MSc Program
Environmental Technology & International Affairs

Hydrogen as a Potential Renewable and Secure Source for Energy Supply

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 12.06.2019

Affidavit

I, **MARCELA JIMENA LOZANO LUNA, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "HYDROGEN AS A POTENTIAL RENEWABLE AND SECURE SOURCE FOR ENERGY SUPPLY", 73 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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ABSTRACT

The concern for energy security dates from early ages, from as something as simple to the implementation of fire to produce heat, to nowadays, as the most complex prototypes of plasma producing technologies, as an endless source of energy. However, the assurance of energy has also made many cultures see it not only as a source to cover basic human needs, but also as a symbol of progress, stability and influence.

Country development relies heavily on its energy supply. Energy can both power war and peace. As an example, in the eve of World War I, as Daniel Yergin mentions in his paper Ensuring Energy Security, energy security was crucial not only for creating weapons but most importantly for creating transport, such as cars, trains, aeroplanes and ships. In times of peace, energy becomes crucial where you need to pump the industry steadily without interference.

The stable flux of energy can sustain dense operations for developed countries. Another author, Löschel, defines in his article that Energy Security as the production, distribution and the final demand is critical in the development of a country. Now more than ever we must ensure energy efficiency. There are a lot of technologies environmentally friendly and renewable, but we need to focus on the security to supply it. Unfortunately, renewables are far less secure, as most of them only produce very intense energy for a small amount of time or they are far away from where it is needed. Renewables at this stage-point are more costly to bring them into the grid than oil/coal technology. Between several renewable energies, there is one that sounds to be consistent with promoting energy security and clean energy: hydrogen. Hydrogen is readily available, convenient to transform from different primary energy sources and has the highest energy content of any common fuel by weight. Some of their downsides are not cost-effective to store, volatile and metal embrittlement inducer.

Nevertheless, this should not push this energy storage element aside. Gasoline, diesel and natural gas are also flammable and require chord storage units with other element inducers characteristics. These hydrocarbon fuels also have their particular expenses, damages and wear and tear characteristics that have been corrected due to a massive infrastructure implemented.

The most pressing issue in the world today is to change the idea on the mind of consumers and stakeholders on the high cost and low efficiency of hydrogen and the great potential to back sustainable energy and the economy of countries through the already implemented infrastructure. What we need at this point is policy that can make hydrogen economy an easier stage to follow into the energy producing market.

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LIST OF ABBREVIATIONS

CCS	Carbon Capture and Storage
CH4, CH_4	Methane
CO2, CO_2	Carbon Dioxide
ES	Energy Security
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GHG	Greenhouse Gases
H2, H_2	Hydrogen
HE	Hydrogen economy
HLT	Heavy Load Trucks
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JAEA	Japan Atomic Energy Agency
KAERI	Korean Atomic Energy Research Institute
LH2	Liquid Hydrogen
NGOs	Non-Governmental organisations
O&G	Oil and gas
PEM	Proton Exchange Membrane or Polymer Electrolyte Membrane
PV	Photovoltaic
RES	Renewable Energy Systems
RO	Reverse Osmosis
SMR	Steam Methane Reforming
USA	United States of America
VHTR	Very High-Temperature Reactor
WNA	World Nuclear Association

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CHAPTER 1. INTRODUCTION

There is no consensus between governments, industry and scientific community concerning the decrease on greenhouse emissions and high production of energy. The question remains if we can power our future steadily and progressively with limited environmental impact. Our society so far requires high and constant amounts of energy to fuel our economies. The following study will do a research to find alternative ways of producing it without harming the environment and transition to a low carbon economy. There is a possibility to provide power in a secure, reliable and sustainable way. It was Jules Verne who in his book "The Mysterious Island" mentioned: "*water will one day be employed as fuel, that hydrogen and oxygen of which it is constituted will be used*." (Verne 1874)

In the report of the Intergovernmental Panel on Climate Change (IPCC) published in 2013 mentioning anthropogenic-driven climate change through Greenhouse Gas (GHG) emissions. Especially concentration of gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) exceed the concentration range in ice cores in the past 800,000 years. (Stocker 2013) It is necessary, more than ever to take measures and propose an integrative action to decrease those emissions.

This thesis aims to bring light into a new way of producing more energy and revive hydrogen technology as a potential energy carrier and source of fuel as an alternative use for energy and a possible source for energy security.

This technology can produce energy differently. The purpose of this work is to propose hydrogen and Fuel Cells (FCs) to promote the hydrogen economy. Hydrogen can link renewable sources, storage and still be sufficient to power the mobility sector and diminish anthropogenic emissions to the environment. This energy carrier, together with FCs can back the power and distribute uniformly into the infrastructure that we already have, becoming a link from other non-renewable (such as oil, coal and gas) and renewable (like biomass, photovoltaics, wave and wind turbines) primary sources of energy through hydrogen.

The thesis will be constructed in the following way. The first chapter will describe the relevance between Hydrogen economy, Energy Security and the link between commonly used primary energy sources and renewable energy systems (RES). This section states the framework, methodology and the research questions.

In the second chapter, mainly three types of productions will be described: steam methane reforming, pyrolysis and gasification, and electrolysis. The state of the art of hydrogen and Fuel Cells can be found in this section.

In the third chapter, further elaboration will be made towards the energy market as a context and some examples of how hydrogen economy is considered together coupled with renewable technology. Hydrogen Economy will be defined; this can lead to a better understanding of the proposition of this study. The interconnectedness of carbon based and RES using hydrogen as a vector of energy will allow us to implement a secure supply of energy and at the same time getting us far away of the fossil fuel consumption.

To make a clear connection of the opportunities that hydrogen together with Fuel cells have, the reader will find end-use cases in chapter 4. This element will show in the cases on islands that it can help secure energy and couple renewable technologies to reduce carbon dioxide (CO_2) emissions. Briefly cases in Japan, the United States of America, and the European Union will be used to illustrate the current state of this technology.

Finally, in the last chapter, there will be a brief panorama of the feasibility of hydrogen in the near future results, the outlook and some recommendations for implementing the Hydrogen Economy. It will also be discussed how hydrogen could be produced with renewable technology (photovoltaic, wind turbines, hydropower) thus harnessing green hydrogen.

1.1 MOTIVATION

In our world, today, we face the three main challenges. The first being, non-renewable fossil fuels (oil, coal and gas) because of their scarcity and pollutant emissions when burned. The second is the security of energy, "*this vast majority was not viewed with disruption and terrorism in mind, but its operations now have to be managed with that continuing danger in view*" (Yergin, Energy Security and Markets 2013). The third is the energy growth demand and supply, as mentioned before, China and India are in the leading positions requiring more energy for their development. This is an immediate process where they cannot stop, and they need a lot of energy: stable and continuous.

Also, in Challenges and opportunities: Energy Security Prof. Xu Yi-Chong mentions that the following "three issues –energy security, climate change and development – presents serious challenges to governments, businesses, individuals and the international community" (Xu 2011). Meaning that the challenge to change from fossil fuels to renewables is costly; other organisations see this change as non-achievable as the percentage of efficiency in renewable is still low and unstable. Renewables by itself will not be the entire solution for switching into a source of green energy free of pollutant emissions causing global warming. (Xu 2011)

The research on securing energy with a different element, as hydrogen today is more critical than ever. Indeed, oil and its derivatives may not be running out as quickly as expected as new sources are being discovered; it is also true that oil is being found in remote and difficult places to drill, e.g. Polar Regions and deep waters in oceans. (Ledenko, Velic and Karasalihovic-Sedlar 2018). Just as an example, the Arctic has been estimated to have 90 billions of barrels of oil deposits beyond the Arctic Circle. This represents 6 % of the world total known oil reserves. This is only for oil, for natural gas 1,669 trillion cubic feet representing the 24.3 % of the world's known gas reserves could potentially be harnessed. (Michaud 2014) So, if oil, as one of the main primary energy sources, is still available the reason to replace it or to try to hinder its use it's mainly the polluting emissions and the growing energy demand. The emissions of fossil burnings produce discharges that impact global warming.

Why do we need to act now? Because there is an imperious need to stop climate change. There is a need to limit global warming to 2 °C. Because of that, according to the Hydrogen Council, we need to increase the share of renewables from 23 % in 2015 to 68 % by 2050. ((Hydrogen Council 2017) p.58)

As well, the World Energy Council in 2016 mentions that the current source of energy comes mainly from oil – 33 %, coal – 29 %, natural gas – 24 %, renewable energy – 10 % and from nuclear – 4 %. That is why it is essential to increase our share, promoting sources of energy that can decrease CO_2 emissions together with other GHGs.

Additionally, the EU has mentioned its intention to reduce their CO_2 emissions by 50 % by 2030. The EU and G-8 countries have agreed stricter climate policies and pledged to lower their CO_2 emissions by 50 % by 2050. New technologies and new ways to harness energy need to be implemented so this can happen and GHG emissions can be lowered.

Writing on hydrogen and fuel cells (FCs) is vital as technology to harness is vast. Research methods on increasing fuel cell efficiency are increasing; practical cases are numerous, especially in the mobility sectors and recently governments and international organisations are producing laws and incentives to promote the research, efficiency and its uses.

Considering hydrogen as an alternative energy source and storage is not something new, this theme has come and goes. The negative aspects: efficiency when coupled to other sources, cost in storage and cost of fuel cell production. Some heavy car or oil industries are considering it because it comes out from oil, coal and gas but also can be produced by renewable energy systems (RES). H_2 offers a wide array of production possibilities as it is a very abundant element. The critical issue is how we can protect the energy production that can align with the energy demand of the world.

1.2 FRAMEWORK

Hydrogen, as an element, can be used and harness in many ways. It is widely known for its use in the aerospace industry to power rockets or a negative connotation as a source of bombs. In this study, the state of the hydrogen and fuel cells will be described, and it is closely linked. There are other types of usage, but this work will concentrate on the following. This work will base its findings built on the knowledge as hydrogen is an energy carrier and an energy source. The current and future production of this element, together with the process of electrolysing through fuel cells, will also be discussed. It is essential to consider that continuous research on fuel cells and electrolysis alone are being done and more effective ways are being discovered every day. The present study is based on a regularly used Proton Exchange Membrane (PEM) fuel cells (FCs).

Additionally, considering the actual policies, a closer look will be done, especially on those international organisations promoting hydrogen together with the leading countries trying to develop it. As a final note, there are more and continuous programs for developing hydrogen and fuel cells. The present study will not be able to cover the G20 Summit in Kyoto, Japan on June 2019 where the mentioned countries in the present study will meet and expose their plans to further expand the use of hydrogen and fuel cells and promote the hydrogen economy. Primarily this is the case for Japan that has publicly mentioned that they want to become a hydrogen economy in the next years. It is advised to check the further steps the G20 will follow towards these strategies, programs and their agreements in the matter.

1.3 RESEARCH METHOD

The method that will be used for the following Thesis will be through literature review, case studies using country comparison and reports from institutions applying this technology.

The justification of this study is that there is much ongoing research and development in both scientific and industry approach.

The research plan is the review of literature, behaviour and perception on hydrogen and fuel cells and Hydrogen Economy (HE). When using case studies, the present study wants to get a more in-depth look into the sector. The case review will be in both comparative approaches and research projects. Besides, there will be a discussion in the conclusion section of the theory and descriptive material.

