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**Comparative Life Cycle Assessment of Hydrogen Production
in Iceland and the EU-27**

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Abstract

As the world looks to limit the use of fossil fuels as the impacts of climate change continue to be realized, hydrogen is set to be a major contributor to decarbonize the global economy. Renewable energy in Iceland, consisting of geothermal and hydropower, can be a part of Europe's decarbonization strategy. Renewable electricity can split water into its molecular components of hydrogen and oxygen. The green hydrogen created by this electrolysis can be used as a sustainable energy carrier.

In this thesis, a comparative life cycle assessment (LCA) of water electrolysis in Iceland and the European Union is presented. The main impact assessment category used to compare the different scenarios was the global warming potential measured in carbon dioxide equivalence. Results for other impact categories were also calculated and can be found in Appendix B, but are not discussed thoroughly in this paper. The research question this thesis sought to answer was: Is the production of hydrogen in Iceland for use in mainland Europe more environmentally beneficial than producing hydrogen in Europe? The functional unit of 1 kg of Hydrogen molecules was utilized to allow for comparison between the scenarios explored in this research, as well as other works on the subject.

The LCA in this paper was conducted using the GaBi software and ecoinvent database. Three electrolyser technologies were considered: alkaline electrolysers, proton exchange membrane electrolysers, and solid oxide electrolysers. The three different types of electrolysers were analyzed in both Iceland and the EU. Three methods of storage for the produced hydrogen were considered: liquid hydrogen, ammonia, and methanol. The life cycle inventory for the electrolysers, their operation, and the storage of the hydrogen were built using data synthesized from sources during literature review. The final scenarios considered in this thesis were of hydrogen production by electrolysis of the three electrolysers using theoretical electricity grids in the European Union in 2030 and 2050 based on their climate policy goals for those years. This comparison serves to help answer the question of whether

producing hydrogen in Iceland for use in mainland Europe would continue to be beneficial in the future from an emissions standpoint.

Based on the results of the GaBi modelling, the lowest environmental impact measured by carbon emissions, comes from producing hydrogen with a solid oxide electrolyser in Iceland then storing and transporting it as liquid hydrogen. This results in carbon dioxide equivalent emissions of 0.946 kg per 1 kg of H₂. The lowest impact in terms of emissions for the European scenarios is electrolysis by a solid oxide electrolyser stored as ammonia at a value of 17.113 kg CO₂ equivalence. This value is greater than all the values for hydrogen production in Iceland even with transport included suggesting that producing green hydrogen for use in mainland Europe is less environmentally impactful.

The best result for the production of 1 kg of hydrogen by electrolysis in the 2030 and 2050 European Union cases were for electrolysis with a solid oxide electrolyser having values 8.91 and 1.56 kg of CO₂ equivalence respectively. Both these values are greater than all the results for electrolysis in Iceland by all three electrolyser types. This suggests that in the future even if/when the European Union is able to reach its climate policy goals for their electricity mix, it will still be less environmentally impactful in terms of global warming potential to produce green hydrogen in Iceland.

Acknowledgements

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1. Introduction

This chapter of this thesis includes the objective and research question. Background information on hydrogen as an energy carrier, electrolysis, the three electrolyzers analyzed in the paper, and the storage and transportation analyzed is then presented. Next, the electricity grids used in the various scenarios are examined. The chapter closes with an introduction of life cycle assessment.

1.1. Objective

This thesis builds upon Kristjan Vilbergsson's thesis: *Comparative LCA of Hydrogen Production via Electrolysis in Austria and Iceland* [1]. The research question to be solved is the following: Is the production of hydrogen in Iceland for use in mainland Europe more environmentally beneficial than producing hydrogen in Europe? This is evaluated by the comparison of impacts per kilogram of Hydrogen (H₂), especially focusing on carbon emissions. It is analyzed at three time periods; current day (the year 2020), the year 2030, and the year 2050; using the EU's goals for their energy system as an assumption for the future scenarios.

The research objective is to compare the overall emissions of producing hydrogen in Iceland based on the energy grid for water electrolysis as well as the transport to Europe, with the emissions of producing hydrogen with electrolysis in the European electricity grid. Three electrolysis technologies are considered. These are alkaline electrolyzers, proton exchange membrane electrolyzers (PEM), and solid oxide electrolysis cells (SOEC). Three different methods for storage and transportation are considered; liquified hydrogen, ammonia, and methanol.

1.2. Background

Hydrogen is the first element on the periodic table and consists of a single proton with a single electron. The chemical energy of H₂ molecules can be converted to other energy forms [2]. The direct conversion of hydrogen to electricity happens in a device known as a hydrogen fuel cell. There are different types of fuel cells which produce electricity with the use of different electrodes and electrolytes. The electrodes are the charged plates or surfaces, with the

anode being the negatively charged side of the fuel cell and the cathode being the positively charged side. The electrolyte is the material which separates the two electrodes and allows a specific type of ion, or charged particle, to travel through it. While different hydrogen fuel cells use different materials as electrodes and electrolytes, operate at different temperatures, and even use different fuel sources for hydrogen, the working principle for them is similar. The electrolyte is designed to only let certain ions pass through them, which then forces electrons to take an alternative path around the electrolyte. This alternate path is the electrical circuit the fuel cell creates. On the other side of the electrolyte, the ions of hydrogen and oxygen combine with the electrons at the end of the circuit to create the byproduct of water (H₂O).

As an alternative to producing electricity in a fuel cell, hydrogen can be burned in a combustion process similar to the way today's fuels like diesel or gasoline are burned. Hydrogen is very flammable and a good candidate as a fuel for combustion engines with its lower heat value (LHV) of 120 MJ/kg, which is higher than both diesel and gasoline with lower heat values of 43.6 MJ/kg and 43.4 MJ/kg respectively [3]. To travel 400 km, a standard vehicle requires only 8 kg of hydrogen in a combustion engine or 4 kg for a fuel cell as opposed to 24 kg of petrol in a traditional combustion vehicle [2]. While burning hydrogen does still have some emissions associated with it, from the production of the hydrogen and possible NO_x emissions from the combustion of air with the hydrogen fuel, if the hydrogen fuel used is green hydrogen, the emissions are significantly less than those associated with the combustion of petrol, diesel, and other carbon-based fuels used today [2].

Hydrogen has the potential to be used as a cleaner fuel source in many sectors, especially in the grid level energy sector and the transportation sector. For the energy sector, hydrogen can offer stability for variable sources such as solar and wind as a form of energy storage. Hydrogen can be transported in tankers similar to the transportation of oil, or through pipelines in a similar manner to natural gas. With infrastructure for that transportation already being available, a switch to the usage of hydrogen can be made relatively easily from a transportation perspective in much of the infrastructure that is hydrogen compatible. Hydrogen can also help with energy trading over great distances or to remote areas where power lines do not exist and are not feasible [4].

Transportation accounts for about 29% of total energy demand globally [5]. Due to this large share of final energy demand, the transportation sector can have a significant impact on the world's efforts to decarbonize. In the transportation sector hydrogen fuel cell can be implemented to further extend the range of electric vehicles. There is a large potential for hydrogen fuel cell vehicles to replace heavy transport vehicles such as shipping trucks due to

their advantages over battery electric vehicles, for example quicker refilling at approximately 3-5 minutes compared to 8 hours to fully charge a vehicle battery [2]. In addition, hydrogen could be used for boats and airplanes where strictly battery electrification is likely not possible. Air travel electrification with only batteries is not currently possible because the number of batteries required to supply enough electricity becomes too heavy requiring more batteries which in turn adds more weight and requires more batteries. Hydrogen has an advantage here by being a light weight element, and also due to the fact that when used as a fuel it physically depletes and therefore the storage tank becomes lighter as it is less full. In contrast, a battery that is empty of charge weighs the same as a battery which is fully charged. In addition to hydrogen's use in fuel cells to power electric motors, hydrogen also proves to have a potential in large ships and airplanes because it can be burned in combustion engines similar to the current methods used by today's ships and planes.

The bulk of hydrogen currently produced is grey hydrogen, which is also known as black or brown hydrogen. This is produced by the use of fossil fuels, mainly natural gas and coal, and therefore will still produce carbon dioxide in the process [6]. In 2018, 99% of hydrogen was made with the use of fossil fuels and therefore can be considered grey hydrogen [4]. The most common way to produce hydrogen is through a process known as Steam Methane Reformation, or SMR. During the Steam Methane Reformation process, methane, with the chemical formula CH_4 and usually in the form of natural gas, is scrubbed of its hydrogen through the use of high temperature steam and a catalyst. When the hydrogen is freed from the methane and the steam, the methane's carbon atoms bond with oxygen from the steam and therefore creates carbon dioxide and carbon monoxide emissions. The environmental impact of the SMR process is still an issue as it produces as much pollution and carbon dioxide as directly burning the natural gas [2]. Steam methane reformation is not the only method using fossil fuels that can create grey hydrogen but it is the most commonly used. Other methods of producing grey hydrogen includes gasification of coal or other hydrocarbons.

If grey hydrogen is combined with carbon capture and storage methods (CCS) then it can be called blue hydrogen [6]. The methods of carbon capture and storage are not specifically defined for grey hydrogen to be rebranded as blue hydrogen, but the idea is to avoid most of the greenhouse gas emissions resulting from the hydrogen formation process. However, carbon capture and storage is not a completely perfect process and thus emissions are still released from the production of blue hydrogen. In addition, the process of extracting natural gas from the earth has its own associated environmental concerns, such as methane (CH_4) leakage which is an even more potent greenhouse gas than carbon dioxide [7].

Therefore, the least emissions intensive process of creating hydrogen today is the production of green hydrogen through the process of water electrolysis. Water electrolysis is the process of splitting water molecules, H₂O, into hydrogen and oxygen molecules by the use of electricity and a device called an electrolyser [2]. When the electricity used to power the electrolyser is supplied by renewable sources, the hydrogen created is considered to be green hydrogen [6]. Green hydrogen has the lowest associated emissions since the electricity comes from renewable sources like solar photovoltaic cells, hydropower, geothermal power, and wind turbines which do not produce emissions during their operation. Therefore, the only emissions associated with green hydrogen are those from the manufacturing of the electrolyser and electricity source, and from the storage and distribution of the hydrogen. Since the electrolysis process splits water to create pure H₂ gas, the only other by-product is clean, pure O₂ gas.

An extension of green hydrogen produced with renewable energy powered electrolysis is yellow hydrogen. Yellow hydrogen, or purple hydrogen as it is also sometimes referred, is hydrogen produced through electrolysers supplied with electricity from nuclear power plants [6]. Yellow or purple hydrogen is not focused on in this thesis.

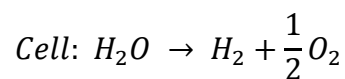
In addition to these main color categories of hydrogen, there are also other in between colors. One example of these in-between hydrogen classifications would be that of turquoise hydrogen. Turquoise hydrogen usually refers to hydrogen produced in the pyrolysis of a fossil fuel which has a by-product of carbon in a solid form [6]. The scope of this thesis is focused on grey and green hydrogen.

1.3. Electrolysis

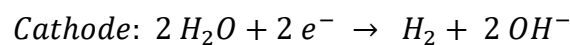
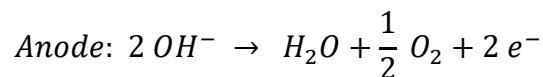
The process of creating hydrogen from water and electricity is through electrolysis. Electrolysis breaks up water molecules into hydrogen molecules and oxygen molecules by applying an electrical current to the water [8]. A device known as an electrolyser is needed for this process. An advantage of electrolysis is the purity of hydrogen gas that is produced. Hydrogen gas with a purity of 99.9% can be created in electrochemical technology without purification steps [9]. There are different electrolyser technologies currently being deployed and researched. This section will review the three technologies that are considered in the thesis analysis: [alkaline electrolysers](#), [proton exchange membrane \(PEM\) electrolysers](#), and [solid oxide electrolysers \(SOEC\)](#). In this section, the working principle of each electrolyser is reviewed.

1.3.1. Alkaline Electrolysis

Alkaline electrolysis is the longest known process for splitting water into hydrogen and oxygen. It therefore is the most established technology and deployed at industrial levels up to the megawatt range [8]. For alkaline electrolysis an electrical current is supplied to the two electrodes, creating a positively charged anode and a negatively charged cathode. The overall equation for the alkaline electrolysis process is the same chemical equation for all electrolysis processes, namely:



Specifically for alkaline electrolysis cells, the overall cell equation can be broken up into the following two equations, one for each electrode [8].



The electrodes are typically made of readily available metals. These electrodes must be resistant to corrosion, while having good conductivity and catalytic properties. Typically, they are made of nickel or chromium-nickel steel [10]. The electrolyte that separates the two electrodes is commonly an aqueous solution of potassium hydroxide (KOH) at concentration of 20-30% [2],[8]. A diaphragm separating the two electrodes is also implemented to keep the produced hydrogen and oxygen gas separate from each other. Formerly, the diaphragm membranes were extensively made from asbestos. However, asbestos is no longer allowed to be used [11]. Novel membranes are now typically made from polysulfone polymers or nickel oxide instead of asbestos [12]. Figure 1 shows a basic schematic of a typical alkaline electrolyser.

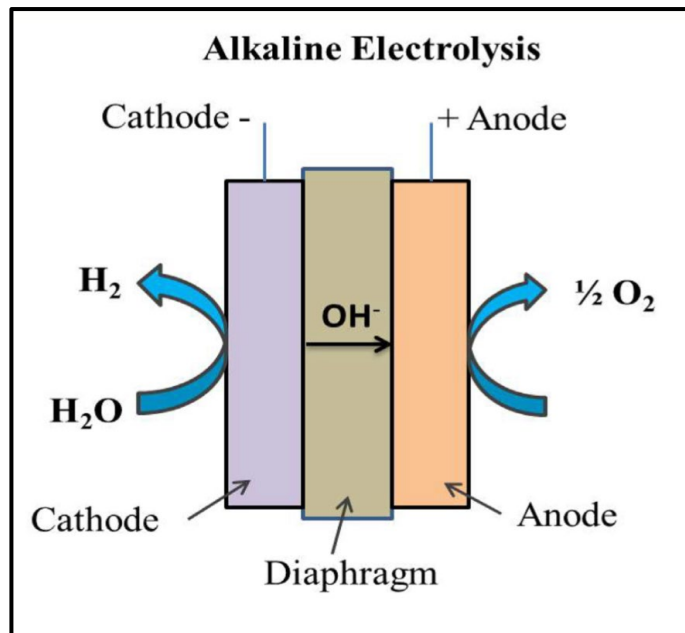


Figure 1: Schematic of Alkaline Electrolysis [8]

A bipolar configuration is typically employed today to create electrolyser cell stacks. The electrolysis cells are stacked on to one another and each electrode then acts as both an anode for one cell, and the cathode for the following cell.

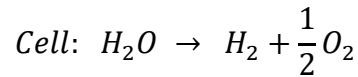
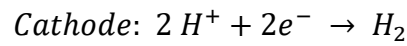
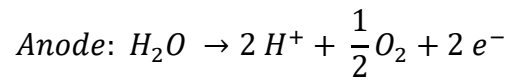
The stacking of electrolyser cells allows for compact designs of electrolyser units. To aid in compactness and more importantly reduce ohmic losses, a “zero-gap” design has been developed in which the electrodes are placed directly on to either side of the separator membrane [12].

From the higher heating value of hydrogen, the theoretical power requirement for producing one normal cubic meter of hydrogen through electrolysis is 3.5 kWh. Typical power consumption is usually higher at 4-5 kWh/Nm³ of hydrogen [10]. The “zero-gap” and other compact designs allows for low voltages to be used by reducing resistance from the electrolyte [12].

1.3.2. Proton Exchange Membrane (PEM)

The second most common process for water electrolysis, and considered the most promising for variable renewable energies, is using a Proton Exchange Membrane (PEM) electrolyser [8]. A PEM electrolyser uses a solid polymer membrane electrolyte to separate the anode and cathode side of the cell [2]. The first developed solid polymer electrolyser was produced by General Electric back in 1967 using a prefluorinated sulfuric acid polymer [12].

The PEM cell operation can be explained by two electrode equations, which can be summarized in one overall cell equation [8].



The operation of a PEM electrolyser starts by pumping water to the anode. Here it is split into oxygen (O₂), protons (H⁺) and electrons (e⁻). The electrons travel through the external cell creating the cell voltage, while the hydrogen protons are able to pass through the polymer membrane. The electrons and protons meet and recombine at the cathode side producing nearly pure hydrogen gas (H₂). Figure 2 shows the operating principle of a PEM electrolyser cell.

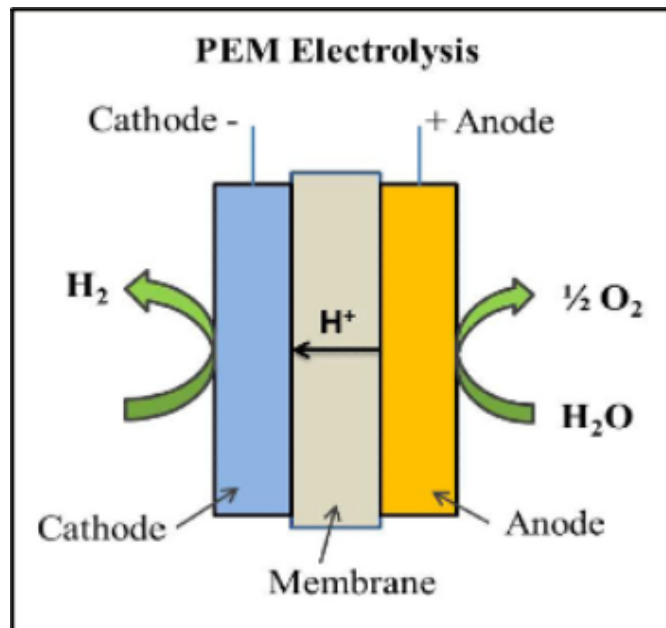


Figure 2: Schematic of PEM Electrolysis [8]

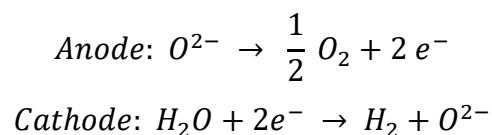
Many of the advantages of PEM electrolysis are due to a solid polymer electrolyte being used. Some of these examples include reduced corrosion, constant electrolyte concentration removing the need for concentration control, and the multifunctionality of the polymer electrolyte to also act as a diaphragm separating the products at either side of the cell [12]. Further advantages of this technology is high efficiency, operation at lower temperatures between 20-80°C, and fast response time [8]. The last two advantages specifically lend

themselves to PEM having an advantage using renewable energy sources to produce green hydrogen as many renewable sources are variable and therefore quick response to changes of supply are beneficial.

The main disadvantages of the PEM electrolysis technique are due to the materials needed. Aside from specialized polymers for the membrane, specific electrocatalysts are needed at each electrode to facilitate the reactions. The noble metals Platinum (Pt) and/or Palladium (Pd) are needed as electrocatalysts at the cathode side. Iridium Oxide (IrO₂) and/or Ruthenium Oxide (RuO₂) are needed at the anode [8]. These elements add both to the overall cost of the cell, but also to the overall environmental impact of the PEM electrolyser.

1.3.3. Solid Oxide Electrolysis

Solid Oxide Electrolysis Cells (SOEC) are the least developed of the three electrolysis technologies to be considered in this thesis. The SOEC was first introduced in the 1980s by Donitz and Erdle [8]. Solid Oxide Electrolysis Cells typically use a ceramic proton conductor or Oxide (O²⁻) conductors made from Nickel/Yttria and stabilized Zirconia (ZrO₂). These solid membranes which allow for the Oxide to pass through them is the origin of these high temperature cells being known as SOECs. The operating equations at each electrode are as follows [8].



One of the major differences for SOEC is the high temperature and pressure used. Solid Oxide Electrolysers operate at temperatures ranging from 500-850° C [13]. The water used as an input in the process is therefore actually utilized as steam. During operation the water is pumped into the cathode side of the cell. The oxide conductor membrane reacts with the water pulling away the oxygen atoms through the membrane in the form of O²⁻ leaving the hydrogen atoms as nearly pure H₂ gas. The oxide travels through the membrane to the anode electrode where it combines with electrons to produce gaseous oxygen (O₂). An illustration of the basic cell operation can be seen in Figure 3.

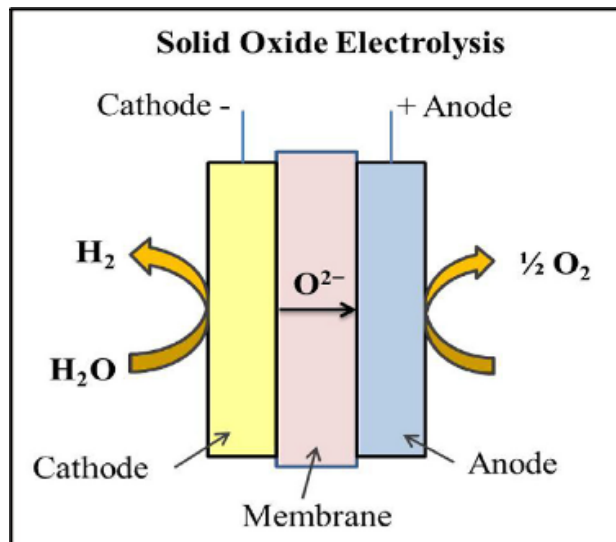


Figure 3: Schematic of SOEC [8]

Solid Oxide Electrolysis Cells tend to have higher efficiencies in the 80-86 % range compared to the typical efficiencies of other electrolyzers in the range of 65-75 % [14]. At higher temperatures, the electrolytes ionic conductivity increases and the rate of electrochemical reactions at the electrodes improves [13]. Furthermore, in these high temperature electrolysis systems heat supplies a portion of the energy required to split the water molecules; thus, less electricity is required overall. About 40% of the energy required to separate the molecule can be supplied by heat [15].

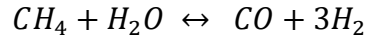
Along with improving the overall efficiency of the cell, the use of thermal energy is often cheaper than electrical energy. It also allows for the electrolysis cell to be coupled with other processes to take advantage of waste heat for example from solar, nuclear, geothermal, or fossil fuel-based sources.

The high temperatures that afford SOEC their improved efficiencies are also their current drawback. The high operating temperatures and high pressures lead to the degradation of materials that decreases or potentially ruins the performance of the electrolysis cell. Maintaining high efficiency and operation is the focus of much of the current research going into solid oxide electrolyzers in order to get them to a fully commercial level [13].

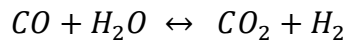
1.4. Steam Methane Reformation

The most common method of producing hydrogen today worldwide is by isolating hydrogen from methane (CH_4) through the steam methane reformation (SMR) process. Steam methane reformation from natural gas produces a gaseous mixture that is 70-75% hydrogen,

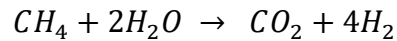
with the other 25-30% being carbon dioxide (CO₂), carbon monoxide (CO), as well as smaller amounts of methane [2]. The production of hydrogen in the SMR process consists of two steps. The first step is the Steam Methane Reforming Reaction described by the chemical equation:



The second step is the Water Gas Shift Reaction described by the chemical equation:



The overall reaction for SMR is thus:



Both partial reactions are endothermic and therefore the overall reaction requires the input of heat. The SMR process is very energy intensive mainly due to the large amount of heat required for these reactions.

The grey hydrogen produced through the SMR process is used as a baseline to compare the various green hydrogen methods in order to help analyze the environmental impact of green hydrogen production. The values for SMR in the same impact assessment categories used for the green hydrogen in this paper come from Susmozas, Iribarren, and Dufour and can be seen in Table 1 [16].

