University of Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

# BACHELOR'S THESIS

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## Abstract:

Hydrogen as a chemical energy carrier for green energy will play an important role in the reduction of $CO_2$ emissions. Today 76% of the world's hydrogen production comes from fossil fuels, from natural gas and coal without carbon capture and storage processes. The emissions form fossil-fuel based hydrogen counts for 830 $MtCO_2$/year according to the International Energy Agency (IEA) which corresponds to the yearly emissions from both Indonesia and the UK. These emissions can be cut removed by converting over to sorption enhanced steam methane reforming methods with carbon capture and storage. The most cost completive method of producing hydrogen is blue hydrogen, which averages between 1.5-2.5 USD per kilo hydrogen produced with CCUS. The production cost for green hydrogen is between 2.5-6.8 USD per kilo hydrogen.

The price differences between blue and green hydrogen is due to cost of renewable energy and the difference in energy efficiency. The production of hydrogen from Polymer electrolyte membrane electrolysis or PEM water electrolysis has a current energy efficiency of 55-62%, which is predicted to rise to 62-74% by 2030. The energy efficiency of alkaline electrolysis between 55-69%, while the energy efficiency of a large scale SMR will have an energy efficiency of 70-85% lower heating value of hydrogen.

## 1. Introduction

The first-time fossil fuels were used on a grand scale was during the industrial revolution. Coal was the main source of energy that was used to power the new steam engines and heating the cities. As the technology progressed the demand for energy increased. The solution was to burn more coal, eventually in the beginning of the 20th. Century petroleum products was introduced. The main side effect from burning fossils fuels are emission of $CO_2$ to the atmosphere. As presented in figure 1, the total emission since 1751 has been estimated to 1615 $GtCO_2$, and the trend is increasing. Since $CO_2$ is one of the main greenhouse gases, the side effect from fossil fuel burning is that the planet earth is heating up.

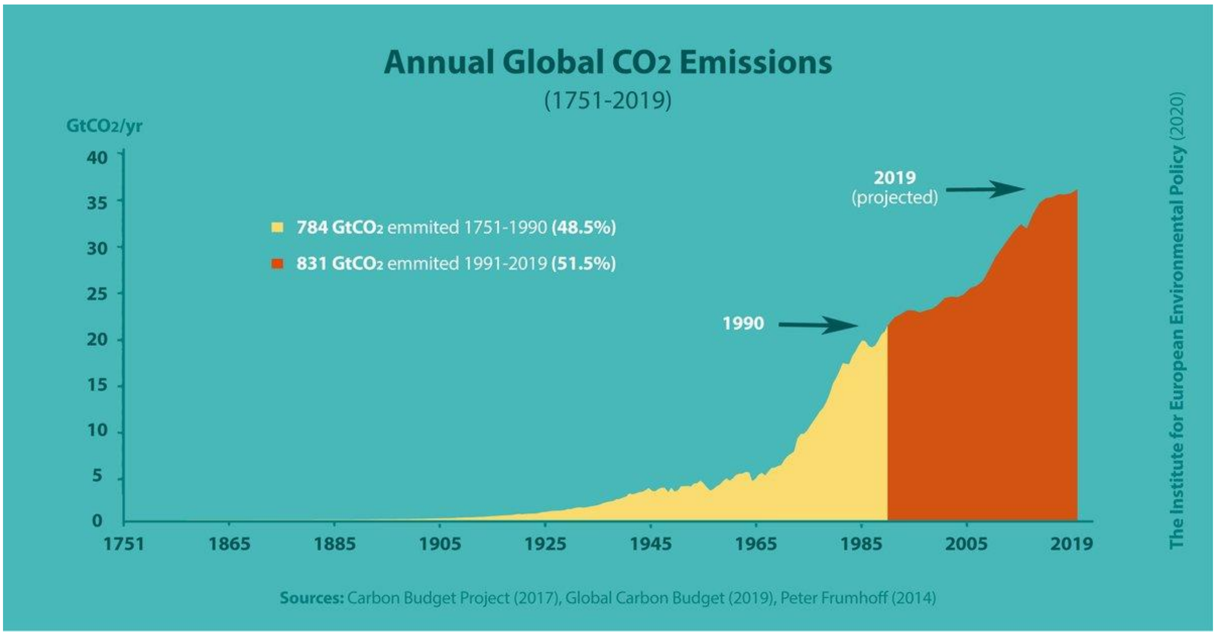


*Figure 1 Annual Global CO2 Emissions from 1751-2019 [IEEP]*

Most of the world leaders agree that if this proceeds the world climate as we know will change to a warmer climate. A world that will not be as pleasant as the current. A warmer climate may cause more inland ice melts, leading to the sea levels rising. The higher temperatures may also increase the likelihood of extreme weather such as cyclones, droughts and heavy precipitation.
To prevent further temperature increases almost every nation in the world has agreed to decrease their $CO_2$ emissions by signing the Paris Accord. The goal of the Paris Accord is to limit global warming to below 2 degrees Celsius above that of pre-industrial levels.

To reach this goal, the world would have to transition its energy production from fossil fuels to renewable energy. The solution would be to stop burning fossil-fuels and to invest in renewable energy sources such as solar panels, windmills or hydro power plants. Although the technology has made major improvements in these sectors, it still will not be enough to satisfy the worlds energy demands to completely replace fossil-fuels. The world needs to continue to invest in these technologies and in batteries to more efficiently store the energy created. During this transitionary period, Hydrogen will play an important role in decreasing the carbon emissions.

Hydrogen does not emit $CO_2$ and is 3 times as energy dense as gasoline [IEA 2019] and more than 1000 times denser than current Li-Ion batteries [Sergei A. Kullinich]. Battery technologies is evolving fast and new technologies are coming up figure 2.  Solid state lithium battery is the next technology with triple of the capacity of Li-Ion [Toyota Norway]. That means that Hydrogen is one of the most important solution to be use as a chemical energy carrier that does not emit green gasses and has sufficient energy density [IEA 2019, p. 32]

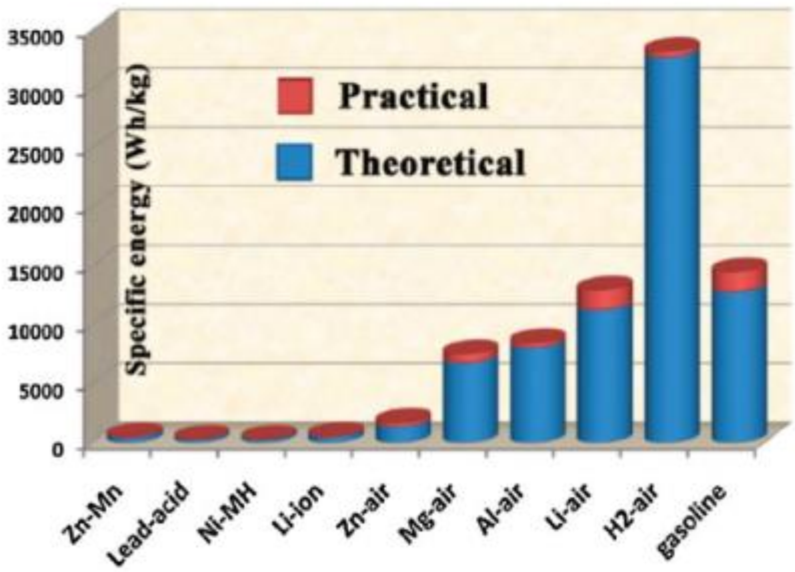


*Figure 2Specific energy (Wh/kg) [Sergei A. Kullinich, Aaron L. Zhu, David P wikinson, Xinge Zhang]*

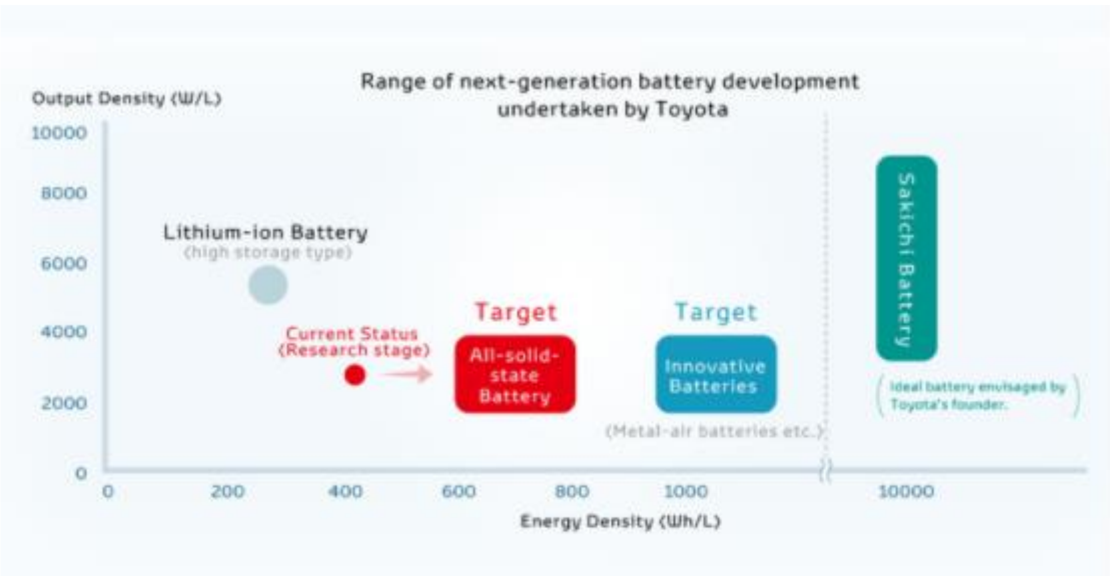


*Figure 3 Energy density and output for the next generation of Toyota car batteries [Toyota Norway]*