By this, this research assumes that hydrogen will be a plausible way to get a renewable and clean technology for the immediate future. The following questions will help to answer current hydrogen usage limitations and its lack of popularity even though proved their efficiency compared to, in the case of the mobility sector, the internal combustion engine (ICE) and, in the electricity sector, the oil industry.

1.4 RESEARCH QUESTION

The present study drives to the research question. As mentioned before, hydrogen and fuel cells are not a new technology. They are technologies that have coexisted since 1800 and 1970s respectively. In the importance to act now and apply different type of mainstream technologies, it is essential to consider those that could not only produce energy in a steady way but also with a low carbon footprint to diminish the effect of global warming, caused by anthropogenic sources. Then the questions that arise are the following:

- Can energy demand be met with a Hydrogen Economy mindset?
- What are the costs factors impeding Hydrogen Economy possible?
- Is it possible to efficiently overcome these cost factors in the short or long term?

These three questions are based on the basis if the hydrogen and fuel cells will be able to meet the demand to make hydrogen economy possible. The second is to assess the cost related to the production of hydrogen and fuel cells to make it a possibility. Moreover, the last research question is associated with the feasibility to overcome these factors and in a determined period. The time is essential to consider as there were commitments to limit the carbon emissions by countries mostly by 2030, according to the Kyoto Protocol. Some experts think this will not be possible, but maybe the application of other types of technologies combined with renewables can be the solution.

CHAPTER 2. HYDROGEN PRODUCTION

2.1 WHAT IS HYDROGEN?

Hydrogen is one of the lightest and abundant elements all over the universe. It is the first element in the periodic table of elements, represented by the symbol H but most commonly expressed as H2 or H_2. Most of the time is presented in the gas form. Similarly, like water, it is odourless, tasteless and colourless. Additionally, it is a non-toxic, non-metallic and highly combustible diatomic[1] gas. (Enghag 2008)

In our planet, hydrogen can be easily found, but it is commonly bounded together with other elements. Hydrogen can bond quickly with oxygen and carbon forming water (H_2O), hydrocarbons like methane (CH_4) and other minerals.

It was initially discovered by Cavendish in 1776 but named by Lavoisier in 1783. One of the exciting aspects of this element is that when it was found when burnt, it produced water. Therefore, when named by Lavoisier, he described its characteristics in Greek: *hydro* – water, *genes* – forming; it means water maker or water forming. This characteristic bounding it to water is the main reason linked to produce energy cleanly without producing carbon emissions. Hydrogen has many properties in several industry branches. Some examples of their different uses are rocket fuel and as fertilizers (ammonia producer). This element is also used for refining fossil fuels and in the food industry (hydrogenating butter to make margarine and recently for making super hydrating water). Another use of Hydrogen is its use in gas leakage method. This is both an advantage and a disadvantage. Hydrogen can embrittle many metals, which makes it challenging to use it in pipelines and storage in metal containers. (Los Alamos National Laboratory for the U.S. Department of Energy's NNSA 2016)

Hydrogen Greek definition is essential as it is one of its most important traits for this study, the possibility to produce water as a by-product of combustion in the mobility and electricity sector, which is one of the leading industries releasing GHG and carbon emissions to the atmosphere greatly influencing the global warming.

It is important to state: hydrogen can be both used as a source of energy as a storage device and as fuel. Hydrogen *per se* is not a primary source of energy as oil, coal or natural gas. As previously mentioned, hydrogen on earth is scarcely found, and when produced, it needs to

[1] Diatomic elements or molecules are those two bonded together with the same or different element. The most well-known homonuclear diatomic elements are the following: Hydrogen, Oxygen, Nitrogen, Fluorine, Chlorine and Bromine. Most of these elements are gases at room temperature with exception of Bromine which is liquid.

be taken from other compounds to become an energy source. That is why is called an energy carrier, that behaves very much like electricity, and that can store energy, and when the energy is needed, it can be released through the conversion of the fuel cell or internal combustion engines. Hydrogen can be used to store energy from renewable sources such as photovoltaic cells, wind turbines, tidal and wave turbines and biomass. This could help connect the problem these renewable sources have with its intermittency. Hydrogen can be produced when these renewable energy systems (RES) are producing too much electricity (usually over the summer) and then stored long-term, so they can be used when needed (in winter and also use the heat they produce when hydrogen converted to electricity again).

Once it is produced, it can be used as fuel, hydrogenating agent, reactant, tracer gas[2] or, as in past decades to lift balloons (as H2 is lighter than air), like in the Zeppelin's case. But most importantly hydrogen can be used as fuel for the transportation and industry sectors, heat and in ICEs, boilers or turbines.

Lastly, hydrogen has the highest energy content of any conventional fuel by weight (three times more than gasoline). On the other hand, because of its gas form, it takes a lot of space as well.

Nowadays, most hydrogen production is either by steam methane reforming (SMR) or as a by-product from nuclear reactors or biomass. The 70 million tonnes of H_2 is mainly for industrial settings, primarily in the chemical industry and for refining oil. (Fukui, Lucchese and Bennett 2019) A small 2 % is destined as fuel or energy storage. (Ewan and Allen 2005) This will be explored in the next section.

2.2 HOW HYDROGEN IS PRODUCED?

Hydrogen can be produced from several sources. In the following chart, different technologies, the input, the source and the production process percentages are described. Some of these technologies will be described in this study, some other will not as they require further study and are still in their infancy. Some technologies are labelled as renewable or non-renewable according to their input. This table was used as a summary of several studies cited in the sources.

[2] A tracer gas is used in a test to detect gas leakages. (Wikipedia 2019)

Table 1. Hydrogen technologies, input, resources and percentages.

Technology	Input	Resource	Production Process percentage
1. Thermal - Steam Methane Reforming (SMR) - Gasification - Thermo chemical	Natural gas, Ethanol Biomass Uranium (Chen, 2018)	Non renewable Renewable Non renewable	96 %
2. Electrochemical - Electrolysis - Photo-reduction	Water, Biomass, Sunlight, Wind Water	Renewable Renewable	4 %
3. Biological - Direct and Indirect Bio photolysis - Dark fermentation	Green algae or cyanobacteria Anaerobic microorganisms	Renewable Renewable	Still under experimentation
Source: Percentages based on (Ewan and Allen 2005), (Zhang, et al. 2016), (Parthasarathy and Narayanan 2014).			

According to previous Table 1, most of the production comes from the oil industry so far accounting to 96 %. Where this 96 % is constituted from natural gas- 50 %, liquid hydrocarbons – 30 % and from coal – 18 %. The most used method is Steam Methane Reforming (SMR) or Steam Reforming. (Ewan and Allen 2005) (Zhang, et al. 2016) (Parthasarathy and Narayanan 2014) (World Nuclear Association 2019). Highlighted in green, are the processes considered to be renewable, namely gasification from biomass and electrolysis and photo-reduction from water, biomass, sunlight, wind and water.

These percentages of production have remained the same for several decades, Tessie du Motay and Marechal first described the chemical process in 1868 and then implemented in 1930 yielding methane, naphtha and fuel oil. We could sum up the reaction in the following way:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H^0_{298} = 206.2 \text{ kJ/mol} \qquad (1)$$

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \qquad \Delta H^0_{298} = 165 \text{ kJ/mol} \qquad (2)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^0_{298} = -41.2 \text{ kJ/mol} \qquad (3)$$

Where this reaction is highly exothermic. (Barelli, et al. 2008)

This is a mature technology and so far, very efficient since the SMR producing Hydrogen with 99.99 % of purity at a competitive cost of USD 5 /kg on average in the USA. ((Hydrogen Production Tech Team Roadmap 2017)p.13)

In the next figures of the Department of Energy (DOE) of the US ((Hydrogen Production Tech Team Roadmap 2017) p. 13) we can see how it is expected that the cost performs. The cost of producing hydrogen ranges between USD 5 and USD 8 for the projections made between 2005 and 2015. Still, the price has continued to bet between those ranges. Because there have been not many changes in the amount of FCEV sold and particularly in the state of California, the price is subsidized by the state government.

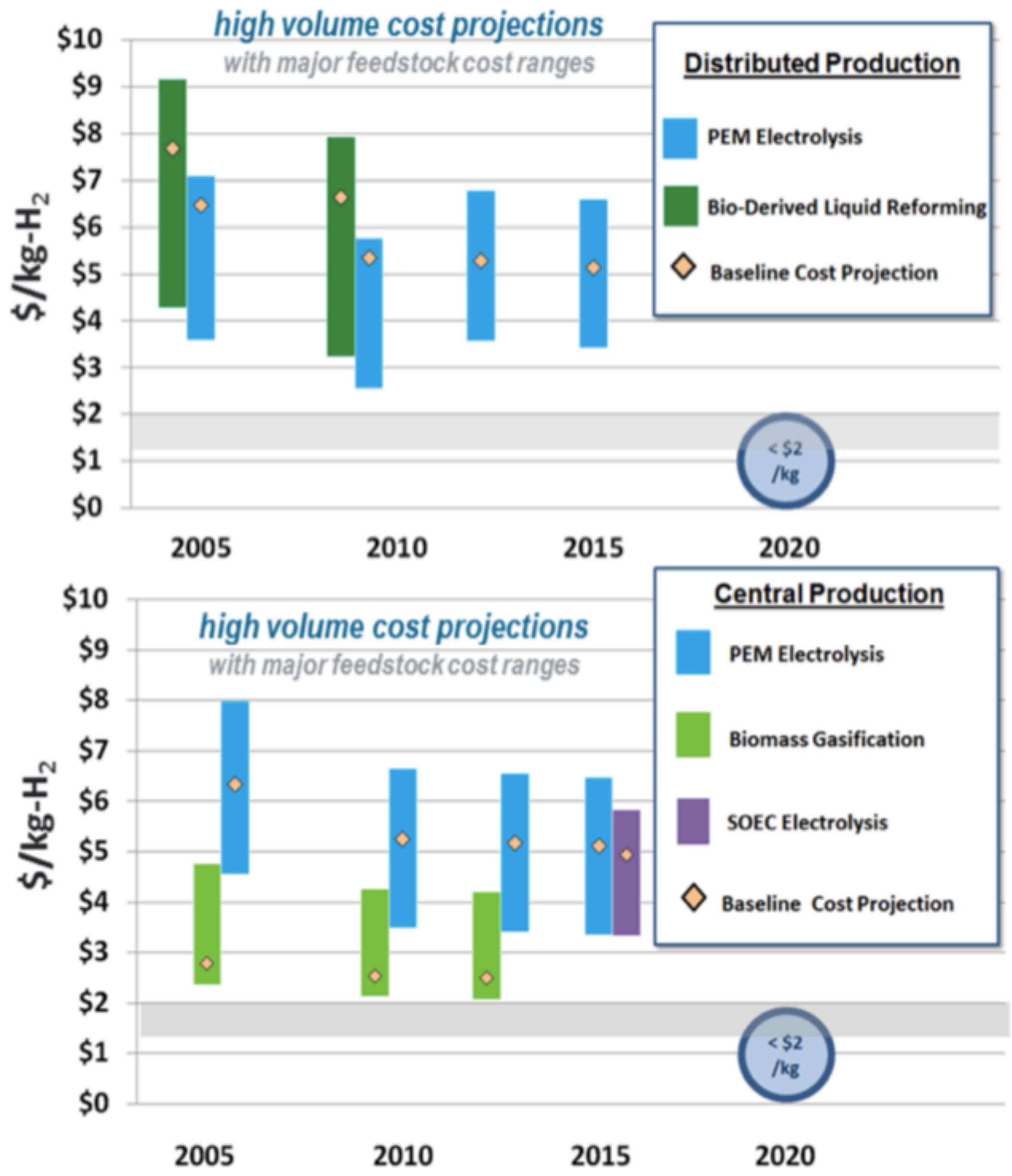

Figure 1. Cost range cost of hydrogen production costs according to DOE USA.
DOE = Department of Energy USA.
Notes: Un-dispensed and untaxed, reported in USD/kg H_2 (where 1 kg H_2 roughly equals 1 gge) including feedstock and capital cost variability for high volume production12. The grey shaded area represents the cost of hydrogen when produced by SMR for natural gas prices ranging from USD 2-7.50 MMbtu. Costs shown in 2007 USD.
Source: Hydrogen Production Technical Team Roadmap Report. ((Hydrogen Production Tech Team Roadmap 2017) p. 13)