Table 1: Life Cycle Impact Assessment of Hydrogen Production via the SMR process [16]

Abiotic Depletion (kg Sb eq / kg H ₂)	8.91E-2
Global Warming Potential (kg CO ₂ eq / kg H ₂)	10.56
Ozone Layer Depletion (kg CFC-11 eq / kg H ₂)	1.21E-6
Photochemical Oxidation (kg C ₂ H ₄ eq / kg H ₂)	5.18E-4
Acidification (kg SO ₂ eq / kg H ₂)	8.44E-3
Eutrophication (kg PO ₄ ³⁻ eq / kg H ₂)	1.64E-3
Cumulative Energy Demand (MJ / kg H ₂)	185.08

1.5.Storage and Transport

Because energy is required to obtain it, hydrogen is not actually a source of energy. Instead, it is commonly regarded as an energy carrier [17]. However, to be considered an energy carrier and prove useful, hydrogen must be able to be stored and transported. Hydrogen storage presents various issues. The first big issue of using hydrogen gas as an energy carrier is its very low volumetric energy density of 0.0108 MJ/L at standard pressure and temperature, which is over 3000 times smaller than gasoline at 46 MJ/L [18]. Being the lightest and simplest of all elements, gaseous hydrogen has high diffusivity as its atoms prefer to spread out and occupy large spaces. And since hydrogen has a very low liquid boiling point of -252.8°C , at atmospheric pressure, it typically becomes gaseous and expands at normal pressures and temperatures. These are problems for storage, especially when considering hydrogen gas as a fuel for transportation. At standard temperature and pressure, nearly 49 m^3 is required for the 4 kg of hydrogen that would be needed to travel a practical driving distance [19]. Therefore, it is clearly infeasible to store and transport hydrogen as a gas at standard temperature and pressure.

Another necessary characteristic needed for hydrogen sources to be used as an energy carrier is reversibility. It has to be relatively easy to regain and extract the energy from the hydrogen source. This is why all covalent hydrocarbon compounds, such as natural gas, cannot be considered as a hydrogen energy carrier since the compound must be heated to temperatures above 800°C in order to break the bonds and release hydrogen [20]. Obviously, this does not exclude natural gas from being used as an energy source, as it currently is being used worldwide, but it explains why it cannot be considered as a means of storage for hydrogen.

Instead, there are numerous alternative methods being explored and utilized that address the volumetric density and reversibility problem to make it viable to store hydrogen; each with different pros and cons. The various options for hydrogen storage are:

- Compressed gas
- Liquid hydrogen
- Liquid chemical compounds
- Metallic hydrides

This thesis considers three methods for storage of hydrogen. The first method considered is liquified hydrogen, also known as cryogenic storage. The other two methods are

liquid chemical compounds that can be used to hold and transport hydrogen, namely 1) ammonia and 2) methanol. Compressed gas is being ignored in this thesis because its limitations in long distance transport make it less feasible for consideration of moving hydrogen from Iceland to mainland Europe. Metallic hydrides are also being ignored in this thesis as the technology is not yet at a maturity level for large scale application as solutions to the gravimetric density and the amount of energy required to release the hydrogen have not yet been fully realized. The following sections will review the storage methods considered in this thesis.

In this thesis, the transport of hydrogen produced through electrolysis in Iceland is considered. The hydrogen is assumed to be produced at the location 40 kilometers away from Þorlákshöfn. Transport of hydrogen by truck from this location to international docks in Þorlákshöfn is considered. Then, international transport by ship is assumed from Iceland to the Port of Rotterdam. The arrival of the stored hydrogen at Rotterdam is the final gate used in this thesis for the scenarios of hydrogen production in Iceland. The scenarios for hydrogen production in the European Union do not include a transportation phase.

1.5.1. Liquid Hydrogen

Hydrogen can be liquified through cooling in a process comparable to that of liquified natural gas (LNG). Similar to the use of LNG within the energy sector, hydrogen gas is converted to a liquid in order to increase its volumetric energy density for transport and storage, before being returned to its gaseous state for utilization, most often in energy production. Liquid hydrogen has a volumetric energy density of 8 MJ/L, over three times greater than the 2.5 MJ/L of compressed hydrogen gas at a pressure of 345 atm [18]. Hydrogen gas can be transported by land and across water through pipelines, but for longer distances, for example internationally, the increased volumetric density as a liquid makes it more feasible and economical for long distance transport by ship.

At a pressure of 1 atmosphere, hydrogen has a boiling point of 20.3 K, equal to -252.85°C. Hydrogen gas can then be easily recovered from its liquid state by heating above its boiling point [17]. Liquid hydrogen storage is also known as cryogenic storage due to the low temperatures required to keep it in a liquid state. To keep the liquid hydrogen at these cryogenic temperatures, it is commonly stored in metallic double walled vessels. Between the two walls of these vessels, various insulations methods are employed, such as creating a vacuum between them in storage systems known as vacuum superinsulation [21].

There are two major challenges of liquid hydrogen for storage and transportation. The first is an efficiency issue in the liquefaction process. The liquefaction of hydrogen requires between 30-40% of the hydrogen's energy content [17]. However, the high efficiency of fuel cells can help offset the overall system efficiency for hydrogen use. In addition, hydrogen has a mass energy density of 143 MJ/kg, three times greater than that of gasoline [17]. Thus improvement in payloads and increased range make liquid hydrogen particularly attractive for heavy surface transport and aircrafts [21]. In January and February of 2022, the world's first trans-ocean shipment of liquid hydrogen was safely completed from the Port of Hastings, Australia, to the Port of Kobe, Japan [22].

The second big challenge to cryogenic storage of liquid hydrogen arises due to the low boiling temperature of hydrogen. Because of the need to maintain cryogenic temperatures for hydrogen to stay in a liquid state, boiling off of liquid hydrogen is an issue. The exothermic reaction of hydrogen nucleuses reversing their spin creates enough heat that makes hydrogen not a stable liquid and some boils off into a gaseous state [19]. This results in a loss of stored hydrogen fuel because some gaseous hydrogen must be released from storage vessels to reduce the pressure to maintain safe levels. There is potential to use this off-gas hydrogen as fuel for the vehicle increase the overall efficiency of the transport process.

1.5.2. Ammonia

The first of the two liquid chemicals that are considered in this thesis as a hydrogen carrier is ammonia (NH_3). Ammonia consists of three hydrogen atoms bonded to a single nitrogen atom. By weight, ammonia is 17% hydrogen [17]. In the early 1900s, German scientist Fritz Haber discovered a reaction that could synthesize ammonia from hydrogen and nitrogen in the presence of an iron-based catalyst. German chemist Carl Bosch was able to industrialize the process in large, narrow steel reactors that can create the high pressures needed for the reaction, up to 250 atmospheres[23]. The Haber-Bosch process's use for agriculture led to the world's Green Revolution as ammonia can be used as a fertilizer to provide nitrogen, an important building block of plants, in a biologically available way. Approximately 180 million tons of ammonia is synthesized yearly, with a large majority of it used in the agricultural industry at almost 90% of the ammonia produced [24]. Other uses for ammonia today include in polymer processing, explosives, refrigerants, cleaning supplies, and pharmaceuticals [25].

Ammonia has potential as a hydrogen carrier. With a volumetric energy density of 10.5 MJ/L it is more than doubly as energy dense as compressed H_2 at 700 bar. Similar to pure

hydrogen, at ambient temperatures and pressures ammonia exists as a gas. The common way to store large volumes of ammonia today is through liquefaction at ambient pressures and the saturation temperature around -33°C in a double walled vessel [24]. It can also be liquified at approximately 9 bar and ambient temperatures [26], [27]. This allows it to be more easily transported and stored than pure hydrogen gas or liquid. Ammonia can then be used as a fuel source in a few ways. The first would be through direct combustion in an internal combustion powered turbine. While viable, this is not the most ideal option because of ammonia's high autoignition temperature of 924 K and its low flame speed of 6 cm/s; as compared to 40 cm/s for natural gas [24]. In addition, the nitrogen found in ammonia can lead to high NO_x emissions when combusted which is a known pollutant. Another option for the use of ammonia as a power fuel would be to separate the hydrogen and nitrogen in order to burn the hydrogen in a combustion turbine. The process for dissociating hydrogen out of ammonia is known as ammonia cracking and usually is performed by heating gaseous ammonia to temperatures between 800 and 900°C [24]. Traces of ammonia often remain after the cracking process so although the issue of NO_x emissions is reduced, it is still present.

An alternative to producing power from an ammonia source without combustion is the use of fuel cells to directly convert the chemical energy to electricity. Some types of fuel cells known as direct ammonia fuel cells (DAFCs), are able to accept ammonia as an input fuel and produce power from the direct oxidation to nitrogen. These include a type of alkaline fuel cell and solid oxide fuel cells (SOFC). For ammonia fuel, the alkaline-type fuel cell employs a hydroxide exchange membrane (HEM) and operates below 100°C at a pressure of 1 atmosphere. Despite the modest operating conditions, the largest detractor for HEM-DAFC is the lack of efficient ammonia oxidation catalysts to keep overpotentials low and encourage the reaction. Solid oxide fuel cells that are able to directly accept ammonia as a power fuel operate at temperatures exceeding 500°C.

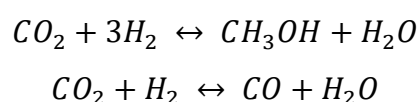
They utilize either a proton or an oxygen anion conducting electrolyte made of ceramic. While high operating temperatures can be a challenge for SOFC, they also provide the advantage of nonprecious electrocatalysts use [27]. Ammonia is unable to be used directly in PEM fuel cells. At concentrations greater than 0.1 ppm, ammonia poisons PEM fuel cells [28]. Therefore in order to use a PEM fuel cell combined with ammonia as a hydrogen energy carrier, the ammonia must be cracked to release the hydrogen from its bonds with nitrogen and then thoroughly purified before use to ensure the safety of the PEM.

The largest safety concerns for storage and transportation of ammonia are that it is both a toxic chemical and highly flammable. This however is not too much of an issue because of a

strong base knowledge of ammonia handling combined with an existing infrastructure. Approximately 20 million tons of ammonia are already transported annually around the world [24]. The large volume of ammonia that is currently being transported safely is real life proof of concept and one of the factors that makes ammonia as a hydrogen carrier so intriguing.

1.5.3. Methanol

The second of the two liquid chemicals considered in this thesis as a hydrogen carrier is methanol. Methanol is considered as a storage chemical for Hydrogen because of its existing use as a fuel and because there are already existing projects in Iceland for green methanol synthesis. Methanol is the simplest alcohol consisting of one carbon atom bonded with three hydrogen and one hydroxide molecule [29]. Methanol has the chemical formula of CH₃OH. Methanol, or methyl alcohol, has a boiling point of 64.6°C and freezing point of -97.6°C at atmospheric pressure. At ambient temperature and pressure it is a colorless, neutral, and polar liquid [29]. Conventionally, methanol is produced from synthesis gas, or syngas as it is often called, a gaseous mixture of H₂, CO, and CO₂ usually derived from coal or natural gas [30]. Processes for direct CO₂ and H₂ to methanol are being developed and pilot plants, such as Carbon Recycling International (CRI) in Iceland, are being commissioned. The reaction equation for this process along with a secondary equation that takes place are:



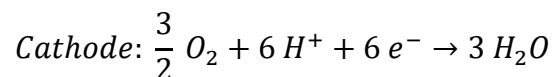
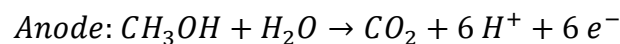
The direct CO₂ to methanol process can have environmental advantages over the traditional methanol synthesis process with the CO₂ being captured from the air and the hydrogen being separated from water by electrolysis using renewable electricity sources. This renewable or green methanol can be a way to store and transport renewable energy through the carrying of green hydrogen.

Currently, methanol is mainly used as a bulk chemical in the production of further chemicals [31]. Some of these chemicals include formaldehyde, which accounts for 32% of methanol use, acetic acid/anhydride, methyl ethers, methyl chlorides, and methanol compounds with sulfur and silicon to be used as secondary building blocks for even further value-added chemicals production. The global methanol production continues to increase reaching about 110 million tons in 2018 [29].

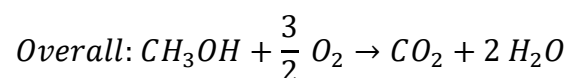
Methanol has great potential as a hydrogen carrier. From its use in the chemical industry, there already exists storage and transportation infrastructure along with technical know-how. In addition, about 40% of the methanol that is produced is already being used in the energy sector. This is mainly due to a push in China to use methanol as a fuel for transportation [29]. Similar to ammonia, there are two ways methanol can be used for energy; by combustion in an internal combustion engine or by converting chemical energy to electricity in fuel cells.

Methanol has high latent heat, no carbon-to-carbon bonds that must be broken, and a high octane rating which allows for higher compression ratios and knock resistance leading to high efficiency in internal combustion engines. It is the main fuel used in competitive motor sports because of its cleaner burning and high performance. It is however corrosive to some metals and can cause issues with rubber and plastic parts so corrosion inhibitors and specific swelling resistant seals must be used in methanol engines [29]. The burning of methanol in combustion engines does lead to carbon emissions, however if the methanol is produced with green hydrogen and CO₂ captured from the air then it is not adding CO₂ emissions, rather just returning them to the air and therefore carbon neutral.

Methanol can also be used in fuel cells to create electricity. This is done in two ways, either by direct methanol fuel cells (DMFC) or by using the hydrogen rich product gas of methanol reforming. A DMFC is a version of a PEM fuel cell that uses a liquid mixture of methanol and water [29]. The reactions at each electrode are as follows:



Which gives an overall reaction for the cell of:



As can be seen in the reaction equation, CO₂ is released when the methanol is run through the fuel cell. The process can still be considered carbon neutral if the methanol is produced using captured CO₂ by the same reasoning as mentioned before with the combustion of methanol in internal combustion engines. The main challenge facing DMFCs is methanol cross over through the membrane. This leads to fuel cell exhaust containing methanol and

possibly formaldehyde. In order to combat this problem, the fuel cell must be hydrated at each electrode. This adds system complexity, limits the operating temperature, and restricts efficiency which are currently low at only about 30% [29].

Another route for using methanol in fuel cells is through methanol reformation to free the hydrogen. Because of the absence of a strong carbon-carbon bond, methanol has one of the lowest reforming temperatures of only 200-300°C [29]. Methanol reformation produces a hydrogen rich gas that contains traces of CO, CO₂ as well as some unconverted methanol-water mixture. This reformat gas can then be run through a high temperature PEM fuel cell run above 100°C or through SOFC also run at higher temperatures to account for impurities in the fuel gas [32]. The PEM fuel cells can reach efficiencies of 50% using reformat gas from methanol as a fuel. In order to protect the PEM fuel cell from contamination, methanol reformation typically is done above 230°C to produce a clean reformat gas that is less than 2% methanol and less than 1% CO [29]. Solid oxide fuel cells fed with reformat gas from methanol can reach electrical efficiencies of approximately 52% [32].

Methanol has potential as a hydrogen carrier that can be synthesized from direct capture of CO₂ with green hydrogen from renewable sources. Being a liquid under ambient conditions, already having a large infrastructure and knowledge base for global transport, and the relative ease of freeing the hydrogen back from the methanol are all reasons pointing towards methanol's potential as an energy carrier. The existence of CRI's pilot plant in Iceland adds further reasoning for methanol's inclusion in this LCA of hydrogen production through electrolysis.

1.6. Electricity Mix

An important variable for the LCA in this thesis is the electricity mix that is used to power the water electrolysis process. For each case that is considered relating to various electrolyser cell technology and various modes of storage and transportation, different electricity mixes are considered. The following subsections describe the different electric supply mixes that are used for the different cases in this LCA.

1.6.1. Icelandic Electricity Mix Compared to Current EU27 Mix

The Icelandic electricity grid is comprised of 99% renewable energy sources. The two main sources of electric power production are hydropower and geothermal energy. With

glaciers covering 10% of Iceland, the island is able to store vast amounts of water in ice and snow. Each spring and summer glacial melt releases water which feeds numerous rivers and waterfalls. These water sources are then exploited for electricity production. In the year 2020, 68.79% of Iceland's electricity was generated from hydroelectric sources [33]. The unique location of Iceland atop a continental divide between tectonic plates provides excellent access to geothermal heat from within the earth. This geothermal energy is utilized both for heating and electricity production in Iceland. Geothermal power produced 31.16% of electricity in Iceland in 2020 [33]. The remaining less than 1% of electricity produced came from wind energy and oil/petroleum production.

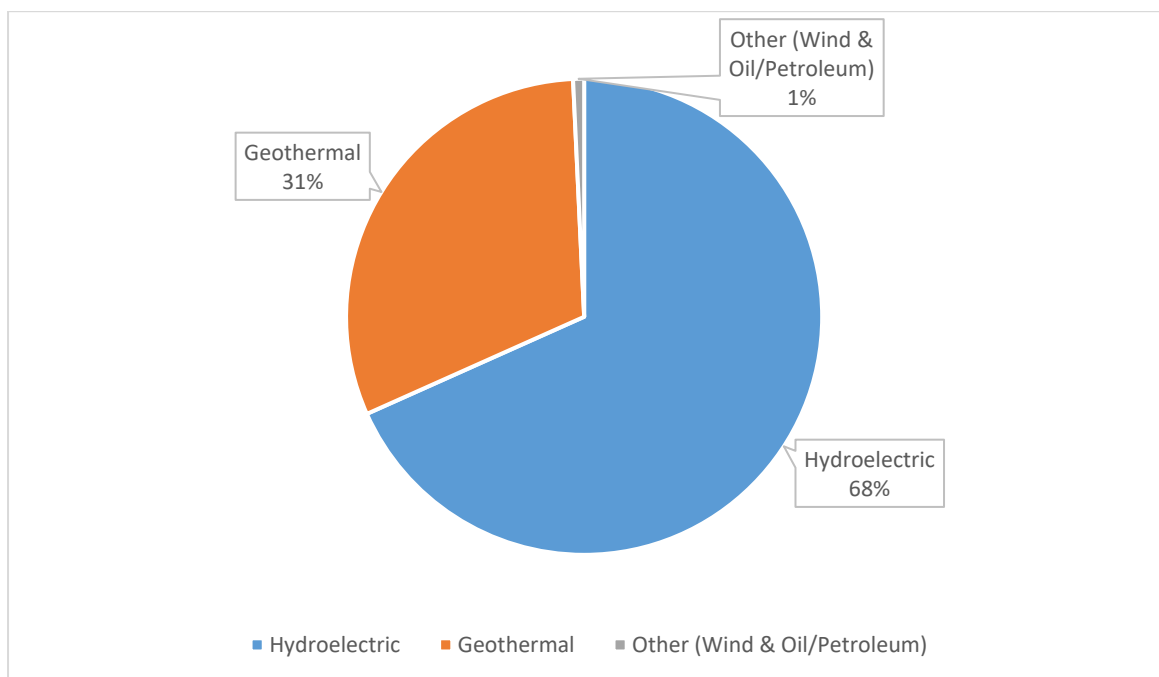


Figure 4: Electricity Production in Iceland, 2020 [33]

The European Union has a much more diverse electricity grid mix. According to data from EuroStat for 2020, electricity produced by conventional fossil fuel power plants accounted for 41.36% of the EU27 electricity. Another 24.57% was produced by nuclear heat, and the remaining 33.88% was from a combination of renewable sources such as hydro, geothermal, wind, and solar energy [33], [34].

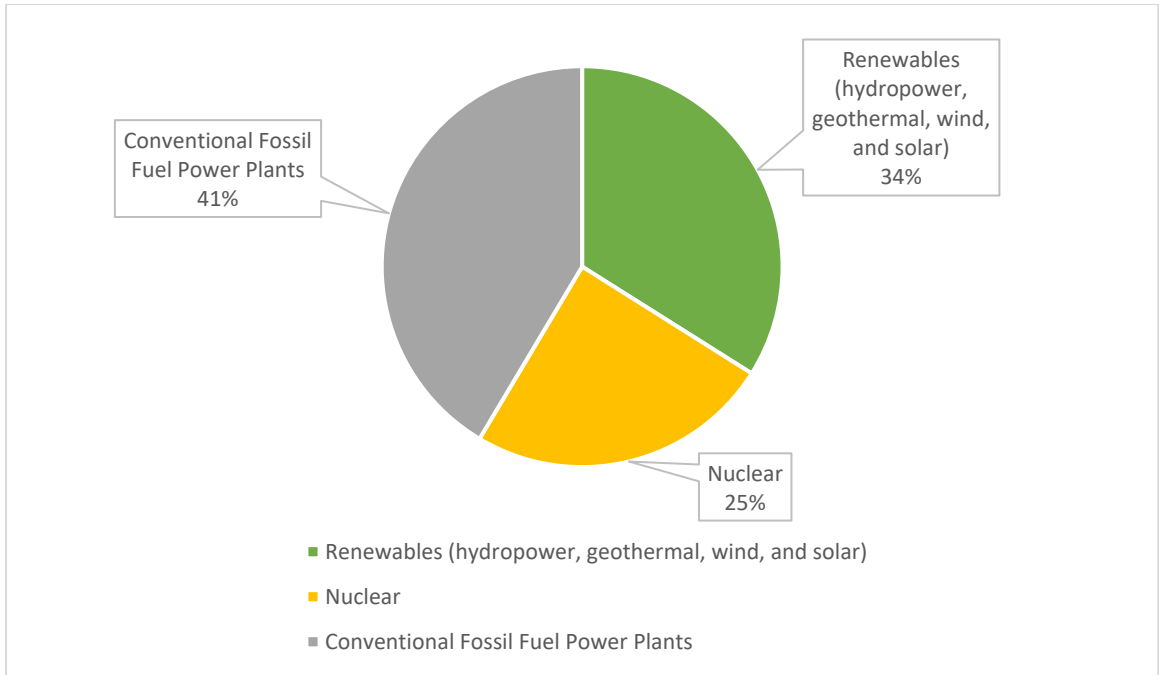


Figure 5: Electricity Production in the European Union, 2020 [33]

1.6.2. EU27 2030 Targets

Similar to many countries around the globe, the European Union has set energy and emission targets for itself in an effort to combat climate change and comply with the Paris Agreement. In 2018 the European Council approved targets of at least 32% renewable energy in final energy consumption by 2030 [35]. As noted earlier, this target has already been reached as renewables combined for 33.88% in 2020. It is likely to assume that with advancements in technology and continued implementation of renewable energy sources that by 2030 the energy share of renewables will far exceed the target of 32%. Therefore, in this thesis the 2030 EU27 grid mix that was modelled was a 42% mix of renewables. The mix of nuclear power was decreased from the 24% in 2020 to 20% in the 2030 prediction. The details of how the 2030 electricity grid mix was modelled in GaBi can be found in Section [2.3.2 Life Cycle Inventory](#).

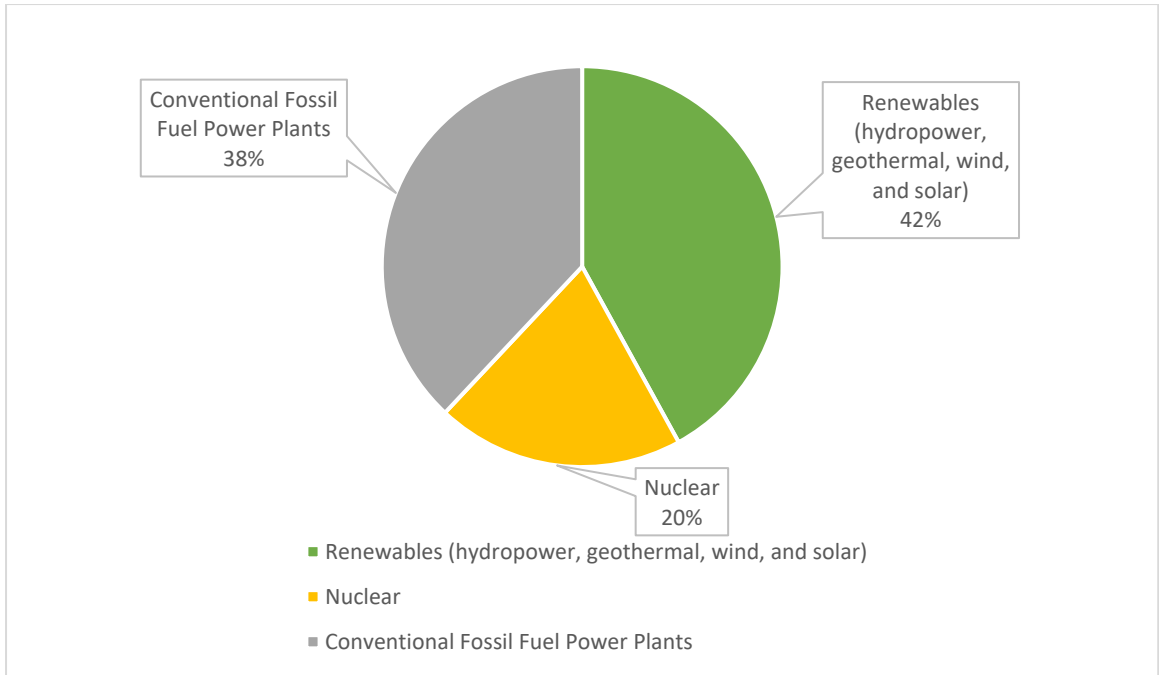


Figure 6: Electricity Production in the European Union, 2030 [35]

1.6.3. EU27 2050 Targets

The Intergovernmental Panel on Climate Change (IPCC) reported that in order to limit temperature increase to 1.5°C, global carbon emissions must reach net zero by 2050 [35]. Therefore they set their targets for 2050 in line with this assumption, namely the European union being able to become carbon neutral. In the 2018 report by the European Council, they set a target of more than 80% renewables and another 15% nuclear energy mix for electricity production [35]. The 2050 EU27 electricity mix modelled in this thesis is 80% renewables, 15% nuclear, and the remaining 5% from conventional fossil fuel combustion plants. For further details of the GaBi model of the 2050 electricity mix see Section [2.3.2 Life Cycle Inventory](#).

