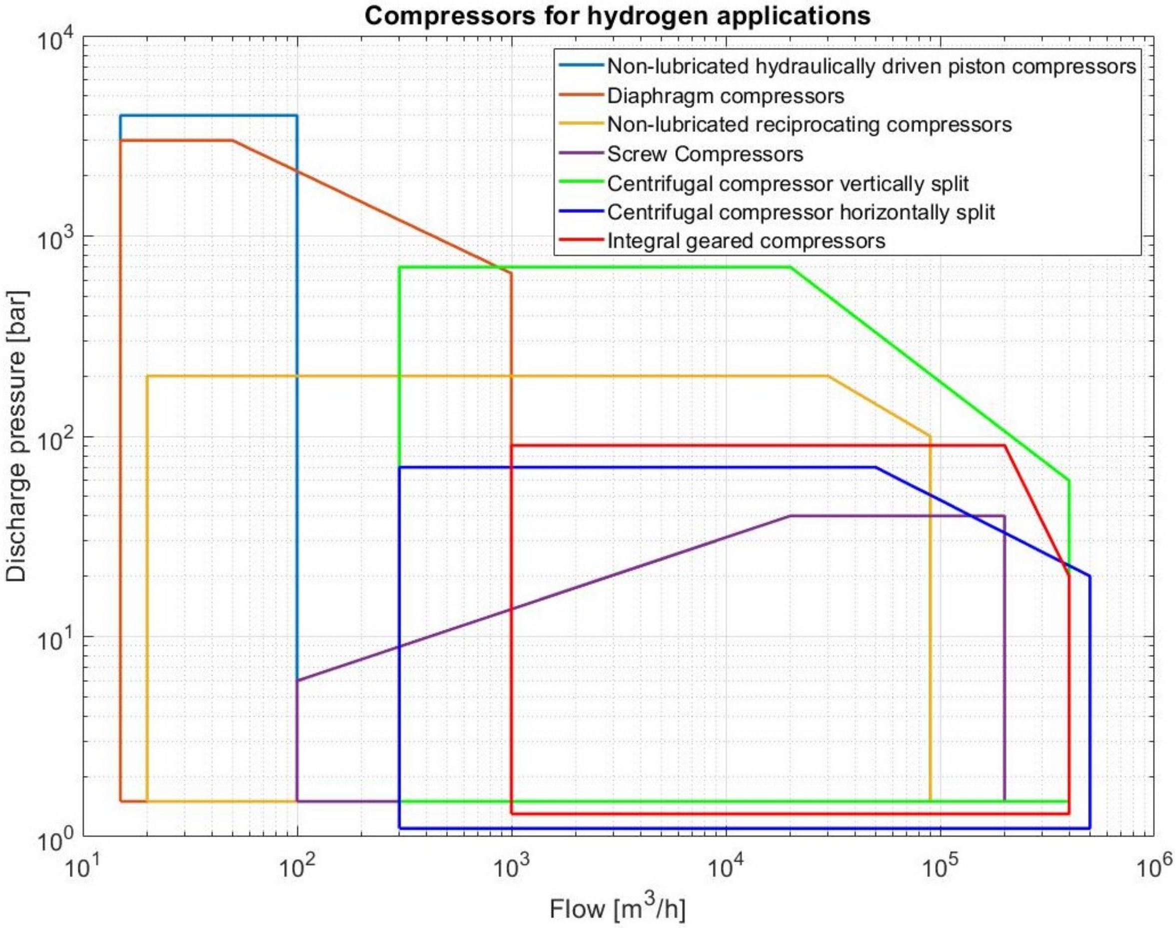

Figure 5.2: Organizing compressor types after discharge pressure and flow rate. Data and inspiration from [54]

The types can be organized as figure 5.2 after pressure and flow rate. As can be seen, the centrifugal compressors achieve higher flow rates at lower pressures, while the reciprocating compressors can achieve higher pressure levels with lower flow rates. The achievable pressures and flow rates in figure 5.2 for the compressor types do however not mean that the compressors are equal during these operating conditions, but rather gives an indication of where they can be used since the types have different operating conditions during which they are appropriate to use.

In quite a lot of applications, multiple compressors can achieve the desired pressure ratios and flow rates, and an evaluation will have to be made from case to case on which compressor is the most appropriate to use. The factors, such as efficiency, and power requirements will have a larger role in these cases [46].

5.2 Compressors in the hydrogen supply chain

A lot of the applications listed in this report require compression and this section aims to showcase where in the supply chain different hydrogen compressors are utilized.

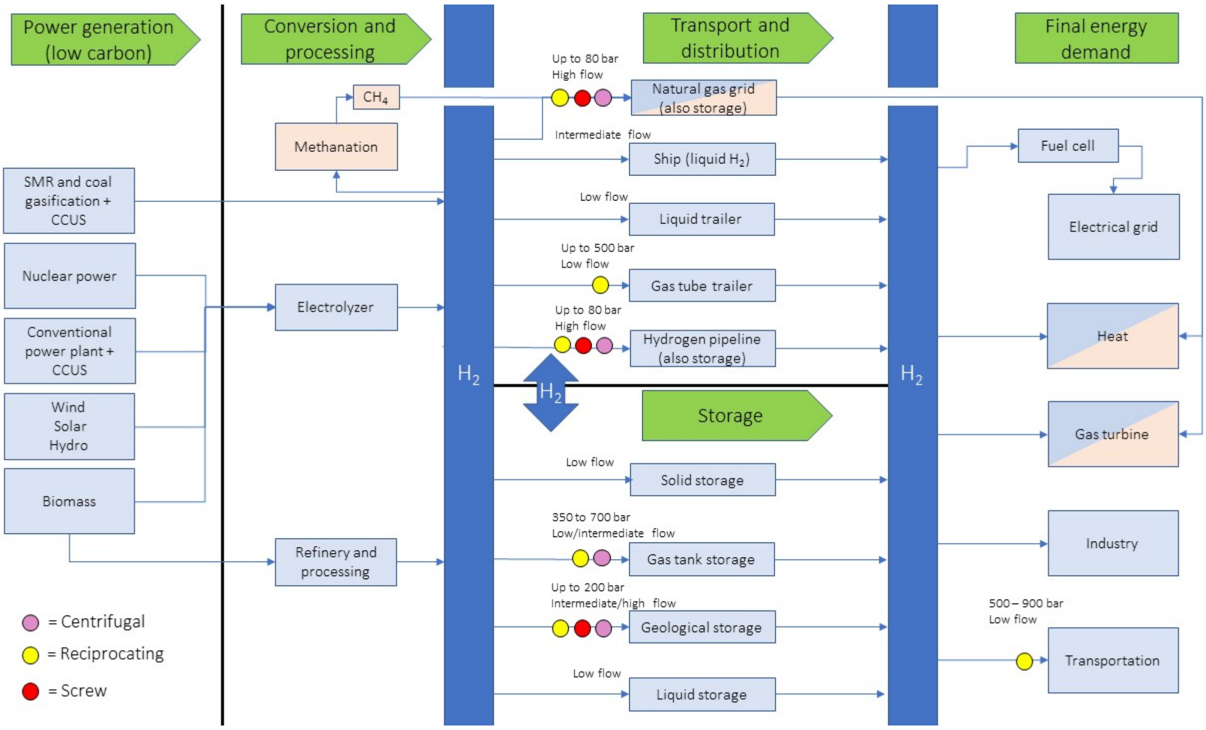

Figure 5.3: Schematic of the hydrogen supply chain

In figure 5.3 the hydrogen supply chain and the compressors for different applications can be seen. Detailed descriptions of the production of hydrogen, storage, and transport and distribution can be seen in sections "Production", "Hydrogen storage", and "Distribution" respectively. The coloured circles represent parts of the chain where compression is required and the colour of the circle shows what compressor might be suitable for the application. Pink circles represent centrifugal compressors, yellow reciprocating, and red screw compressors. The discharge pressure and flow of the required compression are specified for the application to show the operating conditions of the compressors. Low flow are flow rates below 5000 m^3/h, intermediate flow is between 5000 and 40 000 m^3/h, and high flow is above 40 000 m^3/h. The light blue boxes display the hydrogen path and the light orange boxes represent the methanation path, where hydrogen has been converted into methane. Boxes with combined colors are applications where both hydrogen and methane can be used and there can also be a blend of the two gases.

In figure 5.3 under the transport and distribution, it can be seen that all three compressor types might be suitable and the suppliers of compressors are rather divided. High flow rates will require more compression capacity and this can be solved either by having one large compressor, or multiple smaller ones. Due to the intermittency of the renewable energy sources, it might be better to have multiple smaller compressors to counter the variability, but if there is more continuous flow a single large compressor is better, since it will be cheaper [1] [2]. In general, high flow means transportation of hydrogen by pipeline, and pressure requirements are typically lower. If the pressure is below 50 bar, it might be sufficient to use multiple screw compressors [2]. However, it is common that gas pipelines require pressures up to 80 bar [55], and in this case multistage integrally geared centrifugal compressors, multiple single stage centrifugal compressors, horizontally split centrifugal compressors, or high speed reciprocating compressors will be needed [56–60]. Hydrogen is light with a high speed of sound, which leads to a low pressure increase for each stage in a centrifugal compressor. This means that more stages or extremely high impeller speeds are necessary. The impeller material needs to have high strength and also be light enough to have the centrifugal hoop stresses during the high speeds under control, which can be difficult to achieve. Hydrogen embrittlement makes this even more problematic since this can reduce the load-bearing capacity, as well as the ductility of the compressor, and might lead to failure. These disadvantages might lead to more use of compressor concepts that rather utilize multiple smaller centrifugal compressors [57]. It is however likely that different compressor types will be used for the hydrogen and natural gas pipeline gas compression, it might be more efficient to first use screw compressors directly after the electrolyzers to increase the pressure of smaller gas streams of gas and thereafter utilize a centrifugal compressor to supply one large stream [3].

In transportation and distribution, there is also a need to compress hydrogen if the hydrogen is to be transported by gas tube trailer. The pressure in these trailers can go up to 500 bar and it is, therefore, necessary to achieve high pressures [4, 61]. The flow rate is, however, low and a reciprocating compressor is therefore suitable for this application. The type of reciprocating compressor that suits this application is the diaphragm compressor, since it can offer cost-efficient compression at the required pressure [62], and this seems to be the consensus between compressor suppliers where most companies suggest using the diaphragm compressor for trailer tube filling [62–66].

In the storage part of the supply chain, gas tank storage and geological storage are the applications that require compression. Gas tank storage requires rather high compression levels and the current levels that are feasible to store hydrogen are between 350 and 700 bar [67–69]. The lower pressure level gas tanks are a cheaper

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[1] Burckhardt Compression; Interview 2022-05-02.

[2] Diet Woekener; Man Energy Systems; Interview 2022-04-12

[3] Magnus Arvidsson; SKF Technology; Interview 2022-05-09

alternative, but the higher pressure level is utilized in applications where weight and volume are critical in the overall efficiency [68]. The gas flow is either low or intermediate, depending on the type of vessel and how many tanks are filled, and this together with the high pressure requirement leads to reciprocating compressors being the most suitable compressor type [59, 70–72]. There is a possibility to use centrifugal compressors that are vertically split that can achieve the high pressure requirements [73, 74], but it is less common to use this type of compressor for this application. Some companies recommend using high- and medium speed compressors, but these compressors can only achieve lower hydrogen gas tank pressures but at intermediate flow rates [59]. To achieve higher pressure levels, low speed reciprocating, or diaphragm compressors will be required [70–72].

The pressure levels of geological hydrogen storage vary, and the pressure levels of current geological storages are between 45 and 152 bar [75]. The highest pressure that would be suitable is 200 bar, because challenges with materials, safety issues, and investment costs that come with storing large quantities of hydrogen start to become too significant [76]. Companies are therefore designing compressors for geological storage that can supply pressures up to 200 bar, and that also can supply high flow rates to fill up the geological storage [58, 77]. At pressures below 80 bar, it is possible to utilize compressors that would be used for pipeline applications, since high flow rates are required but the pressure is still relatively low. For higher pressures, it will be necessary to have a compressor that can offer higher discharge pressures, such as a vertically split centrifugal compressor [56][4], larger horizontally split compressors [73, 77][4], or single stage centrifugal compressors [57]. To handle larger flow rates it might be necessary to have multiple of these compressors that can work in parallel and that can handle the variability from the output of renewable energy sources [57][5] [6]. If the load is continuous it is, however, better to utilize the multistage integrally geared centrifugal compressor, since it is a more economic solution that can offer high flow rates and pressures up to 200 bar [56, 72, 78].

Transportation, in the "Final energy demand" part of figure 5.3, requires hydrogen compression between 500 and 900 bar with a low flow rate [4, 33], and FCEVs, such as trains and buses that require lower pressure could utilize the same compressors as have been suggested for gas tube trailers. For the higher pressure levels, it is fitting to use hydraulically driven reciprocating compressors or diaphragm compressors, since they can offer high pressures [79–83].

5.3 Compressor bearings

In this section, the results of the market investigation are presented and can be seen in table 5.1. There has been no focus on screw compressors since SKF already have

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[4] Shohei Kobayashi; Hitachi Industrial Products, Ltd; Interview 2022-04-11

[5] Burckhardt Compression; Interview 2022-05-02.

[6] Diet Woekener; Man Energy Systems; Interview 2022-04-12

knowledge of bearings for this compressor type.

In the centrifugal compressors the most common bearing types are the hydrodynamic bearing or active magnetic bearing. The reason for this is the high speeds at which these compressors operate and this means that friction has to be reduced as much as possible and the magnetic bearing has no friction while in operation [84], and hydrodynamic bearings have very low friction [85]. The double acting reciprocating and diaphragm compressors have less need of bearings with very low friction, since they have lower operating speeds and therefore utilize bearings that are more basic [7]. The type of bearings also depends on the size of the compressor, larger compressors might have higher loads on the bearing and might therefore require a component that can withstand the higher load [8].