## 1.1 Hydrogen production and carbon capture and storage

There are two main solution for production of hydrogen, from natural gas and through water electrolysis. They are classified as Gray, Blue, Turquoise, and Green hydrogen. The classification is based on their impact on the environment. [IREA]

### 1.1.1 Green hydrogen:

Hydrogen gas that is produced without any greenhouse gas emissions is called Green Hydrogen. It is produced with water electrolysis powered by renewable energy from solar, wind, geothermal or hydropower. Today electrolysis accounts for 2% of the global hydrogen production. However, it is expected that the production will increase in the next few years. [IREA]

### 1.1.2 Turquoise hydrogen:

Future natural gas base technology is based on pyrolysis of natural gas, where solid carbon, also called black carbon, is produced instead of $CO_2$. The black carbon can be stored or sold as product. The technology is still under development and may be a valid alternative to the blue hydrogen. [IREA]

### 1.1.3 Blue hydrogen and Grey hydrogen

Blue and grey hydrogen gas is produced from fossil fuels (natural gas or coal) and is converted to hydrogen gas and $CO_2$ is emitted. The name Gray hydrogen means that this hydrogen emits $CO_2$ and is not part of the green solution. [IREA] Today, circa 76% of global hydrogen is produced from natural gas. The annual carbon emission from hydrogen is 830Mt $CO_2$/year, which corresponds to the combined yearly emissions of the UK and Indonesia. The $CO_2$ emitted must be captured and stored for this to be considered a part of the green solution.

### 1.1.4 Carbon capture and storage (CCS)

One of the main technologies of the transition process to a carbon free society is CCS, Without capturing $CO_2$ from the major emitters, the world will have problems reaching the goals of the Paris agreement. The main technologies available for carbon capture are absorption by enhanced steam methane reformation, membrane, and chemical absorption.

By using this technology industries such as grey hydrogen production, steel industry, fertilizer manufacturers and cement factories can get a net-zero in $CO_2$ emissions.

The captured $CO_2$ is to be transported to a designated storage well stored deep underground. [SINTEF]. Norway has the potential for large-scale carbon storage under the Norwegian continental shelf in the North Sea. Since 1996, almost one million tonnes of $CO_2$ have been stored in the Utsira formation. Norway [Norsk petroleum, Hofstad(SNL)].

### 1.2 The purpose of this thesis

Hydrogen is a main contributor in meeting the requirements of the Paris agreement. Hydrogen facilities will be built, and a solution must be chosen. I will give an in-depth review of the different types of blue and green hydrogen production solutions and include an assessment regarding the difference in efficiency and production costs. Chapter 2, 3 and 4 presents a technical description of the Green, Blue and future solutions as well as their energy efficiency.
Chapter 5 present an overview of the production costs of green, blue and grey hydrogen. Chapter 6 present an overview of the usage of hydrogen as an energy carrier and Chapter 7 presents a discussion between the two alternatives and suggest which alternative is the best for solving the climate challenge.

## 2. Green hydrogen production

### 2.1.1 Basics of electrolysis:

Electrolysis is a part of electro chemistry where energy is supplied to non-spontaneous redox reactions. Redox reactions are reactions where one element or molecule will be oxidized, and the other element will be reduced [Theordore L.]. Non-spontaneous redox reactions are reactions with a cell voltage which is negative and therefore requires energy to facilitate the reaction. One example of this is the electrolysis of 1 molar HCl solution, hydrochloric acid [Nils Chr.].

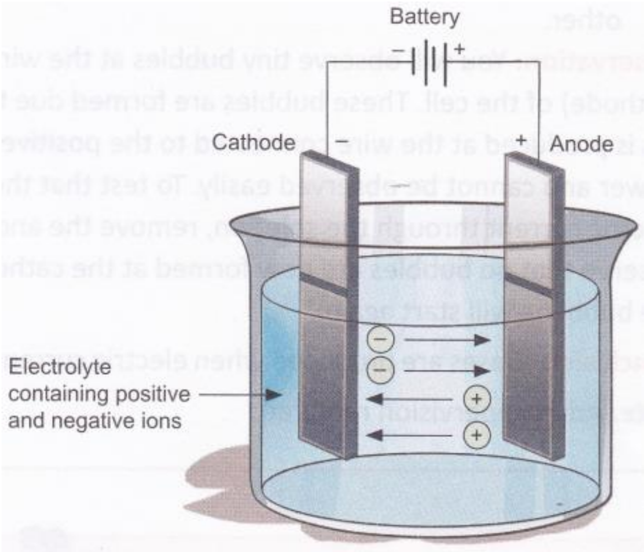


*Figure 4 Electrolysis basics [sastry]*

Electrolysis reactions transpire in electrolytic cells, consisting of two half-reactions at the two electrodes see figure 5. The electrolytic cell consists of two electrodes, the cathode and the anode. The electrodes are submerged in either molten salt or a solution, like an acid. At the cathode the reduction half-reaction will occur, while at the anode the oxidation half-reaction will occur [Nils Chr.].

At the anode the reaction will be $2Cl^{-}(aq) \rightarrow Cl_2(g) + 2e^{-}$ , $E°_{red} = -1.36\ V.$
While at the cathode the reaction will be $2H^{+}(aq) + 2e^{-} \rightarrow H_2(g)$, $E°_{red} = 0\ V.$
The total reaction will be $2Cl^{-}(aq) + 2H^{+}(aq) \rightarrow Cl_2(g) + H_2(g)$, $E°_{total} = -1.36\ V$

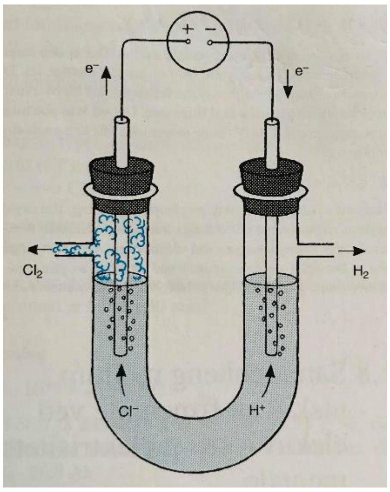


*Figure 5 Example of electrolysis of a HCl-solution [Nils Chr.]*

### 2.1.2 Standard hydrogen reference electrode:

A standard hydrogen reference electrode is used when comparing all other half-cells. This electrode is a typical gas electrode. The standard hydrogen reference electrode consists of a salt bridge, a metal conductor with a plate of platinum or platinized with black platinum, acid solution, and a power source. the platina plate is used as a catalyst and for extended surface area for the reaction. The acid is an aqueous solution where the hydrogen concentration is known and constant.

$$2H^{+}(aq) + 2e^{-} \rightleftharpoons H_2(g)$$

The potential of a hydrogen electrode is dependent on the temperature and pressure. Where the standard hydrogen reference electrode has an assigned value of 0.0V at all temperatures at a pressure of one atmosphere.