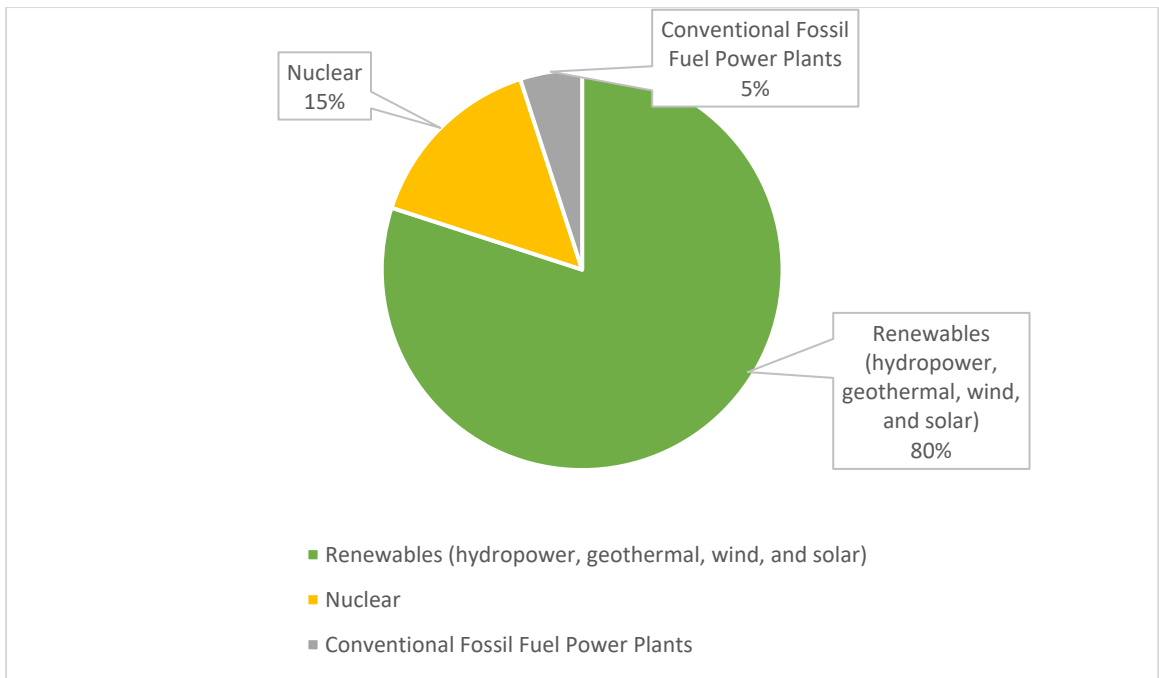


Figure 7: Electricity Production in the European Union, 2050 [35]

1.7. Life Cycle Assessment (LCA)

As sustainability and environmental impact have gained interest among the public, the use and prevalence of life cycle assessments has increased. Life cycle assessment (LCA) is defined by H. Scott Mathew's textbook on the subject as "a framework for viewing products and systems from the cradle to the grave" [36]. Life cycle assessment works to create a systematic line of thinking that can be used to analyze and assess the impacts products and processes have on the environment. It is important to note that the -A in LCA stands for assessment not analysis. This is because an LCA must not only examine the life cycle of the study material, but take it a step further and make impact evaluations based on the analysis.

The purpose of LCA according to the International Organization for Standardization (ISO) is to model the life cycle of a product as its product system. A product system is defined as a collection of processes that provide a certain function. The function then represents the performance characteristics of that product system [37]. Life cycle assessment is a relative approach based on the function. This allows for different products and systems to be more easily compared. The ISO states that LCA can therefore assist in [37]:

- identifying opportunities to improve the environmental performance of products at various points in their life cycle
- informing decision-makers in industry, government, or non-government organizations
- the selection of relevant indicators of environmental performance
- marketing

The development of LCAs is considered to have begun and take off in the 1990s. Researchers were debating the question of "paper vs plastic", a common choice in grocery stores. As the idea was debated and looked into more and more, it became apparent that the answer essentially boiled down to "it depends". This is because the "correct answer" all was in reference to what factors and impacts you consider; including where and how the product was produced, transported, used, and disposed of. This issue illustrated the need for a more standardized framework for reviewing and analyzing the full life of products and systems [36].

The definition of LCA referenced earlier mentions viewing products and systems from the "cradle to the grave". This term means the entire life cycle of the product is included all the way from extracting the elementary material from the Earth until after the final end use in the waste disposal phase. In addition to cradle to grave assessments, evaluations are made on

portions of the products or systems life cycle by considering gates. A gate is then defined for each assessment and allows for cradle to gate, gate to gate, or gate to grave LCAs to be conducted. This allows for focus on specific sections of the life cycle that are of particular interest. For example, a manufacturing company may look at the cradle to gate impact of their product and thus set the final gate as when the product leaves their factory. Most hydrogen energy systems use cradle to gate boundaries and most assessments on hydrogen used in mobility employ gate to grave boundaries [9].

This thesis will use cradle to gate boundaries for the intended assessment of different hydrogen electrolysis production. The gate boundaries used in this thesis are further detailed in the system boundary section of this paper.

In an attempt to create a clear and widely accepted structure for the process of LCA, the ISO created the standard ISO14040. The ISO is a worldwide federation of national standards bodies. Their international standards are normally prepared by ISO technical committees and every member body interested in a subject has a right to be represented. In addition, both governmental and non-governmental international organizations often assist in creating ISO standards [37].

The ISO14040 standard lays out four phases need for life cycle assessments:

Phase 1: Goal and scope definition phase

Phase 2: Inventory analysis phase

Phase 3: Impact assessment phase

Phase 4: Interpretation phase

The goal and scope phase must include statements of intent for the study and are part of the study design parameters. This phase explicitly notes the reason for doing the study and the study's reach. The inventory analysis phase is where the data collection happens for the study. Data which is needed to meet the goal and scope of the study is collected and documented during this phase. Typical data collected in LCA such as energy use and emissions of greenhouse gases would be part of this phase. The impact assessment phase transitions from tracking simple inventory results to looking at impacts associated with them. The interpretation phase then looks at the results from the study and puts them into perspective depending on the appropriate context. This is the phase that may contain recommendations for improvement or changes to reduce negative impacts, if that is in line with the defined goal and scope of the study [36].

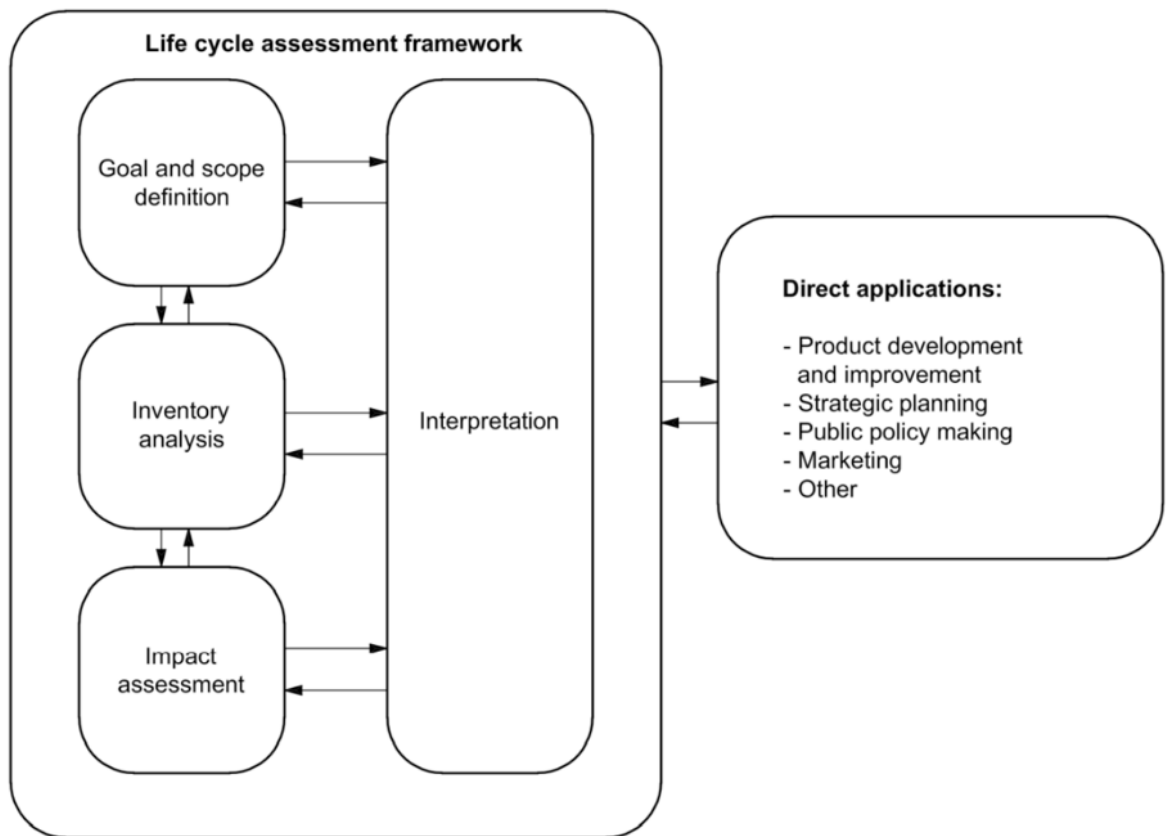


Figure 8: Life Cycle Assessment Framework [37]

As can be seen in Figure 8 the LCA process is an iterative one. These phases are not linear or independent. They are constantly interacting with each other and as new data or results are found during one phase, then it is usually necessary to move to another or phase to amend information.

2. Methodology

This chapter describes the methodology used for this thesis. The choices for software and databases, the scope and system boundary, and the functional unit are designated within this chapter. The life cycle inventory (LCI) and life cycle impact assessment (LCIA) are also defined.

2.1. Software usage

The software used in this thesis for life cycle assessment is GaBi Software for Life Cycle Assessment by Sphera. This software was chosen due to its extensive Sphera database and its ability to easily pull in extra data such as from the Ecoinvent database.

2.1.1. GaBi

The GaBi LCA software is a next generation product sustainability solution. The software allows for products and their value chains to be assessed on their environmental impacts. GaBi allows for value chains to be created in “Plans” which consist of various “Processes” connected to each other by “Flows”. Processes can be a single operation as simple as bending a piece of metal, or an aggregate of many operations encompassing multiple operations; such as collecting raw materials, assembling an electrolyser, and then using electricity and other inputs to run the electrolyser and produce hydrogen gas. For each plan, one process must be fixed so that all other process blocks can appropriately scale to match their quantities. The process that is selected as fixed is marked with a red X in the corner of the process block. All inputs and outputs between the plan and process blocks can be tracked as flows. These flows can enter, exit, or remain only within the technosphere of the project.

The technosphere for each project can be different and is set by the project’s defined system boundary.

2.1.2. Ecoinvent Database

Within the GaBi software, the ecoinvent database was utilized for life cycle inventory data. The ecoinvent Database is an LCI database for various types of sustainability assessments. It is a repository that covers a wide range of sectors at both global and regional levels. There are over 18,000 datasets that exist in the ecoinvent Database modelling a variety of processes. Some of the key datasets that are applied to this thesis are the measuring of natural resources withdrawn from the environment, the emissions released to water and air, and the products demanded from other processes such as electricity. The ecoinvent Database is consistently being updated and changed in order to assure the most accurate data possible. The version of the ecoinvent Database used for this thesis is ecoinvent v3.7.1.

2.2. Scope of Study

The goal of this study is to apply LCA to evaluate and compare the environmental impacts of a) production of green hydrogen in Iceland and then transporting it to mainland Europe with b) the production of green hydrogen in Europe. Results for multiple impact categories were calculated and included, with the Global Warming Potential measured in carbon dioxide equivalence being focused on. This study was done for the completion of a master's thesis and is publicly available online. In order to make a comparative assertion based on the results of the study, four scenarios are created.

The first scenario is that of producing hydrogen in Iceland, using the current geothermal and hydropower grid mix, and then transporting the hydrogen to mainland Europe via the Port of Rotterdam.

The second scenario is that of producing hydrogen in Europe based on the current electricity grid mix.

The third scenario is that of producing hydrogen in Europe based on the electric grid mix expected in 2030 based on EU-27 policy goals.

The fourth scenario is similar to the third scenario of producing hydrogen in Europe based on a future electricity mix, but based on the 2050 EU-27 policy goals.

In all the scenarios the variables are the type of electrolysis used and the different methods of hydrogen storage. The variable of electrolysis has three degrees of freedom: Alkaline electrolysis, PEM electrolysis, and SOEC. The hydrogen storage variable also has three degrees of freedom: liquified hydrogen, ammonia, and methanol. All these scenarios are

compared to each other, as well as to the baseline of SMR production numbers taken from literature. Steam methane reformation is chosen as a baseline for comparison because it is currently the most common method of hydrogen production worldwide.

2.3. System Boundary

The system boundary to be considered is cradle-to-gate. Cradle-to-gate life cycle assessment means that the assessment begins at the start of the system process with the raw materials and inflows of energy from the earth. The assessment is then carried through the system process to a specific point, the chosen gate [36]. In this study the gate chosen as the end point for analysis is when the hydrogen fuel gets to Europe, at the Port of Rotterdam for the Iceland scenarios. By ending at this gate, the analysis will ignore the final steps of transportation and end-use of the hydrogen fuel. If all the hydrogen is assumed to get to the Port of Rotterdam before distribution across the rest of Europe, then everything after that will contribute to the emissions tally independent of where and how the hydrogen is produced. By ignoring the end-use, it also makes for a fairer comparison. The results would be significantly skewed if for example, hydrogen from one source was considered to be used in a fuel cell producing electricity with no extra emissions while hydrogen from another source was considered to be used in a combustion process.

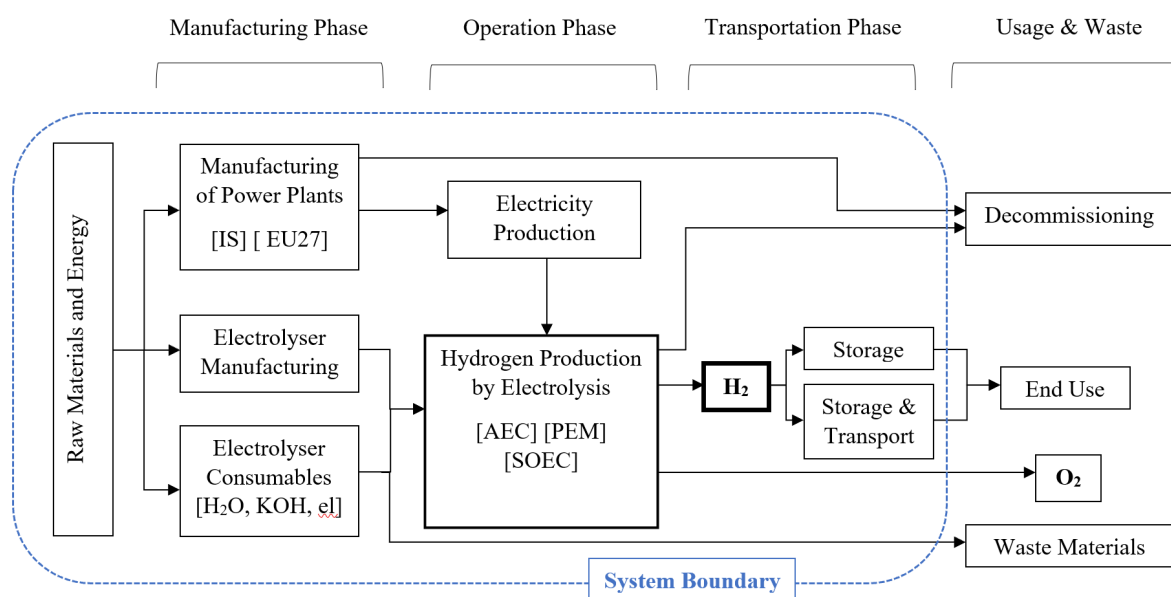


Figure 9: System Boundary of the Presented Cases

2.3.1. Functional Unit

A functional unit is a clearly defined and quantitative measure that relates the inputs and outputs of the study to a function of the product system [36]. It is important to set an appropriate functional unit in LCAs in order to standardize the results allowing units to be easily compared in a study or even across many studies. The functional unit for cradle-to-gate analyses are typically mass or energy based [9]. It is common to choose a functional unit for Hydrogen LCAs which directly identifies an amount of hydrogen [20]. Therefore, the functional unit used for this analysis is 1 kg of H₂. Since the goal of this assessment study is to compare various environmental emissions for differing hydrogen production, the results at every stage are standardized using the functional unit and therefore reported in units of emissions per 1 kg of H₂. For the different storage mediums examined, they are compared per the functional unit of 1 kg of H₂ stored within the chemical.

2.3.2. Life Cycle Inventory (LCI)

The second phase of the LCA process is Inventory Analysis. This is the phase where the inventory of data for processes and flows to be modelled are collected. The collection of data in this phase comprises the Life Cycle Inventory (LCI) of the model. In the LCI, all the data that is used to build the model, as well as assumptions made, are compiled. The following section lays out the life cycle inventory for this thesis that was modelled in the GaBi software. It is going to be sub-divided into two sections: the electrolysis and the storage and transport.

2.3.2.1 Electrolysis Inventory

The modelling of each electrolyser type was separated into two parts, the assembly of the electrolyser and the operation of the electrolyser. The operation of the electrolyser inventory requires the nesting of the assembled electrolyser process as the electrolyser stack is an input. Table 2 details the inputs for the assembly of a 1 MW Alkaline Electrolyser cell stack used in this thesis. The right-hand side of the table specifies the flow selected in the GaBi software for modelling the process.

Table 2: Life Cycle Inventory for the assembly of a 1 MW Alkaline Electrolyser [11], [20], [38]

Alkaline Electrolyser Assembly		
Inputs		GABI
Electricity	278 kWh	Electricity [Electric Power]
Acetic Anhydride	9 kg	Acetic Anhydrid [Organic intermediate products]
Acrylonitrile Butadiene Styrene	26.67 kg	Acrylonitrile butadiene styrene (ABS) [Plastics]
Aluminum	75 kg	Aluminum Billet [Metals]
Aniline	8.167 kg	Aniline [Organic Intermediate products]
Calendered Rigid Plastic	130 kg	calendering, rigid sheets [allocatable product]
Carbon Monoxide	25 kg	Carbon monoxide [inorganic intermediate products]
Copper	0.33 tons	Copper [Metals]
Graphite	71.67 kg	Graphite [Inorganic intermediate products]
Hydrochloric acid	21.67 kg	Hydrochloric acid (100%) [Inorganic intermediate products]
Lubricating oil	0.08 kg	Lubricating oil [Operating materials]
Nickel	3.167 tons	Nickel (99.95%; electrolyte nickel) [Metals]
Nitric Acid	5.5 kg	Nitric acid [Inorganic intermediate products]
N-Methyl-2-pyrrolidone	0.2167 tons	N-Methyl-2-pyrrolidone [allocatable product]
Plaster mixing	130 kg	Plaster mixing [allocatable product]
Polyphenylene Sulfide	56.67 kg	Polyphenylene sulfide granulate (PPS) [Plastics]
Polytetrafluoroethylene	13 kg	Polytetrafluoroethylene fibers (PTFE) [Plastics]
Polysulfones	43.33 kg	Polysulfone (PSU) [Plastics]
Steam	116.67 kg	Steam (for credit) [Thermal energy]
Unalloyed Steel	33.33 tons	Steel plate [Metals]
Terephthalic Acid	14.67 kg	Terephthalic acid [Organic intermediate products]
Heat	14.67 GJ	Thermal energy from heating (GJ) [Thermal energy]
Decarbonized water	1.83 tons	Water (decarbonised, softened) [Operating materials]
Deionised water	14.3 tons	Water (desalinated; deionised) [Operating materials]
Zirconium Oxide	0.183 tons	Zirconium oxide [Inorganic intermediate products]

Figure 10 illustrates the GaBi modelling of the alkaline electrolyser assembly in Iceland built in the program based on the LCI laid out in Table 2. This plan is saved within the GaBi project as the process block titled “Hydrogen Production via Alkaline Electrolyser DJB” that can be seen used in the plan in Figure 10 below. As a note, the flow arrows are sized according to relative mass input and thus the unalloyed steel input is much larger than the others. Also, many of the inputs from the database are not available as Iceland specific, therefore a large majority are modelled using the global input blocks specified by the country code: GLO. A list of the relevant GaBi country codes can be found in Appendix A along with the GaBi model for the electrolyser assembly in the European Union. The GaBi model for the Hydrogen Production via AEC in the European Union can be found in Appendix A.

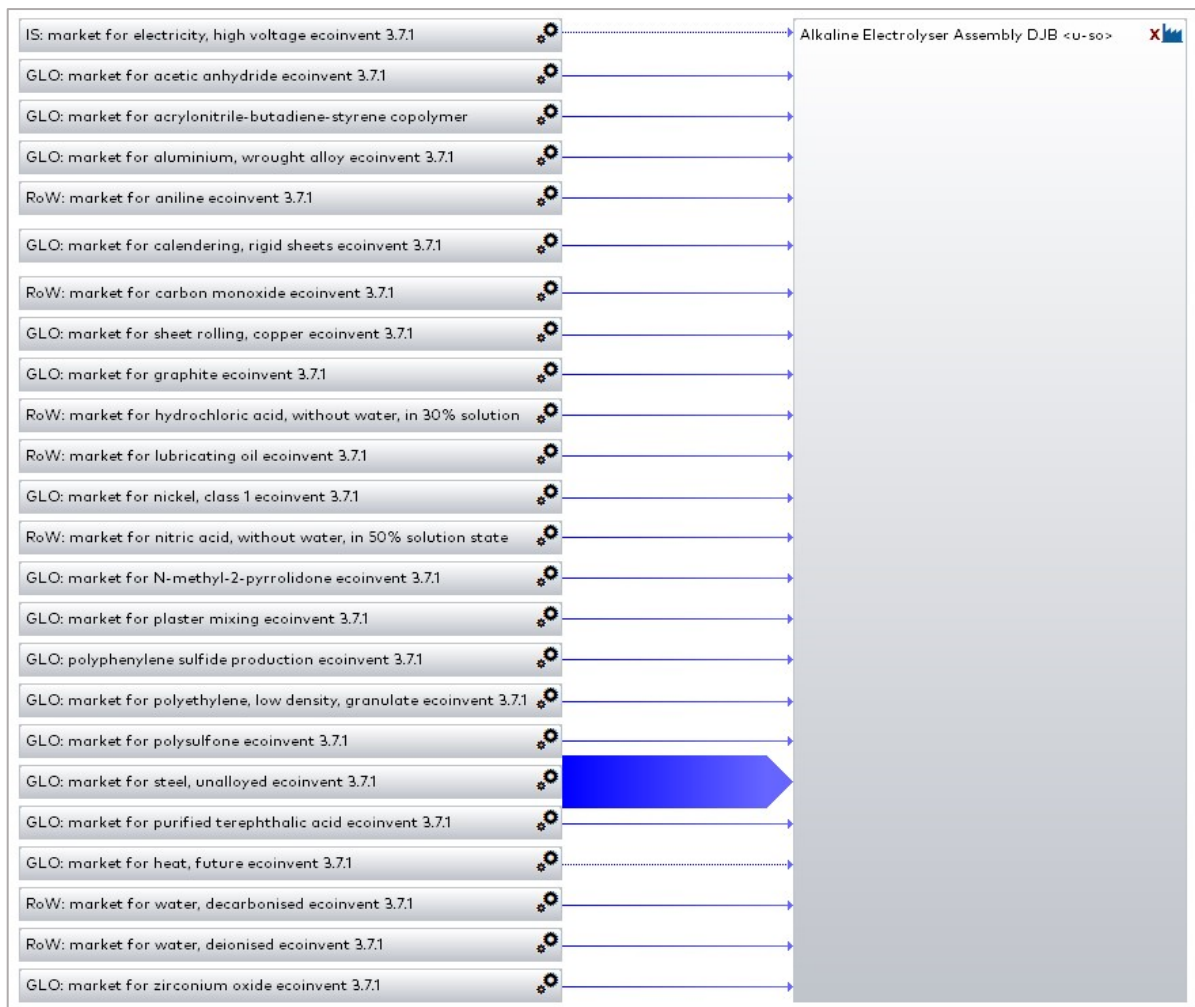


Figure 10: GaBi model for the assembly of a 1 MW Alkaline Electrolyser in Iceland using LCI data from Table 2

With the electrolyser assembly process completed in GaBi, the operation of the electrolyser to produce hydrogen is modelled. In Table 3, the LCI for the Alkaline Electrolyser

Operation is detailed. As in Table 2 above, the input and their quantities are on the left side of Table 3 with the accompanying flow that is used in GaBi on the left-hand side.