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[7] Magnus Arvidsson; SKF Technology; Interview 2022-05-09

[8] Karl Heinz Hammes; Neuman Esser; Interview 2022-04-12

Table 5.1: Bearings used in the most common compressors for hydrogen applications. Bearings with (H) next to them are hydrodynamic bearings and bearings with (B) next to them are bushing bearings. Results are based on [56, 58, 73, 86–102] [9]

Compressor type	**Bearings**
Double acting reciprocating	Unspecified hydrodynamic bearings
	Precision tri-metal half shell (H)
	Rod (B)
	Crankpin (B)
Diaphragm	Unspecified hydrodynamic bearings
	Sleeve (H)
	Babbitt sleeve (B)
	Tapered roller bearings
Horizontally split centrifugal	Journal (H)
	Tilting pad (H)
	Thrust (H or B)
	Active magnetic
Vertically split centrifugal	Journal (H)
	Tilting pad (H)
	Thrust (H or B)
	Active magnetic
Integrally geared centrifugal	Journal (H)
	Sleeve (H)
	Tilting pad (H)
	Deflection pad (H)
	Tapered land (H)
	Thrust (H or B)
	Deep groove
	Radial

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[9] Burckhardt Compression; Interview 2022-05-02. Diet Woekener; Man Energy Systems; Interview 2022-04-12

6

Theory and calculations

The theory section covers the hydrogen embrittlement phenomena, how hydrogen is generated through electrochemistry, and then adsorbed and absorbed by the material. Hydrogen trapping is then explained, as well as some mechanisms of hydrogen embrittlement and preventative measures that can be taken to avoid hydrogen embrittlement.

6.1 Hydrogen embrittlement

Handling hydrogen is not without issues. One problem that might be encountered is 'hydrogen embrittlement', which refers to a metal's loss of ductility and lowered load bearing capacity due to the metal absorbing atomic hydrogen [5]. Hydrogen that is dissolved into metals affect their mechanical properties negatively, primarily through interaction with the material defects. It occurs at low stress levels with brittle fracture, often leading to major economic losses or even catastrophes [103]. The degree of hydrogen embrittlement depends on both the amount of hydrogen absorbed and the microstructure of the material, where microstructures that provide high strength are more susceptible to it [104]. It is a complex phenomenon that affects a variety of metals and despite extensive research efforts to understand the mechanisms of failure and potential mitigation solutions are hydrogen embrittlement mechanics not completely understood [105]

Failure due to hydrogen embrittlement requires three things: a susceptible material, exposure to a hydrogen rich environment, and the presence of tensile stress [5, 106]. There are primarily three hydrogen rich environments that are responsible for hydrogen embrittlement at ambient temperatures, those being: hydrogen sulfide (H_2S), hydrogen fluoride (HF), and hydrogen cyanide (HCN) [107]. Cathodic protection may also lead to a significant amount of hydrogen in the material, thus leading to hydrogen embrittlement [108]. When atomic hydrogen is produced it normally combines into molecular form again but when this is prevented or reduced the concentration of atomic hydrogen is increased. Atomic hydrogen in alloys causes several types of damage, broadly classified as hydrogen blistering (HB), hydrogen induced cracking (HIC), hydrogen embrittlement (HE), sulfide stress cracking (SSC), high temperature hydrogen induced cracking (HTHIC), and hydrogen induced disbondment (HID). The terms for each category of damage are sometimes used interchangeably, and other terms might also be used [107].

The damage caused by hydrogen is divided into two types: reversible and irreversible hydrogen embrittlement. Reversible hydrogen embrittlement refers to when the atomic hydrogen accumulates in potential cracking locations, leading to delayed fractures which can be healed by hydrogen removal treatments [103], e.g. by removing all hydrogen sources from the metal and then heat treating it to 200°C [107]. Irreversible hydrogen embrittlement is caused by hydrogen atoms combining to form hydrogen molecules, thus generating gas pressure and causing hydrogen induced cracking, which cannot be healed [103]. The source of the hydrogen can also divide hydrogen embrittlement into two different types. Internal hydrogen embrittlement is the result of hydrogen already inside the material. External hydrogen embrittlement, also known as hydrogen environmental embrittlement, is when hydrogen comes from the environment. Damage occurs when hydrogen accumulates in the hollow spaces of the lattice, and when some of that diffuses into the crystalline substrate lattice, it reacts with hydride-forming metal atoms to form brittle metal hydrides [109]

6.1.1 Electrochemistry of hydrogen

Hydrogen atoms can evolve through a cathodic reduction reaction in aqueous environments according to equations (6.1) and (6.2) below, depending on the pH of the solution. The evolved hydrogen atoms are adsorbed onto the metal's surface and some of it is absorbed through hydrogen adsorption processes [110].

$$H^+ + e^- \longrightarrow H_{ad} \tag{6.1}$$

$$H_2O + e^- \longrightarrow H_{ad} + OH^- \tag{6.2}$$

It is often the evolution of hydrogen atoms that is the main cathodic reaction of less noble metals, like iron, during metallic corrosion in acidic media. The amount of protons is low in both neutral and alkaline solutions, thus leading to a slower evolution of hydrogen. The hydrogen evolution reaction process can however still occur in solutions with a relatively high pH during metallic corrosion, depending on the corrosion potential. If the corrosion potential is lower than the equilibrium electrode potential of the hydrogen evolution reaction at the current pH can the hydrogen evolution reaction take place thermodynamically, thus resulting in adsorbed hydrogen [110].

Cathodic protection is a common method to reduce the corrosion rate of high strength steels. Hydrogen embrittlement will easily occur if the potential of a high strength steel is too low and there are no obvious signs before hydrogen induced cracking. The limiting factor at higher potentials is the oxygen depolarization reaction, where the main cathode reaction on the metal surface is the reduction reaction of oxygen as seen in equation (6.3) [108].

$$O_2 + 2H_2O + 4e \longrightarrow 4OH^- \tag{6.3}$$

As the potential decreases does the rate controlling step change to oxygen diffusion and then the hydrogen evolution reaction, shown in equation (6.4), which intensifies, making the hydrogen depolarization reaction the rate controlling step [108].

$$2H_2O + 2e \longrightarrow 2OH^- + 4H_2 \tag{6.4}$$

The hydrogen evolution reaction intensifies at what is commonly referred to as the hydrogen evolution potential, which is viewed as the most negative potential allowed for cathodic protection. By going below this, the material is put at risk of hydrogen embrittlement. This may not be entirely reliable however, as the cathode reaction is the result of both hydrogen and oxygen reactions. Thus, it will be accompanied by the reduction reaction of hydrogen when the cathode potential reaches a certain value and the hydrogen is only able to escape from the metal surface once the cathode polarization reaches a certain potential. Before this can the generated hydrogen enter the metal, thus influencing the material performance [108].

6.1.2 Hydrogen adsorption and absorption on metals

The small size of hydrogen atoms allows atomic hydrogen to enter steel, commonly from high pressure hydrogen gas, electrochemical hydrogen charging, and corrosion reactions. Hydrogen embrittlement could occur during any stage of the products life, such as fabrication, assembly operations, or operational use. Essentially anytime that the metal is in contact with hydrogen [5, 109], and failure of high strength steel occurs at low hydrogen concentrations of several parts per million. It is therefore important to measure the hydrogen content in metals but even though this has been investigated, it is still difficult to do [103].

In principle atomic hydrogen is necessary for hydrogen absorption, which is present as adsorbed hydrogen at the surface of the metal and subsequently absorbed. There are three basic routes for a metal to absorb hydrogen. The first route is through absorption under pressure, referred to as pressurized hydrogen charging [111]. In dry conditions, where no electrochemical reactions such as corrosion occur, is the only possible source of hydrogen hydrogen gas (H_2) [106]. Physical adsorption adsorbs molecular hydrogen on the metal surface through Van-der-Waals forces, where the molecules dissociate, making atomic hydrogen present and absorbable by the material. The second route of hydrogen absorption is through corrosion reactions, often referred to as electrolytic hydrogen charging, where hydrogen is produced through the Volmer reaction, described in equation (6.1). The adsorbed hydrogen is then either absorbed or desorbed according to the Tafel reaction in equation (6.5) [111].

$$2H_{ad} \rightleftharpoons (H_2)_{ad} \tag{6.5}$$

Another possibility of desorption is the Heyrovsky mechanism which leads to the recombination of the hydrogen molecule according to the following equation.

$$H_{ad} + H^+ + e^- \rightleftharpoons (H_2)_{ad} \tag{6.6}$$

The third route is through an applied potential, known as cathodic hydrogen charging. This can be carried out in neutral mediums as hydrogen is generated through the chemical reduction of water at the cathodically polarized electrode. During cathodic charging is the current density the main influencing factor. Whether the solution is neutral or acidic matters as acidic solutions lead to increased absorption through corrosion reactions. Recombination poisons are used since they inhibit the recombination reaction of atomic hydrogen, thus increasing the amount of atomic hydrogen available for absorption [111].

6.1.3 Hydrogen trapping

As mentioned above does the damage caused by hydrogen occur when hydrogen accumulates in the hollow spaces of the lattice [109] and thus is hydrogen in steel not homogeneously distributed [112]. Hydrogen trapping refers to when the passage of hydrogen through steel is hindered by lattice imperfections, such as voids, dislocations, grain boundaries, carbide interfaces, solute atoms, boundaries of second phase particles, and impurities that attract and bind hydrogen, making it immobile at temperatures where it would normally diffuse [112–114]. Increasing the apparent solubility and decreasing the apparent diffusivity are the two noteworthy effects of trapping [103, 112], where steel will absorb more hydrogen when being balanced against an external hydrogen source, up to the solubility limit of the lattice. Additional hydrogen will accumulate until balance is achieved when the chemical potential of the hydrogen in the lattice and trap sites is equal to the external chemical potential [112]. The apparent solubility, or atomic ratio of dissolved hydrogen in steel is thus significantly higher than the lattice solubility calculated through Sievert's law since trapped hydrogen requires more energy to escape the trap compared to the lattice migration energy [103, 112]. In duplex materials of austenite and ferrite is the diffusion of hydrogen much higher in ferrite than in austenite, in which the solubility is much higher, thus making it a macroscopic hydrogen trap relative to ferrite [114].

The hydrogen traps are divided into either reversible or irreversible traps based on the hydrogen trap activation energy, where the reversible traps have a low trap activation energy compared to the high trap activation energy required for irreversible traps [103, 112, 113]. The irreversible traps consist of carbide interfaces, inclusions, incoherent precipitates, and high-angle grain boundaries. Among the reversible traps are interstitial sites, dislocations, lath boundaries, low-angle grain boundaries, coherent precipitates, and twin boundaries [103, 113]. The reversible traps are relatively easy to detrap and hydrogen that gets trapped in these is thus still considered to be diffusible [113]. An alloy's susceptibility to hydrogen embrittlement is correlated with the presence of reversible traps [103], and they are considered to have an influence on both hydrogen diffusion and on the hydrogen embrittlement of steel [113]. Reversibly trapped hydrogen, found dissolved in e.g. the austenite phase and defects like dislocations and interfaces can be detrapped by heating the metal up to 300°C [114]. The microstructure of the metal plays a crucial role in the solubility of hydrogen, where the solubility of pure iron in recrystallized and severely plasticized conditions is a factor of 4000 apart. Tempered martensite shows a good resistance to sulfide stress cracking, but increasing the strength of the material increases it's sensitivity. By retaining austenite in the alloy is the hydrogen solubility significantly increased and the ductility of hydrogen charged martensitic steel decreased [106].

6.1.4 Mechanisms of hydrogen embrittlement

Hydrogen induced cracking is a form of hydrogen embrittlement that is common in carbon and low-alloy steels that occurs when the atomic hydrogen diffused into the material forms molecular hydrogen in trap sites. The formation of molecular hydrogen exerts an internal pressure in the material, and thus does hydrogen induced cracking not require any external stress to form [107, 115]. It propagates in a step-like manner, linking small laminar cracks, and as the internal pressure increases, they start to link with other adjacent cracks [115].

Hydrogen blistering, also know as "soft zone cracking", refers to when relatively soft steels blister in a corrosive environment where the cathodic reaction is a hydrogen ion reduction [107]. It is commonly associated with low strength steels [107, 115] and occurs when there are inclusions or voids present which the atomic hydrogen can diffuse into. There, it forms molecular hydrogen which is unable to diffuse, thus increasing the concentration of hydrogen gas and the local pressure within the defect until local yielding, or the formation of blisters, eventually occur [115].

Sulfide stress cracking is the embrittlement of metal caused by atomic hydrogen produced by acid corrosion on the metal surface. The main source of hydrogen here is H_2S and the presence of both H_2S and CO_2 in the gas phase lowers the pH below the depassivation pH of the alloy, thus increasing the proton discharge rate. The depassivation can even occur in pits and crevices, and thus localized corrosion can be a precursor for sulfide stress cracking in some systems. Similarly, since sulfur has been shown to act as a poison for hydrogen recombination, the sulfide present increases the amount of atomic hydrogen that can diffuse into the metal [115].

When stainless steel clad carbon steel is in the presence of hydrogen at higher temperature and pressures, hydrogen induced disbondment may occur. This occurs when atomic hydrogen diffuses into the bond between the carbon steel and the stainless steel and form hydrogen molecules there. Steel that is supersaturated with hydrogen starts to flake or crack, and the most susceptible conditions for hydrogen in steel is when the concentration exceeds 3 ppm and the temperature is lower than 150°C [107].

There us a multitude of mechanisms that can be used to explain the hydrogen embrittlement phenomena, such as hydrogen pressure theory, hydrogen induced phase transformation (HIPT) theory, hydrogen-enhanced strain-induced vacancies (HESIV), hydrogen-enhanced decohesion mechanism (HEDE), hydrogen-enhanced localized plasticity mechanism (HELP). To explain the irreversible damage caused by hydrogen, the hydrogen pressure theory and the HIPT theory can be used. The mechanisms most commonly used to explain reversible hydrogen embrittlement are HEDE, HELP, and the HESIV. There are multiple mechanisms used and there is a consensus that not any single mechanism explains the entirety of reversible hydrogen embrittlement [103]. These measures can also be used to look at different ways to delay or prevent hydrogen embrittlement in steels.