Besides, according to the IEA, the price of hydrogen could be considered the same on average so far according to this graph presented by Cédric Philibert from IEA on the conference of “Producing ammonia and fertilizers”. It was mentioned that:

“*Where solar or wind resources are excellent, the cost of electricity from solar or wind power plants could be at or below USD 30/MWh, as suggested by the prices recently announced for new-built wind farms in Morocco and solar plants in Chile and Dubai. At such prices and with sufficient load factors, the cost of hydrogen would not exceed USD 2/kg and compete with SMR.*

Cédric Philibert, IEA, Producing ammonia and fertilizers: new opportunities from renewables*, May 16, 2017.”* (Brown 2017)

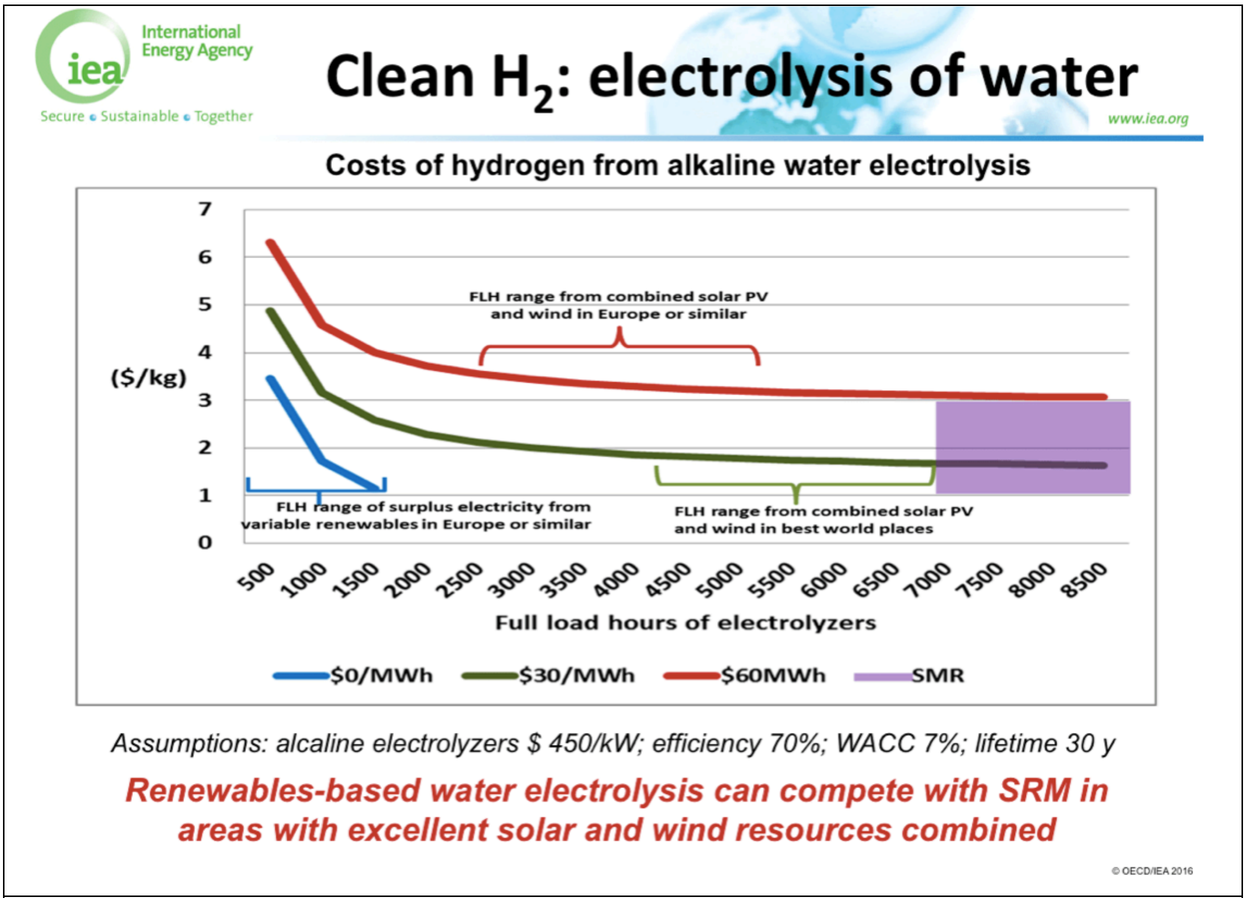

Figure 2. Cost of hydrogen from alkaline water electrolysis.
Source: Cédric Philibert, IEA, Power to Ammonia conference, Rotterdam, 19 May 2017. (Brown 2017)

Hydrogen, as mentioned in the previous section, is mainly used on inside industrial settings, primarily for making nitrogen fertilizers. In the oil industry is heavily used, as part of the purification process of low-grade crude oil (like heavy crude and tar sands). “World consumption is 50 million tonnes per year, growing at about 10 % per year” (Hore-Lacy 2009).

The SMR process hasn't changed for decades as it is one of the most efficient and cheapest ways to produce Hydrogen with a purity of 99.99 %. There is a great interest from oil companies to continue using Hydrogen. It could be a backup process as Hydrogen is made from Natural Gas and can also produce Syngas (synthetic gas), a mixture of carbon monoxide (CO) and hydrogen (H_2). Previous reports from the International Energy Agency have prognosticated that when oil runs out or becomes too expensive to use as fuel, natural gas together with hydrogen could substitute it. That is why many oil and gas companies are interested in H_2 production - using the gas pipes to transport hydrogen. At these moments, experiments are on the making to see if current gas pipes could support the embrittlement characteristic of hydrogen.

Additionally, hydrogen from the oil and gas (O&G) industry could be produced with less CO_2 production by using the Carbon Capture and Storage (CCS) method.

A second way to produce hydrogen is as a by-product from Nuclear Power Plants. The Very High-Temperature Reactor (VHTR) design within the Generation IV of Nuclear reactors type could be used as Hydrogen producer through cogeneration. (IAEA. Nuclear Hydrogen Production. 2019) Hydrogen is produced thanks to the high heat the power plants generate and the electricity they produce. The 4th Generation Nuclear Power Plants plan to produce hydrogen as a by-product and used in other industries, mainly the chemical industry. Three central Asian countries are researching this possibility, mainly Japan, South Korea and China. A particular case is Korea, where the Korean Atomic Energy Research Institute (KAERI) has submitted a design of a VHTR. This type of reactor plans to produce 30,000 tonnes of Hydrogen per year with the help of 300 MW modules, construction began in 2016 and is expected to start operations next year. In Japan, the Japan Atomic Energy Agency (JAEA) set a Generation IV reactor to see the possibility to produce hydrogen through the iodine-sulphur process. They manage to be successful, and by January 2019, they created it "over 150 hours of continuous operation." (World Nuclear Association 2019).

Finally, it is worth to mention the prices that these two processes yield hydrogen. According to the World Nuclear Association (WNA), the prices are the following: "At 2003 prices, steam reforming of natural gas yields hydrogen at USD 1.40/kg, and sequestration of the CO_2 would push this to USD 1.60/kg. Such a plant could produce 800 tonnes of hydrogen per day, "enough for 1.5 million fuel cell cars" (@1 t/day for 1800 cars). JAEA aims to produce hydrogen at less than USD 3/kg by about 2030 with VHTR. (World Nuclear Association 2019)" The WNA makes a reflection that even though the prices are cheap new, the environmental source is not cheap as they are still in the research and development process.

The 4 % remaining percentage of production is mainly done by electrolysis producing hydrogen expensively way and depending on the technology used with a low purity percentage. The main problem is the low pressure provided that generates most of the hydrogen produced lost in the process. In the following section on electrolysers, more information will be written concerning its state-of-the-art and efficiencies.

The Fig. 3 shows the multiple ways to produce it, dividing it among Biomass, Hydrocarbons, Electricity and Solar and linking it to green and brown Hydrogen and its CO_2 emission.

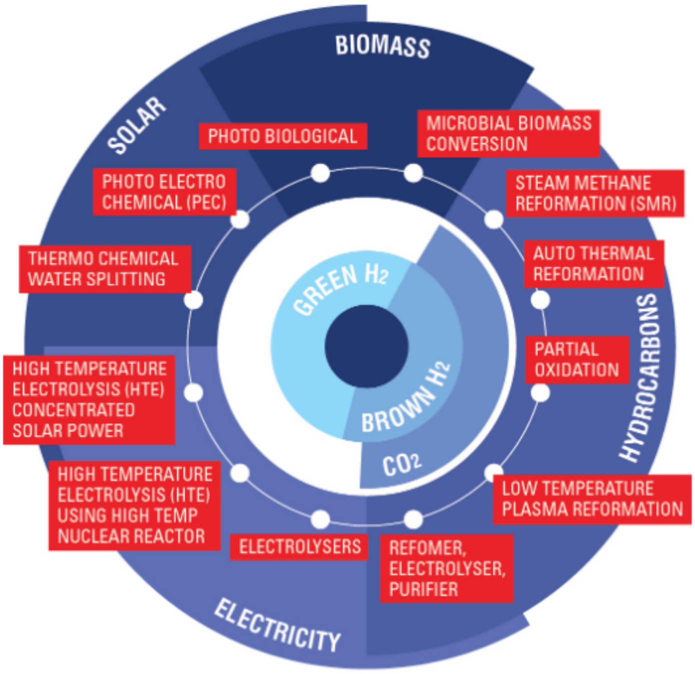

Figure 3. Hydrogen Production types.
Source: (CMB nv. Hydroville 2019)

It is essential to divide hydrogen into three colours as the industry mentions and defines it. Even though there is no formal definition of "green" hydrogen yet. According to IRENA, the meaning is endorsed by the CertifHy project by the FCH JU. ((IRENA 2018) P.15)

- Brown/Grey Hydrogen. When Hydrogen is produced from fossil fuels, and therefore the process creates carbon emissions.
- Blue Hydrogen. A climate-neutral way to produce is thanks to carbon capture and storage (CCS).
- Green Hydrogen. This will be the one that comes from renewable technologies such as photovoltaic, wind turbines, hydropower, biomass and even waste collection.

An important method is Carbon Capture and Storage (CCS), as previously mentioned. CCS is the method that can be applied after fossil fuels are burned (oil and coal) and then CO_2 is captured by then sending it through pipes to oil or coal empty deposits or salt mines through existing pipes avoiding the release of this critical pollutant into the atmosphere.

Figure 4 shows a visual model of how CCS could operate in power plants and CO_2 transportation and storage.