Table 3: Life Cycle Inventory for Alkaline Electrolyser Operation to produce the functional unit of 1 kg hydrogen [20], [38]

Alkaline Electrolyser Operation		
Inputs		GABI
Electricity	50 kWh	electricity, high voltage [allocatable product]
Deionized water	10 kg	water, deionised [allocatable product]
Potassium hydroxide	0.0019 kg	electrolyte, KOH, LiOH additive [allocatable product]
AEL 1MW cell stack	1 pcs.	Alkaline Electrolyser [Assemblies]

Figure 11 shows the GaBi modelling for the Alkaline electrolyser operation in Iceland. The process block “Hydrogen Production via Alkaline Electrolyser DJB” was created using the LCI data that can be found in Table 2. When the inputs are then modelled in the larger plan shown in Figure 11, the closest existing input flow available must be selected to most nearly model the intended scenario. Therefore, for this scenario of Alkaline Electrolysis in Iceland, the electricity inputs selected are specifically of Iceland, denoted by the IS country code in the titles of the electricity process blocks in Figure 11. There does not exist an Iceland specific process block for deionized water so instead it is modelled with an aggregated mix of the markets around the world not separated into their own block in the database, denoted by the country code RoW: Rest of World. Similarly, the potassium hydroxide electrolyte data is not in the database exclusively for Iceland and is thus modelled as an aggregated mix of the markets globally, denoted by the country code GLO.

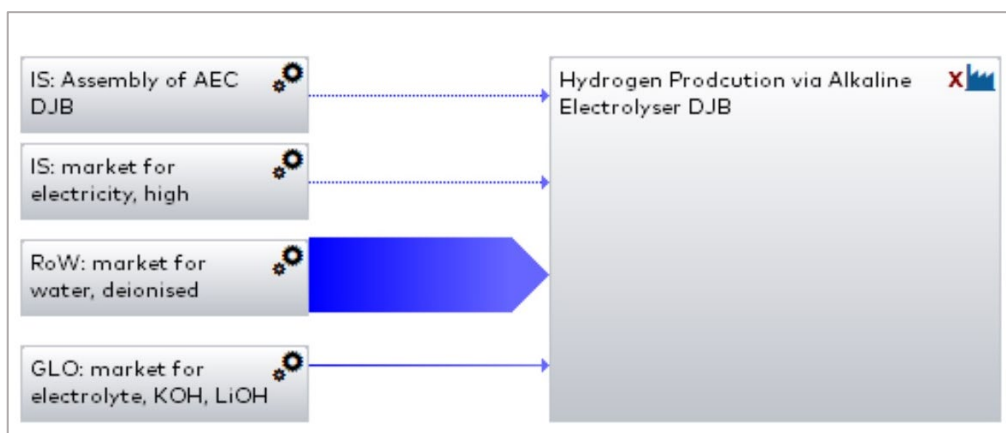


Figure 11: GaBi model for the Operation of Alkaline electrolyser in Iceland

The masses and energies listed in Table 2, the AEC assembly LCI, are for a 1 MW stack. The output of the hydrogen production process therefore is modelled as the amount of

hydrogen the electrolyser will produce over its lifetime to match the input of one 1 MW AEC stack. The electrolyser’s lifetime in this thesis is assumed to be 10 years, operating at 8,000 hours per year based on average electrolyser lifetimes and operations found in literature [39]. Based on these time parameters the 1 MW AEC is assumed to produce 1,600,000 kg of hydrogen gas. When the output of the electrolyser operation plan depicted in Figure 11 is set to match the functional unit of 1 kg of H₂, GaBi automatically scales all other quantities within the plan to match.

The LCI for the PEM electrolyser assembly built in GaBi for this thesis can be found in Table 4. Similar to the earlier AEC assembly LCI, this LCI is also for a 1 MW electrolyser cell stack.

Table 4: Life Cycle Inventory for the assembly of a 1 MW PEM Electrolyser [20], [40]

PEM Electrolyser Assembly		
Inputs		GABI
Electricity	1.95 kWh	Electricity [Electric Power]
Carbon and Ink Materials	14.1 kg	GLO: carbon black [allocatable product]
Rubber Gaskets	0.777 kg	GLO: synthetic rubber [34800: synthetic rubbe[...]]
Platinum	0.819 kg	Platinum [allocatable product]
Nafion	6.179 kg	Polytetrafluoroethylene granulate (PTFE) [Plastics]
Stainless steel	43.8 kg	Stainless steel sheet part [Metal parts]
Titanium plate	358 kg	Titanium [Metals]

The GaBi model for the PEM assembly incorporates the LCI data from Table 4. As can be seen in Figure 12, the majority of the inputs for the Iceland scenario had to implement the global process data, signified by the GLO country codes. Only the electricity was able to be modelled as specific to Iceland. The output of the process depicted in Figure 12 is a 1 MW PEM electrolyser cell stack assembled in Iceland. The GaBi model for the PEM electrolyser assembled in Europe can be seen in Appendix A.



Figure 12: GaBi model for the Assembly of PEM Electrolyser in Iceland using LCI data from Table 4

With the assembly of a 1 MW PEM electrolyser modelled in GaBi, the operation of the electrolyser is then built in the software. The LCI input data and its corresponding title modelled in GaBi are listed in Table 5. The electricity and deionized water input requirements are for the production of the functional unit; 1 kg of hydrogen gas. The input of the electrolyser cell stack is appropriately scaled to match this functional unit during the calculations of results in GaBi. The scaling is done by again assuming an electrolyser lifetime of 10 years with operation of 8,000 hours per year [39]. Based on these parameters, a 1 MW PEM electrolyser cell stack is assumed to produce 1,465,201 kg of hydrogen gas over its lifetime.

Table 5: Life Cycle Inventory of PEM Electrolyser Operation to produce the functional unit of 1 kg hydrogen [15]

PEM Electrolyser Operation		
Inputs		GABI
Electricity	54.6 kWh	electricity, high voltage [allocatable product]
Deionized water	18.04 kg	water, deionised [allocatable product]
PEM 1MW cell stack	1 pcs.	Alkaline Electrolyser [Assemblies]

The model built in GaBi for the electrolysis of water by PEM electrolyser in Iceland is shown in Figure 13. The model for the electrolysis by PEM in Europe can be found in Appendix A. The model utilizes the process block for the assembly of the PEM electrolyser cell stack explained previously. The output of this model is scaled to one kg of H₂ in order for the results to match up with this thesis's functional unit.

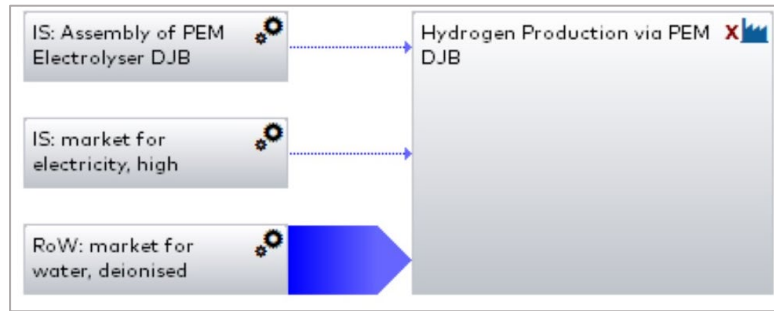


Figure 13: GaBi model for the Operation of PEM Electrolyser in Iceland

The final electrolyser modelled in this thesis was the SOEC type. The LCI data used to build the model of the electrolyser is listed in Table 6. Remaining consistent with the modelling of the previous two electrolysers, the LCI data is for a 1 MW cell stack.

Table 6: Life Cycle Inventory for the assembly of a 1 MW Solid Oxide Electrolyser [32], [41]

Solid Oxide Electrolyser Assembly		
Inputs		GABI
Electricity	49.8 MWh	Electricity [Electric power]
Benzyl alcohol (solvent)	33 kg	benzyl alcohol [allocatable product]
Carbon black	1.84	GLO: carbon black [allocatable product]
ethanol 96% (solvent)	112 kg	Ethanol (96%) [Organic intermediate products]
Ethylene glycol (binder)	36 kg	GLO: ethylene glycol [allocatable product]
Lanthanum -Strontium -Manganite (LSM)	2.48 kg	lanthanum-cerium oxide [allocatable product]
Methyl ethyl ketone (solvent)	216 kg	methyl ethyl ketone [allocatable product]
Nickel Oxide (NiO)	600 kg	GLO: nickel, class 1 [41422: Unwrought nickel]
Stainless Steel interconnect and casing	14 tons	Stainless steel (cold rolled) [Metals]
Starch blends	42 kg	Starch blends (PLA) [Plastics]
Yttrium-stabilized Zirconium (Yttrium 8% mol)	268 kg	Zirconium [Non renewable elements]

The model built in GaBi for the SOEC assembly is displayed in Figure 14. The displayed model is for the electrolyser assembly in Iceland. A picture of the assembly model for Europe can be found in Appendix A.



Figure 14: GaBi model for the Assembly of a 1 MW SOEC in Iceland using LCI data from Table 6

The model for the SOEC stack is then nested as an input into the operation model for the electrolyser. The LCI data for the operations model of the SOEC stack is listed in Table 7. The input data for electricity and deionized water is again for the production of 1 kg of hydrogen through water electrolysis, with the 1 MW electrolyser cell stack scaled in GaBi to match the functional unit. The same assumption for lifetime and operating parameters as the previous electrolysers is assumed, 10 years and 8,000 hours per year [39]. With the assumption of these parameters the lifetime production of a 1 MW SOEC stack is assumed to be 2,213,613 kg of hydrogen gas.

The electricity requirement for this type of electrolyser is reasonably less than the other two types because of the high operating temperatures. Since heat adds a portion of the energy required to split water, the electrical energy requirements fall. In this thesis the heat is not modelled as an input in the LCI. It is assumed that there are available waste heat sources in both locations that heat could be recouped from and the rest of the energy needed for the hydrogen production comes from the included electric input. This assumption is inline with the model laid out in [42] for hydrogen production by a 1 MW SOEC where waste heats of 130°C can be used with electric input of 35.2 kWh/kg H₂.

Table 7: Life Cycle Inventory of Solid Oxide Electrolyser Operation to produce the functional unit of 1 kg hydrogen [15]

Solid Oxide Electrolyser Operation		
Inputs		GABI
Electricity	36.1 kWh	electricity, high voltage [allocatable product]
Deionized water	9.1	water, deionised [allocatable product]
SOEC stack 1MW	1 pcs.	Alkaline Electrolyser [Assemblies]

The LCI data from Table 7 was input into GaBi software to build plans for the electrolysis of water by SOEC. The GaBi model for the operation of the SOEC in Iceland is seen in Figure 15, while the corresponding model for Europe is seen in Appendix A.

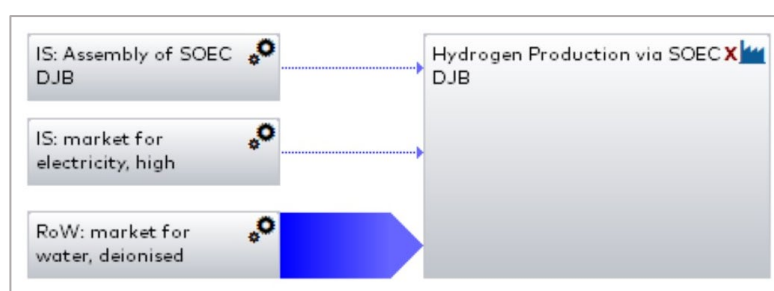


Figure 15: Gabi model for the Operation of the SOEC in Iceland

For the scenarios of electrolysis in the EU during future years, specifically 2030 and 2050, the same electrolyser operation GaBi plans were but with different electricity inputs. Instead of a single process block for the electricity input from a country, various input blocks for different forms of electricity production were connected to the electricity input of the Hydrogen Production process block and then the flows weighted accordingly. The percentage of each electricity production used as an input for the EU 2030 scenarios are listed in the section [1.7.2 EU27 2030 Targets](#). The percentages were chosen by looking at the data from the 2020 European Union grid, and finding the percentage that each technology contributed to its appropriate category. This was the percentage then used in relation to the categories new grid-mix level for the future cases. For example, in 2020 wind energy was responsible for approximately 14.3 % and renewables as a whole category contributed 33.88% of total electricity production. Assuming then that the renewables share of total electricity increases to 42% in 2030 the share of wind power in 2030 can be found by solving for x using the following equation to preserve the energy mix ratio:

$$\frac{14.3}{33.88} = \frac{x}{42}, \quad x = 17.27$$

The model for the electrolysis of water in the European Union in 2030 by an alkaline electrolyser is shown in Figure 16. Using the same percentages for each energy source found following the procedure explained in the previous paragraph, the energy mix was modelled for each electrolyser type in the year 2030.

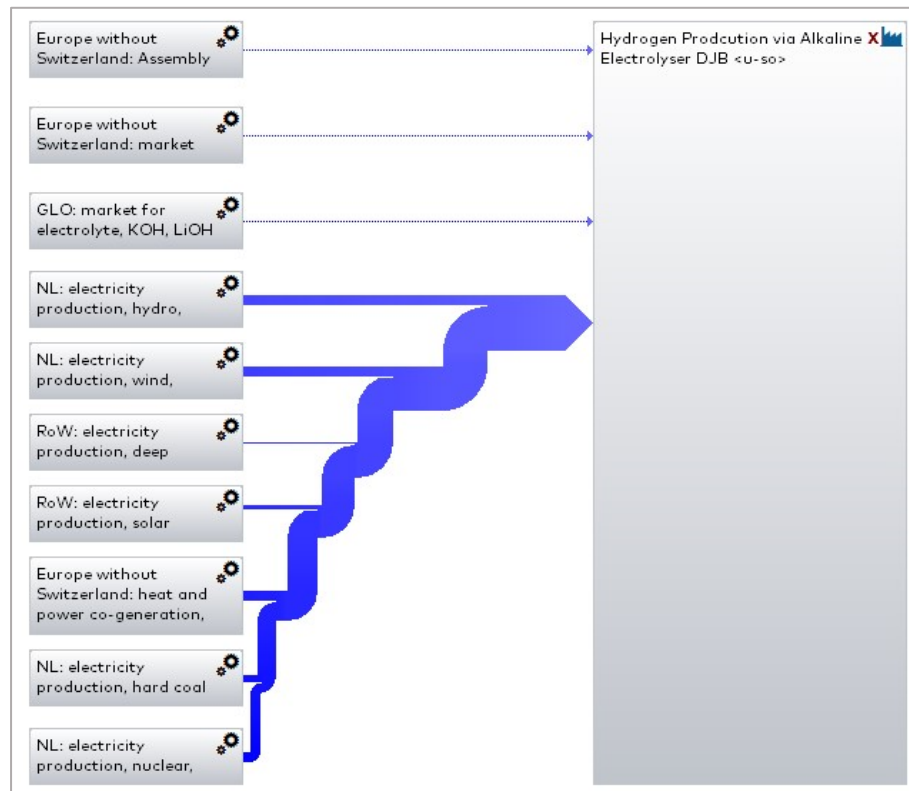


Figure 16: GaBi model of the Operation of Alkaline Electrolyser in EU27 with assumed Energy Mix in 2030

The electricity mix in the EU27 during the year 2050 was modelled in GaBi as well to be in line with their energy goals. The percentages of each category to be modelled were found using the same procedure described before using the ration from the actual 2020 electricity production data. An example of the EU2050 modelling can be seen in Figure 17, showing a mix of energy sources being input to the process block for Hydrogen production by an alkaline electrolyser.

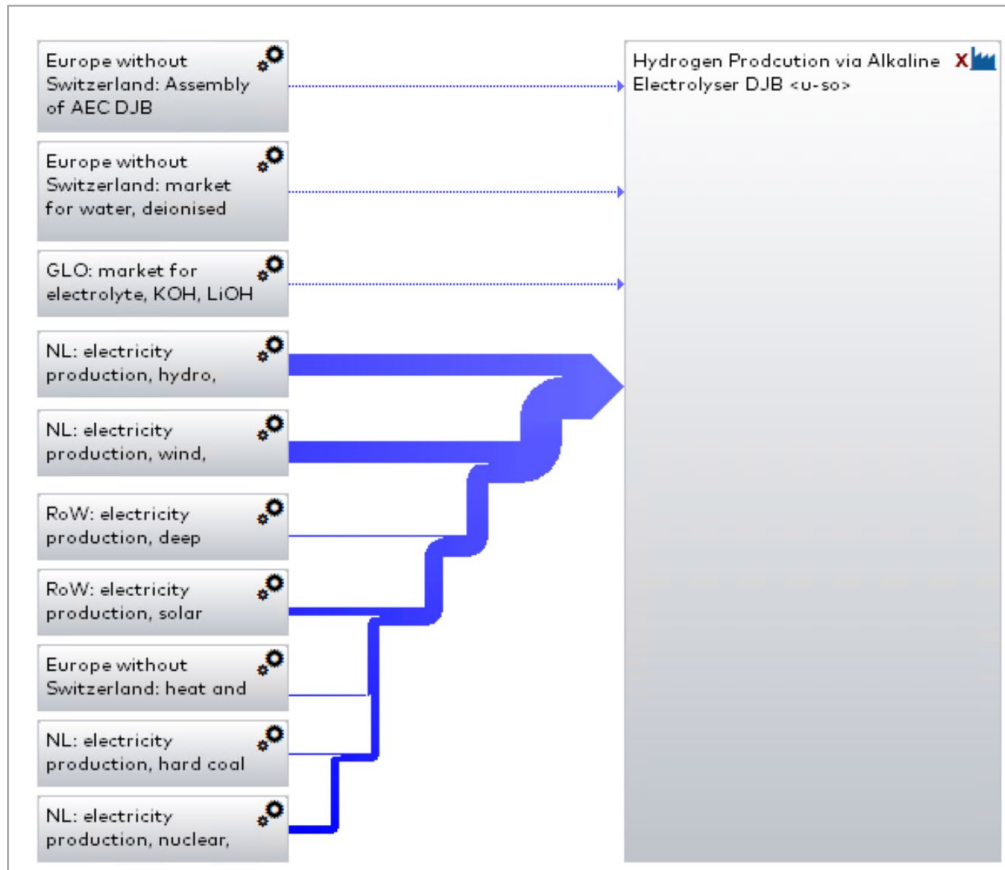


Figure 17: GaBi model of the Operation of Alkaline Electrolyser in EU27 with assumed Energy Mix in 2050

2.3.2.2 Storage and Transport Inventory

The life cycle inventory section continues now with explanations of the LCI data used for the three different storage methods: liquefaction, ammonia synthesis, and methanol synthesis. To begin, the life cycle data for the liquefaction of hydrogen is examined. A summary of the LCI used for the hydrogen liquefaction modelling is presented in Table 8. The values in Table 8 are then explained.

Table 8: Life Cycle Inventory for Liquefaction of 50 tons per day of Hydrogen [43]–[45]

Liquid H₂ (50 tpd)		
electric power	750,000	kWh
chillers	8	pcs
tanks	51,000	kg
coolant	55,280	kg
compressor	6	pcs
hydrogen	55,000	kg

The liquefaction process for hydrogen takes hydrogen gas and both compresses and cools the gas to create a liquid. To create the life cycle inventory data for the liquefaction process, the design from the IDEALHY Project was used as a guide [45]. The liquefaction process described contained 4 stages: a compression stage, a chilling stage, a pre-cooling stage, and finally a cryo-cooling stage.

During the compression stage, the gaseous hydrogen is compressed from 20 bar to 82 bar. The power required for this was calculated from the isentropic compression power equation:

$$P = R \left(\frac{k}{k-1} \right) \left(\frac{T_2 - T_1}{M} \right) Q_m$$

In this equation R is the universal gas constant and equal to 8.314 J/kg-K. The parameter k is the isentropic gas coefficient, for hydrogen gas it is used as 1.41. The T parameters are the temperature before and after compression, with units Kelvin, denoted by the subscripts 1 and 2 respectively. The starting temperature is known as $T_1 = 273.15$ K and the second temperature was found by relating temperature pressure via:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}}$$

Where p_1 is equal to the starting condition of 20 bar and p_2 is the pressure at the end of the compression stage of 82 bar. The M parameter is the molar mass, 2.02 g/mol for hydrogen gas. The parameter Q_m is the mass flow in the units of kg/sec.

Taking the mass flow rate to be 50 tons per day (tpd) from the IDEALHY Project's plant design, this calculation yielded a power requirement of 1218.04 kW. Choosing a common low end estimate an efficiency of 70% was assumed for the compressors, raising the power requirement to 1740.06 kW [46]. In the ecoinvent database on GaBi, the available air compressor data was for a 300 kW compressor. Dividing the total power requirement by the rating of the compressor, 5.80 compressors were needed. Therefore, in the modelling of the hydrogen liquefaction on GaBi the number of compressors was input as 6 for the compression stage.

After the compression stage is the chilling stage. During this step the hydrogen is cooled from T_2 from the compression stage, 441.85 K, down to 279 K. To calculate the power requirement for cooling the hydrogen gas, the heat capacity equation was used:

$$Q = \dot{m} * c_p * \Delta T$$

The mass flow rate was again taken as 50 tons per day. The c_p was taken as an average between the values of c_p for hydrogen gas at the two temperatures. The results of this calculation were 1352.84 kW. Based on the 2016 European ecodesign regulations, the minimum energy performance standard was chosen so a performance value of 4.5 is assumed for the chillers [47]. Thus, the power required for cooling in this chilling stage is assumed to be 300.63 kW.

The next step of the process is the pre-cooling stage, where the hydrogen gas is cooled from 279 K down to 130 K. The power requirement for cooling in this stage was calculated in the same manner as for the chilling stage. Again assuming a chiller performance coefficient of 4.5, the calculation yielded a result of 260.21 kW.

The final step of the process is the cryo-cooling stage. This stage takes the hydrogen's temperature from 130 K down to cryogenic temperatures of 26.8 K. In this stage the gas is liquified. The power requirement for this cooling stage was once again calculated in a similar manner as the previous two. This calculation yielded a result of 728.74 kW. The latent heat of vaporization for hydrogen was also added to this step due to the change of state from gas to liquid. At 0.44936 kJ/mol the latent heat for this step yielded 128.74 kW. Summing the two values and considering a chiller performance value of 4.5 the power requirement for the cryo-cooling step came to 189.86 kW. Summing the chiller power requirements for the whole process gives a total of 750.67 kW. The chiller data in GaBi is for chillers rated at 100 kW so therefore 7.5 are required. Rounding up to a whole number, the number of chillers for the LCI of hydrogen liquefaction was input as 8.

The coolant requirement for the liquefaction was taken from a design model for a process similar to the one used in the IDEALHY Project. The model used various mixed refrigerants at different quantities, but as the ecoinvent database on GaBi only holds data for one type of refrigerant, R134a, the various quantities were summed and used to approximate the refrigerant needs. Therefore, for the operation of the 50 tpd liquefaction plant, it was assumed that 55.28 tons of refrigerant is required [44].