6.1.5 Preventative measures

The negative effects hydrogen has on metals can generally be avoided by using the appropriate materials, by using a coating that is impermeable to hydrogen atoms, by using corrosion inhibitors to reduce the production of hydrogen atoms, or by removing poisons that prevent hydrogen atoms from forming molecules [107]. The severity of the hydrogen embrittlement depends on the temperature and most metals are relatively immune to it above approximately 150°C [104].

The effects on the metal caused by the hydrogen concentration and stress gradient makes the atomic hydrogen diffuse toward and accumulate in the stress concentration region. Based on the two types of hydrogen embrittlement based on the hydrogen source mentioned above, internal and external hydrogen, there are two approaches to prevent it. The first approach is to use surface treatments to prevent the external hydrogen from reaching the metal, such as surface coatings and surface modification treatments[103]. Through the use of corrosion inhibitors is the production of hydrogen atoms reduced, and removing recombination poisons that prevent hydrogen atoms from forming molecules reduces the amount of hydrogen atoms in the surrounding environment [107]. The second approach addresses the internal hydrogen by modifying the material microstructure by either adding or eliminating different alloy elements to optimize the microstructure [103].

By coating a metal with a film, the entry of hydrogen into the alloy is suppressed, thus providing a high resistance to hydrogen embrittlement. Ni, Zn, Cu Al or PVD-Ti-DLC films can effectively suppress hydrogen infusion and reduce the susceptibility to hydrogen embrittlement [116]. Surface blackening treatment can also be used, which adds an oxide layer, approximately 1-3 μm thick on the metal surface, in an alkaline oxidizing solution where no hydrogen evolves in the process [117], thus improving the corrosion resistance of the metal. [118]

Surface nitriding and carburizing treatments are used to enhance the hydrogen embrittlement resistance by reducing the lattice spacing of the material, which generates compressive strength at the surface of the material. The nitriding layer consists mainly of interstitial diluted nitrogen and the carburizing layer carbon, which reduce the diffusion speed of hydrogen since the interstitial sites are blocked by nitrogen and carbon, respectively [119]. Austenite has a high stability and this combined with the compressive stress, which counteract the operational tensile stresses, makes the material highly resistant to hydrogen embrittlement [119]. Surface peening treatment is another treatment that introduces compressive stress to the material, and also increases the density of the hydrogen trap sites, which are the sites near the surface that hydrogen occupies before diffusing further into the interior of the alloys. Thus, the peening layer allows the alloy to display a low sensitivity to hydrogen embrittlement [103].

Alloy elements play a key role in a metal's susceptibility to hydrogen embrittlement, where the metal can be protected by reducing the amount of carbon, silicon, phosphorus, and sulfur, or by increasing the amount of nickel, aluminum, or molybdenum [103]. Hydrogen embrittlement of steel depends on the microstructure of the steel, where a martensitic structure is the most susceptible, followed by bainite, pearlite, and finally austenite [120, 121]. Since austenite is the least susceptible to hydrogen embrittlement is it common to use it for hydrogen-related equipment. Austenite is however not immune to hydrogen embrittlement and thus, after some time, does hydrogen embrittlement still occur [121]. The susceptibility of an austenitic alloy is directly tied to its hydrogen permeation properties, which depend on its content, shape, and stability. Since austenite has a low hydrogen diffusion and high hydrogen solubility, does increasing the amount of austenite in an alloy lead to less hydrogen embrittlement [122].

The heat treatment used also makes a significance in a material's susceptibility to hydrogen embrittlement. The kinetics of hydrogen transportation are impacted by the presence of traps, such as grain boundaries, interfaces, dislocations, and precipitates. Different heat treatments lead to different trap characteristics, and thus has a varying sensitivity to hydrogen. Looking at controlled rolling, normalized, and quenched and tempered steels, it is preferable to use controlled rolled steel since it has the highest resistance of hydrogen embrittlement, while normalized steel has the lowest [123].

6.1.6 Mode of failure

Metal spalling is a mode of failure originating in fatigue and is related to thermal and mechanical stresses applied during operation. It can be divided into two subcategories, surface-initiated spalling and subsurface-initiated spalling. Surface-initiated spalling originates from thermal shock or a stress raiser e.g., bruise or roll on the metal surface from which it propagates until the crack growth eventually leads to brittle overload failure. Subsurface-initiated spalling originated from material discontinuities such as inclusions or pores, which act as a stress-concentration point. It could also originate from contact stress fatigue (Hertzian contact). The presence of angular and brittle inclusions may lead to subsurface cracks forming due to fatigue, resulting in spalling [124].

6.2 Calculations

The Cottrell equation was used to make rough estimations of the charging of hydrogen into the inner ring and was based on formulations from Bard-Faulkner [125]. The Cottrell equation is formulated as:

$$i(t_c) = \frac{nFAD_{O,c}^{1/2}C_O^*}{\pi^{1/2}t_c^{1/2}} \tag{6.7}$$

In equation (6.7) t_c is the charging time in seconds, $i(t_c)$ is the current in ampere as a function of t_c, n is the number of electrons, F is the Faraday constant and is equal to 96485 C/mol, A is the area of the planar electrode in m^2, $D_{O,c}^{1/2}$ is the diffusion coefficient in m^2/s, and C_O^* is the initial surface concentration of hydrogen, where O represents the oxidized form of the standard system, denoting quantities pertaining to hydrogen which is the species, in $\mathrm{mol/m}^3$.

The initial hydrogen surface concentration of the inner ring is desired, and all other variables are known, so it is possible to reformulate equation (6.7) as:

$$C_O^* = \frac{i(t_c)\pi^{1/2}t_c^{1/2}}{nFAD_{O,c}^{1/2}} \tag{6.8}$$

The concentration profile of the inner ring can be derived in a similar fashion to the Cottrell equation and is formulated as:

$$C_{O,c}(x,t_c) = C_O^* erf\Big(\frac{x}{2(D_{O,c}t_c)^{1/2}}\Big) \tag{6.9}$$

where C_O^* from equation (6.8) is used. In equation (6.9) x is the depth into the material in meters from the surface, and $C_{O,c}(x,t_c)$ is the concentration as a function of the depth, and the charging time. x is set to be the core of the ring. *erf* is the error function:

$$erf(z) \equiv \frac{2}{\pi^{1/2}}\int_0^z e^{-y^2}dy \tag{6.10}$$

The error function is commonly used in diffusion problems and as z becomes very large it approaches the limit, which is 1. The error function rises quickly and any value of z larger than 2 essentially reaches the limit.

After these steps the charging of hydrogen is complete, and the diffusion time until only 10% of the charged hydrogen remains can be calculated, and a plot of the diffusion over time can be made, where $C_{O,c}(x,t_c)$ is the initial concentration of hydrogen. 10% was chosen as the limit due to the rate of diffusion decreasing with the amount of hydrogen in the material, making it take a very long time for the amount of hydrogen to drop even further. Equation (6.9) is then reformulated as:

$$C_{O,D}(x,t_D) = C_{O,c}(x,t_c)erf\left(\frac{x}{2(D_{O,D}t_D)^{1/2}}\right) \tag{6.11}$$

$C_{O,D}(x,t_D)$ is the concentration of hydrogen in the inner ring after the time, t_D, as the test is initiated, and $D_{O,D}$ is the diffusion coefficient at 80°C.

Since temperature has a relatively large effect on the diffusion of hydrogen, the diffusion constant for temperatures between 20° C and 100°C were calculated and used to estimate how much hydrogen would be charged into the ring after 1 minute and 35 minutes of charging. The temperature interval was chosen to go from room temperature to a bit over 80° C, which was the initial charging temperature for the pre-trials. During the tests, friction would lead to elevated temperatures within this interval as well.

Table 6.1 shows the different diffusion data for hydrogen in ferritic and austenitic materials. With higher temperatures and fewer traps, the diffusion coefficient increases which leads to faster diffusion of hydrogen out of the material.

Table 6.1: Diffusion coefficients, D_O, in m^2/s for hydrogen in austenitic and ferritic materials. Amount of traps and temperature has large effects on the diffusion coefficient. Coefficient data is based on [126]

Traps	**No traps**	**Some traps**	**A large number of traps**
100°C	$10^{-7.75}$	$10^{-8.53}$	$10^{-10.40}$
90°C	$10^{-7.77}$	$10^{-8.58}$	$10^{-10.48}$
80°C	$10^{-7.79}$	$10^{-8.66}$	$10^{-10.62}$
70°C	$10^{-7.80}$	$10^{-8.78}$	$10^{-11.79}$
60°C	$10^{-7.82}$	$10^{-8.85}$	$10^{-10.92}$
50°C	$10^{-7.86}$	$10^{-8.94}$	$10^{-11.09}$
40°C	$10^{-7.89}$	$10^{-9.05}$	$10^{-11.27}$
30°C	$10^{-7.91}$	$10^{-9.17}$	$10^{-11.45}$
20°C	$10^{-7.96}$	$10^{-9.29.}$	$10^{-11.72}$

The tests were run at room temperature, and thus calculations were performed to check how much hydrogen would be charged at this temperature using the diffusion data for 20°C from table 6.1.

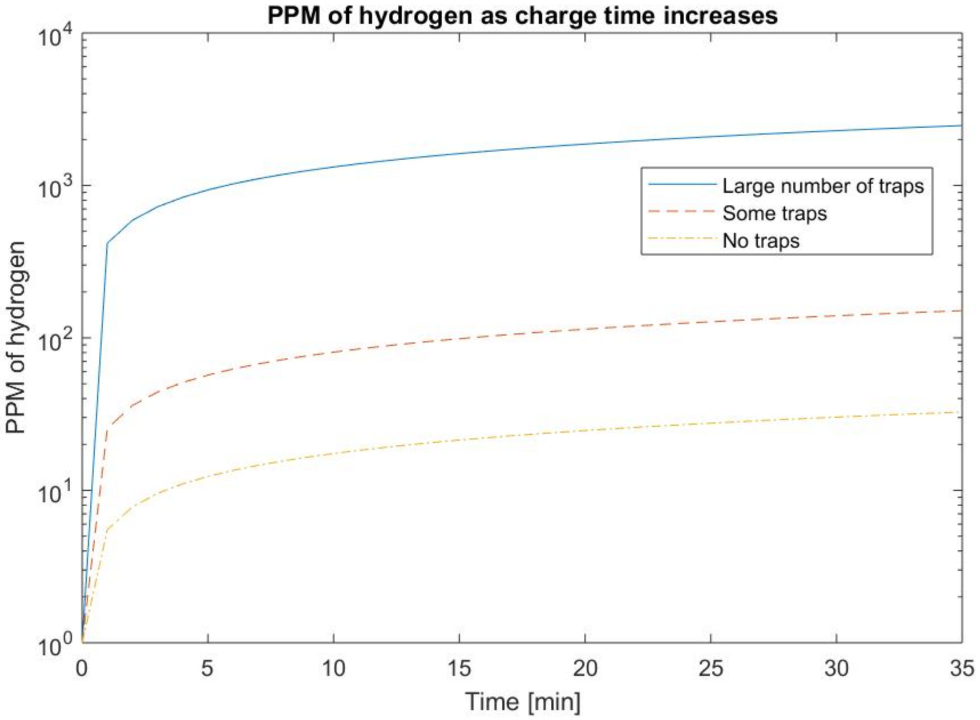
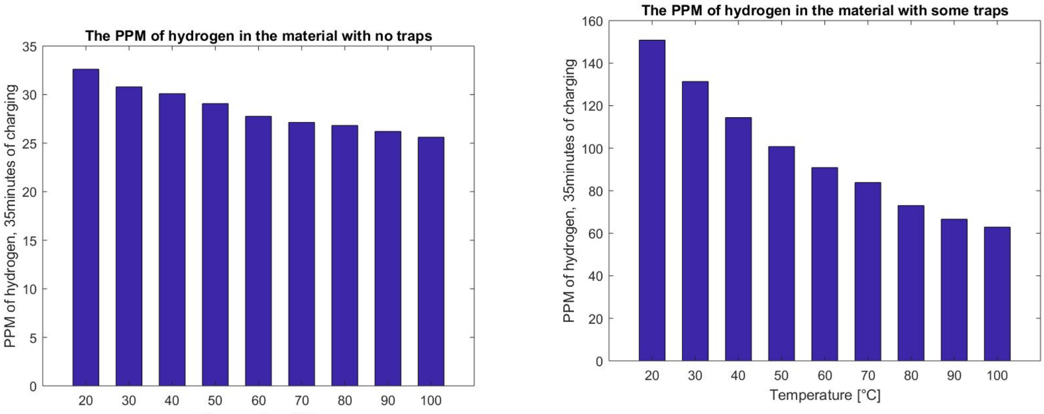


Figure 6.1: The part per million share of hydrogen increasing with charging time at different degrees of traps in the material at room temperature

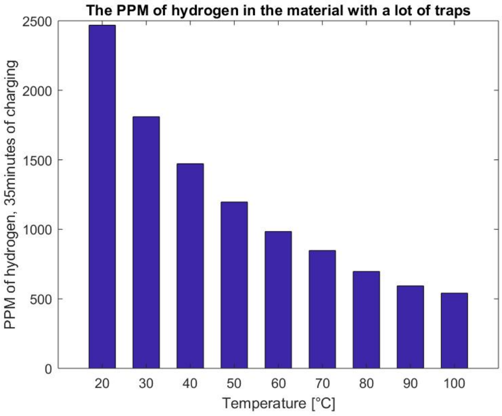
Figure 6.1 shows how the concentration, in PPM, of hydrogen in the inner ring increases during the 35 minutes of charging. As can be seen in the figure does the amount of traps have a huge influence on the hydrogen in the material. The difference after 35 minutes is significant, when going from no traps to some traps the amount of hydrogen increases from 33 PPM to 151 PPM but when there are a large number of traps, the difference is even larger, 151 PPM to 2451 PPM.

A comparison between how the temperature affects the concentration was also made, where the PPM for no traps, some traps, and a large number of traps was calculated at temperatures between 20°C and 100°C. The calculations were performed in a similar fashion to figure 6.1.