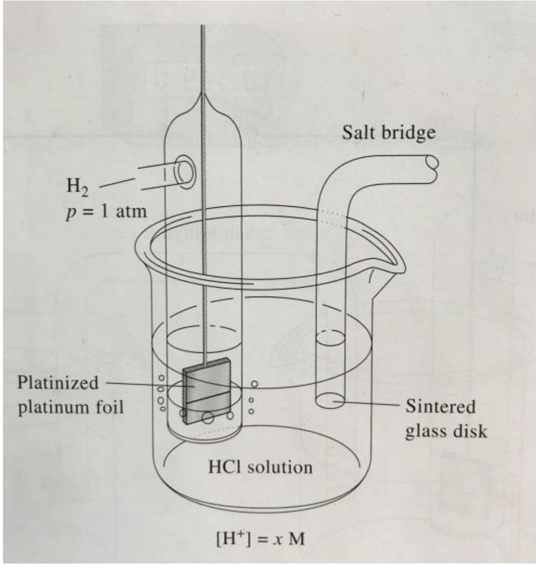


*Figure 6 Hydrogen gas electrode (SHE elkectrode) [Douglas A.Skoog, Donald M. West, F. James Holler, Stanley R. Croucch]*

### 2.1.3 Hydrogen production in smaller amounts* (Lab):

In a laboratory setting, hydrogen gas can be synthesised through redox reactions between a diluted acid and a metal. The metal will be oxidised, and the acid will be reduced. For example, the reaction between zinc and diluted hydrochloric acid is a redox reaction which will produce hydrogen gas [Geoff Rayner]. With the reaction equation:

$$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$$

### 2.1.4 Alkaline electrolysis:

Alkaline water electrolysis is an easy, though expensive method, to produce clean hydrogen gas and is currently used in the chemical industry. Norsk Hydro produced hydrogen gas 1920 by the use of alkaline electrolysis.[R.M Navarro, Hydro]. An alkaline medium is used to donate hydroxide anions (OH) to the water solution to increase the production of hydrogen gas. The concentration of the alkaline medium is 25-30% of the total weight of the water solution. The alkaline medium used are potassium hydroxide (KOH). The catalyst used is sodium hydroxide (NaOH) and sodium chloride (NaCl). The electrolytes in the water solution allows the hydroxide anions (OH) to be transported between the electrodes. [R.M Navarro, Coutanceau] The reactions at the electrodes are:

Anode reaction: $2OH^{-1}(aq) \rightarrow \frac{1}{2}O_2(g) + H_2O(l) + 2e^-$

Cathode reaction: $2H_2O(l) + 2e^- \rightarrow 2OH^-(aq) + H_2(g)$

The total reaction: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

The energy efficiency of alkaline electrolyser is between 65-82% HHV (higher heating value) and for the lower heating value 63-70% [IEA,2019]. The lifetime of an alkaline water electrolysis system is between 60 000- 90 000 hours. IEA suggested an initial investment of 850-1500 USD per kW. [IEA,2015]

### 2.1.5 PEM electrolysis:

Polymer electrolyte membrane electrolysis or PEM water electrolysis uses proton exchange membranes of solid polysulfonated membranes. The water molecule gets split up at the anode to oxygen and hydrogen ions. The hydrogen ions migrate through the membrane to the cathode to form hydrogen gas. [S. Shiva Kumar, V.Himabidu]

Anode reaction: $H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^+(aq) + 2e^-$

Cathode reaction: $2H^+ + 2e^- \rightarrow 2OH^-(aq) + H_2(g)$

The total reaction: $H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g)$

PEM water electrolysis yields greater hydrogen production rate and a high purity hydrogen gas (99.99%), than alkaline electrolysis. Though the energy efficiency of PEM is lower than alkaline electrolysis, which is between 55-60%, and the initial investment system cost is between 1500-3800 USD per kW [IEA,2019]. Element energy and E4tech predicted in 2014, that PEM water electrolysis plants would have an increase in energy efficiency to 62-74%.

## 3. Blue hydrogen production from methane:

### 3.1 Steam Methane reforming

One of the industrial methods of synthesising hydrogen gas is steam reforming process. The first step in the steam reforming process is heating up the natural gas together with steam over a nickel-based catalyst system. Note that the steam in most plants are generated from gas. Hence the main source of energy to complete the process comes from methane. In the blue version may include usage of electrical energy for generating steam. [Geoff Rayner-Canham, Energy.gov]

$$CH_4(g) + H_2O(g) \xrightarrow{Ni-catalyst,\ 500℃} CO(g) + 3H_2(g)$$

In order to separate the hydrogen gas from the carbon monoxide, the gas mixture needs to be cooled down to temperatures below -205°C. At this temperature the carbon monoxide will condense and can be removed from the gas mixture. Additional hydrogen gas can be produced from the steam methane reforming reaction by a using water-gas shift reaction. In water-gas shift reactions, the gas mixture is cooled and additional steam is injected. The new gas mixture is passed through a pressure-swing absorption system, where the carbon monoxide is oxidized to carbon dioxide. The carbon dioxide can be removed from the gas mixture by cooling the gas to -78°C. [Geoff Rayner-Canham, Energy.gov]

$$CO(g) + H_2O(g) \xrightarrow{water-gas\ shift\ reaction} CO_2(g) + H_2(g)$$

The removal of carbon dioxide by cooling the gas is an expensive way to remove the carbon dioxide from the hydrogen gas, as one has to spend energy to cool the gas. [Geoff Rayner-Canham]. The removal process can be done with the use of a carbon dioxide sorbent, Pressure swing absorption with or without a chemical looping system or membrane set up.

Steam methane reformation energy efficiency is dependent on the scale of the reformer. At large scale the energy efficiency of steam is between 70-85% lower heating value of hydrogen. For small scale steam methane reformation, the energy efficiency is 51% LHV. [IEA, 2015]

- Intital investment cost Large scale 400-600 USD/kW (2015) lifetime 30years [IEA, 2015]
- Initial investment cost small scale 3000-5000 USD/kW (2015 lifetime 15 years[IEA, 2015]

## 3.2 Sorption enhanced steam methane reforming with $CO_2$ sorbent

The steam methane reforming process is enhanced by using a carbon dioxide absorption material to capture the produced carbon dioxide. A basic design of a hydrogen production plant based on having an absorption regeneration reactor and a steam methane reforming reactor. The desired carbon dioxide absorbent material properties have a high reaction rate in the temperature interval 450-650°C, high abortion rate of carbon dioxide, stable under adsorption reaction, cost effective, highly regenerable with a low temperature interval between carbonation and calcination. [L. Barelli*, 2007,2005 Sept. Des.]

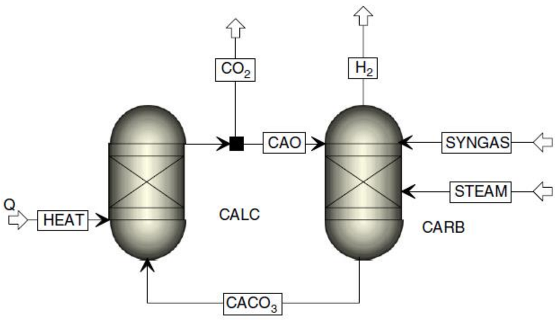


*Figure 7 Basic scheme of a SE-SMR hydrogen plant [L. Barelli, 2005 Sept.]*

The absorbent material used in a sorption enhanced steam methane reforming process can be natural or synthetic. Calcium carbonate and dolomite are natural minerals with high adsorption rates and are also inexpensive. The abortion ability of calcium carbonate is 0.79 grams of carbon dioxide per grams of sorbent and 0.46 grams carbon dioxide for dolomite. The active absorption portion is the calcium oxide, which will react with carbon dioxide to form solid calcium carbonate. [L. Barelli*, 2007,2005 Sept. Des.]

$$CaO(s) + CO_2(g) \rightleftharpoons CaCO_3(s)$$

The calcium oxide from calcium carbonate and dolomite can be reused up to 45 times with a 60% reduction in sorption effect. The regenerating temperature of calcium oxide is high, but some of the heat is recycled back into the steam methane reforming process. Synthetic sorbents are lithium orthosilicate and lithium zirconate. These sorbent materials have a lesser adsorption ability compared to calcium carbonate and dolomite, with adsorption rates of 0.37 grams and 0.29 grams carbon dioxide per grams sorbent. The main advantage of the synthetic sorbents are that they are stable for 100 cycles of regeneration. [L. Barelli*, 2007]

## 3.3 Sorption enhanced steam methane reforming with a pressure swing adsorption

Pressure swing adsorption or PSA is an adsorption process for gas purification. Where sorption material is used in combination with pressure to bind gas molecules to the adsorption material. [Joakim beck]. In hydrogen production the PSA process is a cyclic process where the reformed gas feed from the steam methane reformation (SMR) process moves into a bed of adsorption material. Where the adsorption bed is at room temperature with pressures between 20-25 bar. The PSA system consists of either two or multiple absorption beds, the gas feed will move over to the next bed, while the previous bed's adsorption material gets regenerated and the adsorbed gas gets purged from the system. [Mohamed A]

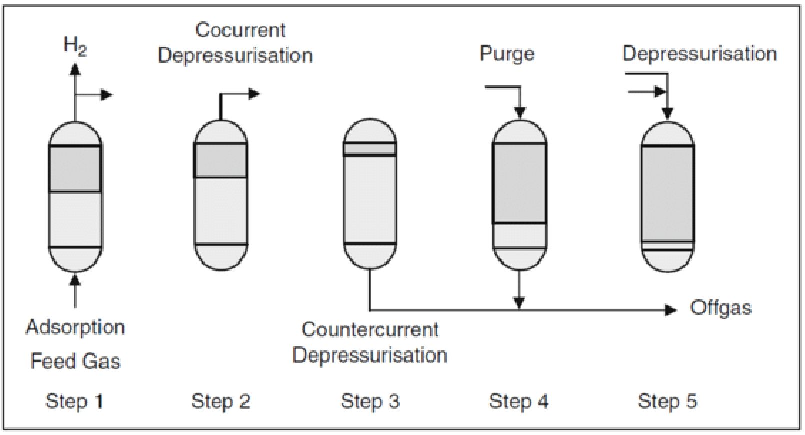


*Figure 8 Elementary Steps of A PSA cycle operation [Márcio R. Vianna Neto]*

The PSA system can also be designed as compacted pressure swing adsorption system. Which allows small pressure drops, instantaneous and continuous separation between hydrogen, carbon mono oxide (CO) and carbon dioxide($CO_2$). [Majlan]

## 3.4 Sorption enhanced steam methane reforming together with chemical-looping combustion

Chemical looping combustion (CLC), is a new technology for oxyfuel combustion, which is being considered for blue hydrogen production. CLC uses solid oxygen carriers to remove carbon monoxide (CO) from the syngas. [Cormos] These solid oxygen carriers are single metal-based oxides, for example iron(III)oxide or iron(II)oxide ($Fe_3O_4$ or $Fe_2O_3$) [NETL]. The CLC process starts with heating the oxygen carrier before it gets introduced to SMR or a fuel reactor. Here, the oxygen carrier will fully or partially oxidize the carbon monoxide and the hydrogen gas, and create solid metal, carbon dioxide and steam.