The electric power requirement for the operation of the compressors, chillers, and all other components was found to be approximately 15 kWh/kg of LH₂. Since the liquefaction process in this thesis is based on 50 tpd, this number was scaled to 750,000 kWh for the LCI of the hydrogen liquefaction.

Liquid storage tanks in GaBi database were used to account for the storage of the liquified hydrogen and also to account for the expansion vessel needed during the liquefaction of the gas. For 50 tons, the required tanks were scaled by 10% and the LCI input was therefore 51,000 kg. Due to the change in spin of hydrogen atoms within liquid hydrogen, some energy is released which causes a portion of the liquid hydrogen to boil and become gaseous. For this thesis the boil of losses was assumed to be 10%, therefore 55,000 kg was used as the hydrogen input instead of just 50,000 kg [48]. Figure 18 is an example of the liquefaction process model in GaBi showing the liquefaction of hydrogen produced by alkaline electrolysis in the European Union.

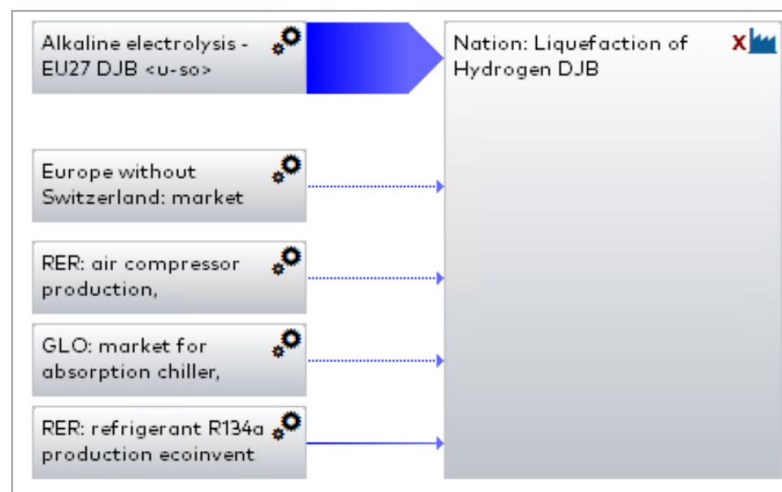


Figure 18: GaBi model for the Liquefaction of Hydrogen produced by Alkaline Electrolysis in the European Union

The next storage method is using hydrogen to synthesize ammonia. Similar to the liquid hydrogen LCI for this thesis, the LCI for ammonia production was based on a plant producing 50 tons of ammonia per day. The ammonia is considered to be synthesized through the Haber-Bosch Process with hydrogen input from electrolysis. Table 9 summarizes the LCI used in this thesis. The values are then further explained after the table.

Table 9: Life Cycle Inventory for 50 tons per day Ammonia Synthesis through the Haber-Bosch Process with hydrogen input from Electrolysis[49]–[51]

Ammonia (50 tpd)		
nitrogen	41,109	kg
electric energy	33,333	kWh
tanks	51,000	kg
iron oxide catalyst	10	kg
hydrogen	8,891	kg
coolant	35,000	kg
chillers	5	pcs
compressor	8	pcs

The Haber-Bosch Process can be executed at a range of pressures, in this thesis the pressure was assumed as 20 MPa. To calculate the number of compressors needed to get the input gases to this temperature for the LCI, the isentropic compression formula was again used:

$$P = R \left(\frac{k}{k-1} \right) \left(\frac{T_2 - T_1}{M} \right) Q_m$$

The temperature for T_1 is taken as 293.15 K and T_2 is found by relating the pressures and temperatures by the relationship:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}}$$

Taking the mass flow rate to be 50 metric tons per day, the equation yields a result of 1606.3 kW. The molar mass, M , used for ammonia is 17.04 g/mol. The k value for ammonia is estimated at 1.4. The compressor efficiency was assumed to be 70% giving an overall power requirement of 2294.7 kW. Since the compressors in the database on GaBi are for a 300 kW compressor, the total power requirement is divided by this capacity. Therefore, 7.65 compressors are needed, which was modelled in GaBi as the next whole number; 8 units.

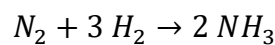
The gaseous ammonia synthesized must be cooled to condense into a liquid and be stored. Ammonia can be stored as a liquid at -33°C and ambient pressures. In order to calculate the number of chiller units required, the heat capacity equation was used:

$$Q = \dot{m} * c_p * \Delta T$$

The mass flow rate of 50 tpd and the c_p for ammonia taken as 2.2 J/kg-K, the power requirement for cooling was found to be 1390.28 kW. Assuming performance value of 4.5 for the chiller, the overall power required is 308.95 kW. To account for the change of state, the power requirement was calculated using a latent heat of 1371.2 kJ/kg. This adds 793.52 kW to the requirement which assuming the chiller performance value of 4.5 yields a power of 176.34 kW. Summing these values, the total power requirement for chilling comes to 485.29 kW. Since the chillers in the GaBi database are rated at 100 kW, then 4.85 units are needed for the modelling of the ammonia synthesis. Rounding to the next whole number, 5 chillers are required. The coolant required was 1.8 tons which was again modelled as the only available refrigerant in the database, R134a.

The life cycle inventory data also includes 51,000 kg of storage tanks and 10 kg of iron oxide catalyst for the production of 50 tons of ammonia per day. The Haber-Bosch Process utilizes an iron oxide bed to react the gases over. These two LCI quantities, and also the chiller and compressor units, were appropriately scaled over the lifetime of the plant in GaBi as they are not used up each day in the production of 50 tons ammonia.

The nitrogen and hydrogen input requirements come from the chemical equation for the formation of ammonia:



Taking 50 tons of ammonia as the output quantity, the input masses of each gas was calculated using the stoichiometric relationship. Thus, for 50 tons of ammonia the input quantities needed are 41,109 kg and 8,891 kg of nitrogen and hydrogen respectively. In the GaBi model, the hydrogen comes from different types of electrolyzers. The nitrogen input is captured from the air through pressure swing adsorption (PSA). The LCI data used to model the PSA process in GaBi can be found in the table in Appendix A.

The electric power LCI data for the synthesis of 50 tons of ammonia comes from the Royal Society of Chemistry report “Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape” [51]. Taking an electric energy requirement of 666.67 kWh per ton of ammonia, the total electricity requirement for 50 tons ammonia is 33,333 kWh. Figure 19 is an example of the ammonia synthesis process model in GaBi showing the production of ammonia with hydrogen produced by alkaline electrolysis in the European Union.

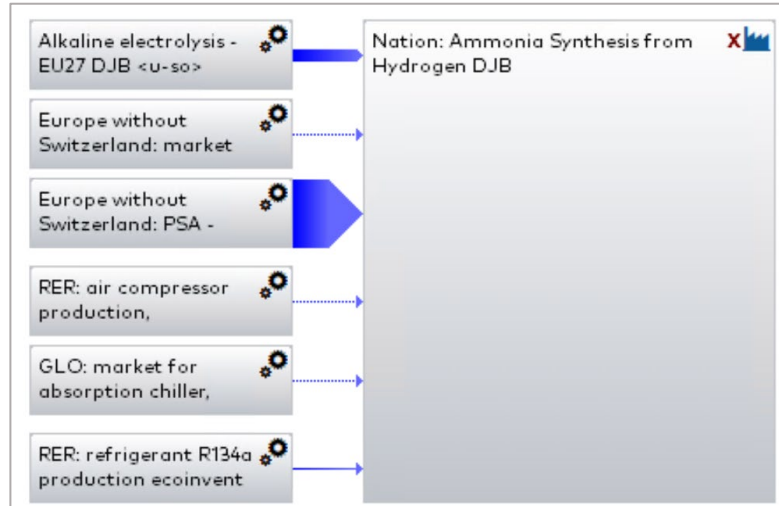


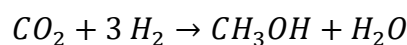
Figure 19: GaBi model for the Synthesis of Ammonia with Hydrogen produced by Alkaline Electrolysis in the EU

The final storage chemical examined in this thesis is methanol production with hydrogen. The LCI data for this method was taken from reports on Carbon Recycling International’s (CRI) pilot plant in Iceland. The plant produces green methanol with hydrogen from electrolysis and the direct carbon dioxide to methanol synthesis process. The capacity of the plant is designed for 10 tons per day, so the LCI data for this portion of the thesis is used as such. The LCI for the production of 10 tons of methanol is summarized in Table 10 with an explanation for the values following.

Table 10: Life Cycle Inventory for 10 tons per day Methanol Synthesis with hydrogen input from Electrolysis [52]–[54]

Methanol (10 tpd)		
CO2	13,732	kg
electric energy synthesis	4,433.5	kWh
tanks	11,000	kg
compressors	2	pcs.
chiller	1	pcs.
catslyst CuO	100	kg
electric energy distill	5444.4	kWh
hydrogen	1,890	kg

The hydrogen and carbon dioxide input requirements for 10 tons of methanol were calculated stoichiometrically by the methanol formation equation:



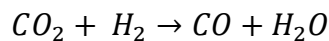
Based on this reaction, the required quantities of gas are 1,890 kg and 13,732 kg of hydrogen and carbon dioxide respectively. The hydrogen input comes from the different electrolyser technologies considered in this thesis. The carbon dioxide input is modelled as coming from PSA of flue gas. The LCI data for the production of carbon dioxide by PSA can be found in the table in Appendix A.

The methanol synthesis process takes place at a pressure of 50 bar. The isentropic compression formula was once again utilized to calculate the power requirement.:

$$P = R \left(\frac{k}{k-1} \right) \left(\frac{T_2 - T_1}{M} \right) Q_m$$

Taking the mass flow rate to be 1.89 tpd for hydrogen and 13.7 tpd for carbon dioxide and assuming 70% compressor efficiency, the compression power requirements are found to be 82.54 kW and 283.56 kW respectively. With the capacity rating of 300 kW for the compressor in GaBi, 1 is needed for each gas so 2 units are considered for the LCI.

The formation of methanol by hydrogen and carbon dioxide is exothermic with a heat of formation of -49.16 kJ/mol. Carbon dioxide and hydrogen will react in an endothermic reaction to produce carbon monoxide by the reaction:



The heat of formation for this reaction is 41.22 kJ/mol. Therefore, the heat released from the methanol synthesis is enough to activate this secondary process. In order to avoid the formation of carbon monoxide, some cooling is required. To calculate the number of 100 kW chillers were needed for the GaBi model, the cooling power requirement was calculated for the difference of the two formations heats. The difference of 7.94 kJ/mol requires only one 100 kW chiller.

With the production rate being set as 10 tons of methanol per day, a mass of 11,000 kg of liquid storage tanks were used for the LCI. The methanol synthesis with direct carbon dioxide process also utilizes a copper oxide catalyst that is set to 100 kg in this life cycle inventory. Both of these quantities are scaled over the lifetime of the synthesis plant in the GaBi model since they are not used up each day in the production of 10 tons methanol per day.

The electricity requirement for the methanol synthesis process is broken into two phases. The first phase is the electrical energy needed for the production of the methanol and water mix. It takes 450 kWh of electricity to produce 1015 kg of methanol [52]. When scaled

to the production of 10 tons of methanol, this results in 4,433.5 kWh. After synthesis, the methanol then needs to be separated from water by a distillation process. The total energy consumption for the distillation is 1.96 MJ/kg of methanol [53]. When scaled to 10 tons of methanol and converted to kWh, this result is 5,444 kWh. Figure 20 shows an example of the methanol synthesis process model on GaBi with hydrogen produced via alkaline electrolysis in the European Union.

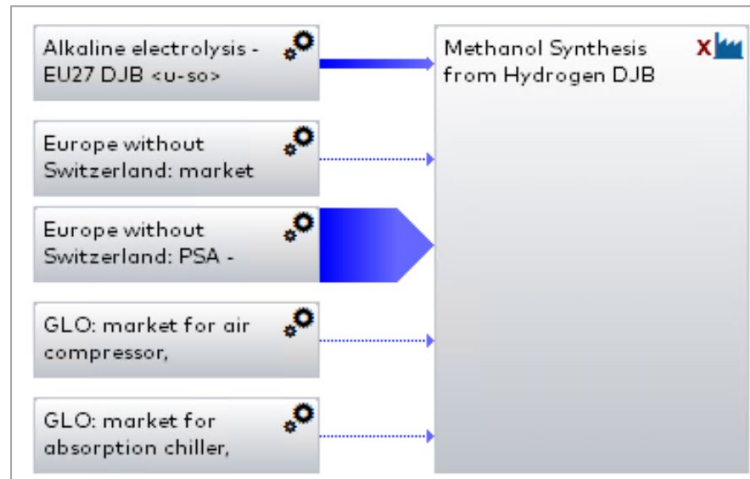


Figure 20: GaBi model for the Methanol Synthesis Process with Hydrogen produced by Alkaline Electrolysis in the EU

The hydrogen and chemical production that takes place in Iceland also includes a transport phase to Europe's Port of Rotterdam in this LCA. The transport phase consists of two steps, transportation in Iceland by land and then transportation by sea to the Port of Rotterdam. The land transportation is modelled in GaBi as transportation by a EURO5 freight lorry with refrigeration over a distance of 40 km. The sea transportation is then modelled as transportation by a freight sea tanker for liquified natural gas over a distance of about 1100 nautical miles, approximately 2040 km, from port at Þorlákshöfn. to the Port of Rotterdam. Figure 21 shows an example of the transportation being included in the plan for production of liquid hydrogen in Iceland by the liquefaction of hydrogen gas produced by alkaline water electrolysis.

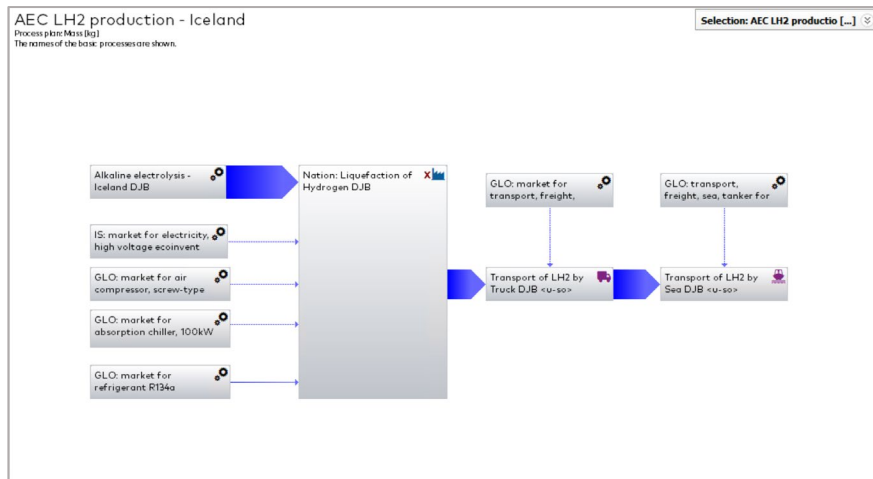


Figure 21: GaBi model for the Liquefaction of Hydrogen Gas produced by Alkaline Electrolysis in Iceland

2.3.3. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) is the third phase of the LCA process. The life cycle inventory is assessed for its impact on the environment. To do this, different methods exist for characterization factors. These factors allow the impact of a product or process on the environment to be broken into different categories and quantified. This thesis uses the CML 2016 method for impact assessment. It was developed by the Institute of Environmental Sciences of the University of Leiden in the Netherlands. The method was developed in 1992 and the most recent version that has been updated was in 2016. It is a midpoint method that assesses several impact categories with the results grouped together according to either common mechanisms or commonly accepted groupings. These categories can be found in Table 12.

Table 11: CML 2016 Impact Categories

Impact Category Abbreviation	Impact Category	Units
GWP	Global Warming Potential	kg CO ₂ eq.
ADPe	Abiotic Depletion	kg Sb eq.
ADPf	Abiotic Depletion of Fossil Fuels	MJ
AP	Acidification	kg SO ₂ eq.
EP	Eutrophication	kg PO ₄ eq.
ODP	Ozone Layer Depletion	kg R-11 eq.
POCP	Photochemical Oxidation	kg C ₂ H ₄ eq.
FAETP	Freshwater Aquatic Ecotoxicity	kg 1.4-DB eq.
HTP	Human Toxicity	kg 1.4-DB eq.
MAETP	Marine Aquatic Ecotoxicity	kg 1.4-DB eq.
TETP	Terrestrial Ecotoxicity	kg 1.4-DB eq.

3. Results

This section contains the results of the LCA model from the GaBi software. The results laid out in this section pertain to the LCIA category of Global Warming Potential (GWP) measured in kilograms of carbon dioxide equivalent. This impact category is used for this section to stay consistent with this thesis's research question of the production of hydrogen in Iceland for use in mainland Europe is more beneficial than producing hydrogen in Europe; evaluated by the comparison of emissions per kilogram of H₂ produced. The results for the other impact categories can be found in Appendix B.

The results for producing hydrogen in Iceland via three different electrolyser technologies and storing the produced hydrogen in either liquid hydrogen, ammonia, or methanol are in Table 12. The results are in units of kilograms of carbon dioxide equivalent and are normalized to the functional unit of 1 kilogram of hydrogen. The least values are close being the SOEC hydrogen production stored as liquid hydrogen and ammonia at 0.946 and 0.948 kg CO₂/kg of H₂ respectively. The greatest result is the value for PEM hydrogen production stored as methanol at 1.976 kg CO₂/kg of H₂. The breakdown of electrolysis, storage, and transport results can be found later in this section.

The overall emission results for hydrogen production and storage in the European Union are in Table 13. The smallest value for the European scenarios is of the SOEC hydrogen production stored as ammonia at a value of 17.113 kg CO₂/kg of H₂. The largest value for these scenarios is for the case of PEM hydrogen production stored as methanol at 39.512 kg CO₂/kg of H₂. Similar to the scenarios in Iceland, the further breakdown of the results categories electrolysis and storage are further in this section. The European Union scenarios do not include transport results due to the nature of this LCA being cradle to gate and the final gate being the hydrogen reaching Europe.

Table 12: Results for producing Hydrogen in Iceland via three different electrolyser technologies and storing it in either liquid hydrogen, ammonia or methanol in kg of CO2-eq and normalized to the functional unit of 1 kilogram of hydrogen

	AEC			PEM			SOEC		
	Liquid Hydrogen	Ammonia	Methanol	Liquid Hydrogen	Ammonia	Methanol	Liquid Hydrogen	Ammonia	Methanol
Electrolysis	0.931	0.846	1.270	1.020	0.925	1.39	0.654	0.595	0.892
Storage	0.242	0.062	0.181	0.242	0.062	0.181	0.242	0.062	0.181
Transport	0.051	0.291	0.405	0.051	0.291	0.405	0.051	0.291	0.405
Total	1.223	1.199	1.856	1.312	1.278	1.976	0.946	0.948	1.478

Table 13: Results for producing Hydrogen in the European Union via three different electrolyser technologies and storing it in either liquid hydrogen, ammonia or methanol in kg of CO2-eq and normalized to the functional unit of 1 kilogram of hydrogen

	AEC			PEM			SOEC		
	Liquid Hydrogen	Ammonia	Methanol	Liquid Hydrogen	Ammonia	Methanol	Liquid Hydrogen	Ammonia	Methanol
Electrolysis	23.60	21.50	32.20	25.80	23.50	35.20	17.10	15.50	23.30
Storage	6.432	1.613	4.312	6.432	1.613	4.312	6.432	1.613	4.312
Total	30.032	23.113	36.512	32.233	25.113	39.512	23.533	17.113	27.612

The results for all the different electrolyser production and storage scenarios in both Iceland and the European Union are shown compared in Figure 22. The columns are grouped together by the three methods of hydrogen storage. Each bar then represents a different electrolyser technology and whether the scenario takes place in Iceland or the European Union, which can be distinguished by the color code in the chart's legend to the side.

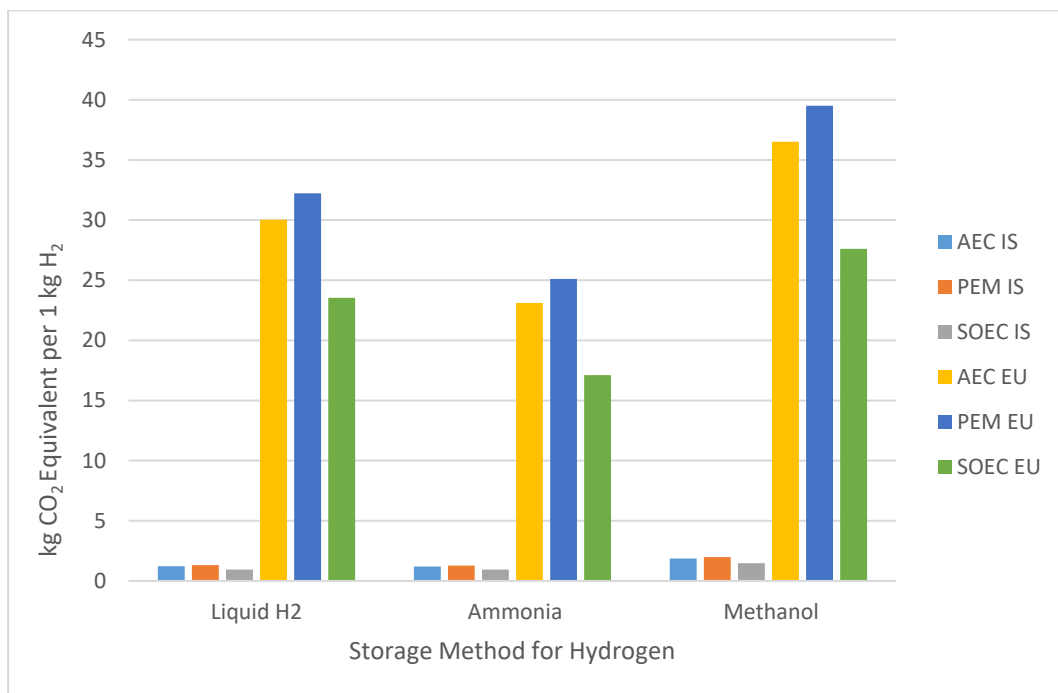


Figure 22: Global Warming Potential for all Scenarios in Iceland and the European Union compared

The overall results presented in Tables 12, 13 and Figure 22 will now be broken down further. The first category presented is the results for the electrolysis of 1 kilogram of hydrogen by the three different electrolysers. Twelve scenarios were examined for these results. The first six scenarios are the comparison of the three electrolyser technologies in Iceland and in the European Union. The final six scenarios are the three electrolyser technologies operated in the European Union under assumed 2030 and 2050 electricity grid mixes. The make-up and assumptions for these future grid mixes are explained in previous sections of this thesis.

The results for the electrolysis of 1 kilogram of hydrogen can be attributed to three (sometimes four) categories: the electrolyser assembly, the electricity used for operation, the deionized water input, and the liquid electrolyte for the alkaline electrolyser. The electricity consumed during the operation of the electrolysers is the bulk of carbon dioxide equivalent emissions. The assembly of the electrolysers are responsible for the second next largest portion of the emissions. The deionized water for splitting, as well as the liquid electrolyte for the

alkaline electrolyser, contributes very little to the overall global warming potential. The global warming potential for the breakdown of the production of 1 kilogram of hydrogen in Iceland via the three different electrolysers is in Table 14.

Table 14: Global Warming Potential of the Production of 1 kg of H₂ in Iceland via three different Electrolysers in kg CO₂-eq

	Alkaline Electrolyser	Proton Exchange Membrane Electrolyser	Solid Oxide Electrolyser
Electrolyte	0.004	-	-
Assembly	0.040	0.045	0.014
Electricity	0.797	0.871	0.576
Deionized water	0.005	0.009	0.005
Total	0.846	0.925	0.594

The results for the three electrolysers in the European Union are in Table 15. With the different electricity grid mix of the European Union compared to Iceland, the electricity during operation is again the leading contributor. The assembly again is the second largest contributing factor, but much less relative to the overall emissions of scenarios. It is worth noting that the assembly values are the same or similar in some cases as the Iceland scenarios. This is due to some of the data used in the Life Cycle Inventory for the electrolysers not existing in the databases as country specific and instead global values having to be used. More information on when this is the case can be found in the LCI section of this thesis.