(a) The amount of hydrogen in the material with no traps after 35 minutes of charging at different temperatures

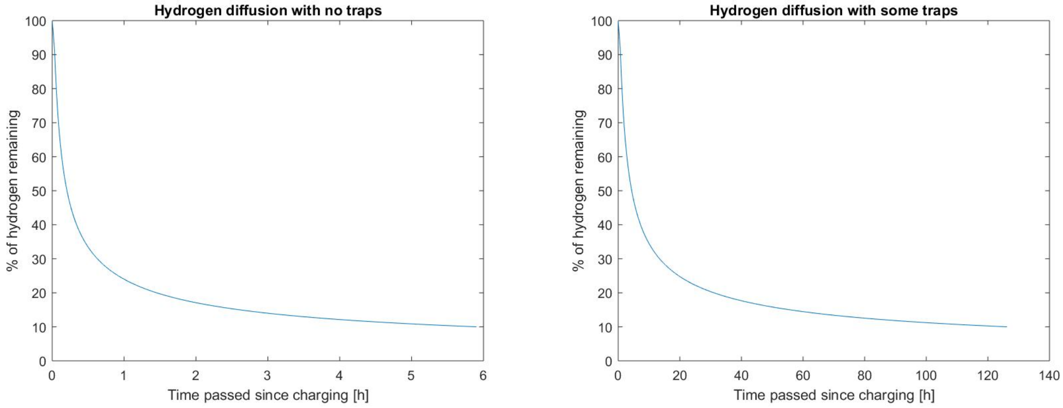
(b) The amount of hydrogen in the material with some traps after 35 minutes of charging at different temperatures



(c) The amount of hydrogen in the material with a large number of traps after 35 minutes of charging at different temperatures

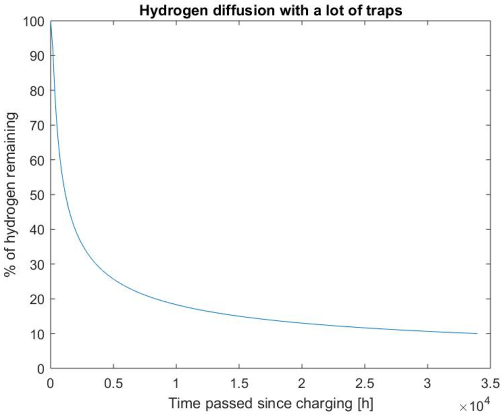
Figure 6.2: The concentration of hydrogen in PPMs increasing with charging time at different degrees of traps in the material at room temperature

Looking at the different graphs in figure 6.2 shows that there is more hydrogen charged at lower temperatures. With a large number of traps present in the material, the concentration of hydrogen differs greatly between the temperature levels. Lastly, calculations for how long the hydrogen would stay in the material at the different levels of traps were performed.



(a) The amount of hydrogen in the material and how long it takes until it reaches 10% of the charged amount with no traps

(b) The amount of hydrogen in the material and how long it takes until it reaches 10% of the charged amount with some traps



(c) The amount of hydrogen in the material with a large number of traps after 35 minutes of charging at different temperatures

Figure 6.3: The amount of hydrogen in the material and how long it takes until it reaches 10% of the charged amount with a large number of traps.

Figure 6.3 shows how long it takes for 90 percent of the charged hydrogen to diffuse out of the material at different levels of traps. With no traps it takes a bit less than six hours, but by adding some traps it goes up to just under 130 hours, and goes all the way to above 34000 hours with a large number of traps.

The bearing material is likely to have diffusion coefficients in the range between some traps and a large number of traps, but it is highly uncertain exactly how much traps there are, and as discussed, the initial concentration and diffusion rate of hydrogen can vary by quite a lot.

In the test rig are the vibrations of the bearing during testing measured, using the unit of g/E, which is the unit used for vibrations within SKF. In this case, g refers to the gravitational constant, 9.81m^2/s while E refers to the Larson-Miller parameter.

6.2.1 Risk assessment

To perform the tests, a risk assessment was performed, since hydrogen gas together with atmospheric oxygen can form combustible or explosive mixtures. With a hydrogen concentration of 4 to 75% the hydrogen is combustible and in the range of 18 to 59% it can be explosive. If the tests are to be safe, it means that the room concentration of hydrogen can not exceed 4% [127, 128].

For this risk analysis it was assumed that all of the created hydrogen went into the surrounding air and a rather small volume of the test room was also assumed. This was to assure that there will be no safety risks associated to the test.

The Faraday constant, which is 96485 C/mol, can be used together with the time and the current used for the tests. For rough calculations, a charging time of 1 hour and a current of 1 A was assumed. The amount of moles created during the hour of charging is then as follows:

$$\frac{Time \cdot Current}{Faraday\ constant} = \frac{3600 \cdot 1}{96485.3329} \approx 0.037\, mol \tag{6.12}$$

Then the amount of moles in the air had to be calculated. The molar mass of air is 28.9647 g/mol, the density of air is 1225 g/m^3 at room temperature, and the room volume was assumed to be 1 m^3, and the amount of moles was then calculated as:

$$\frac{Density \cdot Room\ size}{Molar\ mass\ of\ air} = \frac{1225 \cdot 1}{28.9647} \approx 42.293\, mol \tag{6.13}$$

The concentration of hydrogen is then:

$$\frac{0.037}{42.293} \approx 0.089\% \tag{6.14}$$

This means that the potential concentration of hydrogen in the room should be far below 4% and it was therefore safe to perform the tests.

6.2.2 Cathodic protection

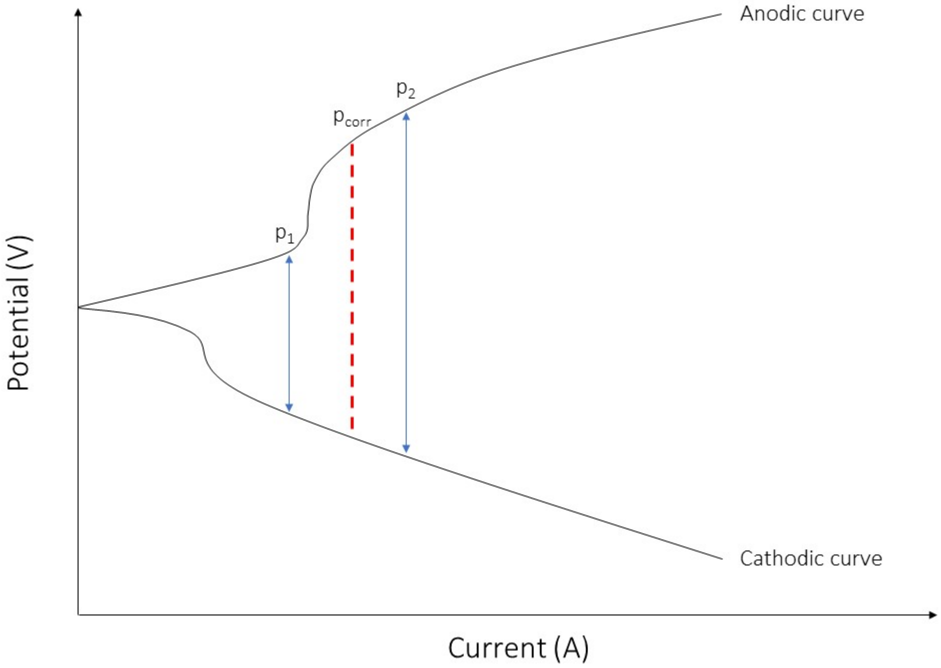


Figure 6.4: Simplified Tafel slope. Made with inspiration from [129]

In figure 6.4 a simplified Tafel slope can be seen. The Tafel slope can be used to determine the potential that is required to achieve cathodic protection for a material, which in this report is over the inner rings of bearings. The y-axis represents the potential between the anode and the cathode, while the x-axis represents the required current to achieve cathodic protection. p_{corr} represents the required potential to put the cathode under cathodic protection, and therefore protect it from corrosion. p_1 represents a potential below the required potential for cathodic protection, and if the potential is too low, there will be corrosion on the cathode. p_2 represents a potential above the required potential to acquire cathodic protection, and there will therefore be no corrosion on the cathode. As can be seen from the figure, the potential required to achieve p_{corr} is the distance between the anodic and the cathodic curves in the Tafel slope. The shape and slope of the cathodic and anodic curves are unpredictable, and it is therefore difficult to determine what potential is required for different materials to achieve cathodic protection [129].

7

Lab tests

In this section are the results from the lab trials presented, where all the data recorded and all the images taken are described.

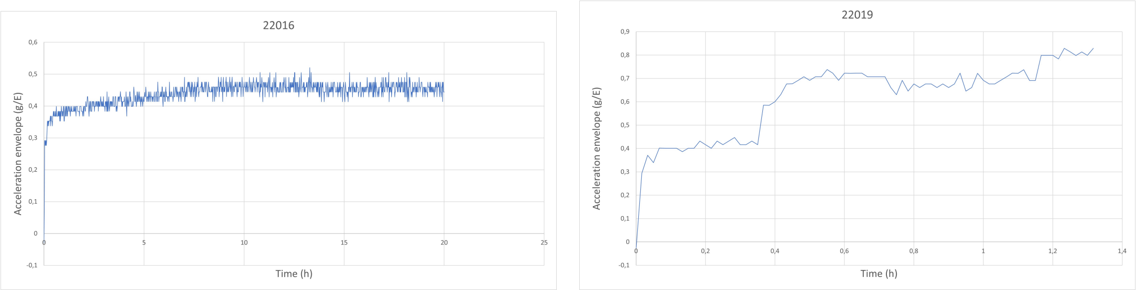
During the charging, of the inner rings and the highly charged outer ring, the current and voltage were recorded and can be seen in table 7.1.

Table 7.1: The average current and voltage during the charging

	Inner ring 80°C	**Inner ring 1**	**Inner ring 2**	**Inner ring 3**	**Highly charged outer ring**
Average current [A]	0.25	0.11	0.10	0.14	1.1
Average voltage [V]	3.0	3.0	3.0	3.0	4.1

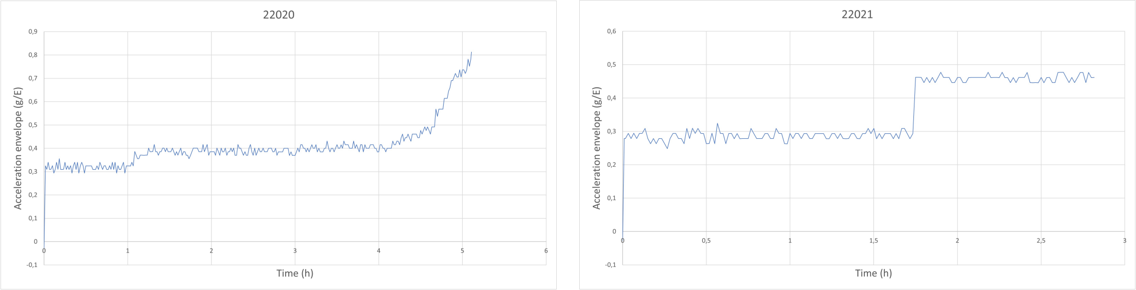
The highly charged outer ring was sectioned and checked in the microscope for damages but neither corrosion nor any signs of hydrogen embrittlement were present.

The bearings with charged inner rings were reassembled and run in the test rig, where not a single bearing, besides the reference, survived the test.



(a) The vibrations of the reference bearing

(b) The vibrations of the first charged bearing



(c) The vibrations of the second charged bearing

(d) The vibrations of the third and last charged bearing

Figure 7.1: Vibration data for the bearings tested in the rig

Figure 7.1a shows the reference bearing which was not charged with hydrogen before testing. It survived for the entire 20 hours with a relatively stable level of vibrations. The first charged bearing saw some damage leading to increased vibrations around the 20 minutes mark, as shown in figure 7.1b, leading to increased vibrations. The break level was set to 1 g/E but after one hour and 19 minutes was it possible to hear clear sounds of spalling, and thus the test was stopped. The second bearing, with a break level of 0.8 g/E, saw minor damages at the one hour mark, leading to a slight increase in vibration which can be seen in figure 7.1c. The bearing then continued until the four hour mark where some damage occurred, escalating the vibrations until it reached the break level shortly after the five hour mark. Figure 7.1d shows the last tested bearing, which was damaged after approximately one hour and 45 minutes. It had a break level at 0.6 g/E but due to the clear sign of damage was the test stopped after about two hours and 40 minutes.

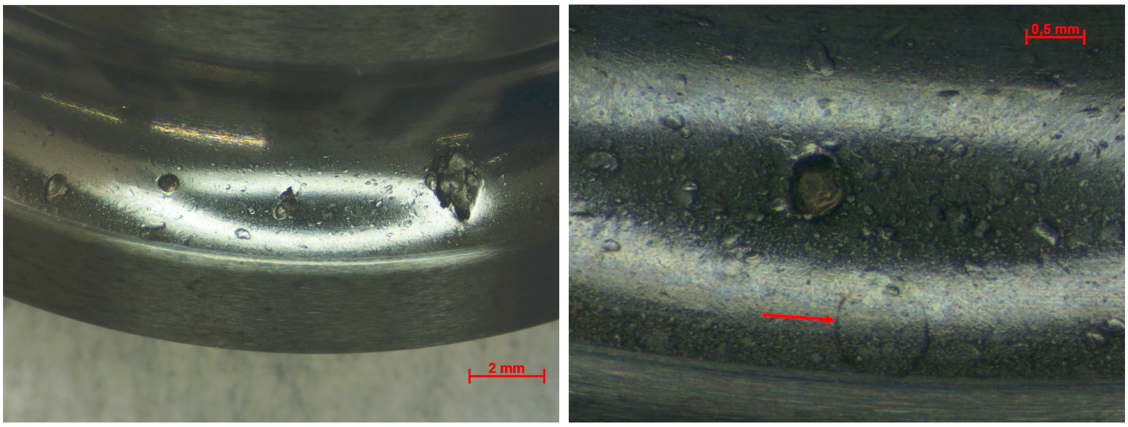


Figure 7.2: Damage on the first charged inner ring after testing

The tests resulted in similar damages across all three samples. Figure 7.2 above shows these damages on the first charged inner ring, where pieces have been chipped off. The right image in figure 7.2 also shows signs of a spall in its early stages, shown by the red arrow.