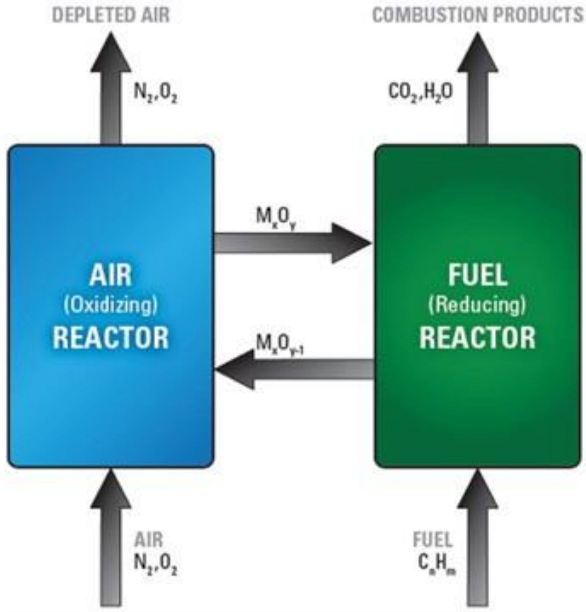


*Figure 9 Simplified system CLC from NETL*

If the oxygen carrier is iron(III)oxide, $Fe_3O_4$, the reaction in the SMR-reactor will be:

$$Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(s) + 3CO_2(g)$$

$$Fe_2O_3(s) + 3H_2(g) \rightarrow 2Fe(s) + H_2O(g)$$

The gas feed from the fuel reactor will be cooled, to separate the $CO_2$ from the steam. The carbon is stored while the steam can be used to regenerate the oxygen carrier. The oxygen carrier can also be regenerated using air or a combination air and steam. [Cormos]

Regeneration with steam:

$$3Fe(s) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 4H_2(g)$$

Regeneration with air:

$$4Fe_2O_4(s) + O_2(g) \rightarrow 6Fe_2O_3(s)$$

The chemical-looping combustion can be connected to the SE-SMR with or without a PSA system to avoid $CO_2$ emissions from the calcination of calcium carbonate [Yonglian Yan]

## 3.5 Membrane separation process

Membrane separation processes uses a semipermeable barrier that allows separation between two or more components from a liquid or a gas. The component will pass through the membrane by the chemical potential between the different sides of the membrane, which is generally provided by the difference in concentration, pressure, temperature or electric potential [Nesse].

There are two classifications of membrane processes which involves gas separation. These are gas diffusion in a porous solid and gas permeation in a membrane. In a gas diffusion in porous solid medium, gas phases are present on both sides of the microporous solid medium.  Due to the size of the pores in the solid medium used for the separation the rate of the separation is dependent on the size of the capillary tubes. Since the gas will follow Knudsen gas diffusion, as the gas molecules will collide with the capillary walls. [Geankoplis]

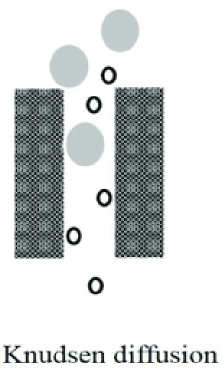


*Figure 10 solid porous medium gas permeation in a membrane [Hang Yin]*

The second membrane process, gas permeation in a membrane, use membranes based on polymers like polyamides and rubber. The gas will be dissolved in the membrane and then diffuses in through the membrane.

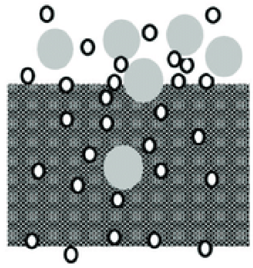

*Figure 11 Gas permeation in a solid medium without pores [Hang Yin]*

Membrane technology can be combined with steam methane reforming, either with a membrane reactor or a sorption-enhanced membrane reactor.  Two examples of membranes used in hydrogen production is an ion transport membrane and a palladium membrane.

Ion transport membrane systems simplify hydrogen production from methane. By combing the steps of hydrogen production with SMR in one step. This archives higher efficiency and cheaper production than non-ion transport membrane systems. The membranes consist of non-porous ceramics, made from multi-components metallic oxides that conduct both electrons and oxygen ions at temperatures above 700°C. The oxygen is derived from steam, the water molecules reacting with a surface catalyst on the wall of the membrane and the partial pressure gradient between the membrane walls.  Once the oxygen reaches the other side of the membrane it will partially oxidize the hot gas mixture of methane and steam, resulting in syngas production. The syngas will be processed in a water gas shift reactor, separating the syngas into hydrogen and carbon dioxide. [L. Barelli*, 2007]

The palladium membrane is proton membrane that allows hydrogen ions to pass through. This membrane is based on a palladium alloy and is used in combination with reforming catalysts to make compact reactors. The design is up to $^1/_3$ or ½ volume of conventional steam methane reforming units. This compact design allows simultaneous generation of hydrogen gas and it lowers the required temperature as the reactions are driven by le Chatelier's principle. The operation temperature of the membrane is between 500-550°C at a pressure of 0.1MPa, instead of the 800-900C required for conventional steam methane reforming reactors. [L. Barelli*, 2007]

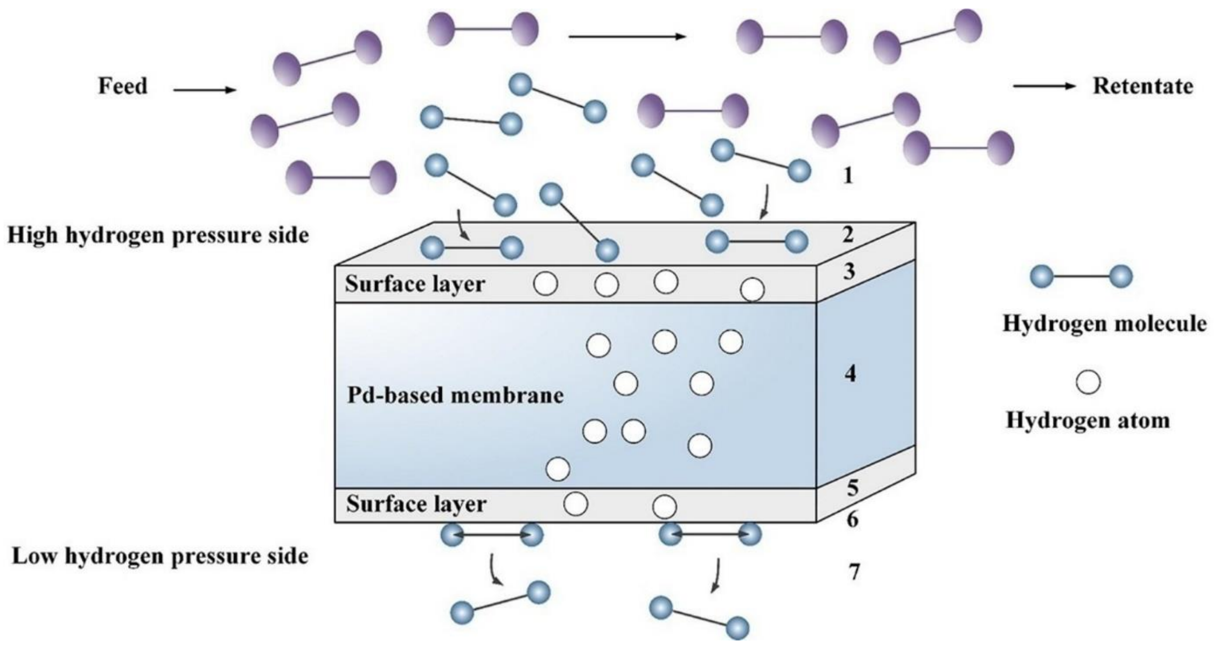


*Figure 12 Palladium membrane separation [M.R.Rahimpour,F.Samimi, A.Babapoor, T.Tohidian, S.Mohebi]*

# 4. Future hydrogen production technology

## 4.1 Pyrolysis of natural gas

Pyrolysis is a method of chemical decomposition of organic material at high temperatures, where oxygen is absent or only present in very low concentration [Britannica, Boslaug]. Therefore, pyrolysis of methane gas will only yield hydrogen gas and carbon. Due to the absence of $CO_2$ there will be no need for a carbon capture and storage system. Pyrolysis will produce high purity hydrogen gas and black carbon which may be sold for profit. However, to conduct pyrolysis one needs a lot of energy in order to reach the temperatures required which may be costly in the long run.