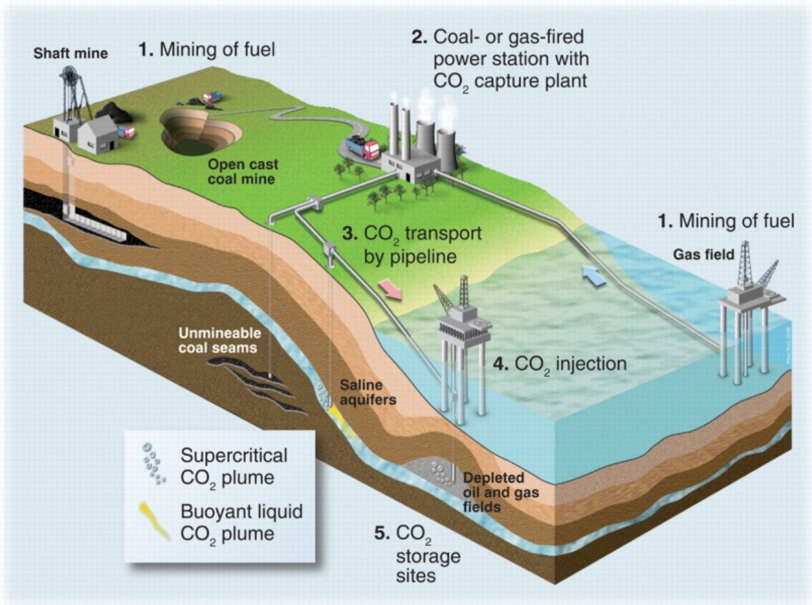

Figure 4. Diagrammatic representation of the life-cycle chain of fossil fuel use.
Source: (Haszeldine 2009)

Furthermore, hydrogen once being separated through methods mentioned before can be transported in individual pipelines (as mentioned before it can embrittle certain types of metals), storage in special tanks (usually compressed in 200 bar in tube cylinders) or cooled down to become liquid hydrogen. The reason to compress hydrogen is not only it is the lightest element on the periodic table, but "*also has a very low energy density per unit volume.*" ((Acar and Dincer 2018) p.590). This means that this light element can occupy a lot of space in its gas form, so it needs to be compressed to take the most energy out of it. This can be regarded in advantageous and disadvantageous ways. To occupy volume could be beneficial to store hydrogen in salt caverns, in depleted natural gas or oil fields or feeding directly into already existing natural gas pipelines. (Harasek 24-May-2019) (Haszeldine 2009)

In Fig. 5 we can see the energy density of Hydrogen compared to other fuels. In the graph we can see that liquid hydrogen and pressurised hydrogen at 200 bar are the two states with the highest specific energy, having around 32.5 kWh/Kg. In the other hand, Diesel, petrol and coal have the highest content kWH/L per specific energy. So compared to weight hydrogen is richer but compared to litre, the fossil fuels rank the highest.

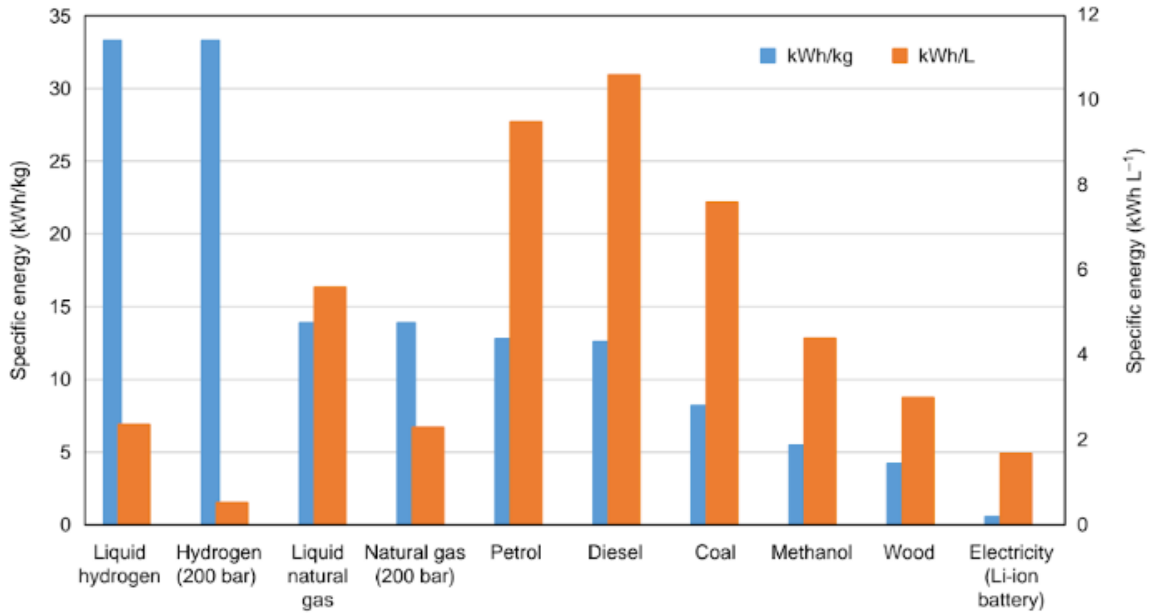

Figure 5.Energy density.
Source: ((Acar and Dincer 2018) p. 590)

Many studies are trying to improve the storage of hydrogen, through the liquid and solid states so it can become easier to transport and to use. Typically, 1 kg of hydrogen at 1 bar pressure occupies a space of 11 m^3. Most commonly it is stored at 200 Pa high-pressure gas cylinders. Three main drawbacks of hydrogen are related to its storage as its low density, leakage by diffusion and cyclic stability. Liquid hydrogen means it needs to be cooled down at 21.2 K, its volumetric density at this stage is at 70.8 kg / m^3. Better liquefaction process improving energy efficiency are under research. (Zuettel, et al. 2010)

Some of the future routes to produce green hydrogen can come from different sources that can help a safer transition to renewables and fewer pollutant emissions to the environment.

In Fig. 6 we can see what the IAEA produced and envisioned as a possibility of how the hydrogen technologies could evolve.

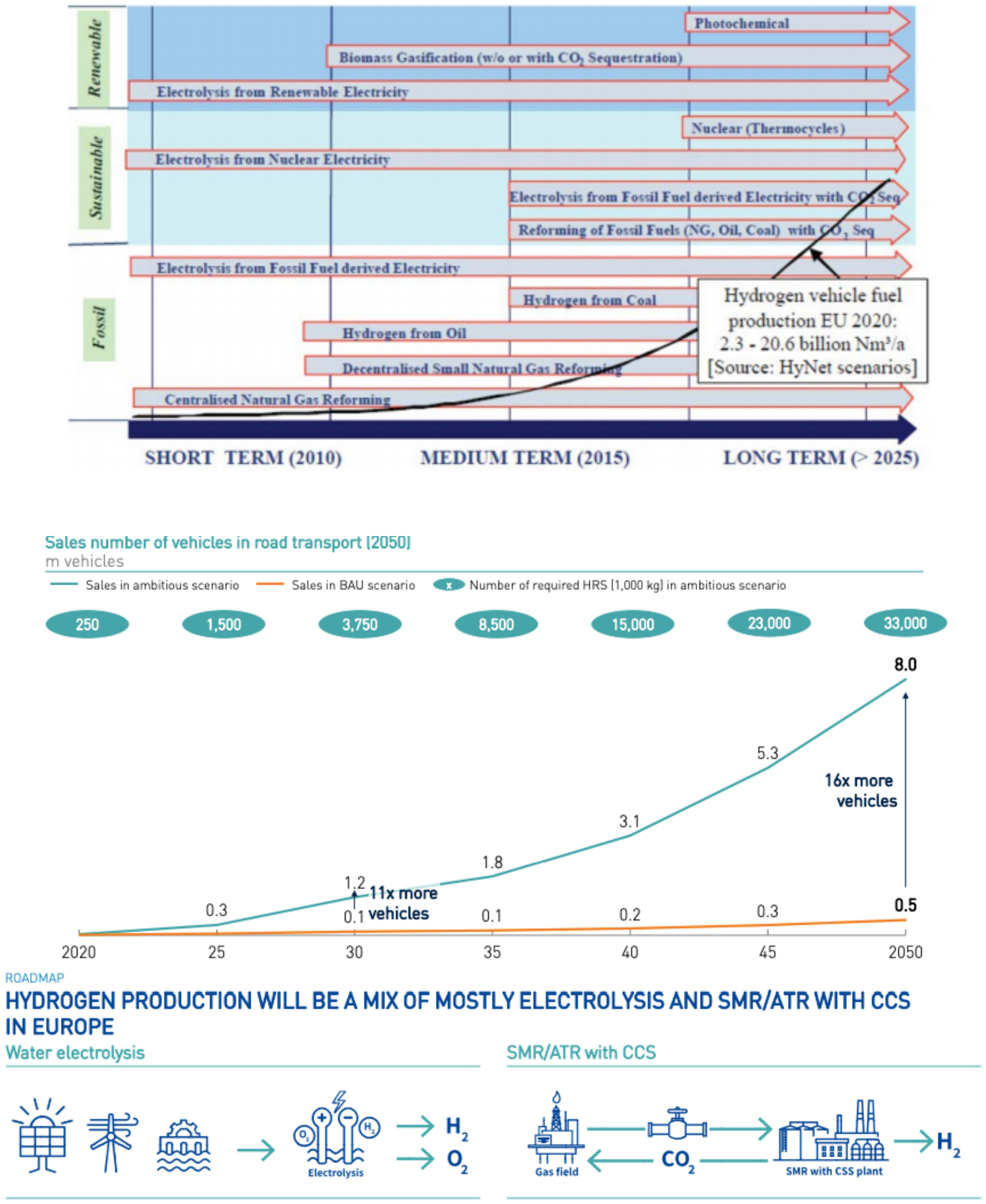

Figure 6. HyNet and Hydrogen Roadmap Europe for hydrogen production technologies comparison.
Source: (IAEA 2013)p.21), (HyWays. European Commission. 2008) (Fuel Cells and Hydrogen Joint Undertaking 2019)

According to Fig. 6, in the short term, we can produce hydrogen by fossil fuels, but in the long-term renewables could be providing even more and more hydrogen. Another critical point in this graph is to see the vision of the Hydrogen Fuel Cell cars to be part and drive the demand for more hydrogen production. This graph was published in 2008 by HyWays, Hydrogen Energy in Europe, an integrated project commissioned partly by the European Commission, Research Institutes and leading energy industry companies. The project aimed to build a roadmap where EU member states could decrease their greenhouse gases emissions using hydrogen production and infrastructure. The project was done from April 2004 to June 2007. (HyWays. European Commission. 2008) The hydrogen roadmap evolved into the Fuel Cells and Hydrogen Joint Undertaking. (Fuel Cells and Hydrogen Joint Undertaking 2019) There is still great hope that more and more of this technology is made attractive to the public and private investors. The reason to compare these two figures from 2008 and 2019, is that in almost ten years, small changes in hydrogen has been produced. But more results in a shorter amount of time is expected to happen as the effects of climate change are felt each year by the population. This study will explain in further sections that the investment may not go to small size private vehicles cars but to utility cars, trains, buses and long-time energy storage.