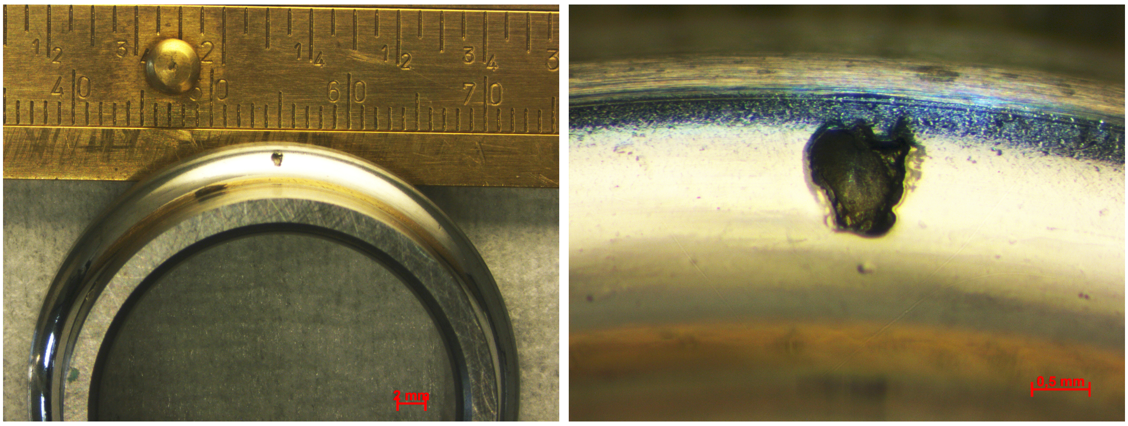


Figure 7.3: Spalling on the last charged inner ring

Figure 7.3 shows a mark where a spall was broken off during testing.

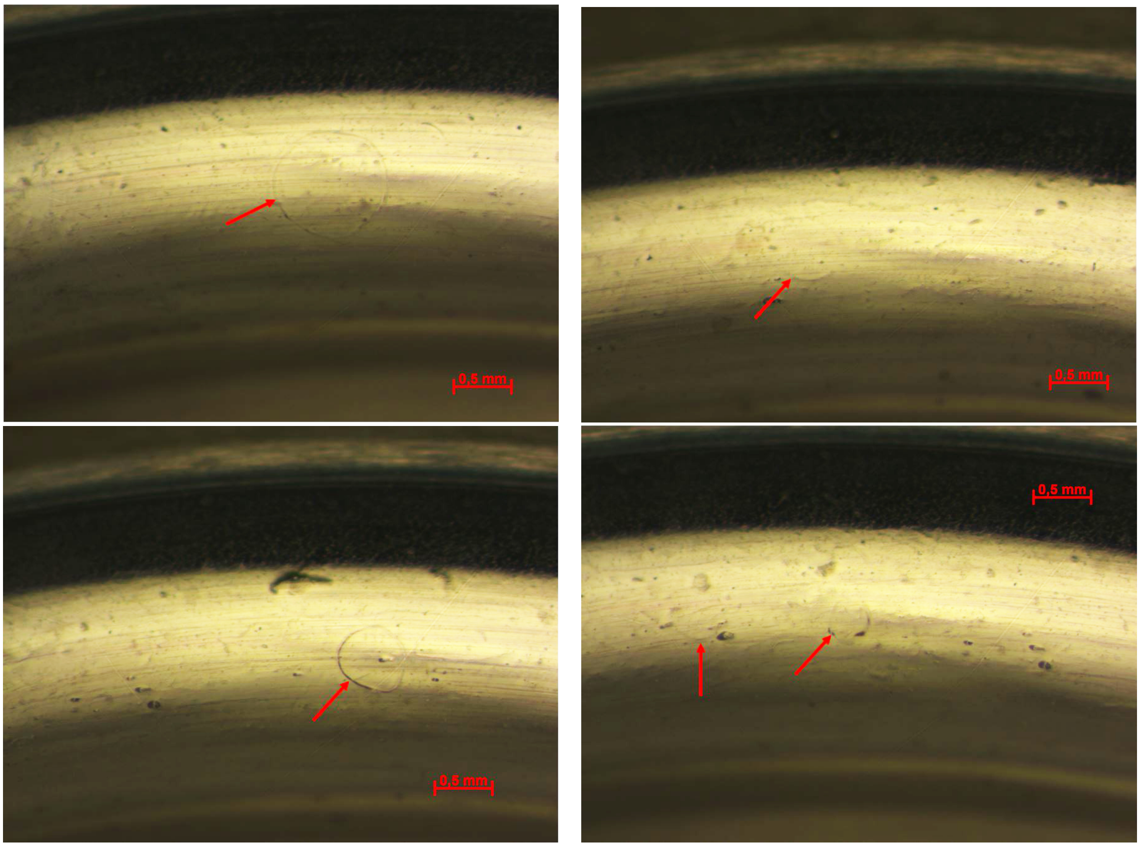
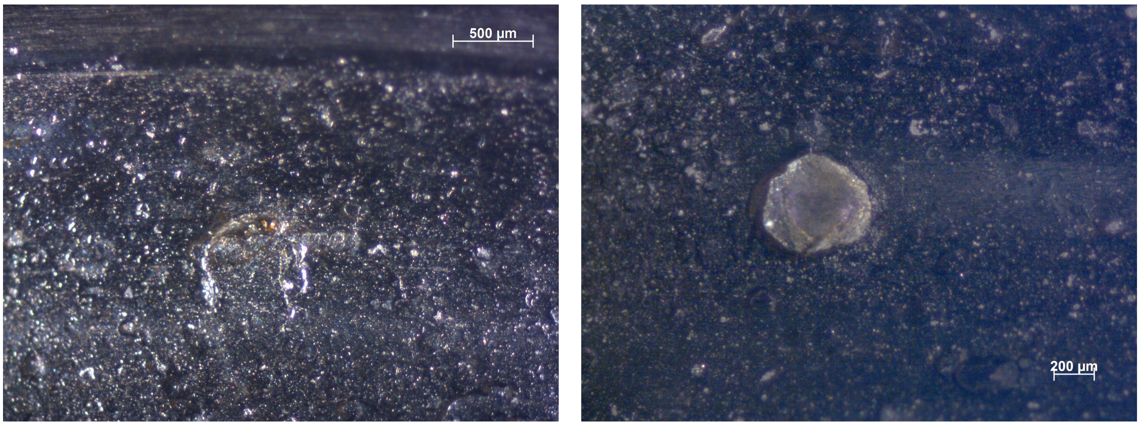


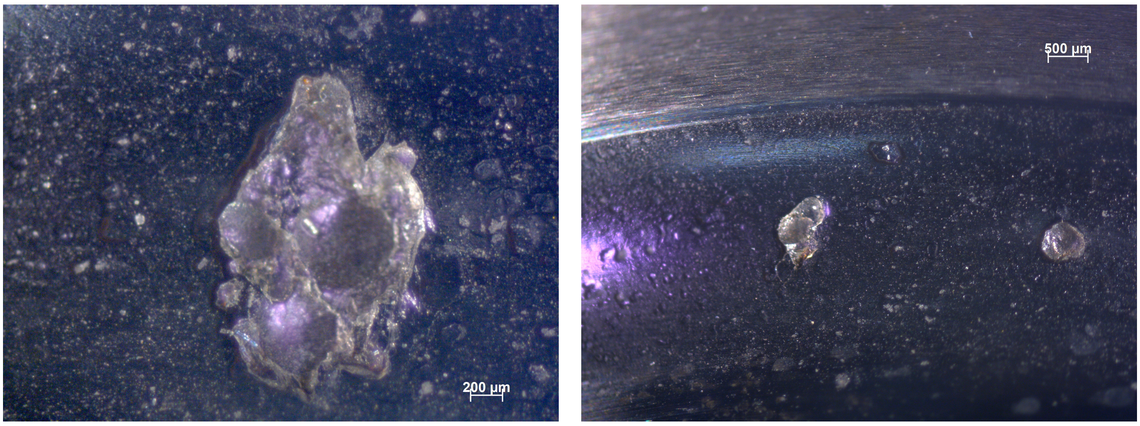
Figure 7.4: Early signs of spalling, indicated by the red arrows

There were more early signs of spalling on the inner rings, as shown in figure 7.4, which could have developed to spalls chipping off if the test had continued for longer.



(a) Early signs of future chip

(b) Mark after chipped off piece

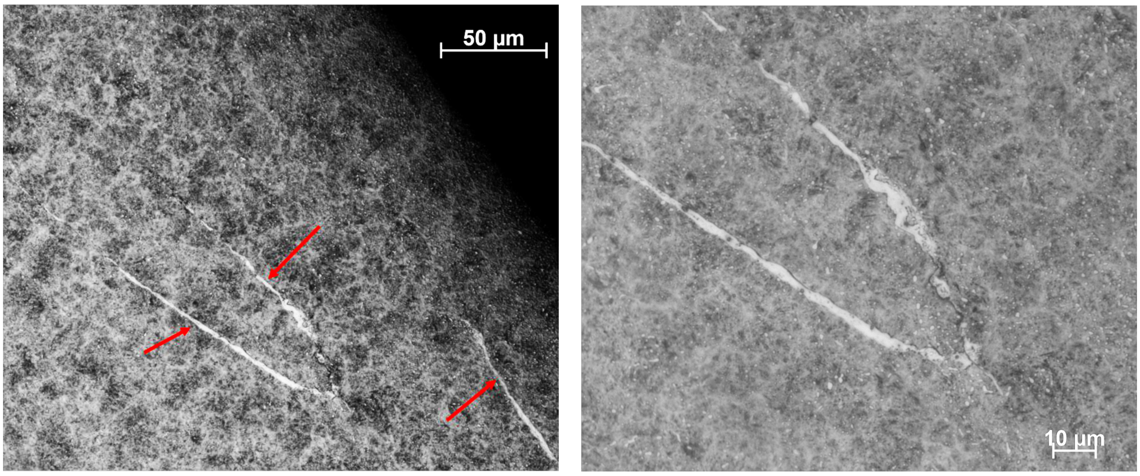


(c) Mark after large chipped off piece

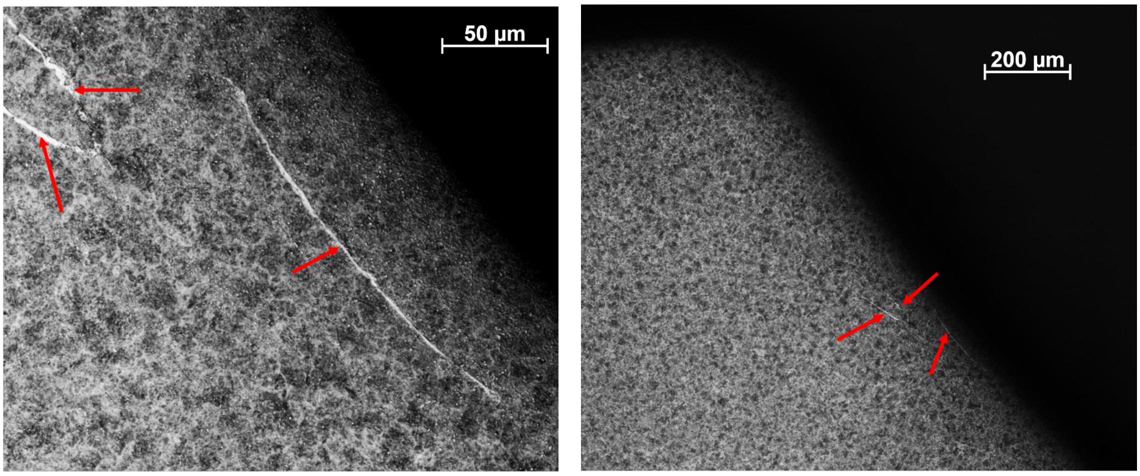
(d) Marks after two chipped off pieces

Figure 7.5: Microscopic images of the damages sustained after the test rig.

Upon closer inspection of the damages with a microscope, the images in figure 7.5 were taken. Figure 7.5a shows early signs of a chip, which would eventually have chipped off had the test continued. The other three images show the marks left after pieces were chipped off.