Table 15: Global Warming Potential of the Production of 1 kg H₂ in the European Union via three different Electrolysers in kg CO₂-eq

	Alkaline Electrolyser	Proton Exchange Membrane Electrolyser	Solid Oxide Electrolyser
Electrolyte	0.004	-	-
Assembly	0.040	0.045	0.023
Electricity	21.40	23.40	15.50
Deionized water	0.005	0.009	0.004
Total	21.448	23.454	15.527

The results for the three electrolysers operating in the European Union in 2030 are in Table 16. These results are assuming a different electricity mix during operation of the electrolysers as explained in previous sections. The assembly values are the same as the other European Union scenarios because the modelling of the assembly has not changed for these scenarios. The future European Union grid scenarios assume that the electrolysers are

assembled and begin operation at the current time, and then are still in operation during 2030. The values of the emissions from the electricity during operation have fallen compared to the previous European Union scenario with the improved electricity grid.

Table 16: Global Warming Potential of the Production of 1 kg H₂ in the European Union via three different Electrolysers in kg CO₂-eq in 2030

	Alkaline Electrolyser	Proton Exchange Membrane Electrolyser	Solid Oxide Electrolyser
Electrolyte	0.004	-	-
Assembly	0.040	0.045	0.023
Electricity	12.25	13.45	8.88
Deionized water	0.005	0.009	0.004
Total	12.30	13.50	8.91

The final three scenarios for the production of 1 kilogram of hydrogen by electrolysis are the scenarios using the 2050 electricity grid mix for the European Union as described in previous sections. The emissions results for these scenarios are found in Table 17. In a similar way as the 2030 European Union scenarios, the assembly emissions values are the same as the current European Union cases. The electrolysers in this thesis are assumed to have a 10-year life-span, so it is not a reasonable assumption that those built and assembled now would still be in operation in 2050. However, the future data required for the assembly portion of the analysis does not yet exist in the databases. And since it can be assumed that the emission values would likely decrease in the future, it can then be assumed that using these values sets a reasonable maximum for the scenarios and still provides useful results.

Table 17: Global Warming Potential of the Production of 1 kg H₂ in the European Union via three different Electrolysers in kg CO₂-eq in 2050

	Alkaline Electrolyser	Proton Exchange Membrane Electrolyser	Solid Oxide Electrolyser
Electrolyte	0.004	-	-
Assembly	0.040	0.045	0.023
Electricity	2.112	2.316	1.533
Deionized water	0.005	0.009	0.004
Total	2.161	2.370	1.560

All twelve scenarios are compared collectively in Figure 23. Three columns corresponding to the three different electrolyser types represent the electrolysers' emissions in

kilograms of carbon dioxide equivalent for the production of one kilogram of hydrogen by electrolysis. These three columns are shown for the four different electricity grid scenarios: current Iceland, current European Union, 2030 European Union, and 2050 European Union. A horizontal line is also added as a reference, showing the emissions associated with producing one kilogram of hydrogen by the steam methane reformation (SMR) process. This value is 10.56 kg CO₂ equivalent/kg of H₂ and comes from Susmozas, Iribarren, and Dufour's paper [55].

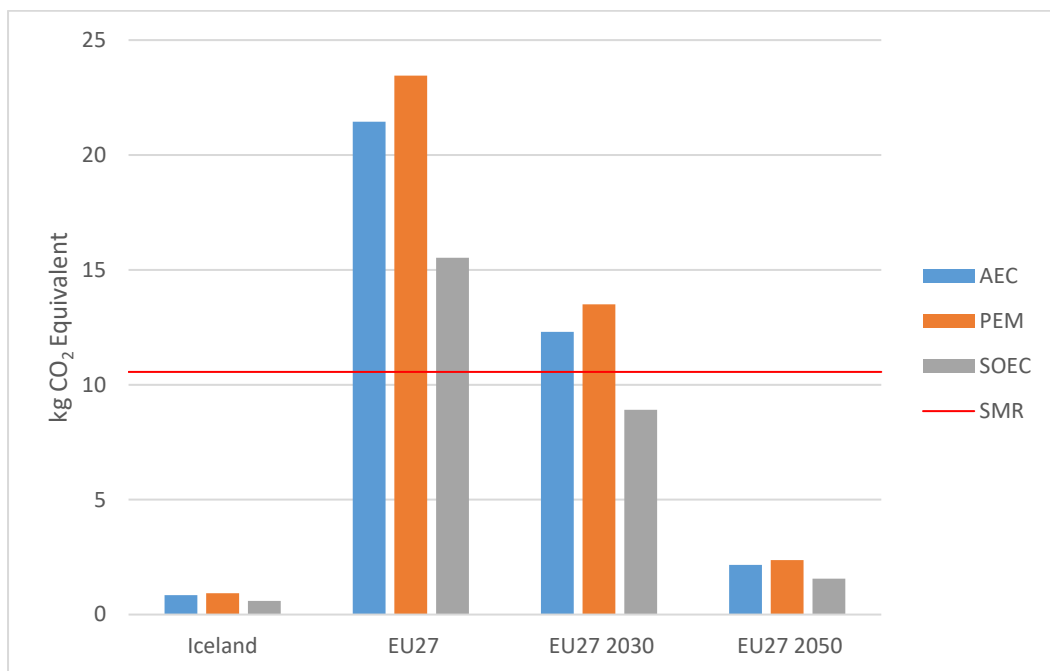


Figure 23: Global Warming Potential of 1kg of H₂ Electrolysis in Iceland, the EU in 2020, the EU in 2030 and the EU in 2050 in kg CO₂-eq per kg of H₂. Displayed are three different Electrolysers

The overall results presented in Tables 12 and 13, and Figure 22 will now be examined further via the second category of storage. The process of liquifying hydrogen, synthesizing ammonia, or synthesizing methanol also has associated emissions. The results for those emissions when the storage process happens in Iceland are in Table 18. Along with the emissions for synthesizing these chemicals with hydrogen as an input, the transportation from Iceland to the Port of Rotterdam contributes emissions. These values are also included in Table 18. All the values in the table are in reference to the functional unit of one kilogram of hydrogen being stored.

Table 18: Global Warming Potential of the Transportation from Iceland to the Port of Rotterdam in kg CO₂-eq per kg of H₂

	Liquid Hydrogen	Ammonia	Methanol
Electricity	0.239	0.060	0.125
PSA	-	2.15E-04	5.22E-02
Chillers	2.27E-03	5.56E-04	8.81E-04
Compressors	2.29E-04	1.70E-03	3.13E-03
Refrigerant	2.51E-06	4.59E-07	-
Truck	0.0277	0.163	0.224
Sea Tanker	0.0228	0.128	0.181
Total	0.292	0.353	0.586

The emission results for the three storage methods taking place in the European Union are found in Table 19. No emissions corresponding to travel are included in this table because no travel is considered in the European scenarios as travel would be past the final gate of this LCA's system boundary. Again, these values are scaled to the functional unit of one kilogram of hydrogen stored.

Table 19: Global Warming Potential of three Storage Methods within the European Union in kg of CO₂-eq per kg of H₂

	Liquid Hydrogen	Ammonia	Methanol
Electricity	6.430	1.610	3.360
PSA	-	5.25E-04	0.948
Chillers	2.27E-03	5.56E-04	8.81E-04
Compressors	2.27E-04	1.68E-03	3.13E-03
Refrigerant	2.96E-06	5.37E-07	-
Total	6.432	1.613	4.312

The results for the various storage methods are compared in one chart in Figure 24. The different columns correspond to the synthesis of a certain chemical as labeled in the legend. The results are grouped by the locations the processes are assumed to take place in for the model.

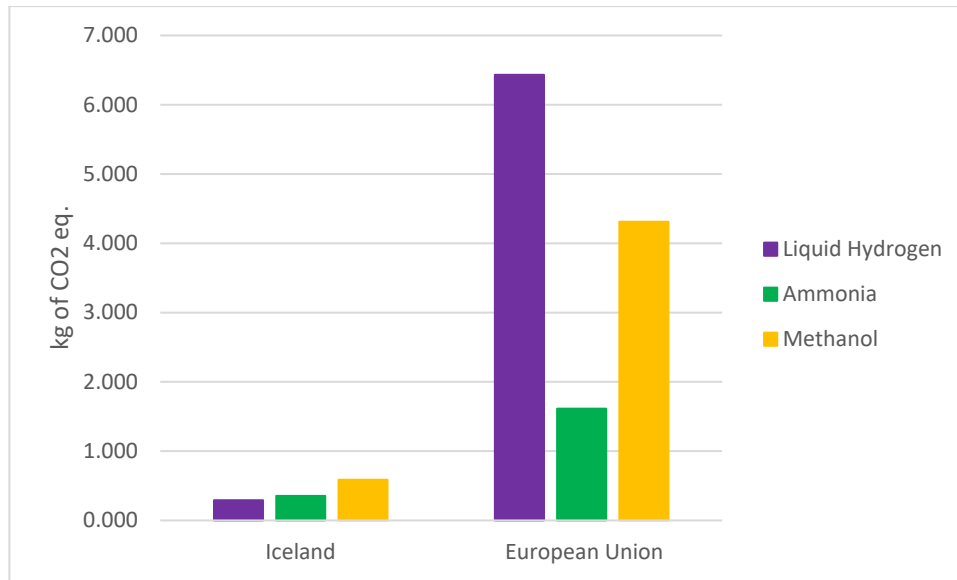


Figure 24: Global Warming Potential of the Storage of H₂ in Iceland vs. in the European Union with three different storage methods in kg of CO₂-eq per kg of H₂

The results presented in this section are for the life cycle impact assessment category of global warming potential. They are measured in kilograms of carbon dioxide equivalence and are all scaled in reference to the thesis' functional unit of one kilogram of hydrogen gas. These results are used to formulate the conclusions in the final section of this thesis. The results from the GaBi model measuring other impact categories can be found in Appendix B.

4. Discussion

This section acknowledges that there are some important considerations to be aware of pertaining to this thesis. The first of these has to do with data uncertainty and assumptions. Since this thesis was not based on any one specific technology or methods the data had to be synthesized from available sources. For the models to be created therefore, many assumptions had to be made. Throughout this thesis those assumptions were noted and their reasoning explained. This is especially significant in the life cycle inventory section. With more specific data for the LCI, the results of an LCA can be more accurate. While this thesis looks at three electrolyser technologies in general, the results would become more precise if data for a specific electrolyser was to be analyzed, for example within a company choosing between two exact models.

Similarly, assumptions about the future energy mix of the European Union have been made. Recent developments, however, show, that energy supply in the European Union is a fragile construct and can change rather quick and unexpectedly. Assumptions about the future energy mix within their set goals might differ from reality, and even more impactful, there is always the chance that the European Union does not hit their energy goals or that the goals drastically change.

Another key consideration is that this is a comparative LCA. Therefore, it is designed to not necessarily make general conclusions about the results, but rather to compare results using similar functional units and life cycle impact assessment categories. Thus, the conclusions in this thesis are not saying exactly what is best, but rather what is better than what.

Two more key considerations arise from this. The first being that of functional units. With LCAs, the functional unit is very important to be aware of and make sure the comparisons are scaled by the same unit. It is also important to note that with functional units, the results can seem unexpected or be potentially looking at the wrong metric. An example of this within this thesis is the choice of one kilogram of hydrogen as a functional unit. This functional unit was chosen as it is the common choice for hydrogen LCAs. The selection of this functional unit to scale results to is a good indication of results for the performance of electrolysers as the product they are producing is hydrogen.

However, this functional unit may not be the best way to normalize results about the storage methods as two of them are not made up of pure hydrogen and therefore can be impacted by other elements especially with larger masses than hydrogen. A problem that can arise from this is when the models are scaled to one kilogram of hydrogen, the amount of

methanol has to be chosen such that it contains one kilogram of hydrogen, not just that the input is one kilogram of hydrogen as there is also the formation of water during the methanol synthesis process. Another potential functional unit for this portion of the thesis could be to instead scale to the masses of the storage fuels equivalent to the same energy. For example, the functional unit could be chosen as 100 kWh. Taking the energy density of liquid hydrogen to be 14×10^7 J/kg, of ammonia to be 1.85×10^7 J/kg, and of methanol to be 2.1×10^7 J/kg the equivalent masses of each to 100 kWh is 2.57 kg, 19.46 kg, and 17.14 kg respectively. The GaBi model was adjusted to these masses and example results recalculated for the alkaline electrolyser scenarios. These alternate results are found in Figure 25.

Comparing these results to those presented in the [Results](#) section, the value of the emissions obviously greatly varies, and also the choice of “best solution” may then be different depending on the functional unit.

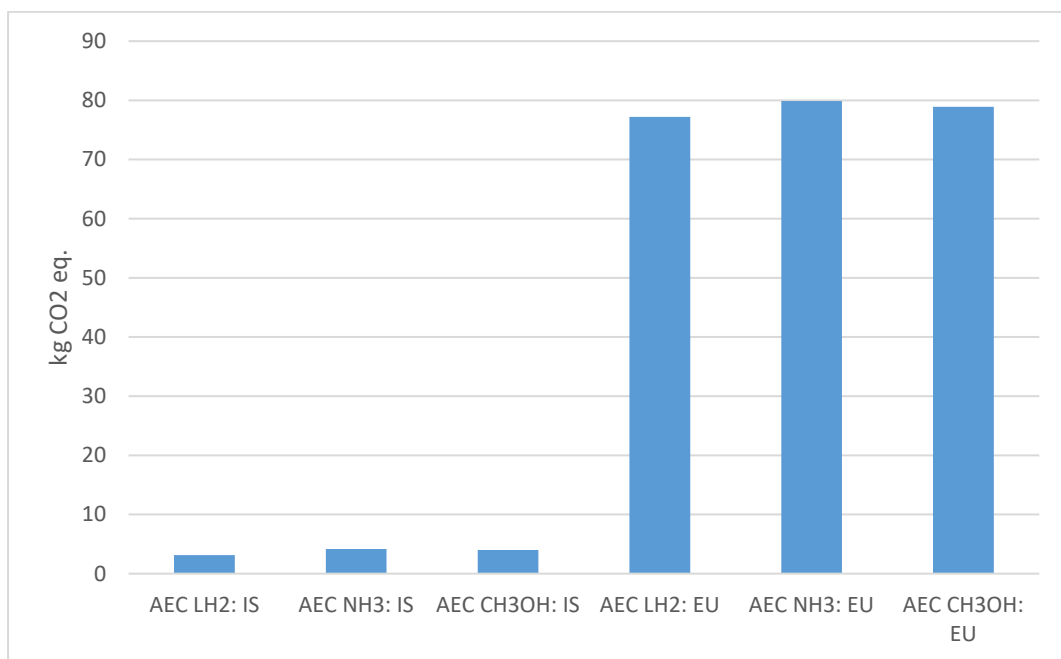


Figure 25: Global Warming Potential in kg CO₂-eq adjusted to the functional unit of 100 kWh

The second key consideration that arises from this being a comparative LCA is that of the impact categories. When comparing results to make conclusions, it must be recognized what LCIA categories the results are measured in. For the main body of this thesis, the choice was to use the global warming potential metric measured in the units of kilograms of carbon dioxide equivalent. Conclusions drawn about a “better” or “worse” scenario based on this metric, may not always be the same for the other impact categories. In Appendix B, results can be found for the other impact categories from the CML 2016 method for LCIA.

5. Conclusion

The research question of this thesis is whether the production of hydrogen in Iceland for the use in mainland Europe is more beneficial than producing the hydrogen in the European Union. The chosen metric to make this assessment is by a comparison of carbon dioxide equivalent emissions per kilogram of H₂. Based on the results of the LCA performed using the GaBi software, producing hydrogen in Iceland and transporting it to Europe is more beneficial in terms of carbon dioxide equivalent emissions.

Producing one kilogram of hydrogen in Iceland with an alkaline electrolyser has 0.846 kg of carbon dioxide equivalent emissions associated it. This is about 96% savings as compared to the emissions value of 21.448 kg carbon dioxide equivalent of producing an equal amount of hydrogen in Europe with the same electrolyser type.

Using a proton exchange membrane electrolyser has higher emissions associated with it in both countries as compared to the other electrolyser technologies. This is due to a larger share of the emissions values being attributed to the electrolyser's assembly, of which approximately 80% is from the supply of platinum for the membrane. The emissions results for producing one kilogram of hydrogen in Iceland by PEM is 0.925 kg of carbon dioxide equivalence. This is still lower than the results of any of the electrolyser types operating in Europe, and approximately 95% emissions savings as compared to the same electrolyser technology operating in Europe with associated emissions of 23.454 kg of carbon dioxide equivalence.

The lowest emissions results for an electrolyser are for the solid oxide electrolyser. This is due to the low emissions associated with assembly of the electrolyser unit and to the lower demand of electricity during operation because of the high efficiencies of the system thanks to thermal energy supplying part of the required energy for water splitting. The value for producing on kilogram of hydrogen in Iceland with an SOEC is 0.594 kg carbon dioxide equivalent, while the value for the same production level in Europe is 15.527 kg carbon dioxide equivalence. This is an emissions savings of approximately 97% when comparing the SOEC in Iceland to in the European Union. The values for the other two electrolyser technologies in Iceland are both still significantly lower than the 15.527 kg carbon dioxide equivalent for the SOEC in Europe.

The conclusion that electrolysis in Iceland is more beneficial in terms of carbon emissions as compared to Europe is due to the current electricity mixes of both. Therefore, another aspect of this thesis was to model the future European Union's electricity mixes based

on the 2030 and 2050 climate policy goals. This allows for inferences to be made about whether it would still be beneficial to produce hydrogen in Iceland for Europe in the future as the European electricity grid becomes cleaner, as measured in terms of carbon emissions.

The electricity mix of the European Union in 2030 was modelled based on the parameters explained in the Life Cycle Inventory section. The results for the production of one kilogram of hydrogen using that electricity mix and measured in kilograms of carbon dioxide emissions equivalence are 12.30 for the AEC unit, 13.50 for the PEM electrolyser, and 8.91 for the SOEC unit. The results are an improvement on those using the current day electricity mix of the EU27, but even the lowest value of 8.91 for the SOEC is still much greater than all three electrolyser types in Iceland. Thus, it can be concluded that in 2030 it will still be beneficial in terms of carbon emissions to produce hydrogen in Iceland and transport it to Europe for use as opposed to producing it in Europe by electrolysis.

The electricity mix for the European Union in 2050 model is also described in the Life Cycle Inventory section of this thesis. The results for the production of one kilogram of hydrogen at that time are 2.16 for the AEC unit, 2.37 for the PEM electrolyser, and 1.56 for the SOEC unit; all measured in kilograms of carbon dioxide equivalence. These values are much closer to the values for electrolysis in Iceland. However, still none of these results yield lower emissions totals than the cases in Iceland. These results suggest it will continue to be beneficial in terms of carbon emissions in 2050 to produce by electrolysis and transport hydrogen from Iceland to Europe instead of producing by electrolysis inside the European Union. A definitive conclusion for that far in the future will depend on many factors including developments in electrolyser technologies, the actual status of the European Union's electricity grid, and the state of both land and sea transport at that time.

In addition to analyzing and comparing three electrolyser technologies and potential future electricity grid mixes, this thesis analyzes three methods of storage for the produced hydrogen. These three methods were as liquid hydrogen, storage in synthesized ammonia, and storage in synthesized methanol. Models for the production of hydrogen and synthesis of these chemicals were created for both Iceland and the EU27. The Iceland scenarios were modelled to include transport phases for those chemicals to get them to Europe, at the Port of Rotterdam.

The process of liquifying hydrogen in Iceland has associated carbon emissions of 0.292 kg carbon dioxide equivalence per one kilogram of liquid hydrogen. The majority of these emissions arise from the energy consumption of the liquefaction process.

The results for the synthesis of ammonia in Iceland is 0.353 kg of carbon dioxide equivalence. This was the least carbon emissions calculated of all the storage scenarios, in both

Iceland and Europe. The energy requirement for the synthesis of ammonia by the Haber process is very low and therefore the majority of the associated emissions for this scenario in Iceland are due to the transport.

The results of the synthesis of methanol in Iceland is 0.586 kg of carbon dioxide equivalence per one kilogram of hydrogen in methanol. The transport makes up a combined 0.405 kg of this result, and the energy requirement for the process contributes another 0.125 kgs.

The production of hydrogen in Iceland and then exporting to the European Union is beneficial in terms of global warming potential measured by carbon emissions. It will more than likely continue to be beneficial from this point of view for years to come. This could be one part of the solution as the world looks to decarbonize the global economy.

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A. Appendix – GaBi Models

Table A-1: Relevant GaBi Country Codes used

GLO	Global
IS	Iceland
RER	Europe (including Switzerland)
Europe without Switzerland	Europe (without Switzerland)
RoW	Rest of World

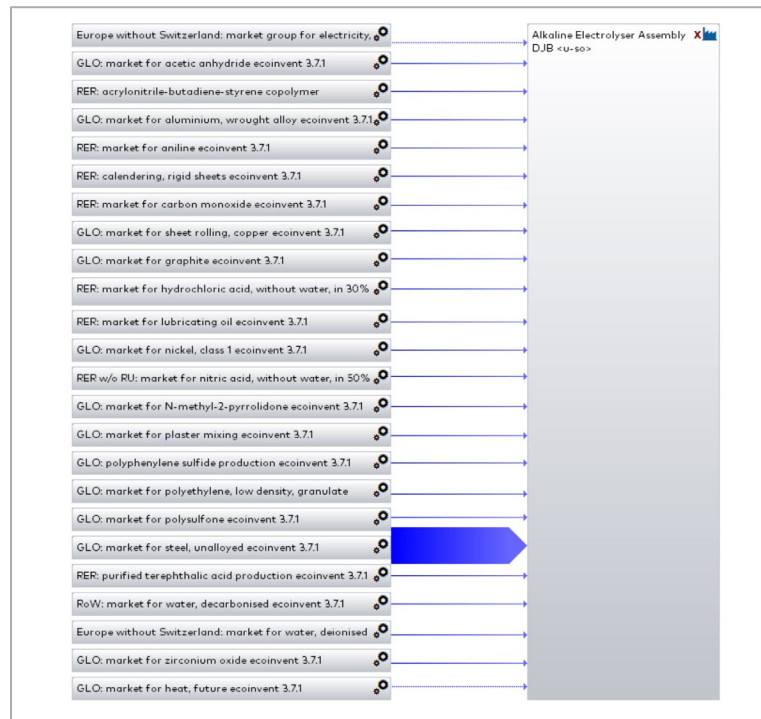


Figure A-1: Assembly of Alkaline Electrolyser in European Union

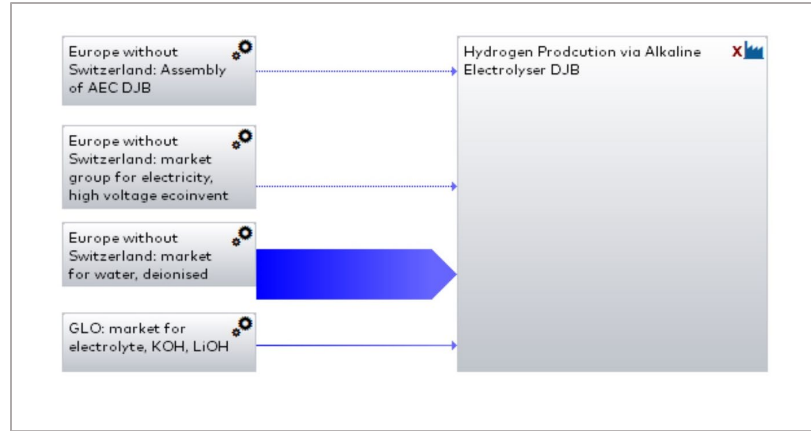


Figure A-2: Operation of Alkaline electrolyser in European Union



Figure A-3: Assembly of PEM Electrolyser in European Union

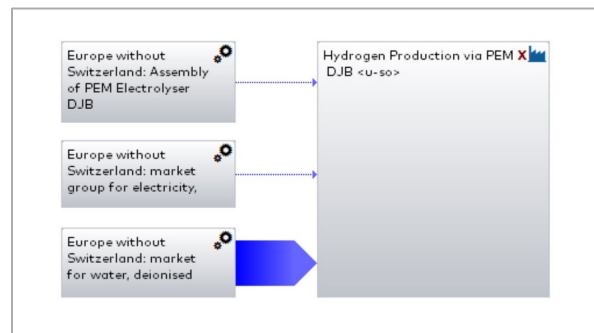


Figure A-4: Operation of PEM electrolyser in European Union



Figure A-5: Assembly of SOEC in European Union

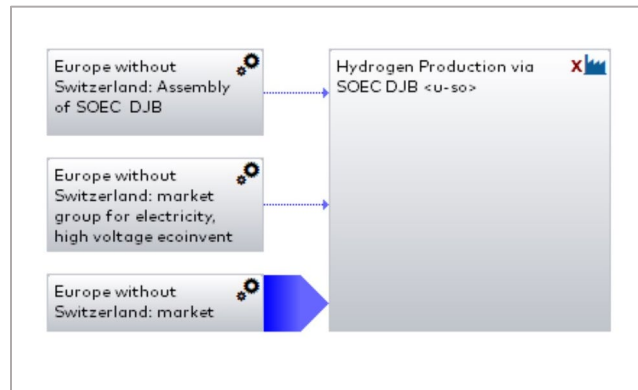


Figure A-6: Operation of SOEC in European Union

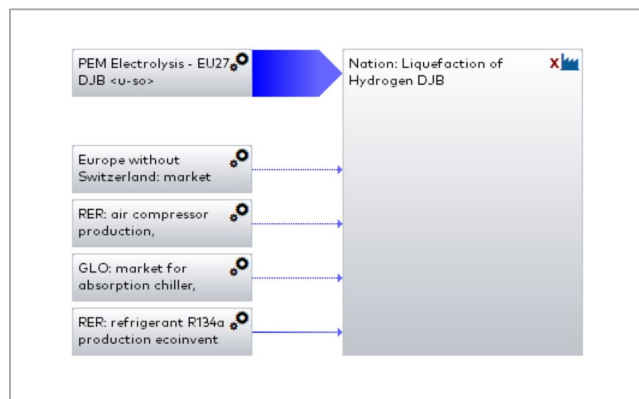


Figure A-7: Liquefaction of Hydrogen produced by PEM electrolyser in the European Union