Black carbon is a bi-product from the partial combustion of hydrocarbons. As the name suggests black carbon are spherical carbon-based particles. Black carbon can be used as a black pigment or as a reinforcement agent in tires and rubber products. Black carbon is also used as resistors for electronic circuits. [Britannica, carbon-black]

*Figure 13 Soot, fine particles of pure carbon [SNL, sot]*

Carbon nanotubes are one graphite sheet thin tube. The carbon atoms are bound by covalent bonds in a hexagonal system. These covalent bonds form a strong material, which is 100 times stronger than steel. The nano tube can also be used in electrical components as conductors, or if there is a twist in the hexagon system, the carbon nanotube will act as a semiconductor. Nanotubes are classified into two classes single-walled nanotubes and multi-walled nanotubes. [Geoff Rayner-Canham]

Graphene is another hexagonal ring system of carbon atoms, consisting of a single flat sheet of carbon hexagonal rings, material that is one atom thick. This material has electrical and magnetic properties like metals. [Geoff Rayner-Canham]

# 5. Production cost of green and blue hydrogen

## 5.1 2018/2019

The production cost of hydrogen production from natural gas in the U.S with carbon capture utilization and storage (CCUS) is 1.5 USD/kg$H_2$. In Europe the production of blue hydrogen with CCUS cost is between 2.0-2.5 USD/ kg$H_2$. The production cost for blue hydrogen without CCUS is between 1.0-1.75 USD/ kg$H_2$. On average the removal and storage of carbon adds 50% to the costs. Fuel counts for the largest cost of production, which varies from 45% to 75%. Therefore, the price of natural gas is the determining factor for steam methane reforming hydrogen production. [IEA 2019, page 42,52]

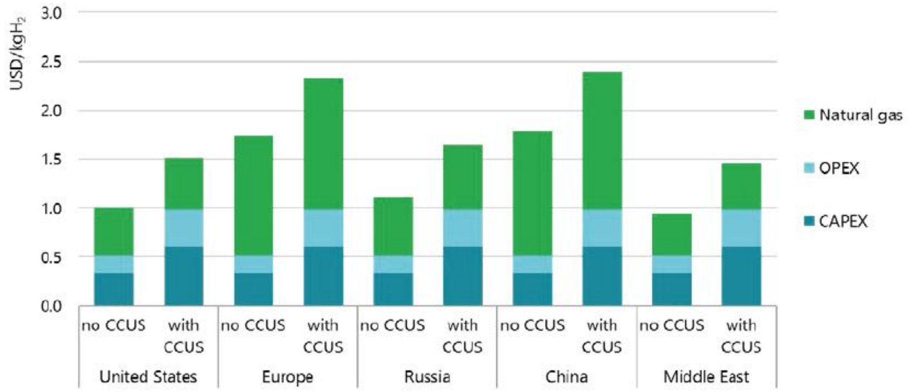


*Figure 14 Hyrdrogen production cost from natural gas 2018 [IEA2019, page 41]*

The production of green hydrogen requires fresh water and electricity from green renewable sources; like solar, wind and hydropower. Green hydrogen cost between 2.5 to 6.8 USD/ $kgH_2$ to produce. [De Blasio, IEA 2019]. If the water used in electrolysis is from sea water, then the cost of reverse osmosis adds a negligible production cost of 0.01-0.02 USD per kg hydrogen gas. [IEA 2019,p.43,47]

## 5.2 2030

Future hydrogen production costs will depend on electricity and methane costs. Until 2030 SMR blue hydrogen will most likely be more cost-competitive than green hydrogen. The IEA predicts the price of green hydrogen will be between 3.0-4.0 USD/ $kgH_2$ and the price of blue hydrogen from SMR with CCUS to be 2.5-3.1 USD/ $kgH_2$. [IEA 2019, p.52]   IEA predicts that the cost of green hydrogen production could fall by 30% by 2030, due to the declining cost of renewable energy and the up scaling of hydrogen production. [IEA 2019, p.14]

## 5.3 H2morrow Steel Project

Equinor has started a blue hydrogen production project with natural gas transmission system operator OGE and steel producer thyssenkrupp Steel Europe (tkSE). Where the goal is to produce 800 000Nm3/h hydrogen gas, with 95% carbon capture. Where 600 000 Nm3/h will be used to produce 7 million metric tonnes climate neutral steel. This hydrogen will be produced at a cost of 2.1€/$kgH_2$, this price is based on a natural gas price of 23 €/mWh. The production will be at either the German or the Dutch coast. The produced carbon will be transported to Norway, for storage in the North Sea.

## 6. Hydrogen and other energy carriers

Every energy carrier encounters efficiency losses each time they are generated, converted or used. As a result, hydrogen produced by electrolysis, may only deliver 30% of the initial electric energy (input)of the energy used to create it, after transport, storage and the conversion back to electricity. [IEA,2019,p.33]

### 6.1.1 Hydrogen fuel cell

A fuel cell is defined as an electrochemical cell, which generates electricity and heat through spontaneous reactions. The fuel or reactants in the fuel cell is supplied continuously, making the cell different from a battery as it is not a self-contained system. Hydrogen fuel cells, uses hydrogen and oxygen gas as the reactants, creating energy and water. The heat generated in the process can be used to heat water for a steam generator if the temperature is sufficient for that. The generated steam can be used in a steam turbine to produce electricity.

The energy efficiency of converting chemical energy to electrical energy by combustion is around 40%, the rest of the thermal energy is usually lost as heat but the energy efficiency can be as low as 30% of initial electrical energy [IEA, 2019]. The loss of energy is due to restrictions in speed for the electrode reactions and the loss from the electrolyte. The downside of fuel cells is the difficulties of transportation and handling of the hydrogen. Therefore, studies have been done with methanol. There are fuel cells based on heavier hydrocarbons and ethanol [Holtebekk,SNL].

The standard Hydrogen-oxygen fuel cell is called PEM or proton-exchange membrane. The cathode and anode electrodes of this fuel cell are separated by a polymer membrane. The electrodes of the cell are made of graphite and the cell has an operating temperature of 80°C. This is a low temperature for an electrochemical reaction. Therefore, a thin layer of platina is applied on both the cathode and the anode, to catalyse the reactions at the electrodes.

Cathode: $4e^- + O_2(g) + 2H_2O\ (l) \rightarrow 4OH^-(aq)$

Anode: $2H_2(g) + 4OH^-(aq) \rightarrow 4H_2O(l)$

Total reaction: $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)\ EMF = 1.23V$

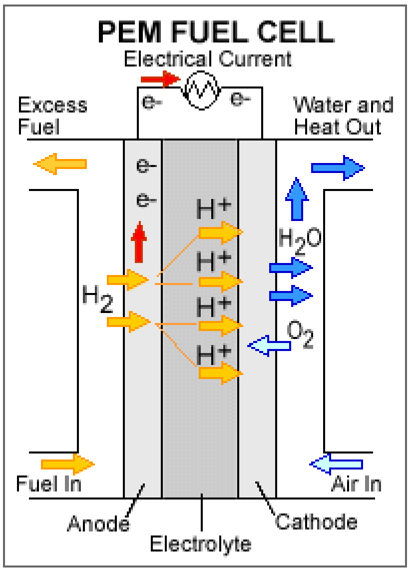


*Figure 15 PEM fuel cell [fuelcellstore]*

## 6.2 Hydrogen:

Since liquid hydrogen contains more energy per unit of mass then natural gas or gasoline, hydrogen is an attractive alternative transport fuel. However, due it being the lightest element, hydrogen has a low energy density per unit of volume. Therefore, large volumes of hydrogen need to be transported in order to replace other fuels like natural gas or gasoline. This can be achieved by using pipelines and larger storage tankers.

*Table 1 Physical properties of hydrogen compared to natrual gas/gasoline*

| Property | Hydrogen | Natural gas [methane] |
|---|---|---|
| Density gas phase [0°C, 1bar] | 0.089 kg/$m^3$ | 0.89 kg/$m^3$ |
| Density liquid phase [-252.76°C, 1bar] | 70.79 kg/$m^3$ | 424.56 kg/$m^3$ |
| Energy density Based on LVH | 0.01 MJ/L | 0.03 MJ/L |
| Specific energy [liquid, LHV] | 8.5 MJ/L | 25.5 MJ/L |
| Ignition energy | 0.02MJ | 0.2MJ |
| Property | Hydrogen | Gasoline |
| Energy per unit mass [LHV] | 120.1MJ/kg /33 kWh | 40.03MJ/kg/11kWh |
| Autoignition temperature | 585°C | 220°C |

[IEA,2019,p.35]

# 7. Discussion

The main market driver as to why hydrogen still isn't used on a grader scale is that it is not yet cost efficient to do so. However, the threat of Global warming and requirement for sustainable green economy has changed the way around how we look upon this. The Paris agreement clearly shows that the world can't continue to overlook the cost of $CO_2$. Today the price of EU emission allowances price is closing 50 € per tonne [FT]. It is expected in near future further increase of price and additional governmental taxes will be added. That means that the Grey Hydrogen will be too expensive and be superseded by Blue or Green Hydrogen. Existing grey Hydrogen production plants must be upgraded to include CCS or be shut down.