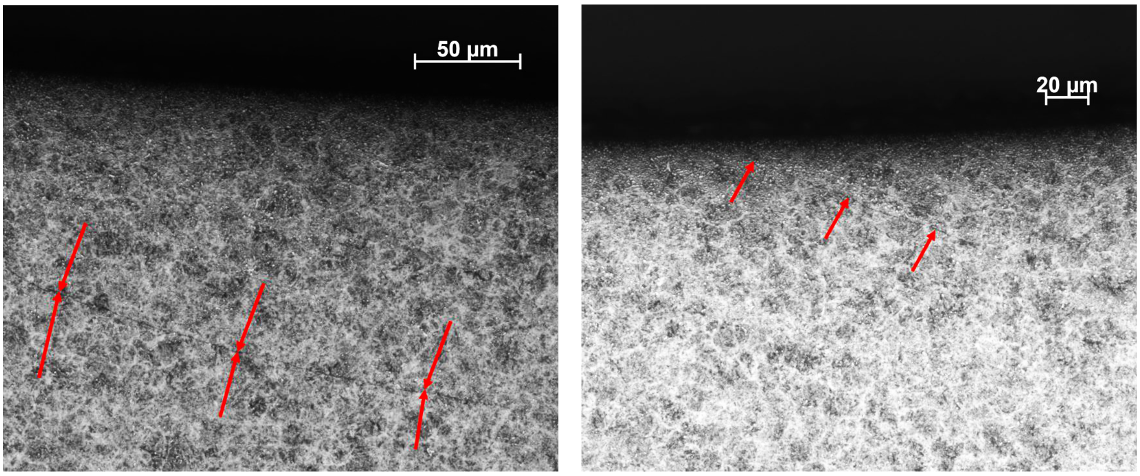
(a) Cracks near the edge of the material (b) Magnified view of the leftmost cracks in figure 7.6a



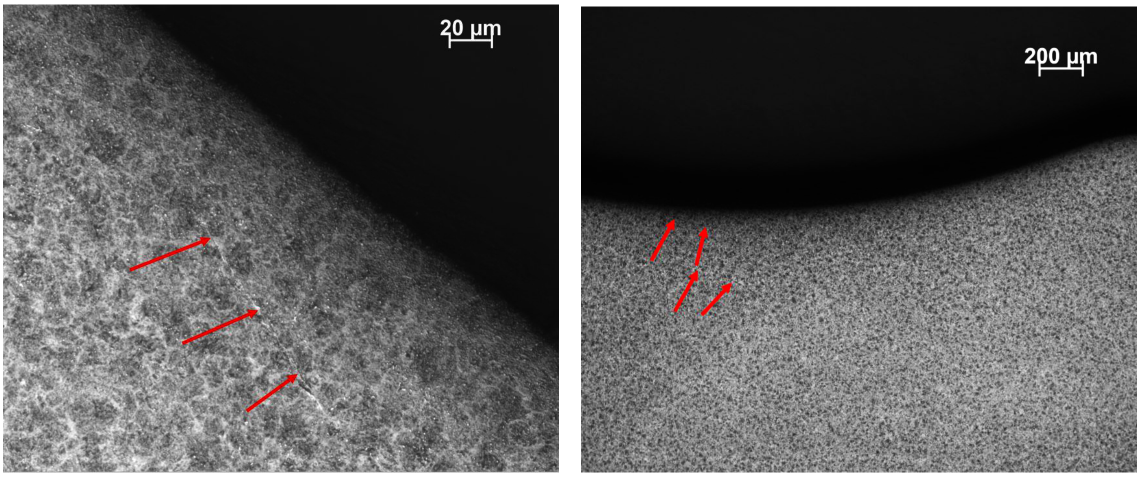
(c) Cracks near the edge of the material (d) Low magnification image showing crack locations

Figure 7.6: Microscopic images of a few cracks developed during testing

The microscopic images that were taken showed that a few sub-surface cracks had formed, parallel to the surface. The images in figure 7.6 show very visible cracks after the etching.



(a) Crack parallel to the surface of the material (b) Crack going to the surface of the material



(c) Crack almost parallel to the surface of the material (d) Low magnification image of crack location of cracks

Figure 7.7: Microscopic images of a few cracks developed during testing

More images were taken, showing more sub-surface cracks running parallel to the surface, and figure 7.7b shows a crack going to the surface. In the low magnification image in figure 7.7d the cracks are barely visible, marked with the red arrows.

8

Discussion

One of the main roles of hydrogen in a future energy system is as an energy carrier that will store energy from the curtailment of excess electricity from renewable energy sources. Electrification is seen as vital to lower carbon emissions, but since electricity is difficult to store, hydrogen can work as an efficient storage alternative and therefore makes it easier for the electrification to take place. The fact that hydrogen can be stored for long periods and is transportable makes it flexible and one of the main contenders when it comes to energy storage and is arguably the most promising energy storage option due to these properties. Some of the applications for hydrogen exist to avoid the conversion of hydrogen back to electricity to increase the energy efficiency but might in some cases not be viable, but it is too early to say which hydrogen concepts there are that will be viable alternatives. Hydrogen can still be a vital part of the energy system even though few hydrogen applications exist, due to the need for energy security, and in a future energy system that is based on renewable energy sources, it will be important to counter the intermittency issues, and hydrogen can have a large part in achieving a more secure energy system.

Hydrogen is today seeing problems in getting the financing it requires and there are a couple of factors that contribute to this. Hydrogen technologies are still immature with relatively low energy efficiencies, and it is still uncertain if they will actually take off and financiers do not want to support technologies with such high uncertainty. Larger efforts in research and development are required to make an evaluation on the prospects of hydrogen to ensure investors that it will be a viable technology, but this requires financing, and therefore there exists a chicken and hen problem that is difficult to solve. It might therefore be necessary for countries and organizations to introduce subsidies towards hydrogen technologies for it to get the development that it needs, and thereafter there will be a snowball effect where more actors start to support hydrogen development. Increasing carbon taxes will also help hydrogen development since this will discourage the use of technologies that are based on fossil fuels and instead focus more on low-carbon technologies. To further increase the adoption of hydrogen will be to educate the population in hydrogen and what it can be used for, but also the downsides and shortcomings of the technologies. This might lead to further support of the technology, and perhaps lead to further innovation for the technology and diminish the downsides when actors take on the technology to ensure its implementation.

Hydrogen helps in achieving energy security, but once the hydrogen storage is depleted and there is not enough energy supply from renewable energy sources, there will be an electricity shortage. It might therefore be good to have a baseload, such as nuclear power, or a conventional power plant that uses fossil fuels but with CCUS to counter the intermittency of the renewable energy sources. These can both be coupled with hydrogen to produce more hydrogen, to ensure the filling of the hydrogen storage, or be used to directly produce electricity and heat. There will then be a baseload that is in constant operation and has a steady electricity supply, while the renewable energy sources produce either above or below the demand, and during hours where electricity would be curtailed, hydrogen is produced and during hours of shortage, hydrogen is used to meet the demand. This leads to a less variable energy system, but that still leads to low carbon emissions.

More blue and green hydrogen production is required to actually achieve carbon neutral hydrogen, but this transition will take time and gray hydrogen will therefore play a large part in the hydrogen development. Currently, SMR is the most common hydrogen production path, but it has the lowest carbon emissions out of the currently existing gray hydrogen production paths. Even though there still are high carbon emissions tied to the current hydrogen production it is still necessary for the development of hydrogen, since there can not be a shortage of hydrogen to use for hydrogen technologies. There will be a transition towards more blue and green hydrogen and it is uncertain how the development will turn out. Blue hydrogen has the advantage of being cheaper but supports further use of fossil fuels which might discourage the adoption of this production path. Green hydrogen is the alternative that is essential for hydrogen to become a significant part of the energy system since it will be used to produce hydrogen from curtailed electricity. Blue hydrogen will be more important if more hydrogen applications are adopted, but if this is not the case, it will be less necessary to implement blue hydrogen production, and instead, green hydrogen will have a larger part in the hydrogen production, since it will always be part of the curtailment strategy of electricity.

The effort required to implement hydrogen is massive, and this is troublesome to societies and companies that are scared that it will slow down their development. The existing energy system is proven to work well, and the innovations required to implement hydrogen will be difficult and the probability of success is uncertain. The pursuit of development and the fear of falling behind, together with the vast usage of fossil fuels are some of the major contributors to why we have such large environmental problems and why it is so difficult to transform the energy system. If a country focuses on the reduction of their environmental impact, they will fall behind other countries and with the current state of the world, this could lead to the degradation of their own country, both economically and in military force. On the other hand, something has to be done and this is difficult to balance. One of the major forces for the reduction of environmental impact is the social pressure to take action, from states, organizations, and the population and the pressure has to increase even further for the implementation of hydrogen to actually occur. It might be more encouraging to implement hydrogen if advancements are made and theory is put into practice by actors. Japan is currently one such actor that is at the forefront when it comes to having a hydrogen strategy and executing it, and hopefully, their strategy will be successful and will pave a way for others to implement hydrogen.

There exists a vast amount of ways to produce hydrogen that have been described in this report and it is uncertain what ways to produce hydrogen will be used. The production methods, such as SMR and electrolysis are some of the more mature ways to produce hydrogen, but less developed concepts such as bio-photolysis or photolysis might be better options, once they have reached a higher degree of maturity. It is therefore good to not only focus on the most developed concepts that currently exist but to put some effort and capital into developing other promising concepts. More effort should however be put towards water splitting technologies since they can be coupled with renewable energy sources to produce hydrogen.

Chemical processes that use hydrogen will be important for the establishment of necessary infrastructure for hydrogen applications and technologies. Current hydrogen demand mostly comes from the chemical sector and it will see an increase in hydrogen demand as the sector is growing, and together with other hydrogen applications that are gradually established, it will help to develop the infrastructure and prepare the energy system to start incorporating hydrogen. The chemical sector will still have a large hydrogen demand in the future, but a prediction is that other applications, such as hydrogen storage and heavy duty FCEVs will become larger sectors for hydrogen in the far future. Another factor that will help with the early establishment of hydrogen is the already existing natural gas grid. As of today, small amounts of hydrogen can be fed into the natural gas grid without requiring major retrofitting. It will be possible to do retrofits in steps and when more hydrogen is produced and it would be possible to feed more hydrogen into the grid and inject less natural gas into the grid and after hand, it could be entirely converted to solely transport hydrogen. This alternative route of establishing a hydrogen transport infrastructure can save a lot of otherwise hefty expenses, and at the same time start to decrease the demand for natural gas. What further incentivizes the blending of hydrogen is that it can also act as a form of hydrogen storage and decreases the need for geological storage or gas tanks. Since hydrogen can be used in similar applications as natural gas, such as heating and gas turbines there are already clear uses of hydrogen and similarly to the retrofitting of the natural gas grid, it is possible to gradually replace equipment that uses natural gas and instead focusing on implementing equipment that utilizes hydrogen in a similar way. It is possible to extract the hydrogen out of the blend, but this is as of today expensive and complex to achieve, but could be another alternative to initially help in the transport and distribution part of the supply chain and use less gas tube trailers for transport. It would be beneficial to have a hydrogen grid since it would mean that no advanced extraction would be required. If a hydrogen grid was established, it would probably mean that hydrogen would already be a major part of the energy system, since the establishment of such a large hydrogen grid would not be made unless it is essential for the energy system, due to the large expenses, time, and effort needed to create the grid. A hydrogen grid is therefore unrealistic to establish immediately and is rather a long term confirmation that hydrogen will be a large part of the energy system for a long time ahead.

The FCEV automobile is the hydrogen application that has seen the most research and development and it is still being developed, but some companies have stopped their development and have instead started to put their focus elsewhere. The FCEV automobile concept is well developed, but the infrastructure required for large scale adoption is far from sufficient. All private owners need to have a refueling station nearby to refuel the vehicle and then there have to be large amounts of hydrogen delivered to these stations. This is why it will either take a long time for the FCEV automobiles to start seeing widespread use or will not see any use at all. The advantages of having a long driving range and fast refueling over BEVs are not large enough advantages, and BEVs are today seeing large improvements in these areas, where the range is increased and charging takes less time. This together with the already well established charging infrastructure, and the fact that BEVs are already many years ahead in development makes it more logical for consumers to purchase a BEV and is why FCEVs will not penetrate the market. Companies have instead started to focus more on heavy duty vehicles, since less refueling infrastructure is required, and routes can be planned ahead to have refueling stops. It is also more important to have long ranges, and quick refueling times than for personal vehicles, since the vehicles can not stand still for multiple hours to recharge the batteries and the same can be said about hydrogen buses. Forklifts have seen adoption in some industries and could also act as a way to start the implementation of FCEVs. Since the market is rather small it should be easier to penetrate it, and could thereafter perhaps branch out into other applications.

Hydrogen trains, ships, and aviation are still in early development, and the future of these concepts is therefore difficult to forecast. Hydrogen trains are less complex than the other two concepts, and the storage is not a large issue, since there is quite a lot of space available on the train. It is also a viable alternative, due to a lot of tracks not being electrified, and can therefore replace diesel trains that are used for these non-electrified tracks. Ships and aviation are however more complex since they have to travel very long distances and have to carry large loads, which leads to the need for large amounts of energy and therefore large hydrogen tanks. Neither of these concepts want to waste space and want to have volume dense fuel, and to achieve this, hydrogen will have to be liquefied or highly pressurized. This is highly energy consuming, and for ships, that have to travel extremely long distances that can take multiple days, this will be a substantial problem. Both ships and aviation vessels will therefore have to be redesigned, and for aviation, the vessel will have to see large configurations to be able to have the large tanks and also have a design that is efficient with regards to wind resistance and energy efficiency. The low-carbon alternatives that exist have not seen major incorporation into these two transport modes, and hydrogen will therefore see further research and development, but if these concepts are realized, it will be in the far future, since there are so many difficulties tied to these concepts, and due to the scale of each vessel, it will be harder for these hydrogen applications to take off.

Transportation of hydrogen using gas tube trucks will see a short term rise if hydrogen becomes a larger part of the energy system. The demand will rise and since trucks is the most established method of transportation, and are flexible their use will increase. However, in the long term, their use will decrease again since it is more economical to use hydrogen pipelines when transporting large amounts of hydrogen. With a larger demand and a more established market will there be more pipelines built, but also natural gas grids that are retrofitted, thus decreasing the need for gas tube trailers.

The development of geological hydrogen storage will be crucial for hydrogen if it will see large scale adoption into the energy system. Storing curtailed electricity in the amounts that will be required in the future will be expensive if done in gas tanks, or as liquefied hydrogen and geological storage are therefore one of the most promising storage alternatives since it can store large amounts of hydrogen at a relatively low cost. The cost is important, since this, together with lower production costs, could lower the hydrogen price and it would be more viable to use hydrogen in more applications. Before large scale storages are established it will not be possible to incorporate hydrogen into the energy system and with geological storage being the most promising storage option it will be important to advance the development to actually deploy this storage type. This quick advancement will also be expensive, and there is hesitation towards the geological storages since there is a low demand for hydrogen which is slowing down the development. This is another chicken and hen problem where there can not be large scale adoption of hydrogen without sufficient storage capacity, but to establish the storages there has to be a large demand. Metal hydrides are also promising options, but it is too early to say if they will see large scale adoption. Having large quantities of stored hydrogen in a small volume is promising, but it will be important to lower the costs for it to take off. Hydrogen can however not be the only form of storage used in a future energy system. Batteries will have to work together with hydrogen, where batteries are used for short-term storage of a few hours or a few days, whereas hydrogen can be stored up to several weeks, or months. These two alternatives will complement each other, where batteries can shift daily variations, whereas hydrogen can shift seasonal variations. Seasonal load shifting is especially important in the Nordic countries since there is a larger demand for electricity during the winter months.