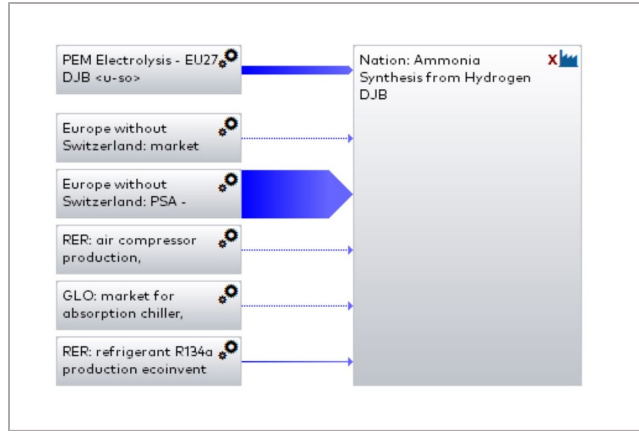


Figure A-8: Synthesis of Ammonia with Hydrogen produced by PEM electrolyser in the European Union

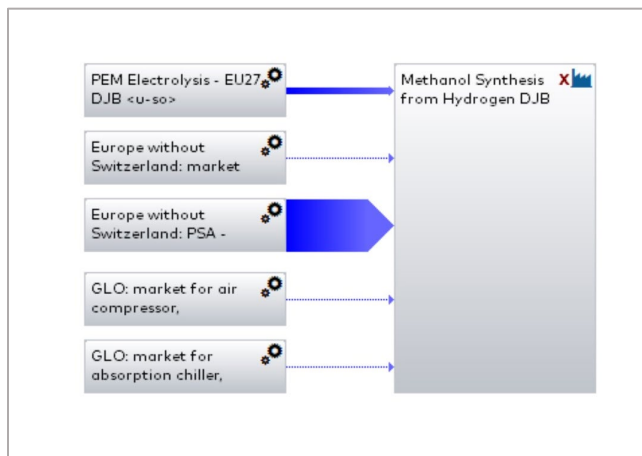


Figure A-9: Synthesis of Methanol with Hydrogen produced by PEM electrolyser in the European Union

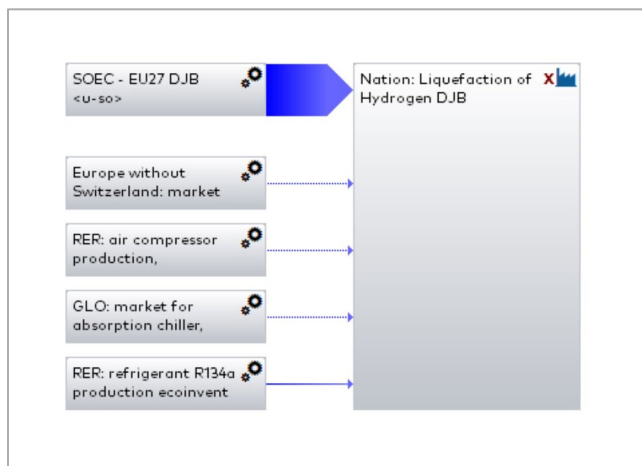


Figure A-10: Liquefaction of Hydrogen produced by SOEC in the European Union

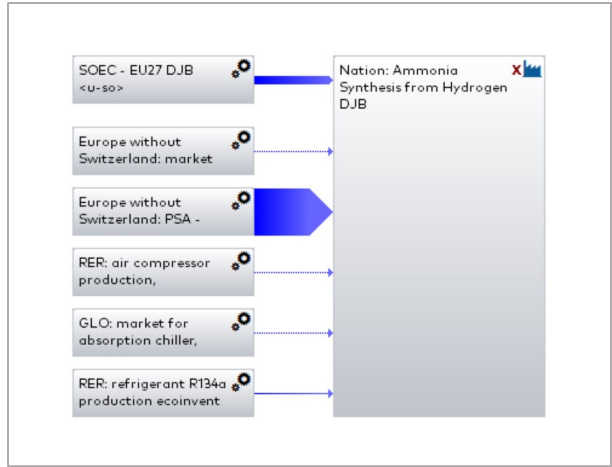


Figure A-11: Synthesis of Ammonia with Hydrogen produced by SOEC in the European Union

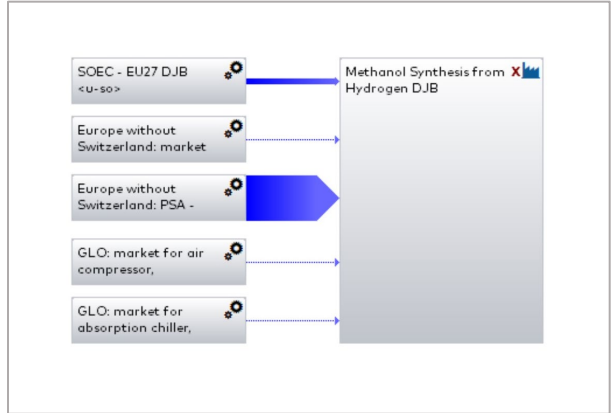


Figure A-12: Synthesis of Methanol with Hydrogen produced by SOEC in the European Union

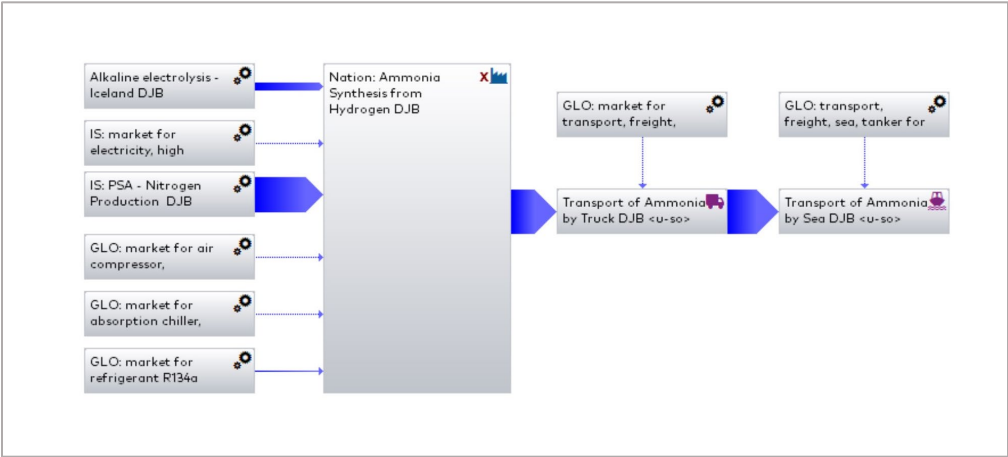


Figure A-13: Synthesis of Ammonia with Hydrogen produced by Alkaline electrolyser in Iceland

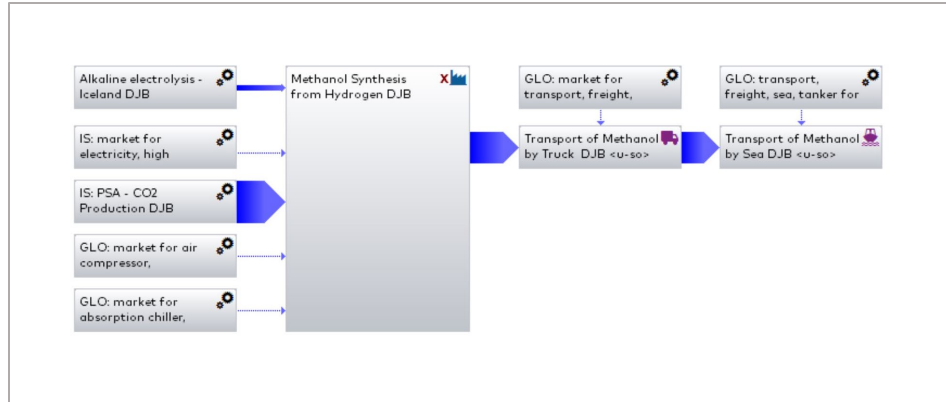


Figure A-14: Synthesis of Methanol with Hydrogen produced by Alkaline electrolyser in Iceland

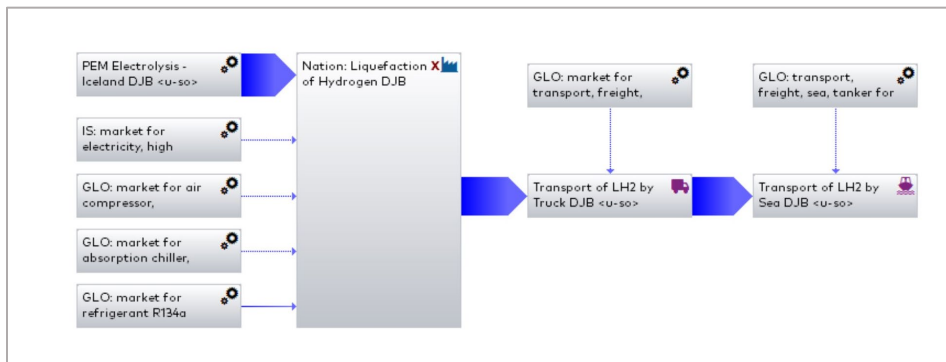


Figure A-15: Liquefaction of Hydrogen produced by PEM electrolyser in Iceland

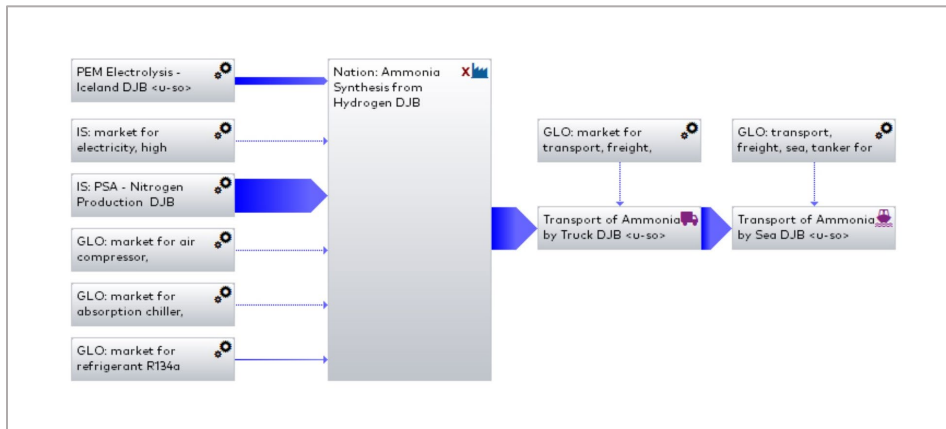


Figure A-16: Synthesis of Ammonia with Hydrogen produced by PEM electrolyser in Iceland

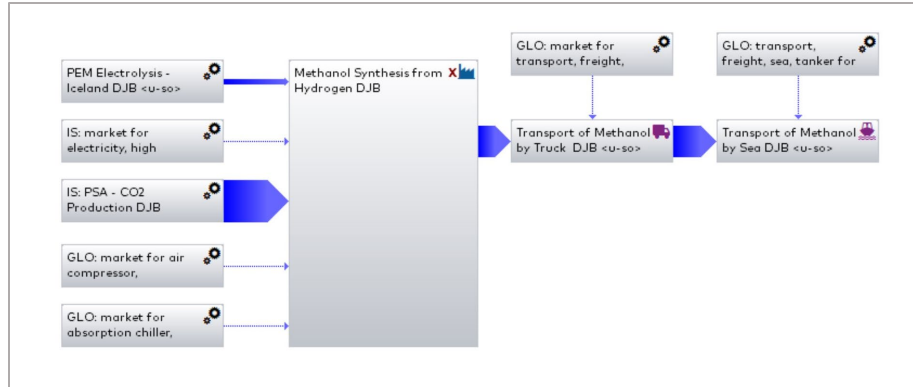


Figure A-17: Synthesis of Methanol with Hydrogen produced by PEM electrolyser in Iceland

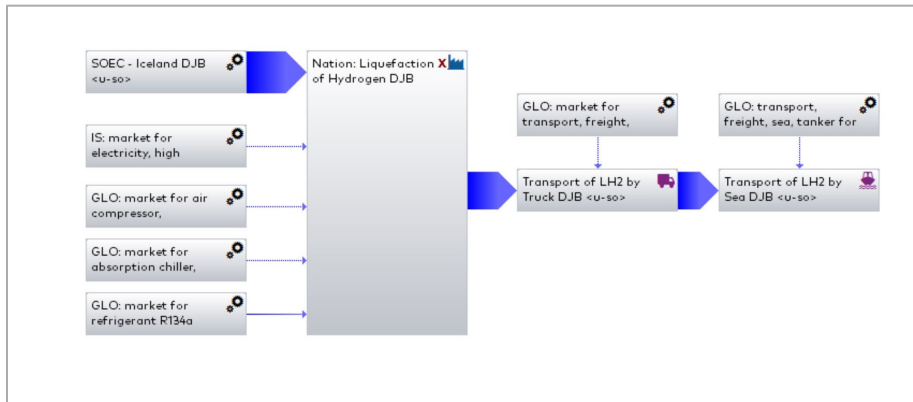


Figure A-18: Liquefaction of Hydrogen produced by SOEC in Iceland

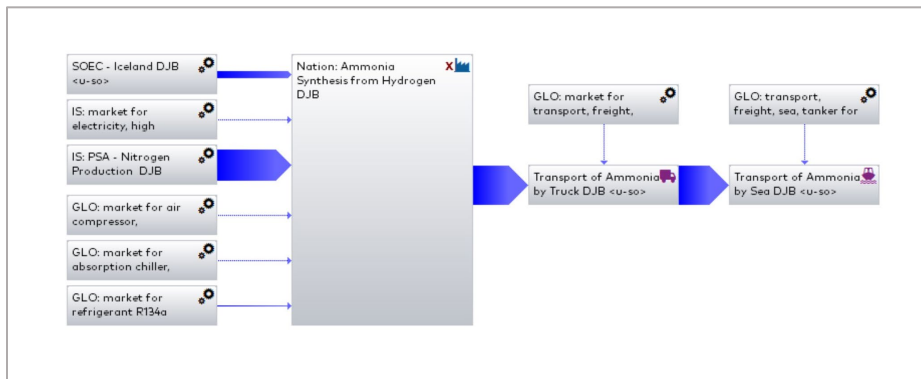


Figure A-19: Synthesis of Ammonia with Hydrogen produced by SOEC in Iceland

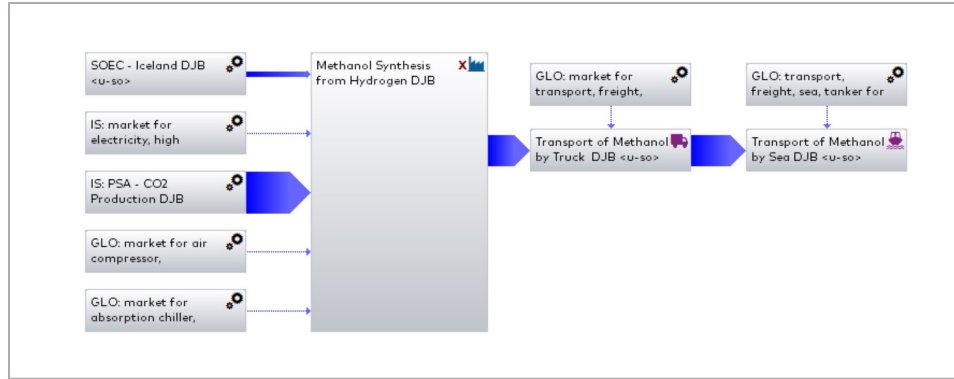


Figure A-20: Synthesis of Methanol with Hydrogen produced by SOEC in Iceland

Table A-2: LCI data for Nitrogen Production by PSA

PSA – N ₂	
inputs:	
Activated carbon [Organic intermediate]	80 kg
Compressed air	920 Nm ³
RoW: expansion vessels, 80l [allocatable product]	2 pcs.
Electric Energy	523.84 kJ
outputs:	
Nitrogen gaseous [Inorganic intermediate]	897 kg

Table A-3: LCI data for CO₂ Production by PSA

PSA - CO ₂	
inputs:	
Flue Gas (for treatment) [Waste for recovery]	303 kg
RoW: expansion vessel, 80l [allocatable product]	2 pcs.
RoW: zeolite, powder [allocatable product]	56 kg
Electric Energy	25,122.22 kJ
outputs:	
Carbon dioxide [inorganic intermediate]	35 kg

B. Appendix – Other Results

Table B-1: Results for AEC in Iceland per 1 kg Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolyte	8.89E-08	0.0534	2.01E-05	1.12E-05	2.56E-03	0.0038	6.64	1.61E-09	1.22E-06	3.05E-05
Assembly of AEC	8.69E-08	0.531	1.38E-04	7.81E-05	0.08	0.0705	1.01E+02	2.33E-09	3.35E-05	9.52E-05
Electricity	5.65E-06	5.36	0.00189	1.15E-03	0.644	0.925	948	2.81E-08	2.88E-04	0.0365
Deionised water	1.52E-07	0.0648	3.44E-05	1.11E-05	4.95E-03	0.00733	8.97	2.44E-09	2.01E-04	7.27E-05
Total	5.98E-06	6.0092	0.00208	0.00125	0.732	1.007	1064.61	3.448E-08	0.00052372	0.0367

Table B-2: Results for AEC in European Union per 1 kg Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolyte	8.89E-08	0.0534	2.01E-05	1.12E-05	2.56E-03	0.00376	6.64	1.61E-09	1.22E-06	3.05E-05
Assembly of AEC	8.67E-08	0.531	1.37E-04	7.81E-05	0.08	5.64	8.09E+03	1.87E-07	2.68E-03	7.60E-03
Electricity	2.01E-05	289	0.0966	0.0701	12.2	10.3	3.59E+04	8.96E-07	5.36E-03	5.77E-02
Deionised water	1.03E-07	0.0625	3.65E-05	9.95E-06	3.37E-03	0.00493	6.70	2.45E-09	2.07E-06	6.30E-05
Total	2.04E-05	289.65	0.097	0.070	12.29	10.38	3.60E+04	9.02E-07	5.40E-03	0.058

Table B-3: Results for PEM in Iceland per 1 kg Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Assembly of PEM	2.05E-06	0.822	2.45E-03	2.78E-04	0.159	0.136	2.29E+02	2.36E-09	1.21E-04	2.25E-04
Electricity	6.17E-06	5.85	0.00206	0.00125	0.703	1.01	1.04E+03	3.07E-08	3.15E-04	3.99E-02
Deionised water	2.73E-07	0.117	6.20E-05	2.00E-05	8.93E-03	1.32E-02	16.20	4.41E-09	3.63E-06	1.31E-04
Total	8.49E-06	6.79	0.00457	0.002	0.87	1.16	1.29E+03	3.75E-08	4.40E-04	0.040

Table B-4: Results for PEM in European Union per 1 kg Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Assembly of PEM	2.05E-06	0.822	0.00245	0.000278	0.159	0.136	2.29E+02	2.36E-09	1.21E-04	2.25E-04
Electricity	2.20E-05	316	0.105	0.0766	13.3	11.3	3.92E+04	9.79E-07	5.85E-03	6.30E-02
Deionised water	1.86E-07	0.113	6.59E-05	1.80E-05	6.08E-03	8.90E-03	12.10	4.42E-09	3.73E-06	1.14E-04
Total	2.42E-05	316.94	0.108	0.077	13.47	11.44	3.94E+04	9.86E-07	5.97E-03	0.063

Table B-5: Results for SOEC in Iceland per 1 kg Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Assembly of SOEC	6.76E-07	0.198	5.36E-04	4.29E-05	0.0632	0.0511	6.61E+01	9.13E-10	2.98E-05	2.09E-03
Electricity	4.08E-06	3.87	0.00136	8.29E-04	0.465	0.669	6.86E+02	2.03E-08	2.08E-04	2.64E-02
Deionised water	1.38E-07	0.0589	3.13E-05	1.01E-05	4.51E-03	6.67E-03	8.17	2.22E-09	1.83E-06	6.62E-05
Total	4.89E-06	4.13	0.00193	0.001	0.53	0.73	7.60E+02	2.34E-08	2.40E-04	0.029

Table B-6: Results for SOEC in European Union per 1 kg Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Assembly of SOEC	6.82E-07	0.324	0.000578	7.38E-05	0.0683	0.0553	8.16E+01	1.30E-09	3.21E-05	2.10E-03
Electricity	1.46E-05	209	0.0698	5.07E-02	8.79	7.46	2.59E+04	6.48E-07	3.88E-03	4.17E-02
Deionised water	9.36E-08	0.0569	3.32E-05	9.06E-06	3.07E-03	4.49E-03	6.10	2.23E-09	1.88E-06	5.74E-05
Total	1.54E-05	209.38	0.070	0.051	8.86	7.52	2.60E+04	6.52E-07	3.91E-03	0.044

Table B-7: Results for AEC in European Union per 1 kg Hydrogen using assumed 2030 electricity mix

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolyte	8.89E-08	0.0534	2.01E-05	1.12E-05	2.56E-03	0.00376	6.64	1.61E-09	1.22E-06	3.05E-05
Assembly of AEC	8.67E-08	0.531	0.000137	7.81E-05	0.08	0.0705	1.01E+02	2.33E-09	3.35E-05	9.50E-05
Electricity	1.78E-05	185.48	2.33E-02	1.43E-02	2.89	3.52	8696.66	7.18E-07	2.19E-03	3.41E-02
Deionised water	1.03E-07	0.0625	3.65E-05	9.95E-06	3.37E-03	0.00493	6.70	2.45E-09	2.07E-06	6.30E-05
Total	1.81E-05	186.00	0.024	0.015	2.98	12.30	15.50	3.61	8.85E+03	7.25E-07

Table B-8: Results for PEM in European Union per 1 kg Hydrogen using assumed 2030 electricity mix

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Assembly of PEM	2.05E-06	0.822	0.00245	0.000278	0.159	0.136	2.29E+02	2.36E-09	1.21E-04	2.25E-04
Electricity	1.88E-05	2.03E+02	2.49E-02	1.58E-02	3.09E+00	3.89E+00	9.49E+03	7.87E-07	2.40E-03	3.73E-02
Deionised water	1.86E-07	0.113	6.59E-05	1.80E-05	6.08E-03	8.90E-03	12.10	4.42E-09	3.73E-06	1.14E-04
Total	2.17E-05	204.00	0.028	0.016	3.33	13.50	17.10	4.01	9.80E+03	7.93E-07

Table B-9: Results for SOEC in European Union per 1 kg Hydrogen using assumed 2030 electricity mix