The current levels of maturity concerning hydrogen technology are steam methane reforming and water electrolysis. For the SMR, it can be with a feedstock of biomethane or biogas with or without carbon capture and storage (CCS). Biomass pyrolysis and gasification are less mature technologies. The technologies that are mostly on the commercial stage are SMR and alkaline electrolysers. The ones that are in the demonstration stage are PEM electrolysers, and continued improvements are being made every day. Concerning anaerobic digestion and dark fermentation, pyrolysis and gasification together with SOEC electrolysers are in prototype and demonstration stages for feedstock coming from renewable electricity and biomass and biogas. Finally, the technologies that are in applied research still are the thermochemical water splitting, and photocatalysis, where improvements towards increasing hydrogen yields are still taking place. ((IRENA 2018)p. 18)

In Figure 7 made by IRENA, it shows the type of feedstock that can be linked in the Hydrogen Economy. This gives an idea where the technology to produce hydrogen could help achieve energy security. It is insightful and brings hope to a more decarbonised economy paired up with push on the protection of the supply.

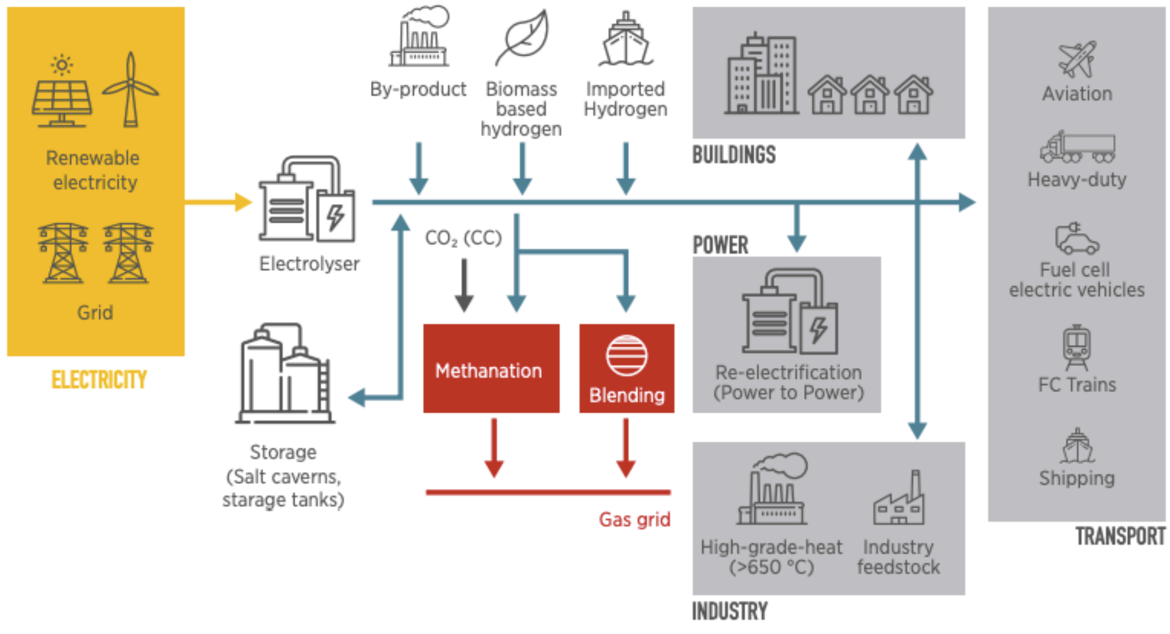

Figure 7. Integration of VRE into end uses by means of hydrogen.
Notes: CC = Carbon Capture, VRE = variable renewable energy.
Source: (IRENA 2018)

This study aims to expose that considering hydrogen production in only two ways as renewable and non-renewable limits the research and therefore its uses.

In the following Table 2, a summary of the efficiencies of the energy consumption production pathways is shown. It is worth to remember that there are inevitable trade-offs according to the scale of production, costs, GHG and the possibility to couple to RES. (Stafell, et al. 2018)

Table 2. The efficiency and energy consumption of hydrogen production pathways.

	Efficiency (LHV)	Energy requirement (kW h per kgH_2)
Methane reforming	72% (65–75%)	46 (44–51)
Electrolysis	61% (51–67%)	55 (50–65)
Coal gasification	56% (45–65%)	59 (51–74)
Biomass gasification	46% (44–48%)	72 (69–76)

LHV = Low Heat Value, also known as Net Calorific Value.
Source: (Stafell, et al. 2018)

This study will concentrate on the production of hydrogen through the pyrolysis/gasification process and the electrolysis process, which is done through fuel cells (FCs) so it can be considered renewable. As seen in Figure 7, renewables can be paired through electrolysers and produce electricity. Biomass producing hydrogen can also be used in electrolysers. All these can help and power aviation, heavy-duty trucks and passenger buses, FCEV, FC trains and ships. Nevertheless, it is worth to check the possibility of carbon capture and storage (CCS) in the future for both process (gasification/pyrolysis and FCs) to could make SMR processes a more environmentally friendly method.

Finally, in Figure 8, when we talk about storage of hydrogen, we can see the most significant potential hydrogen has in the long run. (Hydrogen Council 2017)

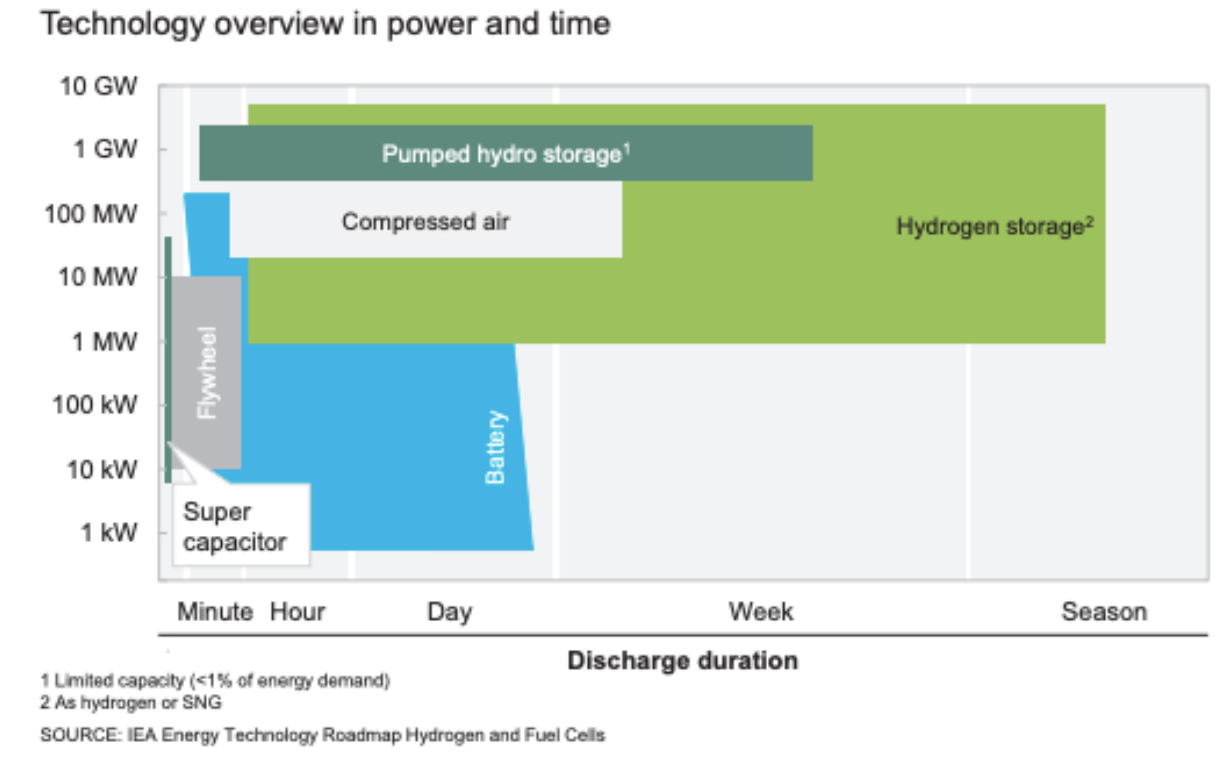

Figure 8. Hydrogen storage advantage.
Hydrogen can be stored for months without losing much of its power
Source: ((Hydrogen Council 2017)p. 58)

2.3 PYROLYSIS AND GASIFICATION FROM BIOMASS

Biomass is an important energy feedstock. It is a source of energy that can be provided by plants, animals or waste. It has been used to power human energy needs since early ages. Biomass is still used as burning wood and produces heat and steam in specific locations as a cheap fuel or as a recreational activity. But biomass is not only wood but has many types that range from wood, crops, garbage, alcohol fuel and landfill gases. Using biomass has many advantages like diversifying energy source mix, diminish greenhouse gas emissions and create jobs. Only in the EU biomass accounted for two-thirds of the renewable energy mix in 2012. (European Commission 2019)

It is essential to note the full range of biomass possibilities[3] and the process to recuperate the energy from it. Gasification and pyrolysis are both thermochemical processes that convert biomass into hydrogen in many liquids and gaseous fuel products. In both methods, there needs to be a reforming agent to have a high hydrogen yield. In the past this process was very tied to coal, nowadays there is resurging research intending to harness hydrogen and other fuel gases from biomass and waste making it a renewable process to use it as combustible to produce electricity and use the heat generated from the exothermic reaction derived from the process.

It is essential to mention the Fischer-Tropsch process, involved in the gasification process, as it is one of the most famous methods nowadays to produce hydrogen with methane and using the steam reforming reaction (SMR), summarized in the following part of the coal gasification equation, after coal is devolatized and shifted with water-gas, and the methanation part is applied: $H_2O + CH_4 \rightarrow CO + 3\ H_2$. From the result, we can see why O&G companies use it as an effective method to produce high yields of hydrogen. (Kaneko, et al. 2012)

According to Häussinger et al. regarding the gasification process, the chemical compounds that lead to more hydrogen yield are the chemically pure compounds as methane. As well, in the gasification process, the process is used at high pressures of at least 2 MPa as hydrogen is used at higher pressure. In the case of the biomass such as wood, refuse, or sludge, the produced hydrogen is less as most of these products contain high levels of moisture and oxygen which results in low results of H_2 gas. That is why usually the gasification of these materials is used to power electricity and heat on site. Crude oil prices affect the research and development of this process, which is why no more research has been done to make gasification of waste more efficient so new procedures could be commercialized. (Häussinger, Lohmueller and Watson 2011) Maybe this is why O&G companies are so interested in developing hydrogen as the next energy vector for the intermediate future. So, we face again with the problem that with the actual technology, hydrogen from hydrocarbons has a lower cost because the technology is already there. While no infrastructure can yield higher hydrogen results from light hydrocarbons.

Gasification has two sides. With high pressure can yield high hydrogen because it will be produced at high pressure, which makes economic sense. But gasification is very sensitive

[3] Biomass examples: "*Wood, agricultural crops, the waste of agricultural byproducts, animal waste, municipal solid waste (MSW), waste from food processing, aquatic plants and algae*". (Hosseini and Wahid 2016)

to pressure and heat. According to Häussinger et al., all coal gasification processes will yield hydrogen; the question is how much and how cost efficient the process will be.

Pyrolysis is a Greek-based term meaning, pyro = fire, -lysis = separating. It means separating by fire. According to the book Hydrogen Storage Techniques, on the chapter Hydrogen Fundamentals, the process is described as to heat biomass between 370 to 550ºC at 100,000 to 500,000 Pa in the absence of air. Waste like plastics, mixed biomass and synthetic polymers have demonstrated to generate through this process high concentrations of hydrogen that could be used for heat, mechanical power or electricity. Pyrolysis is a promoting technology as it can bring many useful fuels from biomass like syngas, biochar, even bring back plastic bags into oil or make waste into safely disposable substances (Godula-Jopek, Jehle y Wellnitz 2012)p.47). So far, two methods to produce hydrogen are being studied: slow and fast pyrolysis.