*Figure 16 EU carbon trading prices in euro per tonne $CO_2$ [FT]*

Today's $H_2$ production is 69 Mt$H_2$ per year and is mainly used for industrial use as oil refining (33%), ammonia production, (27%), methanol production (11%) and steel production via the direct reduction of iron ore (3%). Nearly all this hydrogen is supplied from hydrocarbons.

If Hydrogen is to supersede oil as an energy carrier for the transport sector as heavy road, sea and air transport total ca 45 % of the current oil consumption, then we will need a tenfold increase in the production of hydrogen. With the current daily oil production of 95 mill bbl/day, about 45.7 is used in the transport sector, which again are equivalent to 71TW and divided by 1.59 kw energy pr kg $H_2$, the daily $H_2$ production must increase with additional 2.1 Mtonne of $H_2$ or 766 Mtonne of $H_2$.

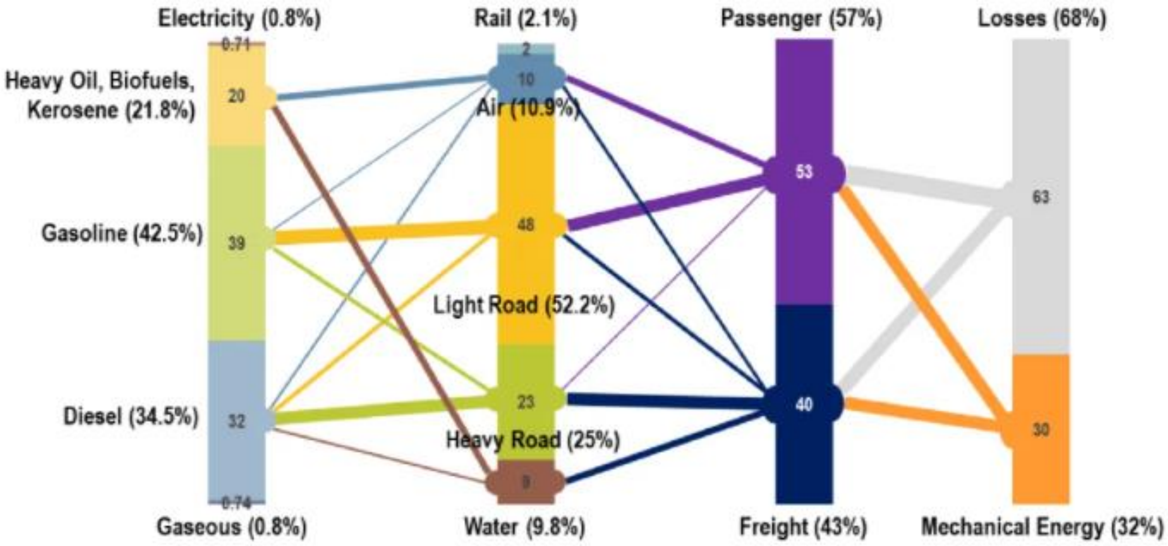


Figure 17 Energy consumption by fuel type by the transport sector [transportgeography.org]

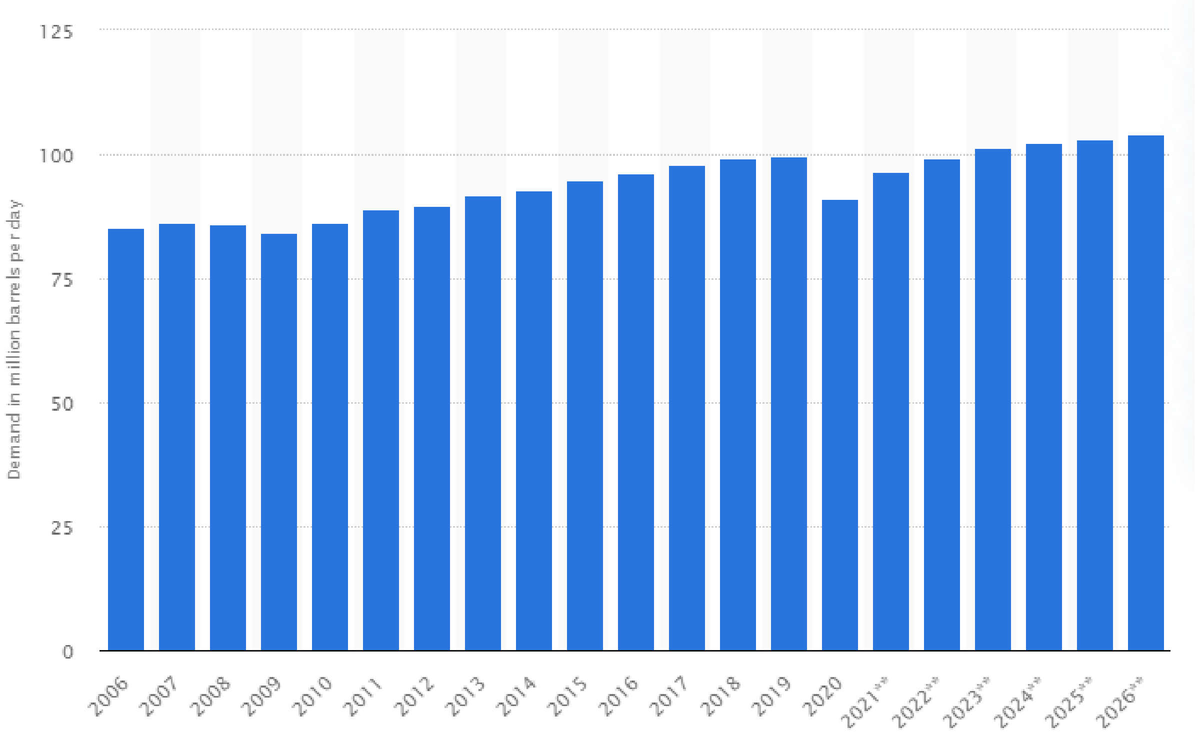


Figure 18 The daily demand for crude oil worldwide from 2006 to 2026 [Statista]

To be able to able to make a sound decision between investments in Blue or Green hydrogen one must consider the following criteria: Production Cost, Efficiency, availability of required process input, and the total emission Carbon footprint.

*Table 2 Differences between grey, blue and green hydrogen production*

| Hydrogen Type | Cost per UDS/kg$H_2$ | Energy Efficiency [LVH] | Electric power requiremen for 11kg of H2 [kWh] | Gas requirement [Bcm$^3$] | Fresh water requirement [kg] for producing 1kg of H2 | Production capacity/ Maturity |
|---|---|---|---|---|---|---|
| Grey | 1 | 70-85% | Process mainly gas powered* | 256* | 6 | Mature |
| Blue | 1.5 | 70%* | 14** | 205** | 6 | New |
| Green [Alkaline] | 2.5 | 63-70% | 47-52 | 0 | 9 | Mature |

[IEA, 2015+2019]
* assume that the steam used in the grey process are generated by gas
** assume that the steam used in the blue process are generated by electrical power

## 7.1 Why using Grey hydrogen production technology

The current $H_2$ grey hydrogen production is the most cost efficient today, and can be upscaled to meet the future $H_2$ demand. The only drawback is that nobody will invest in it due to it large $CO_2$ emission and the high possibility of been heavily emission taxed. Existing plants must be upgraded with CCS capabilities or been shut down.

## 7.2 Why using Blue hydrogen production technology

Blue hydrogen production plant is in its early development stages. The main reason for this is that the production price is 50 % higher than for grey hydrogen. With the transition to green energy in mind and the probability that grey hydrogen will be heavily taxed, many companies are now looking into setting up blue hydrogen production plants. In Norway, $H_2$ production is planning to setting up a pilot plant with a production capacity of 600kg $H_2$/hr based on sorption Enhanced Reforming with CCS [Haugstad,TU.no]. Despite that the aren't many large scale productions plant, will the technology be the main contributor of carbon free $H_2$. The main reason is the vast availability of natural gas and lower power consumption requirements, compared to the green hydrogen solution. It is possible to reduce it further by using natural gas to make steam. But the solution requires additional cost for CCS from the

biproduct. However, the solutions require 6 kg of fresh water pr kg produced $H_2$. This may restrict capacities and location. However, the water will be returned upon usage of $H_2$.
Is blue hydrogen truly blue? It depends on the oil production facilities. They are mostly gas/oil powered. Nevertheless, also those facilities are getting greener by installation of electrical power.