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Assembly of SOEC	6.82E-07	0.324	0.000578	7.38E-05	0.0683	0.0553	8.16E+01	1.30E-09	3.21E-05	2.10E-03
Electricity	1.29E-05	1.34E+02	1.69E-02	1.04E-02	2.10E+00	2.56E+00	6.26E+03	5.19E-07	1.58E-03	2.49E-02
Deionised water	9.36E-08	0.0569	3.32E-05	9.06E-06	3.07E-03	4.49E-03	6.10	2.23E-09	1.88E-06	5.74E-05
Total	1.36E-05	135.00	0.018	0.011	2.16	8.91	10.70	2.61	6.39E+03	5.23E-07

Table B-10: Results for AEC in European Union per 1 kg Hydrogen using assumed 2050 electricity mix

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolyte	8.89E-08	0.0534	2.01E-05	1.12E-05	2.56E-03	0.00376	6.64	1.61E-09	1.22E-06	3.05E-05
Assembly of AEC	8.67E-08	0.531	1.37E-04	7.81E-05	0.08	0.0705	1.01E+02	2.33E-09	3.35E-05	9.50E-05
Electricity	2.23E-05	30.88	5.44E-03	2.97E-03	1.49	2.53	2396.66	1.27E-07	5.27E-04	3.94E-02
Deionised water	1.03E-07	0.0625	3.65E-05	9.95E-06	3.37E-03	0.00493	6.70	2.45E-09	2.07E-06	6.30E-05
Total	2.25E-05	31.40	0.006	0.003	1.59	2.16	5.31	2.62	2.47E+03	1.33E-07

Table B-11: Results for PEM in European Union per 1 kg Hydrogen using assumed 2050 electricity mix

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Assembly of PEM	2.05E-06	0.822	2.45E-03	2.78E-04	0.159	0.136	2.29E+02	2.36E-09	1.21E-04	2.25E-04
Electricity	2.38E-05	3.37E+01	5.93E-03	3.28E-03	1.59E+00	2.79E+00	2.59E+03	1.40E-07	5.96E-04	4.32E-02
Deionised water	1.86E-07	0.113	6.59E-05	1.80E-05	6.08E-03	8.90E-03	12.10	4.42E-09	3.73E-06	1.14E-04
Total	2.66E-05	34.60	0.008	0.004	1.81	2.37	5.94	2.92	2.82E+03	1.46E-07

Table B-12: Results for SOEC in European Union per 1 kg Hydrogen using assumed 2050 electricity mix

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Assembly of SOEC	6.82E-07	0.324	5.78E-04	7.38E-05	0.0683	0.0553	8.16E+01	1.30E-09	3.21E-05	2.10E-03
Electricity	1.61E-05	2.22E+01	3.97E-03	2.14E-03	1.09E+00	1.84E+00	1.70E+03	9.18E-08	3.78E-04	2.89E-02
Deionised water	9.36E-08	0.0569	3.32E-05	9.06E-06	3.07E-03	4.49E-03	6.10	2.23E-09	1.88E-06	5.74E-05
Total	1.69E-05	22.60	0.005	0.002	1.16	1.56	3.34	1.89	1.79E+03	9.53E-08

Table B-13: Results for Liquefaction of Hydrogen produced by AEC in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	6.58E-06	6.61	0.0023	1.37E-03	0.81	1.11E+00	1170	3.80E-08	3.58E-04	0.0404
Electricity	1.70E-06	1.61	5.66E-04	3.44E-04	0.193	0.278	285	8.43E-09	8.65E-05	0.0110
Chiller	7.31E-07	0.0302	1.80E-05	1.25E-05	1.69E-02	0.0268	21.1	1.16E-10	1.51E-06	1.65E-04
Compressor	7.93E-08	0.00309	1.73E-06	1.26E-06	1.90E-03	3.02E-03	2.29	1.10E-11	1.58E-07	1.92E-05
Refrigerant	2.43E-11	1.66E-05	7.63E-09	2.38E-09	6.73E-07	1.12E-06	2.12E-03	1.61E-10	1.67E-09	9.16E-09
Truck	2.02E-07	0.401	8.63E-05	3.04E-05	1.14E-02	0.0131	14.6	4.48E-09	8.64E-06	9.73E-05
Tanker	2.49E-08	0.291	6.02E-04	7.13E-05	2.36E-03	0.0127	5.7	3.69E-09	3.31E-05	1.58E-04
Total	9.32E-06	8.945	0.0036	1.83E-03	1.031	0.283911	1.444	1498.7	5.49E-08	0.00049

Table B-14: Results for Liquefaction of Hydrogen produced by PEM in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	9.34E-06	7.47	0.0050	1.71E-03	0.96	1.28E+00	1410	4.12E-08	4.84E-04	0.0442
Electricity	1.70E-06	1.61	5.66E-04	3.44E-04	0.193	0.278	285	8.43E-09	8.65E-05	0.0110
Chiller	7.31E-07	0.0302	1.80E-05	1.25E-05	1.69E-02	0.0268	21.1	1.16E-10	1.51E-06	1.65E-04
Compressor	7.93E-08	0.00309	1.73E-06	1.26E-06	1.90E-03	3.02E-03	2.29	1.10E-11	1.58E-07	1.92E-05
Refrigerant	2.43E-11	1.66E-05	7.63E-09	2.38E-09	6.73E-07	1.12E-06	2.12E-03	1.61E-10	1.67E-09	9.16E-09
Truck	2.02E-07	0.401	8.63E-05	3.04E-05	1.14E-02	0.0131	14.6	4.48E-09	8.64E-06	9.73E-05
Tanker	2.49E-08	0.291	6.02E-04	7.13E-05	2.36E-03	0.0127	5.7	3.69E-09	3.31E-05	1.58E-04
Total	1.21E-05	9.805	0.0063	2.17E-03	1.185	1.614	1738.7	5.81E-08	0.0006	0.0556

Table B-15: Results for Liquefaction of Hydrogen produced by SOEC in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	5.39E-06	4.54	0.0021	9.70E-04	0.59	7.99E-01	836	2.58E-08	2.64E-04	0.0314
Electricity	1.70E-06	1.61	5.66E-04	3.44E-04	0.193	0.278	285	8.43E-09	8.65E-05	0.0110
Chiller	7.31E-07	0.0302	1.80E-05	1.25E-05	1.69E-02	0.0268	21.1	1.16E-10	1.51E-06	1.65E-04
Compressor	7.93E-08	0.00309	1.73E-06	1.26E-06	1.90E-03	3.02E-03	2.29	1.10E-11	1.58E-07	1.92E-05
Refrigerant	2.43E-11	1.66E-05	7.63E-09	2.38E-09	6.73E-07	1.12E-06	2.12E-03	1.61E-10	1.67E-09	9.16E-09
Truck	2.02E-07	0.401	8.63E-05	3.04E-05	1.14E-02	0.0131	14.6	4.48E-09	8.64E-06	9.73E-05
Tanker	2.49E-08	0.291	6.02E-04	7.13E-05	2.36E-03	0.0127	5.7	3.69E-09	3.31E-05	1.58E-04
Total	8.13E-06	6.875	0.0034	1.43E-03	0.812	1.133	1164.7	4.27E-08	0.00039	0.043

Table B-16: Results for Synthesis of Ammonia with Hydrogen produced by AEC in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	5.98E-06	6	2.08E-03	1.25E-03	0.73	1.01	1070	3.45E-08	3.25E-04	0.0367
Electricity	4.24E-07	0.402	0.000141	8.60E-05	0.0483	0.0694	71.1	2.11E-09	2.16E-05	0.00274
PSA: Nitrogen	2.30E-10	0.00313	1.31E-06	3.66E-07	7.38E-05	1.12E-04	0.254	5.54E-12	7.87E-08	1.08E-06
Chiller	1.79E-07	7.41E-03	4.41E-06	3.05E-06	0.00413	6.56E-03	5.17	2.84E-11	3.70E-07	4.03E-05
Compressor	5.88E-07	0.0229	1.28E-05	9.35E-06	0.0141	0.0224	17	8.19E-11	1.17E-06	1.42E-04
Refrigerant	4.46E-12	3.04E-06	1.40E-09	4.37E-10	1.23E-07	2.05E-07	3.88E-04	2.96E-11	3.05E-10	1.68E-09
Truck	1.19E-06	2.36	5.09E-04	1.79E-04	0.0673	0.0773	85.9	2.67E-08	5.09E-05	5.73E-04
Tanker	1.40E-07	1.64	3.39E-03	4.01E-04	0.0133	0.0711	32	2.08E-08	1.86E-04	8.91E-04
Total	8.50E-06	10.435	6.14E-03	1.93E-03	0.878	1281.4	8.43E-08	0.000585	0.0411	1281.4

Table B-17: Results for Synthesis of Ammonia with Hydrogen produced by PEM in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	8.49E-06	6.79	4.57E-03	1.55E-03	0.87	1.16	1280	3.75E-08	4.40E-04	0.0402
Electricity	4.24E-07	0.402	0.000141	8.60E-05	0.0483	0.0694	71.1	2.11E-09	2.16E-05	0.00274
PSA: Nitrogen	2.30E-10	0.00313	1.31E-06	3.66E-07	7.38E-05	1.12E-04	0.254	5.54E-12	7.87E-08	1.08E-06
Chiller	1.79E-07	7.41E-03	4.41E-06	3.05E-06	0.00413	6.56E-03	5.17	2.84E-11	3.70E-07	4.03E-05
Compressor	5.88E-07	0.0229	1.28E-05	9.35E-06	0.0141	0.0224	17	8.19E-11	1.17E-06	1.42E-04
Refrigerant	4.46E-12	3.04E-06	1.40E-09	4.37E-10	1.23E-07	2.05E-07	3.88E-04	2.96E-11	3.05E-10	1.68E-09
Truck	1.19E-06	2.36	5.09E-04	1.79E-04	0.0673	0.0773	85.9	2.67E-08	5.09E-05	5.73E-04
Tanker	1.40E-07	1.64	3.39E-03	4.01E-04	0.0133	0.0711	32	2.08E-08	1.86E-04	8.91E-04
Total	1.10E-05	11.225	8.63E-03	2.23E-03	1.019	1.407	1491.4	8.73E-08	0.0007	0.0446

Table B-18: Results for Synthesis of Ammonia with Hydrogen produced by SOEC in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	4.90E-06	4.13	1.93E-03	8.82E-04	0.53	0.727	760	2.35E-08	2.40E-04	0.0285
Electricity	4.24E-07	0.402	0.000141	8.60E-05	0.0483	0.0694	71.1	2.11E-09	2.16E-05	0.00274
PSA: Nitrogen	2.30E-10	0.00313	1.31E-06	3.66E-07	7.38E-05	1.12E-04	0.254	5.54E-12	7.87E-08	1.08E-06
Chiller	1.79E-07	7.41E-03	4.41E-06	3.05E-06	0.00413	6.56E-03	5.17	2.84E-11	3.70E-07	4.03E-05
Compressor	5.88E-07	0.0229	1.28E-05	9.35E-06	0.0141	0.0224	17	8.19E-11	1.17E-06	1.42E-04
Refrigerant	4.46E-12	3.04E-06	1.40E-09	4.37E-10	1.23E-07	2.05E-07	3.88E-04	2.96E-11	3.05E-10	1.68E-09
Truck	1.19E-06	2.36	5.09E-04	1.79E-04	0.0673	0.0773	85.9	2.64E-08	5.09E-05	5.73E-04
Tanker	1.40E-07	1.64	3.39E-03	4.01E-04	0.0133	0.0711	32	2.08E-08	1.86E-04	8.91E-04
Total	7.42E-06	8.565	5.99E-03	1.56E-03	0.680	0.974	971.4	7.30E-08	0.0005	0.033

Table B-19: Results for Synthesis of Methanol with Hydrogen produced by AEC in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	8.96E-06	9	0.0031	0.00187	1.10	1.51	1600	5.17E-08	4.87E-04	0.0550
Electricity	8.66E-07	0.839	2.96E-04	1.80E-04	0.101	0.145	149	4.41E-09	4.52E-05	5.72E-03
PSA: CO2	5.65E-07	0.474	1.72E-04	9.31E-05	0.0519	0.0643	79.2	4.68E-09	1.92E-05	1.76E-03
Chiller	2.84E-07	0.0117	6.99E-06	4.84E-06	0.00654	0.0104	8.2	4.50E-11	5.86E-07	6.39E-05
Compressor	1.08E-06	0.0422	2.36E-05	1.72E-05	0.026	0.0413	31.3	1.51E-10	2.16E-06	2.62E-04
Truck	1.64E-06	3.24	6.98E-04	2.46E-04	0.0925	0.106	118	3.62E-08	6.99E-05	7.87E-04
Tanker	1.98E-07	2.31	4.78E-03	5.66E-04	0.0187	0.1	45	2.93E-08	2.62E-04	1.26E-03
Total	1.36E-05	15.917	0.0091	0.0030	1.397	1.977	2030.9	1.26E-07	0.000886	6.49E-02

Table B-20: Results for Synthesis of Methanol with Hydrogen produced by PEM in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	1.27E-05	10.2	0.007	0.0023	1.3	1.74	1920	5.62E-08	6.59E-04	0.0603
Electricity	8.66E-07	0.839	2.96E-04	1.80E-04	0.101	0.145	149	4.41E-09	4.52E-05	5.72E-03
PSA: CO2	5.65E-07	0.474	1.72E-04	9.31E-05	0.0519	0.0643	79.2	4.68E-09	1.92E-05	1.76E-03
Chiller	2.84E-07	0.0117	6.99E-06	4.84E-06	0.00654	0.0104	8.19	4.50E-11	5.86E-07	6.39E-05
Compressor	1.08E-06	0.0422	2.36E-05	1.72E-05	0.026	0.0413	31.3	1.51E-10	2.16E-06	2.62E-04
Truck	1.64E-06	3.24	6.98E-04	2.46E-04	0.0925	0.106	118	3.62E-08	6.99E-05	7.87E-04
Tanker	1.98E-07	2.31	4.78E-03	5.66E-04	0.0187	0.1	45.2	2.93E-08	2.62E-04	1.26E-03
Total	1.73E-05	17.117	0.013	0.0034	1.607	2.207	2350.9	1.31E-07	0.0011	0.0702

Table B-21: Results for Synthesis of Methanol with Hydrogen produced by SOEC in Iceland per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	7.34E-06	6.19	0.0029	0.00132	0.80	1.09	1140	3.52E-08	3.60E-04	0.0428
Electricity	8.66E-07	0.839	2.96E-04	1.80E-04	0.101	0.145	149	4.41E-09	4.52E-05	5.72E-03
PSA: CO2	5.65E-07	0.474	1.72E-04	9.31E-05	0.0519	0.0643	79.2	4.68E-09	1.92E-05	1.76E-03
Chiller	2.84E-07	0.0117	6.99E-06	4.84E-06	0.00654	0.0104	8.19	4.50E-11	5.86E-07	6.39E-05
Compressor	1.08E-06	0.0422	2.36E-05	1.72E-05	0.026	0.0413	31.3	1.51E-10	2.16E-06	2.62E-04
Truck	1.64E-06	3.24	6.98E-04	2.46E-04	0.0925	0.106	118	3.62E-08	6.99E-05	7.87E-04
Tanker	1.98E-07	2.31	4.78E-03	5.66E-04	0.0187	0.1	45.2	2.93E-08	2.62E-04	1.26E-03
Total	1.20E-05	13.107	0.0089	0.00243	1.096	1.557	1570.9	1.10E-07	0.00076	0.0527

Table B-22: Results for Liquefaction of Hydrogen produced by AEC in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	2.25E-05	319	0.106	0.08	13.50	11.40	39600	9.93E-07	5.94E-03	0.0637
Electricity	6.04E-06	86.8	0.029	0.021	3.65	3.1	10800	2.69E-07	1.61E-03	0.0173
Chiller	7.31E-07	0.0302	1.80E-05	1.25E-05	0.0169	0.0268	21.1	1.16E-10	1.51E-06	1.65E-04
Compressor	7.93E-08	0.00305	1.72E-06	1.25E-06	0.0019	0.00302	2.29	1.11E-11	1.57E-07	1.91E-05
Refrigerant	2.24E-11	1.95E-05	9.10E-09	2.68E-09	5.95E-07	9.80E-07	0.0022	1.92E-10	1.97E-09	9.49E-09
Total	2.94E-05	405.8333	0.135	0.098	17.169	14.530	50423	1.26E-06	0.0076	0.081

Table B-23: Results for Liquefaction of Hydrogen produced by PEM in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	2.66E-05	349	0.119	0.08	14.80	12.60	43300	1.08E-06	6.58E-03	0.0697
Electricity	6.04E-06	86.8	0.029	0.021	3.65	3.1	10800	2.69E-07	1.61E-03	0.0173
Chiller	7.31E-07	0.0302	1.80E-05	1.25E-05	0.0169	0.0268	21.1	1.16E-10	1.51E-06	1.65E-04
Compressor	7.93E-08	0.00305	1.72E-06	1.25E-06	0.0019	0.00302	2.29	1.11E-11	1.57E-07	1.91E-05
Refrigerant	2.24E-11	1.95E-05	9.10E-09	2.68E-09	5.95E-07	9.80E-07	0.0022	1.92E-10	1.97E-09	9.49E-09
Total	3.35E-05	435.8333	0.14802	0.105614	18.4688	15.72982	54123.392	1.34932E-06	0.008192	0.087184

Table B-24: Results for Liquefaction of Hydrogen produced by SOEC in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	1.69E-05	230	0.077	0.06	9.75	8.28	28600	7.17E-07	4.30E-03	4.83E-02
Electricity	6.04E-06	86.8	0.029	0.021	3.65	3.1	10800	2.69E-07	1.61E-03	0.0173
Chiller	7.31E-07	0.0302	1.80E-05	1.25E-05	0.0169	0.0268	21.1	1.16E-10	1.51E-06	1.65E-04
Compressor	7.93E-08	0.00305	1.72E-06	1.25E-06	0.0019	0.00302	2.29	1.11E-11	1.57E-07	1.91E-05
Refrigerant	2.24E-11	1.95E-05	9.10E-09	2.68E-09	5.95E-07	9.80E-07	0.0022	1.92E-10	1.97E-09	9.49E-09
Total	2.38E-05	316.8333	0.10642	0.076914	13.4188	11.40982	39423	9.86319E-07	0.005912	0.065784

Table B-25: Results for Synthesis of Ammonia with Hydrogen produced by AEC in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	2.04E-05	290	0.10	0.07	12.20	2.04E-05	290	0.10	0.07	12.20
Electricity	1.51E-06	21.7	0.00724	0.00526	0.912	0.774	2690	6.72E-08	4.02E-04	0.004
Chiller	1.79E-07	0	4.41E-06	3.05E-06	0.00413	0.00656	5	2.84E-11	3.70E-07	0.000
Compressor	5.88E-07	0.0226	1.27E-05	9.27E-06	0.0141	0.0224	17	8.24E-11	1.16E-06	0.000
Refrigerant	4.11E-12	3.57E-06	1.67E-09	4.91E-10	1.09E-07	1.80E-07	0	3.52E-11	3.60E-10	0.000
Nitrogen	4.47E-10	0.00739	2.73E-06	1.40E-06	0.000247	0.000253	1	1.86E-11	1.55E-07	0.000
Total	2.27E-05	311.7374	0.10406	0.075474	13.13048	0.803234	3002.9474	0.096800067	0.070604	12.20451

Table B-26: Results for Synthesis of Ammonia with Hydrogen produced by PEM in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	2.42E-05	317	0.108	0.08	13.40	11.40	39400	9.86E-07	5.98E-03	0.063
Electricity	1.51E-06	21.7	0.00724	0.00526	0.912	0.774	2690	6.72E-08	4.02E-04	0.004
Chiller	1.79E-07	0	4.41E-06	3.05E-06	0.00413	0.00656	5	2.84E-11	3.70E-07	0.000
Compressor	5.88E-07	0.0226	1.27E-05	9.27E-06	0.0141	0.0224	17	8.24E-11	1.16E-06	0.000
Refrigerant	4.11E-12	3.57E-06	1.67E-09	4.91E-10	1.09E-07	1.80E-07	0	3.52E-11	3.60E-10	0.000
Nitrogen	4.47E-10	0.00739	2.73E-06	1.40E-06	0.000247	0.000253	1	1.86E-11	1.55E-07	0.000
Total	2.65E-05	338.7374	0.11526	0.082174	14.33048	12.20321	42112.947	1.05336E-06	0.006384	0.067914

Table B-27: Results for Synthesis of Ammonia with Hydrogen produced by SOEC in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	1.53E-05	209	0.070	0.05	8.86	7.52	26000	6.51E-07	3.91E-03	0.044
Electricity	1.51E-06	21.7	0.00724	0.00526	0.912	0.774	2690	6.72E-08	4.02E-04	0.004
Chiller	1.79E-07	0	4.41E-06	3.05E-06	0.00413	0.00656	5	2.84E-11	3.70E-07	0.000
Compressor	5.88E-07	0.0226	1.27E-05	9.27E-06	0.0141	0.0224	17	8.24E-11	1.16E-06	0.000
Refrigerant	4.11E-12	3.57E-06	1.67E-09	4.91E-10	1.09E-07	1.80E-07	0	3.52E-11	3.60E-10	0.000
Nitrogen	4.47E-10	0.00739	2.73E-06	1.40E-06	0.000247	0.000253	1	1.86E-11	1.55E-07	0.000
Total	1.76E-05	230.7374	0.07766	0.056074	9.790477	28712.947	7.18365E-07	0.004314	0.048414	28712.947

Table B-28: Results for Synthesis of Methanol with Hydrogen produced by AEC in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	3.06E-05	435	0.145	0.10500	18.40	15.6	53600	1.35E-06	8.09E-03	0.0868
Electricity	3.16E-06	45.3	1.51E-02	1.10E-02	1.91	1.62	5620	1.40E-07	8.40E-04	0.0090
PSA: CO2	1.19E-06	12.8	4.28E-03	3.09E-03	0.552	0.473	1600	4.24E-08	2.40E-04	0.0027
Chiller	2.84E-07	0.0117	6.99E-06	4.84E-06	0.00654	0.0104	8	4.50E-11	5.86E-07	0.0001
Compressor	1.08E-06	0.0422	2.36E-05	1.72E-05	0.026	0.0413	31	1.51E-10	2.16E-06	0.0003
Total	3.63E-05	493.1539	0.164411	0.119112	20.89454	17.7447	60859.49	1.5326E-06	0.009173	0.098846

Table B-29: Results for Synthesis of Methanol with Hydrogen produced by PEM in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	3.63E-05	475	0.162	0.11500	20.20	17.10	59100	1.48E-06	8.97E-03	0.0950
Electricity	3.16E-06	45.3	1.51E-02	1.10E-02	1.91	1.62	5620	1.40E-07	8.40E-04	0.0090
PSA: CO2	1.19E-06	12.8	4.28E-03	3.09E-03	0.552	0.473	1600	4.24E-08	2.40E-04	0.0027
Chiller	2.84E-07	0.0117	6.99E-06	4.84E-06	0.00654	0.0104	8	4.50E-11	5.86E-07	0.0001
Compressor	1.08E-06	0.0422	2.36E-05	1.72E-05	0.026	0.0413	31	1.51E-10	2.16E-06	0.0003
Total	4.20E-05	533.1539	0.181411	0.129112	22.69454	19.2447	66359.49	1.6626E-06	0.010053	0.107046

Table B-30: Results for Synthesis of Methanol with Hydrogen produced by SOEC in the European Union per 1 kg of Hydrogen

	ADP element	ADP fossil	AP	EP	FAETP	HTP	MAETP	ODP	POCP	TETP
Electrolysis	2.30E-05	314	0.106	0.07610	13.30	11.30	39000	9.77E-07	5.86E-03	0.0658
Electricity	3.16E-06	45.3	1.51E-02	1.10E-02	1.91	1.62	5620	1.40E-07	8.40E-04	0.0090
PSA: CO2	1.19E-06	12.8	4.28E-03	3.09E-03	0.552	0.473	1600	4.24E-08	2.40E-04	0.0027
Chiller	2.84E-07	0.0117	6.99E-06	4.84E-06	0.00654	0.0104	8	4.50E-11	5.86E-07	0.0001
Compressor	1.08E-06	0.0422	2.36E-05	1.72E-05	0.026	0.0413	31	1.51E-10	2.16E-06	0.0003
Total	2.87E-05	372.1539	0.125411	0.090212	15.79454	13.4447	46259.49	1.1596E-06	0.006943	0.077846