According to Häussinger et al. on the chapter of Hydrogen Production, coke oven gas (COG) used the pyrolysis process, in the past, as a significant source to produce hydrogen, resulting in 99.9 % of purity and compositing 50 to 64 % in the resulting gases. The demand for H_2 has risen sharply since 1950, and according to actual research, it looks it will continue. (Häussinger, Lohmueller and Watson 2011)

The relation between gasification/pyrolysis in the book "Hydrogen Technology: Mobile and Portable Applications" in chapter Hydrogen Production shows that there are significant advantages associated with the pyrolysis and gasification process. This, because they produce several combustion fuels of high quality that can be used in different energy processes such as gas engines and turbines to produce electricity and heat. The primary feedstock for pyrolysis and gasification can range from biomass, human waste, plastics and even polyurethane. The higher interest on these two processes is because (especially pyrolysis) can use organic material such as biomass, crop residues, waste disposal, municipal solid waste and refuse-derived fuel to produce hydrogen and other synthetic fuels. These two processes average efficiency of 50 %. Nevertheless, the effectiveness and the quantity of hydrogen production that can be extracted from biomass residues are dependent on the composition, heterogeneity and moisture content. Biomass and crop refuse are highly advised to waste as its composition and humidity can be easily predicted and therefore adapted. (Hočevar and Summers 2008) p.68).

The difference between gasification and pyrolysis is that the first uses air in the combustion process while the latter decomposes materials, like biomass or waste, due to the heat induced in the process in the absence of air. As both methods have carbon-based materials, the yield will be a mix of carbon monoxide and hydrogen gas and liquids, that can be used as fuel as previously mentioned. Bartels et al. suggest that pyrolysis and gasification can convert biomass into hydrogen. The explanation given is that pyrolysis will be done in an inert environment, while gasification will be done in a reactive environment. Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology is possible through pyrolysis and gasification and its different methods of co-production of pure hydrogen (vol % 99.9). Sometimes pure H_2 production does not happen cheaply with waste biomass gasification/pyrolysis processes. (Bartels, Pate y Olso 2010)

The pyrolysis and gasification process are highly intertwined. These processes are most of the times used together. In waste incineration, these two processes are used as a process to obtain hydrogen, natural gas substitutes, gas engine and reaction gas. In the end, when combusted can help to produce electrical energy and heat and as by-product ash and slag. (Thomé-Kozmiensky, et al. 2011)

Hočevar et al. mention that the different pathways of how hydrogen can be harnessed but mainly, the method of Life Cycle Assessment (LCA) should be applied to evaluate this type of less GHG technologies further ((Hočevar and Summers 2008)p. 72). This LCA method will be used again on some end-cases for hydrogen (Island case) to have a comprehensive analysis of environmental impact. Finally, more research needs to be done with other renewables and new technologies.

Regarding fast pyrolysis, according to Bridgwater et al. mentions the great potential this process has over slow pyrolysis (Fig. 9). As the results are useful liquids to use in many energy appliances like boilers, engines and turbines. In their study it gives information about how long the process from biomass has been: 30 years from 2000, meaning it started in the late 1970s. As well, the great value of fast pyrolysis is to produce high valued chemicals that could be used for other processes. Additional advantages are the easiness to storage the liquid fuels formed in the process over the gas and heat produced. (Bridgwater and Peacocke 2000)

We can summarize the process of fast pyrolysis to an update from Bridgwater in 2012. About the most critical primary products and especially synthesis gas (or syngas a mixture of hydrogen (H_2) and carbon monoxide (CO) specially produced when gasified from bio-oil and biochar), that can serve to see how pyrolysis and gasification are intertwined. (A. Bridgwater 2012)

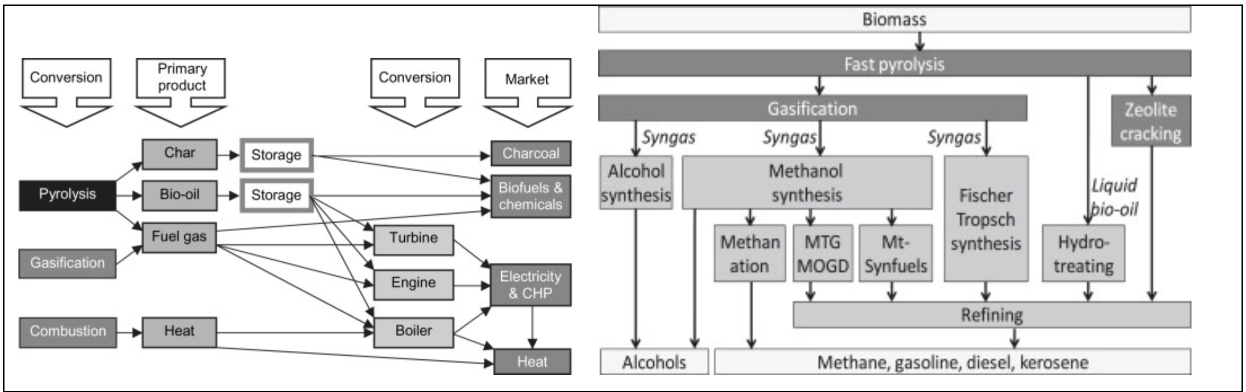

Figure 9. Products from thermal biomass conversion.
CHP = combined Heat and Power (heat capture)
Source: (A. Bridgwater 2012)

Some cases using pyrolysis can also be found on the next article from 2018 from Saleh Al Arni concerning the advantages over slow and fast pyrolysis where through a case study on sugarcane bagasse using pyrolysis the case study obtains a high percentage of H_2 compared to CH_4. It is important to note that the yields will depend on the type of pyrolysis and the temperature of the reactor. In the experiment, many high valuable gases were harnessed like H_2 and CH_4 and some light hydrocarbons like C_2H_4 and C_2H_6. Depending on each country, crop refuse could be used in the pyrolysis process and adapted to the crop composition. In the case of Al Arni, the study focus on sugarcane but also mentions it can be changed and lead to high yield of hydrogen for the instance of dates palm fibre; more research should be done adapting each country crop refuse (Al Arni 2018).

Regarding the membranes on the reactor bed, research from Konlechner in 2015 (TU Vienna) was done in the biomass gasification plant “Burgenland Energie” in Oberwart, Austria. In his thesis, Konlechner researched on the biomass gasification method using membrane technology. In his findings, he mentions that the gas permeation process could be used to separate hydrogen of biomass on the gasification process. Again, as previous experiments showed, different results will be achieved on different process conditions, meaning that hydrogen production is susceptible to the biomass composition and heat during the gasification process. The case study was done using wood chips, yielding after the gasification process, 40 % v/v hydrogen with almost no nitrogen. The advice of this study is that for further applications where hydrogen would like to be the main product, to use the SER gasification process. The SER gasification process stands for Sorption Enhanced Reforming, a promising technology that enables the effective capture of CO_2 and leads to higher hydrogen gas production. This effectiveness of the SER process is due to the use of calcium oxide and calcium carbonate in the bed material that could lead to 75 % of hydrogen. The temperature range goes from 30 to 80ºC that leads to an increase in the tans membrane flow and therefore, a high result of H_2.

Additionally, gasification and hydrogen separation through membrane technology could be a high possibility to harness H_2 from biomass and be part of the green energy mix of the future. This type of technology is promising as it allows to supply carbon dioxide-neutral hydrogen, and it can operate continuously. What is fitting is research on the long-term stability of the SER gas process (Konlechner 2015).

Finally, gasification and pyrolysis are processes that are increasing on the diversity of methods to harness potentially useful gases and liquid fuels from several sources and types of biomass, crop refuse and waste. More and upgrading catalyst are being under research and in enhancing the more efficient process.

The literature review here wants to show the evolution these processes have experimented over the years. There is still more research that can be done to perfect the process and make hydrogen to fuel the hydrogen economy towards a low carbon emission fuel technology. Yet there are few examples of on place reactors. As well, research of fast pyrolysis has lacked extensive reviews of past research publications. It would be worth to continue more depth research on that topic and looking for more on-site reactor types and in industrial plants and results on real-life conditions. Commercial plants nowadays face the disadvantages of being placed on a small scale, and their cost is expensive when compared to fossil-based energy.

2.4 ELECTROLYSIS FROM RENEWABLES

Hydrogen could also be provided by water, besides being produced from fossil fuels or biofuels. Electrolysis is an electrochemical process that can use water to produce hydrogen, among other elements. The technique uses direct current (DC) to create a non-spontaneous chemical reaction where elements get separated. The word electrolysis uses the Greek words: “ἤλεκτρον [ɛ̌ːlektron] "amber", which since the 17th century was associated with electrical phenomena, and λύσις [lýsis] meaning "dissolution".” (Electrolysis 2019)

The electrolysis process is attributed to Michael Faraday in 1834, who provided a mathematical explanation for electrochemistry and electromagnetism laws. (Ehl and Ihde 1954) Electrolysis has four parts: anode, cathode, a membrane or a substance through which elements are permeated and finally an electrical load that actives the process to separate the ions.

Electrolysis is an advantageous method, widely used in metallurgical processes to extract or deposit metals in a solution and to produce fuel.

The electrolysis process then can be carried out by an FC. The first FC was invented in 1838. It took many years after to be used again by NASA, where they used it for human-crewed space missions and satellites and to power forklifts and tractors in the past. As well, FCs are used in remote locations where fossil fuels are scarce or difficult and expensive to supply.

As previously mentioned only 4 % of H_2 is produced by FCs (Ewan and Allen 2005) (Zhang, et al. 2016) (Parthasarathy and Narayanan 2014) FCs are considered to deliver green hydrogen as the primary emission is water vapour and heat, therefore there is no CO_2 produced, as the only elements brought into the chemical equation are hydrogen and oxygen.

Hydrogen together with FC could revolutionise the way we produce, store and use energy.

The electrolysis process to produce hydrogen is not something new. It has more than 100 years, and it was in Norway with its hydro-electrical plant in Norks Hydro where it was built one of the largest plants. An economic decision to place an electrolysis plant is based on the availability of cheap electricity, generally related to hydropower stations. Usually small hydro plants can produce around 50 – 500 m^3/h. (Häussinger, Lohmueller and Watson 2011)

FC work in a simple process. FC convert chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent (usually called redox reaction). It is essential to mention that FCs are not energy storage units but energy converters. The redox reaction happens through an anode and cathode through a Polymer or Proton Electrolyte Membrane (PEM) where only protons pass. They can also be used in the reverse mode using hydrogen, alcohol or other hydrocarbons.