## 7.3 Why use Green hydrogen production technology

Green hydrogen is the environmentally friendly solution for production of $H_2$. 2% of the world $H_2$ production is made through electrolysis. It is heavily dependent on the price of electricity. Hence the price of 2,5 USD a kg based on a power price of around 0,04 USD kWh. To be price competitive with blue Hydrogen, the price of electricity must be reduced by 60%, But green hydrogen has a lot of benefits. Power generating Windmills at sea can produce $H_2$ instead of sending the electricity through expensive cables with high losses and Solar parks can produce $H_2$ on remote places.

One of its major drawbacks, is that it is heavily dependent on electrical power, requiring 47 to 50 kWh pr kilogram $H_2$. To convert all existing grey $H_2$ production plants to green $H_2$, the world power grid has to supply the green $H_2$ plants with over 3600 TWh or the annual electricity production of the EU and would require 617 million $m^3$ of fresh water, or 1.3% of the worlds annual water consumption. [IEA,2019,p.37].

## 7.4 Conclusion

As discussed in this chapter, there are no doubts that $H_2$ will play an important role in achieving the goals from the Paris agreement. The grey solution is disqualified due to its large carbon print. Some will say that the green solution is the only suitable due to its independency from hydrocarbons. However, as it is clearly shown above, there is not enough green power available to produce the amount of $H_2$ a carbon free society requires. The world is therefore still dependent on oil hydrocarbon production to be able to produce required amount of blue $H_2$. What is the most important is to make the whole production cycle from retrieving oil from the soil to $CO_2$ capture & storage with lowest $CO_2$ emissions as possible.

The answer to which solution to be used:  is to proceed with both blue and green $H_2$ production plants and then later phase out the blue $H_2$ production plants once the green plants become sufficiently efficient.

## 8. Reference:

Boslaugh, Sarah E.. "Pyrolysis". Encyclopedia Britannica, 17 Aug. 2018, accessible from: https://www.britannica.com/science/pyrolysis . Accessed 5 May 2021

Britannica, The Editors of Encyclopaedia. "Carbon black". *Encyclopedia Britannica*, 8 Feb. 2016, https://www.britannica.com/science/carbon-black. Accessed 20.april.2021

Nils Chr. Boye, Kjemi og miljølære, Gyldendal, Oslo, Fourth edition, chapter 11, pages 116, 128 and 129, ISBN: 978-82-05-39810-8

Christe John Geankoplis, Transport processes & Separation Process Principles (Includes Unit Operations), 2014, Person Education, England, Fourth edition, Chapters 13, 6.5 and chapter 7.6 page 502, ISBN 978-1-292-02602

Douglas A. Skoog, Donald M. West, F. James Holler, Stanley R. Crouch, Skoog and West's Fundamentals of Analytical Chemistry, 2014, Cengage Learning EMEA, United Kingdom, 9th edition, chapter 18C-2 pages 456-457, ISBN: 978-1-4080-9373-3

Geoff Rayner-CanHam and Tina Overton, Descriptive Inorganic Chemistry, 2013, W.H Freeman and company, New York, Sixth edition, chapter 10, pages 249 and 342. ISBN 978-1-4641-2557-7

Theordore L. Brown, H. Eugene LeMay, Jr., Bruce E. Bursten and Cathrine J. Murphy, Chemistry, compiled from Chemistry: The Central Science by Mohamad Osman, 2011, Person Education, United Kingdom , Eleventh edition, chapter 4 page 20 and chapter 20 page 370, ISBN: 978-0-85776-454-6

Trygve Holtebekk (UiO), Bjørn Pedersen (UiO), Geir Martin Haarberg (NTNU). Store Norske leksikon (SNL), Brenselcelle, last updated 04.01.2021, downloaded 17.04.2021, accessible from: https://snl.no/brenselcelle

Jostein Mamen (Meteorologisk institutt), Store Norske leksikon (SNL), Klimaendringer, last updated 07.05.2021, downloaded 13.05.2021, accessible from https://snl.no/klimaendringer

Knut Hofstad, Store Norske leksikon (SNL), Karbonfangst og -larging, last updated 01.11.2018, downloaded 13.05.2021, accessible from: https://snl.no/karbonfangst_og_-lagring

FK1954, Sot, Store Norske leksikon (SNL), picture of pure carbon particles, downloaded 14.05.21, accessible from: https://snl.no/sot
Nesse, Norvald, Store Norske leksikon (SNL), membranseparasjon, downloaded 10.04. 2021, accessible from:https://snl.no/membranseparasjon - gass-separasjon

Equinor, OGE, thyssenkrupp Steel Europe (tkSE), Clean hydrogen for a market ramp-up and for climate-neutral steel, downloaded 13.05.2021, accessible from: https://www.equinor.com/content/dam/statoil/documents/climate-and-sustainability/H2morrow%20steel_Infoflyer_ENG_20210112.pdf

Luca Bertuccioli (E4tech), Alvin Chan (Element Energy), David Hart (E4tech), Franz Lehner (E4tech), Ben Madden (Element Energy), Eleanor Standen (Element Energy), Development of Water Electrolysis in the European Union, E4tech and Element Energy , 07.02.2014, page 69, downloaded 05.05.2021, accessible from https://www.fch.europa.eu/sites/default/files/study%20electrolyser_0-Logos_0_0.pdf

National Energy Technology Laboratory (NETL), Chemical Looping Combustion, downloaded 27.04.2021, accessible from https://netl.doe.gov/node/7478

Energy Efficiency & Renewable Energy, Energy.gov, Hydrogen Production: Natural Gas Reforming, downloaded 17.04.2021, accessible from: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

European Commission Website, Paris agreement, downloaded 10.05.21, accessible from: https://ec.europa.eu/clima/policies/international/negotiations/paris_en

https://www.shell.com/energy-and-innovation/new-energies/hydrogen/_jcr_content/par/keybenefits/link.stream/1496312627865/6a3564d61b9aff43e087972db5212be68d1fb2e8/shell-h2-study-new.pdf

Tormod Haugstad, Her lages hydrogen med integrert $CO_2$-fangst, Teknisk ukeblad, published 12:00 22.09.20, downloaded 14.05.2021, accessible from: https://www.tu.no/artikler/her-lages-hydrogen-med-integrert-co-fangst/499732

David Sheppard, Harry Dempsey and Peggy Hollinger, Financial Times (FT), published 29.04.2021, downloaded 14.05.21, accessible from: https://www.ft.com/content/17e157b2-21ea-4e22-9278-35f157046e85 from: https://www.norskpetroleum.no/en/environment-and-technology/carbon-capture-and-storage/ -02.04.2021-

*Hydro,1919: Research as driving force and inspiration, last updated 18.08.2020, downloaded 09.05.2021, accessible from: https://www.hydro.com/en/about-hydro/company-history/1918---1928/1919-research-as-driving-force-and-inspiration/

SINTEF, Dette må du vite om fangst og lagring av CO2, published 2019, downloaded 14.05.2021, accessible from: https://www.sintef.no/siste-nytt/2019/dette-ma-du-vite-om-ccs-karbonfangst-og-lagring/

Sergei A. Kulinich, Aaron L. Zhu, David P Wilkinson, Xinge Zhang, Yalan Xing, Alex Rozhin, Zinc regeneration in rechargeable zinc-air fuel cells—A review, The Journal of Energy Storage 8:35-50, DOI: 10.1016/j.est.2016.09.007 , September 2016, downloaded 14.05.2021, accessible from: https://www.researchgate.net/publication/308746501_Zinc_regeneration_in_rechargeable_zinc-air_fuel_cells-A_review

Hang Yin, Alex C.K. Yip, A Review on the Production and Purification of Biomass-Derived Hydrogen Using Emerging Membrane Technologies, Catalysts 7(10):297, DOI: 10.3390/catal7100297, October 2017 , downloaded 15.05.2021, accessible from https://www.researchgate.net/figure/Mechanism-for-gas-separation-through-a-c-porous-and-d-dense-membranes-30-Black_fig3_320210474

N. E. G. Costa, P. C. P. Patrício, R. V. Ferreira, Márcio R. Vianna Neto, Marcelo Cardoso, SIMULATION AND ANALYSIS OF A HYDROGEN GENERATION UNIT, Brazilian Journal of Petroleum and Gas 12(3):159-168, DOI: 10.5419/bjpg2018-0015, downloaded 15.05.2021, accessible from: https://www.researchgate.net/figure/Elementary-steps-of-a-PSA-cycle-operation_fig1_328345402

Sastry, What is the Process of Electrolysis, AplusTopper, published 01.12.2020, downloaded 15.05.2021, accessible from: https://www.aplustopper.com/process-electrolysis/

Toyota Norway, Slik Virker Fremtidens Superbatteri, 2018, downloaded 14.05.2021, accessible from: https://www.toyota.no/world-of-toyota/articles-news-events/2018/superbatteri.json