It is challenging to determine what type of compressor will be the most common type for the listed hydrogen applications, and this is because of the uncertainty of the hydrogen supply chain and the required amount of hydrogen. Hydrogen is currently not part of any major energy system and there is therefore no widespread knowledge on what compressors are best suited for each application. In the transport, distribution, and storage part of the chain there will initially be little hydrogen that will be supplied, and small size compressors will be used, but thereafter when the demand increases it is difficult to say how much hydrogen the energy system will need. The intermittency of renewable energy sources further increases the uncertainty, since hydrogen production will vary on an hour to hour basis. These two arguments support the use of smaller compressors, such as screw-, double-acting reciprocating-, and single stage centrifugal compressors, and instead have multiple compressors that be used to handle the variability from available electricity and demand. Screw compressors are generally limited to pressures up to 50 bar and have relatively small flow rates, but will probably see use in applications that do not require high pressure and flow. The trend is, however, that it is desirable to have high pressure so that more hydrogen can be either stored or transported for the applications, and screw compressors might therefore not see much use in the future. This is especially true if hydrogen is produced from high-pressure electrolyzers that can already supply pressures above 50 bar. Instead, centrifugal compressors and high-speed double acting reciprocating compressors will see more widespread use. If the demand is continuous, then larger compressors such as multistage integrally geared centrifugal compressors will be used more, due to it being more economical, but will be less economical if the variability is high. Large centrifugal compressors are also exposed to difficulties due to the need for high impeller speed and stages, which make it less likely that they will be adopted. High pressure compressors, such as the diaphragm compressor and the hydraulically driven reciprocating compressor are more certain to see use in the applications that they are required for if the applications actually are adopted in a future energy system. The industry agrees that these two compressor types are the two main candidates to compress hydrogen for gas tube trailers and FCEVs, but as previously discussed, gas tube trailers and FCEV automobiles will probably see less use and therefore the demand for compressors that are required for these applications will decrease. The market survey might also be skewed since companies want to promote their products and in some cases want to sell a certain type of product to have a higher profit. For the most part, however, companies agreed on what compressors are most suitable for hydrogen use, but varied between applications, as can be seen from the results. There is also a possibility that other compressor concepts might be developed that are better suited than the current compressors that might be used for hydrogen.

The theoretical estimations of the amount of hydrogen in the material show that the diffusion constant depends more on the number of traps than temperature. Looking at figure 6.1, it can be seen that the amount of hydrogen charged increases drastically from the no traps scenario to the a large number of traps scenario. Figure 6.2 then shows the impact of temperature is less significant, especially with no traps, where the difference between the different temperatures is really low, but increasing the number of traps greatly exaggerates the difference caused by the temperature. Similarly, the time taken for the hydrogen to diffuse is significantly increased with the number of traps. The parameter that has the largest impact on the amount of hydrogen in a material is therefore the number of traps. This is due to hydrogen traps increasing the apparent solubility, thus making the material capable of holding more hydrogen, and decreasing the apparent diffusivity, thus making it take longer for the hydrogen to exit the material.

The pre-trials required a lot of trial and error testing. The corrosion encountered at first had to be reduced since it caused severe damage to the bearings. It took a few tests to confirm that the potential was too low, and when it was increased, it was not increased as much as it could have been, since there was still some corrosion present after charging. When the voltage was increased to 3V it was too late to increase it even further, due to time constraints. The corrosion was however negligible for the tests, which could safely be carried out after charging the samples at 3V for 35 minutes. The hardness test performed during the pre-trials shows a seemingly temporary decrease in the material's hardness after charging, which is especially clear on the outer ring samples. The bearing left out for one hour before the test shows a higher hardness than the reference for the inner ring, but this could be due to material variance as all other samples indicate the opposite. It shows that the process of charging the samples affected the material in some way and likely due to the hydrogen since the effect was seemingly temporary.

During the tests in the rig, all bearings broke within a considerably shorter time than the bearing of that type should under a load of 13 kN at 2000 RPM. Using L10h to calculate how long the bearing should survive at this load it was calculated that 90% of the bearings should survive for longer than 66.3 hours. Going even more strict, to L1h, it was calculated that 99% of the bearings should survive more than 16.6 hours. The reference bearing survived the entire 20 hours, while not a single charged bearing survived without damage for even two hours. It is thus clear that something happened to the bearings during charging which made them experience failure faster than normal.

It is hard to say whether the failures of the samples are due to hydrogen or not. The imaging in the microscope shows that the failures were subsurface initiated. The presence of subsurface cracks also indicates that the failure is not likely due to corrosion which attacks the material surface. The amount of corrosion present on the surface of the tested samples was also very low, to a degree where it is unlikely that it had any significant impact on the material. The cracks formed could be due to the charged hydrogen, the high load, or a mix of both. Due to the cracks forming after a relatively short time in the test rigs, it can be assumed that if the test bearings were allowed to run for longer, these cracks would have propagated, leading to more severe damages. Since there were no obvious signs of failure on the reference bearing after 20 hours, and the charged bearings broke relatively fast, is it likely that the charged hydrogen played a part in the bearings breaking. It would have been beneficial if another method had been used to confirm that hydrogen had diffused into the material. The only thing that could be concluded using our method was that something had happened after charging and that the cause was most likely hydrogen. Being able to detect hydrogen would thus allow for more precise conclusions to be drawn.

As mentioned did some corrosion occur during charging, especially in the pre-trials before the voltage between the electrodes was increased to 3V. The low voltage lead to the bearings failing due to standstill corrosion, and increasing the voltage to 3V did drastically reduce the corrosion on the bearing, although not completely. After the increase, the amount of corrosion on the charged samples was deemed to be negligible for the tests. During the attempt to charge a sample with as much hydrogen as possible for four hours, the voltage was increased to 4.1V, leading to no corrosion on the sample. The voltage was initially kept relatively low due to the uncertainties of the potential between the platinum electrodes and the electrolyte. The amount of platinum wire available was limited so a cautious stance was taken to ensure that the potential would remain below where platinum dissolves. By implementing a potentiostat into the setup, it would have been possible to tell the potential between the electrodes and electrolyte. That would allow for a higher voltage to be used without putting the electrodes at risk, thus making it easier to avoid corrosion and more efficiently charge the samples with hydrogen.

Most literature found for the report came from Europe, North America, and East Asia since this is where most developments on hydrogen have been made. It would have been interesting to bring the work of other regions into the report since this might give other perspectives on hydrogen since they might have other needs for their energy systems that hydrogen could solve, or perhaps hydrogen would not have any significant impacts that could be made.

For future tests, it would perhaps be favorable to use an alkaline electrolyte instead of the acidic one. The reason that this was not tried for this report was due to time limitations for further tests and that it early on was stated that an alkaline solution would require substantially longer charging times. With an alkaline electrolyte, the problem of corrosion would not occur and it would be more likely that the test effects from the hydrogen charging would be due to hydrogen diffusion into the material and not corrosion. Having an increased voltage leads to the dissolution of the platinum, but would increase the cathodic protection of the bearing and therefore lead to less corrosion, as well as increasing the current so that more hydrogen could diffuse into the material. It might therefore be a valid idea to have the higher voltage and potentially dissolve the platinum anode ta acquire better charging results. Overall more time for tests would have been valuable to determine an even better charging method to ensure that a large amount of hydrogen would be present in the material.

9

Conclusions

There are still uncertainties tied to hydrogen and what role it will play in a future energy system. There are clear benefits, such as using hydrogen to utilize otherwise curtailed energy and thus play a role in evening out the inherent variations of renewable energy sources or as an alternative method to store energy, helping to provide energy security to the system. There are, however, some issues regarding financing and public acceptance that has to be addressed for hydrogen technologies to break through. Gray hydrogen is likely to play a significant role in hydrogen development as it is the easiest way to produce hydrogen currently, but as the technology matures blue and green hydrogen are expected to become more prevalent. Blue hydrogen, being the cheaper alternative, will play a large role if there is a sudden development of hydrogen applications, as green hydrogen needs more new infrastructure and thus more time to become a viable large scale option. For hydrogen to become a full-blown fossil-free fuel is it however necessary to utilize green hydrogen, procured purely through renewable sources. It can be concluded that hydrogen is likely to play a significant role in the future energy system, capable of replacing fossil fuels as a chemical energy carrier, but more development is necessary for it to become a fossil-free alternative.

Use and need for hydrogen applications will grow with the increase in hydrogen demand and production. Currently, many applications are seeing research and development, and it is difficult to say what applications will be viable as a part of the future energy system. A lot of applications will see growth and eventually fall off or see adoption and further development. Of the applications mentioned in this report, the infrastructural applications are the ones that will most probably see further use, since they are essential for hydrogen to become a part of the energy system.

There will be a wide variety of compressors used in the hydrogen supply chain that works to compress hydrogen for different applications. They will most likely work together to achieve the high pressures that are required, where one type will increase the pressure from low pressure and another will bring it to the final usage pressure. Different variants of reciprocating and centrifugal compressors are being put forward by companies as the most promising options for hydrogen compression, and the size of the compressors will depend on the future energy system and its variability.

The life of the charged bearings was consistently shorter than the reference bearing, indicating that the charging process had a clear impact on the mechanical properties of the bearings. It can be concluded that hydrogen was successfully charged due to the lack of other influences on the material, meaning that the only significant difference between the reference and charged bearings could be hydrogen. The charging parameters used were based on estimated diffusion parameters and the Cottrell equation. An initial fractography of the inner rings after the test rig showed long cracks running parallel to the raceway, and this combined with the other microscopic images suggesting that the failures were subsurface initiated leads to the conclusion that the failures occurred due to hydrogen. With a charging time of only 35 minutes leading to early failure indicates that the material used in the bearings, 100Cr6 EN ISO 683-17 grade steel, is sensitive to hydrogen and thus not suited for use in hydrogen applications.

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A

Appendix: Pre-trials

To reach the method used in the test rig, several tests were performed, in which different setups were attempted. At first, all charging attempts were performed at an elevated temperature of 80°C, which eventually was stepped away from due to the heat increasing the speed of the corrosion reactions. The voltage between the electrodes was initially set at $2V$, which also was changed later on. Before charging it is necessary to clean the bearing, and for the first attempts an ultrasound bath was used, where the bearing was in a bath of petroleum ether 60-80°C for three minutes. It was then dipped in propanol to clean the bearing of petroleum ether and make it dry faster after the bath.

In the first attempt was only half of the bearing submerged in the electrolyte during charging for one hour, with the intent of doing a comparison between the uncharged and charged halves. However, cathodic protection only works on the half submerged in the electrolyte, and thus there are severe corrosion on the half above the surface and clear signs of waterline corrosion, as can be seen in figure A.1 below. There were also signs of corrosion on the submerged half, though significantly less severe than on the half outside of the solution.

Figure A.1: Waterline corrosion seen on the bearing charged indicated while only being halfway submerged. The waterline is indicated by the arrows

The test was thus modified to submerge the entire bearing in the electrolyte in an attempt to reduce the corrosion. The only difference was the submersion, so the charging remained at 80°C for one hour.

Figure A.2: Comparison between bearing fully submerged and charged for one hour at 80°C (upper) and an uncharged bearing (lower)

There were, however, once again, clear signs of corrosion on the bearing, this time of similar severity over the entire bearing, as seen in figure A.2. This bearing was still tested in the test rig, where the bearing broke as soon as the load was applied.

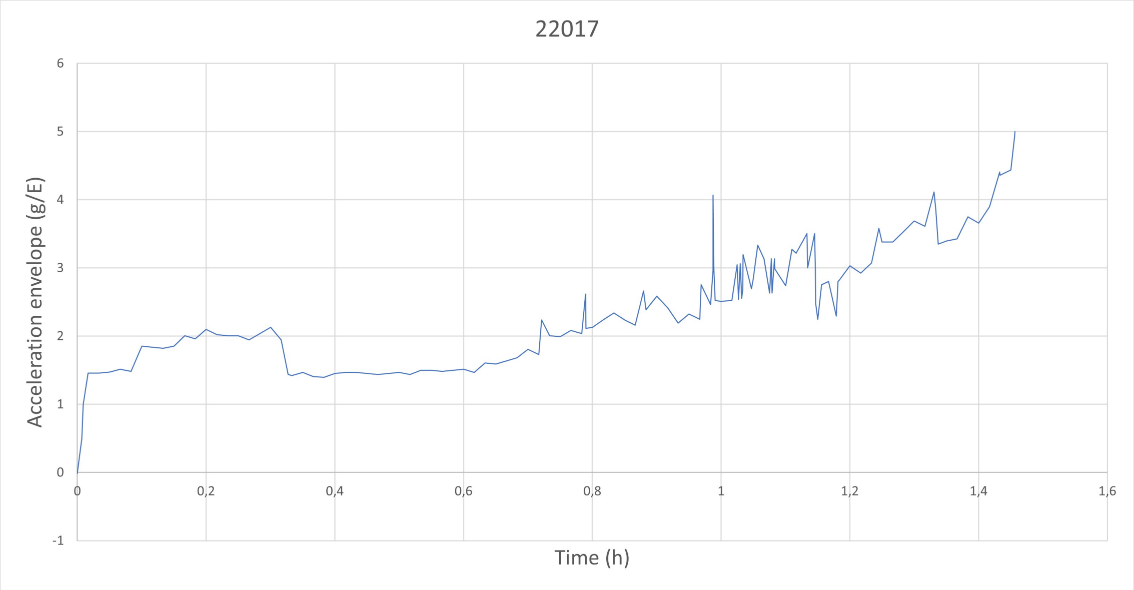

Figure A.3: The vibrations of the fully submerged bearing that was charged for an hour

The rig was set to stop once the vibrations reached 10 times that of the uncharged reference bearing and this level was reached after one hour and 27 minutes as shown in figure A.3. Pieces were chipped off as shown in figure A.4 and three of the balls had clear damage.