According to Hosseini and Wahid, hydrogen from water electrolysis production from renewable and sustainable energy resources can become a promising green energy carrier for clean development. Specifically, if the electricity comes from RES like biomass, geothermal, wave, tide wind or solar energy. Hydrogen is an environmental process according to the following reaction: $H_2O + 2F \rightarrow H_2 + 1/2\ O_2$, (where F stands for the Faraday constant meaning 1 mol of electricity). This reaction can also be used in reverse to generate electricity from hydrogen: $H_2 + 1/2\ O_2 \rightarrow H_2O + 2F$. This is the main point and the basis to mention that hydrogen can be an energy carrier, saving the intermittences in the RES and then stored as hydrogen so in the reverse reaction can produce electricity. One of the main constraints of the electrolysis process is the cost of electricity as it is mainly dependent on it and water cost is not taken into account (yet). As well another constraint is the materials used in the fuel cell, most of the times it is because of the platinum used in the catalyst and the need for very pure hydrogen. New technology using nanoparticles is still in experimentation phases. The most important take away is that in order to make electrolysis possible is that the electrical energy cost has to be four times cheaper than the actual commercial process. (Hosseini and Wahid 2016)

FCs are an attractive energy converter that offers greater efficiencies compared to mature generation technology such as ICE engines and turbines. FCs offer a promising power increase in the last years and promise to continue its way in the global energy matrix. (da Silva Veras, et al. 2017)

There are many types of FC. In the following table 2 mentioned in Hotza and Diniz da Costa, the kind of fuel for the cell and efficiencies are depicted.

Table 3. Fuel cell types and typical characteristics.

Fuel cell type	Operating temperature (°C)	Electrolyte	Charge carrier	Catalyst, anode	Fuel for the cell	Electrical efficiency (%)	Qualified power (kW)
Alkaline (AFC)	70–100	KOH (aqueous solution)	H^+	Ni	H_2	60–70	10–100
Proton exchange membrane (PEM)	50–100	Perfluor-sulphonated polymer (solid)	H^+	Pt	H_2	30–50	0.1–500
Direct methanol (DMFC)	90–120	Perfluor-sulphonated polymer (solid)	H^+	Pt	Methanol	20–30	100–1000
Direct ethanol (DEFC)	90–120	Perfluor-sulphonated polymer (solid)	H^+	Pt	Ethanol	20–30	100–1000
Phosphoric acid (PAFC)	150–220	Phosphoric acid (immobilized liquid)	H^+	Pt	H_2	40–55	5–10000
Molten carbonate (MCFC)	650–700	Alcaline carbonate (immobilized liquid)	CO^{2-}	Ni	Reformate or CO/H_2	50–60	100–300
Solid oxide (SOFC)	800–1000	Yttria-stabilized zirconia (solid)	O^{2-}	Ni	Reformate or CO/H_2 or direct CH_4	50–60	0.5–100

Source: (Hotza and Diniz da Costa 2008)

As a summary, the ones that show more efficiency are the proton exchange membrane and the alkaline fuel cell. NASA massively developed both of these cells since the 1950s and used in the space program as most of them produce pure water as a by-product, something useful for the astronauts to drink.

In this study, the proton exchange membrane (PEM) is used as the primary fuel cell together with hydrogen as fuel, regardless of the others. Mainly the PEM is used because of its many applications such as mobile, portable and low power generation and because of its higher power density. PEM cells are easy to adapt and place in power stacks which make their usability in a wide range of applications. (Edwards, et al. 2008) The three primary purposes of considering PEM FCs are: in the mobility sector, as storage of excess energy from renewables and for electricity production.

The down-sides of FCs are the use of non-renewable metals in their production and the carbon footprint that they will require. PEM FCs are very sensitive to Particular Matter (PM) particles. Nevertheless, this is the same case for other renewable technology such as wind turbines, solar panels and lithium batteries in electric cars (EV).

Some countries have already set some limits coming from this technology; such is the case of the European Union setting the limit to 1 GW of distribution of power generation capacity coming from fuel cell technology by 2015 and 0.4 to 1.8 million Hydrogen vehicles sold per year by 2020. Till today the limits have not been achieved. The EU has put this technology forward, and many applications can come from it. (Fuel Cells and Hydrogen Joint Undertaking (FCH JU) 2005)

In Fig. 10, "Global water electrolyser additions" made by the International Energy Agency (IEA) shows how much the investment and therefore the electrolyser development has grown in the last year (International Energy Agency 2019):

Figure 10. Global water electrolyser additions for energy applications by technology type.
Source: (International Energy Agency 2019)

The graph on global water electrolysers shows how much the research and development have come through. It gives a good hint of a trend that is going forward. It also points out that more PEM electrolysers are considered to be built. The forecast for electrolysers looks like they will be smaller, and their cost will be drawn down. It also points the flexibility of electrolysers and the possibility to add it to RES.

CHAPTER 3. ENERGY SUPPLY SECURITY AND SAFETY

When talking about hydrogen, the term Hydrogen Economy (HE) is interlinked. It was first mentioned as a proposition in a technical report named "Toward a liquid hydrogen fuel economy" by Lawrence W. Jones in 1970, where it says that fossil fuels are finite, and their reserves will last for a short time. Therefore, another energy vector is needed, as a proposition is hydrogen as it is widely abundant in our planet (Jones 1970). The central thesis is that a new set of economy and energy security should be created, basically because of the pollutant hazard of carbon-based fuels. This set of ideas marked a different way of thinking about how we harness energy. At this moment, we harness energy mostly from fossil fuels. These fuels once were plants and animals that stored the power from the sun. So, a different way to see it is, fossil fuels are the storage of solar energy. This study mentioned in the section of hydrogen production that one of the most used processes to harness hydrogen is through SMR and that a possibility to keep CO_2 reaching the atmosphere would be through the use of CCS. Renewables solely will not be able to match the increasing global energy demand. The hydrogen economy envisions making a bridge between actual applications of carbon-based fuels to renewables through hydrogen. So, renewables can make their way and can fuel the future with better, environmentally friendly technology.

Indeed, SMR using CCS will not stop producing CO_2, but at least it will make the CO_2 be presented in a single location so it can be easier to use the CCS method.

Today, besides the global warming caused by anthropogenic activities, we face the issue to secure the energy supply. Security in the amount of energy is of vital importance because it supports the development of nations. Energy supply needs to be reliable and secure. It needs to be reliable because nowadays most of the human activities are based on digital businesses, and tendency looks like it is going to keep rising. Digitalization is very sensible because it means communication and information, a vital resource for economies worldwide. As well, there is a high degree of automation in the world, which is economical sensible. Energy supply needs to be secure through their various supply chain modes, which includes primary sources, electrical generators, transmission, distribution and the stability of energy prices. All this together makes the energy transmission safer and capable of enduring physical or digital risks from tsunamis to digital hacking.

Therefore, the importance to secure the structure is critical. Nowadays, energy infrastructure needs to reconfigure and renovate according to the actual and fore coming energy needs to prevent interruption of supply. In this section, this definition will be explored.

3.1 ENERGY SECURITY

The definition of energy security (ES) is very elusive. Partly because the way countries secure their energy is different. One of them is Löschel et al., which defines ES as critical in the development of a country, so the production, distribution and final demand should be protected. (Löschel, Moslener and Ruebbelke 2010) This study concentrates its definition based on several reviews and publications of the energy specialist and economic historian, Dr Daniel Yergin. Energy security should be supplying energy in a sustained and economical way. (Yergin, Ensuring Energy Security 2006)

He approaches the problem of energy according to the following dimension that can be divided into two: infrastructure and resources.

The infrastructure dimensions can be divided into two as well: physical and cybersecurity. For the resource's dimensions, there is the "Integrated Energy Shock" and Climate change.

Physical infrastructure is the concrete and robust infrastructure that can be seen and touch. The power plants, the supply routes, the oil, the transport vessels and pipelines where coal and gas are transported, all these need to be preserved and sustained.

Cybersecurity infrastructure is relevant more than ever. The electrical grid is getting every day more connected to the internet, and terrorists have targeted the electricity grid in some of their attacks. A recent attack targeted the Ukrainian electricity grid which caused a massive blackout.

The integrated energy shock and climate change talk about how resistant the energy structure can be to natural events beyond human control and with little data to forecast, like tsunamis and increase on temperatures due to global warming.

Yergin describes the supply of energy and puts oil in the centre of the economy and as part of daily life. This divides the world between exporters and importers. According to Yergin, "o*il importing countries think in terms of security of supply. Energy-exporting countries […] talk about "security of demand" … on which they depend to generate economic growth and a substantial share of government revenues-and to maintain social stability. They want to know that the markets will be there, so they can plan their budgets and justify future levels of investment*." ((Yergin, 13. The Security of Energy 2012) p. 267)

With these four dimensions, a clear map of supplying energy can bring solutions to decrease the amount of carbon in the energy grid that can sound appealing to both exporters and importers.

As mentioned before, as the EU and G-8, have agreed to decrease their GHG emissions by 50 % by 2050 only through a different way to harness the energy, hydrogen economy could be an accurate way to make this possible. (Yergin, Ensuring Energy Security 2006)

There exist the chicken and egg problem, where the cause of the problem is not known where is routed. In this case, it is not clear if there needs to be more investment to make the technology that makes the hydrogen production a possibility or if the technology needs to exists, so the prices are driven down. However, hydrogen cars are into the market, nowadays is more of a possibility to find a niche market than in the past.

Also, the economics of air pollution, effects on climate change are being felt, and new policies against climate change could be a drive for a more decarbonised energy security.

3.2 HYDROGEN ECONOMY

Hydrogen Economy (HE) puts hydrogen in the middle point as fuel and energy storage. HE considers a low-carbon economy. This is an important point as HE envisions the link between carbon fuels and RES. This type of mindset could help the transition as hydrogen is being produced by natural gas mainly but can also be produced by RES. HE is using hydrogen as a fuel to power electricity and long distance transport and storing energy for long periods. Its objective is to change the mindset in thinking on primary sources of energy such as fossil fuels (oil, coal and gas), hydro or biomass. It means being able to consider hydrogen as the primary carrier of electricity production. Another critical aspect of HE is it targets mobility and storage of energy. This is the case with hydrogen vehicles using FC technology and storing the surplus of energy produced by the RES.

The most significant advantage is the possibility of long-term storage and long-distance transport. Combustion of hydrogen only releases water, thus helping the Mobility sector. Therefore, hydrogen becomes a link between renewable technologies and energy storage. Additionally, it also becomes a link between reducing emissions for electricity production, generating heat in the process and powering the mobility sector.

Hydrogen as a fuel is considered to be a clean fuel as when combusted generates no carbon dioxide in the atmosphere and only releases pure water.

Concerning the safety as fuel and storage in cylinders, H_2 has extraordinary safety records. Some people refer concern regarding the hydrogen fuel pumps, but the security should be the same as operators and public have done for when refuelling gasoline, diesel or LPG for other vehicles. New technology is being developed for cylinders and refuelling pumps as well as hydrogen gas leakage sensors.

It is also worth to remember that hydrogen can help small and distant communities. That is why islands are good examples and experiments to apply and connect renewable that energy sources will become more independent and less centralized.

The following chapter wants to use end-user cases of hydrogen and fuel cells (particularly PEM cells) as examples of how this technology could be of use and how it can pair with renewables. The energy transition can be seen in an integrative form. For a valid transition, it should consider many types of technologies and how to connect them to support the development and production stages of countries.

As discussed in previous sections, hydrogen can be implemented in a unifying form as Fig. 11 shows.