International Renewable Energy Agency, Green Hydrogen: A guide to policy making, November 2020 ISBN: 978-92-9260-286-4, accessible from: https://www.irena.org/publications/2020/Nov/Green-hydrogen

International Energy Agency, The future of hydrogen: seizing today's opportunities, Report for Japan G20, June 2019, downloaded 05.05.2021, Chapters 1, 2 and 5 , accessible from https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

International Energy Agency, Technology Roadmap: Hydrogen and FuelCells, 2015, pages 28,32,56-57, downloaded 05.05.2021, accessible from https://iea.blob.core.windows.net/assets/e669e0b6-148c-4d5c-816b-a7661301fa96/TechnologyRoadmapHydrogenandFuelCells.pdf

Intergovernmental Panel on Climate change (IPCC), Special Report: Global Warming Of 1.5 ºC, Projected Climate change, potential impacts and Associated Risks, chapter 15B, published 06.10.2018, downloaded 13.05.2021, accessible from: https://www.ipcc.ch/sr15/chapter/spm/

International Renewable Energy Agency, Green Hydrogen: A guide to policy making, November 2020, Abu Dhabi, ISBN: 978-92-9260-286-4, accessible from: https://www.irena.org/publications/2020/Nov/Green-hydrogen

Fridolin Pflugmann, Nicola De Blasio, Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World, 2020, Harvard Kennedy School Belfer Center, page 19, downloaded 07.05.21, accessible from: https://www.researchgate.net/publication/339749976_Geopolitical_and_Market_Implications_of_Renewable_Hydrogen_New_Dependencies_in_a_Low-Carbon_Energy_World

FuwlCelll Store, Hydrogen Air / Oxygen Fuel Cell MEAs, downloaded 14.05.2021, accessible from: https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/hydrogen-air-oxygen-fuel-cell-mea

N. Sönnichsen, Statista, Daily demand for crude oil worldwide from 2006 to 2026*(in million barrels), published 22.03.2021, downloaded 14.05.2021, accessible from: https://www.statista.com/statistics/271823/daily-global-crude-oil-demand-since-2006/

Thorfinn Stainforth, More than half of all CO2 emissions since 1751 emitted in the last 30 years, Institute European Enviromental Policy, published 09:45 29.04.2020, downloaded 14.05.2021: accessible from: https://ieep.eu/news/more-than-half-of-all-co2-emissions-since-1751-emitted-in-the-last-30-years

Yonglian Yan, Dhinesh Thangangdar, Peter T. Clough, Sanjay Mukherjee, Kumar Pathigolla, Vasilije Manovic, Edward J. Anthony, Process simulation of blue hydrogen production by upgraded sorption enhance steam methane reforming (SE-SMR) processes, Energy Conversion and Management, Volume 222, 15.10.2020,113144, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2020.113144. downloaded 03.04.2021 accessible from: https://www.sciencedirect.com/science/article/abs/pii/S0196890420306889

C.-C Cormos, IGCC With Carbon Capture and Storage, Editor(s): Martin A. Abraham, Encyclopedia of Sustainable Technologies, Elsevier, 2017,Pages 327-338, ISBN: 9780128047927,https://doi.org/10.1016/B978-0-12-409548-9.10139-3. Downloaded 15.05.2021, accessible from: https://www.sciencedirect.com/science/article/pii/B9780124095489101393 -

Mohamed A. Fahim, Taher A. Alsahhaf, Amal Elkilani, Chapter 11 - Hydrogen Production, Editor(s): Mohamed A. Fahim, Taher A. Alsahhaf, Amal Elkilani, Fundamentals of Petroleum Refining, Elsevier, 2010,Pages 285-302, ISBN: 9780444527851, https://doi.org/10.1016/B978-0-444-52785-1.00011-, downloaded 09.05.2021, accessible from: https://www.sciencedirect.com/science/article/pii/B9780444527851000115

Joakim Beck, Daniel Friedrich, Stefano Brandani, Serge Guillas, Eric S Fraga, Surrogate based Optimisation for Design of Pressure Swing Adsorption Systems, Editor(s): Ian David Lockhart Bogle, Michael Fairweather, Computer Aided Chemical Engineering, Elsevier, Volume 30, 2012, Pages 1217-1221,ISSN: 1570-7946, ISBN: 9780444594310, https://doi.org/10.1016/B978-0-444-59520-1.50102-0. downloaded 09.05.2021, accessible from: https://www.sciencedirect.com/science/article/pii/B9780444595201501020

Edy Herianto Majlan, Wan Ramli Wan Daud, Sunny E. Iyuke, Abu Bakar Mohamad, A. Amir H. Kadhum, Abdul Wahab Mohammad, Mohd. Sobri Takriff, Nurhaswani Bahaman, Hydrogen purification using compact pressure swing adsorption system for fuel cell, International Journal of Hydrogen Energy, Volume 34, Issue 6, 2009, Pages 2771-2777, ISSN:0360-3199, https://doi.org/10.1016/j.ijhydene.2008.12.093. downloaded 09.05.2021, accessible from: (https://www.sciencedirect.com/science/article/pii/S0360319909000263)https://www.sciencedirect.com/science/article/abs/pii/S0360319909000263

Niloufar Fouladi, Mohammad Amin Makarem, Mohammad Amin Sedghamiz, Hamid Reza Rahimpour, Chapter 11 - CO2 adsorption by swing technologies and challenges on industrialization, Editor(s): Mohammad Reza Rahimpour, Mohammad Farsi, Mohammad Amin Makarem, Advances in Carbon Capture, Woodhead Publishing, 2020, Pages 241-267, ISBN: 9780128196571, https://doi.org/10.1016/B978-0-12-819657-1.00011-6.,downloaded 09.05.2021, accessible from: https://www.sciencedirect.com/science/article/pii/B9780128196571000116

S. Shiva Kumar, V. Himabindu, Hydrogen production by PEM water electrolysis – A review, Materials Science for Energy Technologies, Volume 2, Issue 3, 2019, Pages 442-454,ISSN 2589-2991, https://doi.org/10.1016/j.mset.2019.03.002. downloaded 05.05.2021, accessible from: https://www.sciencedirect.com/science/article/pii/S2589299119300035 [S. Shiva Kumar, V.Himabidu]

M.R. Rahimpour, F. Samimi, A. Babapoor, T. Tohidian, S. Mohebi, Palladium membranes applications in reaction systems for hydrogen separation and purification: A review, Chemical Engineering and Processing: Process Intensification,Volume 121, 2017, Pages 24-49, ISSN 0255-2701, https://doi.org/10.1016/j.cep.2017.07.021, downloaded 15.05.2021, accessible from: https://www.sciencedirect.com/science/article/abs/pii/S0255270117301551#fig0135

R.M. Navarro, R. Guil, J.L.G. Fierro, 2 - Introduction to hydrogen production, Editor(s): Velu Subramani, Angelo Basile, T. Nejat Veziroğlu, In Woodhead Publishing Series in Energy, Compendium of Hydrogen Energy, Woodhead Publishing,2015,
Pages 21-61, ISBN: 9781782423614, https://doi.org/10.1016/B978-1-78242-361-4.00002-9. downloaded 09.05.2021, accessible from:
https://www.sciencedirect.com/science/article/pii/B9781782423614000029

Christophe Coutanceau, Stève Baranton, Thomas Audichon, Chapter 3 - Hydrogen Production From Water Electrolysis, Editor(s): Christophe Coutanceau, Stève Baranton, Thomas Audichon, In Hydrogen Energy and Fuel Cells Primers, Hydrogen Electrochemical Production,Academic Press, 2018, Pages 17-62,ISBN 9780128112502, https://doi.org/10.1016/B978-0-12-811250-2.00003-0. downloaded 09.05.2021, accessible from:
https://www.sciencedirect.com/science/article/pii/B9780128112502000030

L. Barelli, G. Bidini, A. Corradetti, U. Desideri, Production of hydrogen through the carbonation–calcination reaction applied to CH4/CO2 mixtures, Energy,Volume 32, Issue 5, 2005 December, Pages 834-843, ISSN 0360-5442,
https://doi.org/10.1016/j.energy.2006.06.008. downloaded 28.04.2021, accessible from:
https://www.sciencedirect.com/science/article/pii/S0360544206001472

L. Barelli, G. Bidini, A. Corradetti, U. Desideri, Study of the carbonation–calcination reaction applied to the hydrogen production from syngas,
Energy, Volume 32, Issue 5,2005 September, Pages 697-710, ISSN 0360-5442,
https://doi.org/10.1016/j.energy.2006.04.016. 28.04.2021, accessible from:
https://www.sciencedirect.com/science/article/pii/S0360544206001162

L. Barelli, G. Bidini, F. Gallorini, S. Servili, Hydrogen production through sorption-enhanced steam methane reforming and membrane technology: A review, Energy,
Volume 33, Issue 4, 2008, Pages 554-570, ISSN 0360-5442,
https://doi.org/10.1016/j.energy.2007.10.018. 03.04.2021, accessible from:
(https://www.sciencedirect.com/science/article/pii/S0360544207002058)