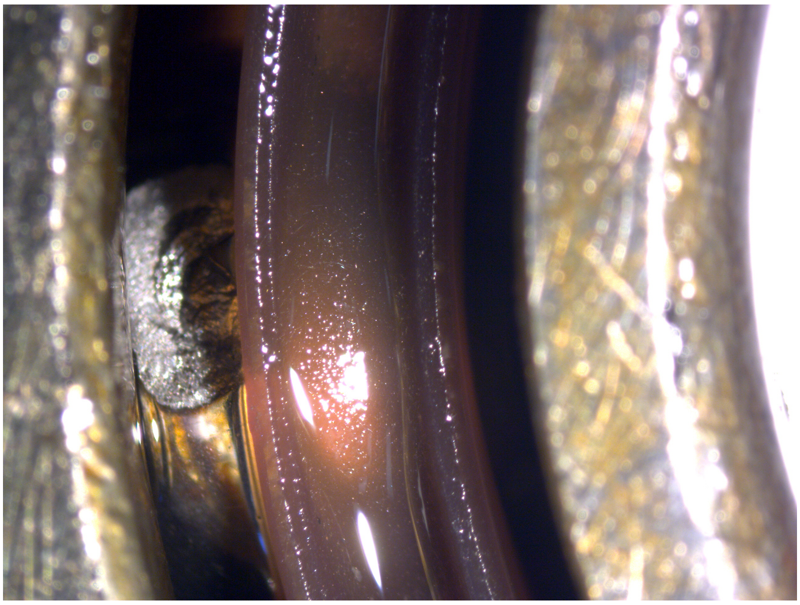

Figure A.4: Chipped off piece from the first bearing in the test rig

Upon closer inspection, it was found that the failure mode is standstill corrosion. This shows that the cathodic protection was faulty, and could depend on either the connection between the bearing and platinum electrode or the potential being too low. To check this, a few thin pieces of steel sheet were charged for 30 minutes each.

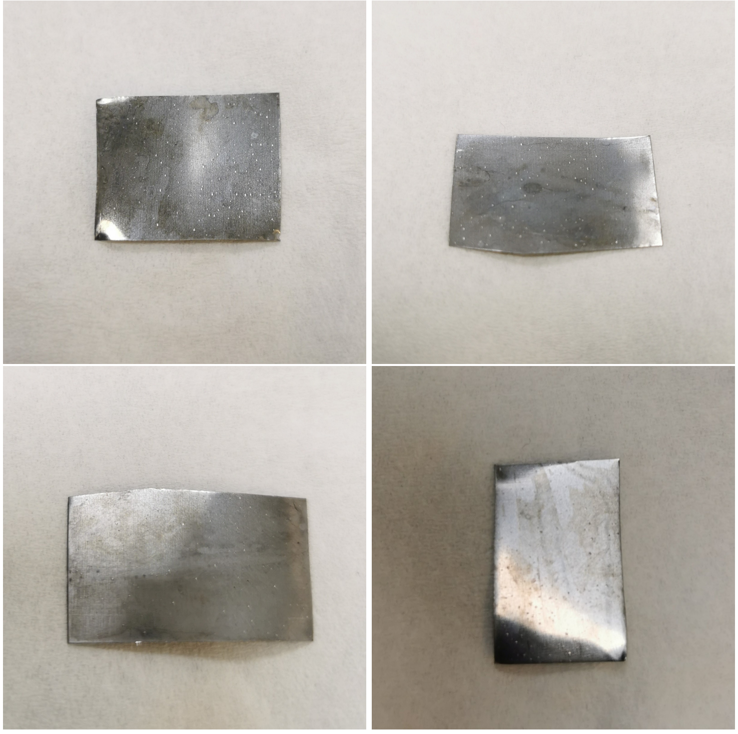

Figure A.5: Steel sheets showing signs of corrosion after 30 minutes of charging at 80°C

As can be seen in figure A.5 are there signs of corrosion on the pieces of steel sheet, making it clear that the voltage needs to increase for the cathodic protection to protect the bearings. For the attempts at charging after this, the voltage was thus increased from $2V$ to $3V$. This also led to an increase in the current, from about 40 to 100 mA. This would mean faster charging, and the charging time was thus reduced from 1 hour to 24 minutes, a proportional decrease to the increase in current. It was also chosen to charge at room temperature instead of 80°C to further reduce the risk of corrosion and a few tests were made to decide how to continue. Three bearing outer rings were charged in slightly different ways to determine temperature and charging time.

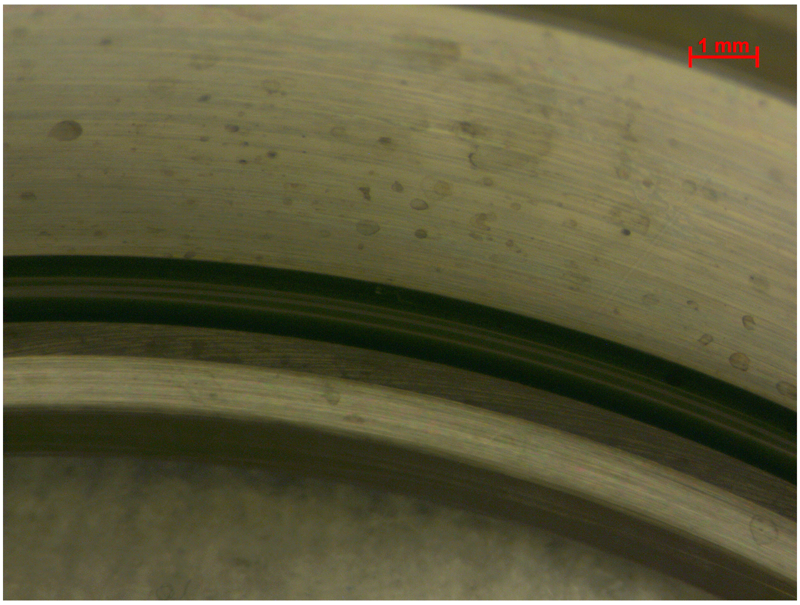

Figure A.6: Image of an outer ring charged for 24 minutes at room temperature.

The outer ring shown in figure A.6 was charged for 24 minutes at room temperature and then checked for corrosion. The outer ring showed no signs of corrosion to the naked eye, but when looked at through a microscope there were signs of pitting corrosion at its initial stages, as can be seen in figure A.6. This degree of corrosion would have a negligible impact on the bearing during the test, and it was decided to attempt to charge for a while longer to let more hydrogen diffuse into the material.

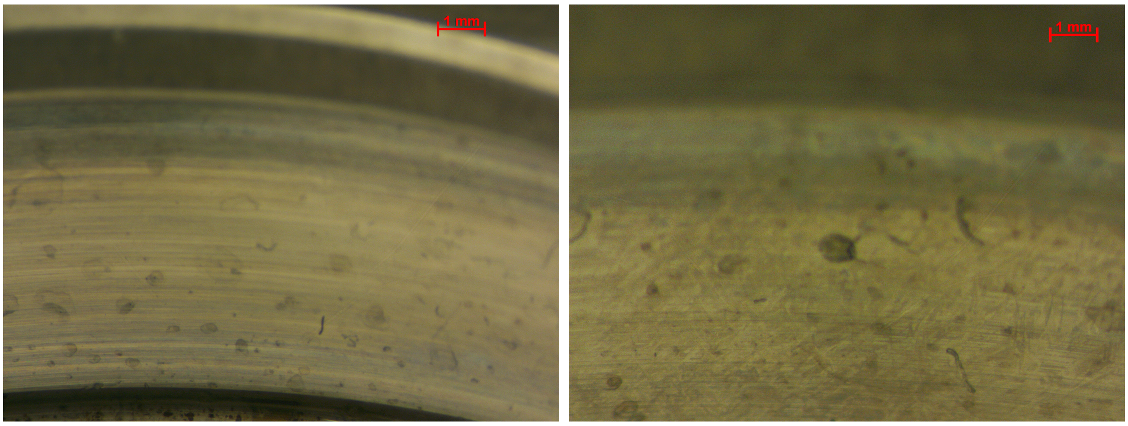

Figure A.7: Images of an outer ring charged for 35 minutes at room temperature.

Figure A.7 shows two closeup images of an outer ring charged for 35 minutes at room temperature. Similarly to the previous outer ring are there early signs of pitting corrosion but at a slightly higher degree. The corrosion is still within acceptable levels for the tests and it was thus decided to do one attempt at an elevated temperature as well.

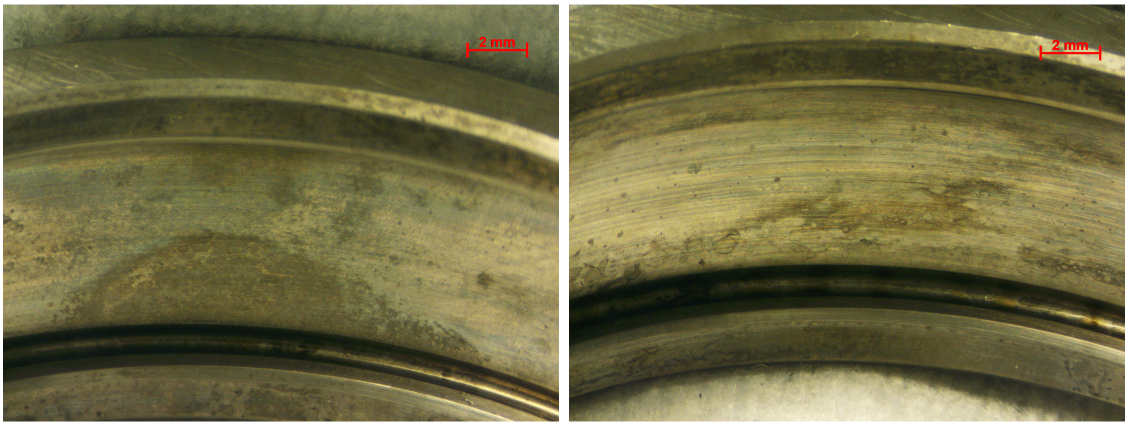

Figure A.8: Images of an outer ring charged for 35 minutes at 80°C.

The outer ring charged for 35 minutes at 80°C experienced a higher degree of corrosion during the charging, as shown in figure A.8. The corrosion progressed significantly further at an elevated temperature, but it was not certain whether it would be too corroded for the test rig or not. To ensure proper connection between the platinum electrode and the bearing was it decided to charge only the inner ring of the bearing with hydrogen and due to the uncertainties regarding corrosion was it also decided to do one attempt at charging an inner ring for 35 minutes at 80°C and running that bearing in the test rig. The cleaning process was easier to perform when only the inner ring was charged, and it was deemed sufficient to wipe the inner ring clean using a cloth and ethanol.

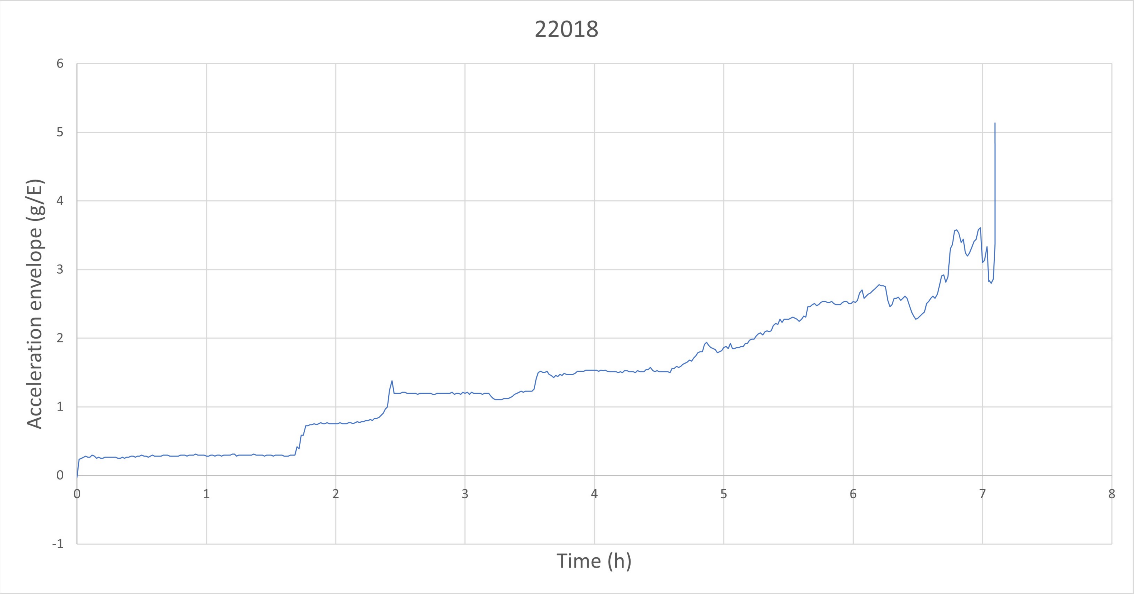

Figure A.9: The vibrations of the bearing with an inner ring charged at 80°C for 35 minutes

The vibration increased after approximately one hour and 45 minutes, showing the first signs of failure, but the test rig was set to keep running until the vibrations reached 5 g/E and thus kept running for about seven hours and 15 minutes. Upon closer inspection, advanced stage spalling was found on the inner ring, with secondary damage on the balls and rings in the shape of indentations. It was then decided that when charging for the tests in the test rig, it will be at room temperature for 35 minutes.

To confirm whether anything had happened to the material during charging, a Vickers hardness test was performed on four samples. The charged bearings were entirely submerged for one hour at 80°C. One bearing had not been charged and acted as a reference, two recently charged, and one left out for an hour after charging. The reference, the one left out for an hour, and one of the recently charged consisted of the entire bearing, while the other recently charged was just of an outer ring. On the samples where the entire bearing was charged the hardness of both the inner ring and outer ring was measured. Three tests were done on each sample, and the final value is the mean of these three values. Table A.1 shows the results from the tests, where it can be seen that the hardness of the newly charged samples have decreased compared to the reference, thus showing that something has happened to the material. The sample left out for an hour has the highest hardness of all samples on the inner ring, showing that the hardness of the sample is regained after being left alone for a while, presumably due to the hydrogen in the material diffusing out of the material. This could be a sign of hydrogen in the material having an impact on the mechanical properties, which then returns to normal once the hydrogen is gone.

Table A.1: Vickers hardness test of different samples. IR refers to the inner ring of the bearing and OR to the outer ring

Sample:	[HV]
Uncharged reference IR	789
Uncharged reference OR	818
Recently charged 1 IR	707
Recently charged 1 OR	784
Recently charged 2 OR	756
One hour since charging IR	804
One hour since charging OR	754

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