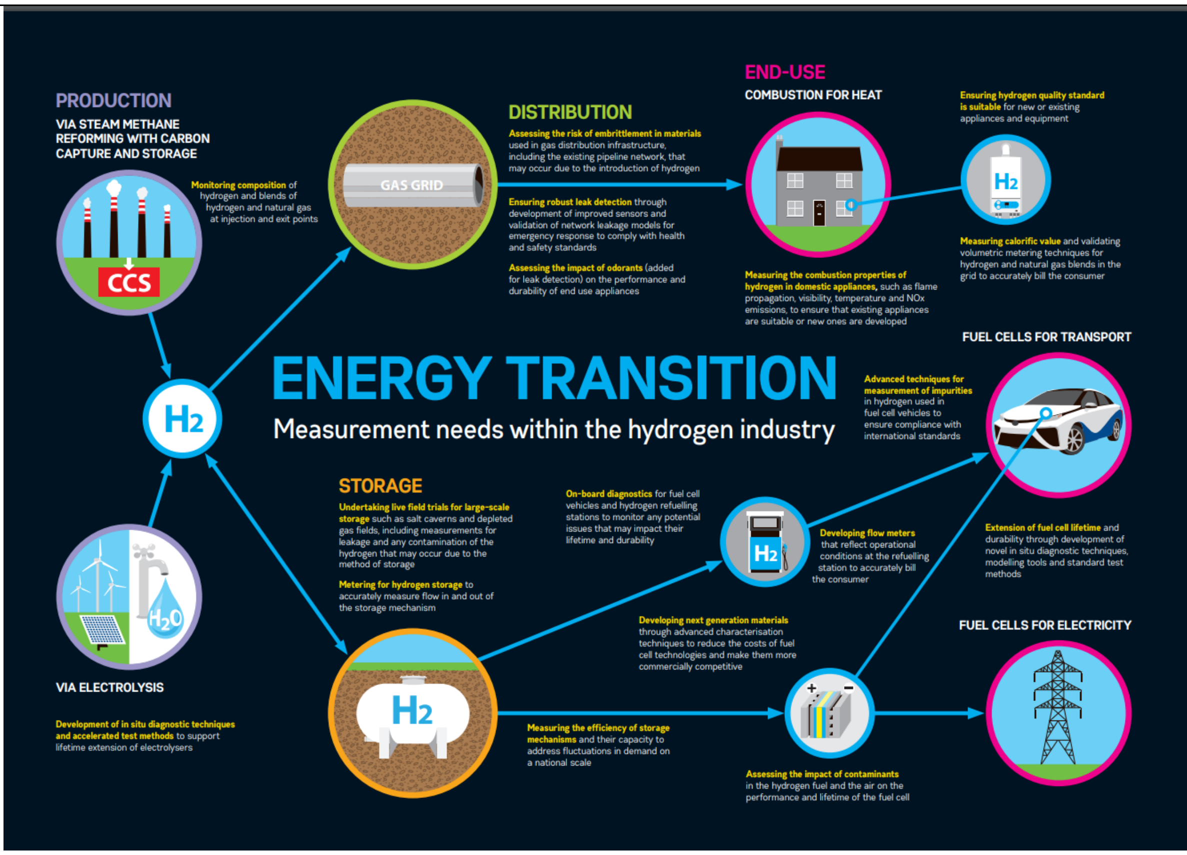

Figure 11. Energy transition infographic.
Source: (UK's National Physical Laboratory 2017)

The previous Fig. 11, Energy Transition, Measurement needs within the hydrogen industry report made by the UK’s National Physical Laboratory (NPL) highlighted and prioritized the challenges for developing the hydrogen technologies. This gives an insight into where there needs to be more research and development to decarbonize the industry and the possible opportunities for the hydrogen economy. Additionally, it shows the high possibility to interconnect this element and look at it as an energy vector securing the supply and helping the electricity grid.

The UK NPL report, mentions that it is advisable to tackle and develop the following issues: development for fuel cell and electrolysers; add an odorant to prevent hydrogen leak detection, as H2 is odourless; determine blend ratio between natural gas in the gas grid; measurement of hydrogen combustion properties for heat applications; suitability of gas infrastructure to transport hydrogen; and, improve hydrogen storage. The result of this study can be applicable big scale to hydrogen and fuel cell. (UK's National Physical Laboratory 2017). More security could be given to stakeholders and government to invest in this technology once these issues are overcome. Most of these subjects are in the process of research and development.

The IAEA has also mentioned and promoted the possibility that hydrogen could power the world economy and therefore, the energy supply of developing countries with the possibility to use nuclear power. In the following Fig. 12 a study on how hydrogen could see in the next years. Nuclear is considered a source to stop the dependence on fossil fuels and have more application on nuclear technology that will allow a resource on saving of up to 40 %. As well the IAEA mentions that if the cost of nuclear heat is low, it could help in the decarbonisation process and produce cleaner technologies. It could also help to reduce our dependence on foreign oil sources and produce in large scale syngas (synthetic gas) and produce hydrogen on a large scale. (IAEA 2013)

Again, in Fig. 12 is only mentioned as a reference, and this study will not consider this type of technology further.

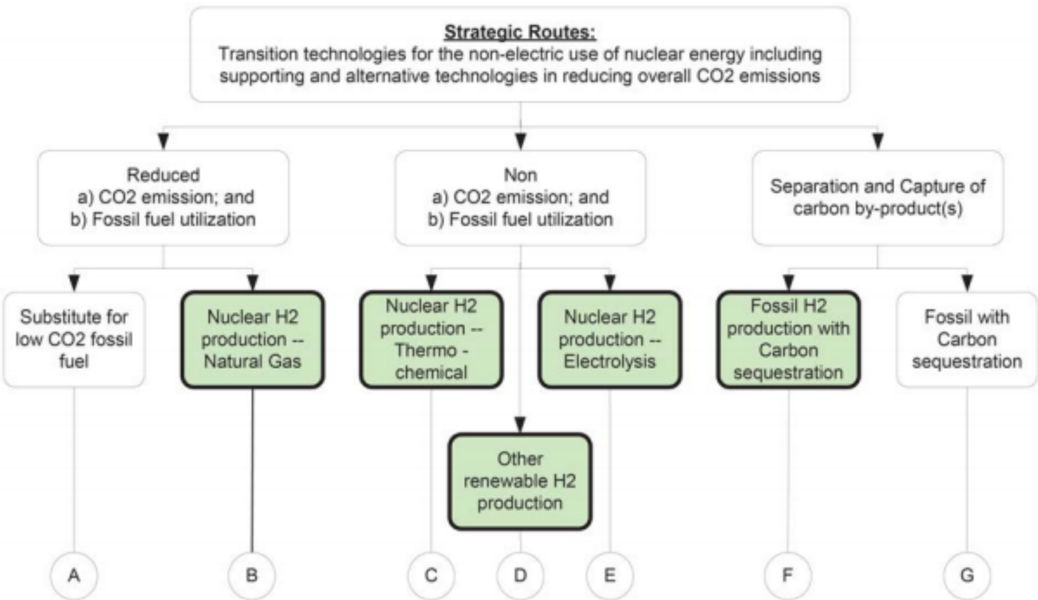

Figure 12. Hydrogen strategic routes for energy technologies to reduce CO2 emissions.
Source: (IAEA 2013) p. 13

4.1 HYDROGEN ON ISLANDS

This study considered three studies for islands. The reason behind it is it acts as an experiment demonstrating in real cases the challenges and opportunities of hydrogen coupling with renewable technologies, in most instances mature renewable energies such as photovoltaics and wind turbines as a bridge to its energy supply variation (intermittency).

The results, in most cases, were based on studies on efficiency and cost savings. Some little cases showed the high possibility to couple hydrogen electrolysers to wind turbines, photovoltaics, and wave generators. Nevertheless, in the study of Denny and Keane from 2012 gives an example from the Aran Islands in the Atlantic coast of Ireland. After considering a smart network scheme with increase insulation and improvements in electrical efficiency when considering three scenarios with different mixes of renewable energies such as wind and wave generators the island the results were “100 % of demand is met from renewable resources... result[ing] in net export of renewable energy” ((Denny and Keane 2013)p. 951) to mainland Ireland. The limitations of the studies depend heavily on material and non-material efficiencies. The non-material efficiency is the accurate readings of energy demand and forecast. The material efficiency depends on electronics and proper insulation of houses, the optimal position of wind farms, heat pumps and use of EV vehicles constant and exacts measurements. By creating a cycle, it can bring cost savings to the community and be energy independent from fossil fuels and coal reducing their CO_2 emissions.

Most of the studies admit that small scale projects on islands have a better result because of the limited number of inhabitants reducing their energy demand and because it is easier to forecast and adapt to local needs. When considering significant populations, energy demand is different and intense. The study of Denny and Keany of 2012 mentions that interconnection is vital and that it should take into considerations the different needs and infrastructure of locations.

4.2 FUEL CELL APPLICATIONS

As mentioned in the section on electrolysis, FCs, through PEM electrolysers have many applications when coupled with hydrogen.

The transportation industry is one particular sector that emits many GHG to the atmosphere. A high possibility to decrease this emission is by using another type of vehicles like FCEV.

Even though the EV sector is growing in the consumer cars, there is an excellent opportunity for utility vehicles for long distances and where the routes are already predetermined so the refuel stations can be strategically placed diminishing the cost of infrastructure by placing new ones.

As well, the European Commission is targeting the transport sector to reduce CO_2 emissions from vehicles. The reason behind it is that as 2014, road transportation accounted for 70 % as the biggest emitter of GHG (which did not include international maritime transportation, a significant pollutant too). If the CO_2 emissions could be cut a considerable amount of GHG emissions could be saved, making the EU goal of diminishing pollutant emissions could be a possibility. So, Europe is committed to a low-carbon economy that will create jobs, investment and modernization in critical infrastructure. (European Commission 2019)

It is worth to mention that vehicles in the intralogistics sector could help to diminish not only CO_2 emission but also NOx emissions. So far, intralogistics vehicles use diesel, which is a heavy polluter. By using other types of vehicles such as hydrogen use vehicles CO_2 and NOx emissions could decrease. The great advantage is that intralogistics vehicles would be comfortable to fuel as station gas would be nearby, and substantial and extensive infrastructure should not be built as compared to passenger and commercial infrastructure, that nowadays we can find for fuelled cars. There is an enormous potential for this sector to decrease their pollutant emissions and great possibilities to bring to the companies using this type of vehicles in the transportation and cargo sector. The problem is the type of hydrogen sourced that could be used. Hydrogen from oil sources and renewables could be used, remembering the decreased of pollutant emissions in case the companies would prioritize this objective together with government policies promoting the use of renewables into their production process.

In the following cases, the type of fuel cell that is being used is the PEM (Proton Exchange Membrane) fuel cell. A “new” type of technology. Researchers have mentioned the high possibility to continue the improvement of their efficiency.

It is essential to mention the CO_2 emission from the transport sector. According to the World Energy Council in 2016, CO_2 emission per sector accounted for the following: transportation 25 %, industry – 55 % and buildings – 20 %. By addressing the mobility sector on diminishing emissions, this could help the environment a lot. Still is part of the process but could help decrease it immensely.

As well, the World Energy Council in 2016 mentions that the current source of energy comes mainly from oil – 33 %, coal – 29 %, natural gas – 24 %, renewable energy – 10 % and from nuclear – 4 %. That is why it is important to increase our share, promoting sources of energy that can decrease CO_2 emissions together with other GHGs.

If we could address the mobility sector with more emission-free vehicles, anthropogenic emissions could be lowered rapidly. Let us take into account the following graph on CO_2 emissions of heavy goods vehicles accounting the percentage of the mobility sector:

What we can see in Fig. 13 is that the carbon dioxide emissions are accounted mainly from cars, heavy duty trucks and buses, light duty trucks and motorcycles, summing up the road transport to a total of 82 % then non-road and aviation a similarly 18 %. From that road transport, heavy-duty and light-duty vehicles account for 31 % and cars for 50 % for GHG emissions.

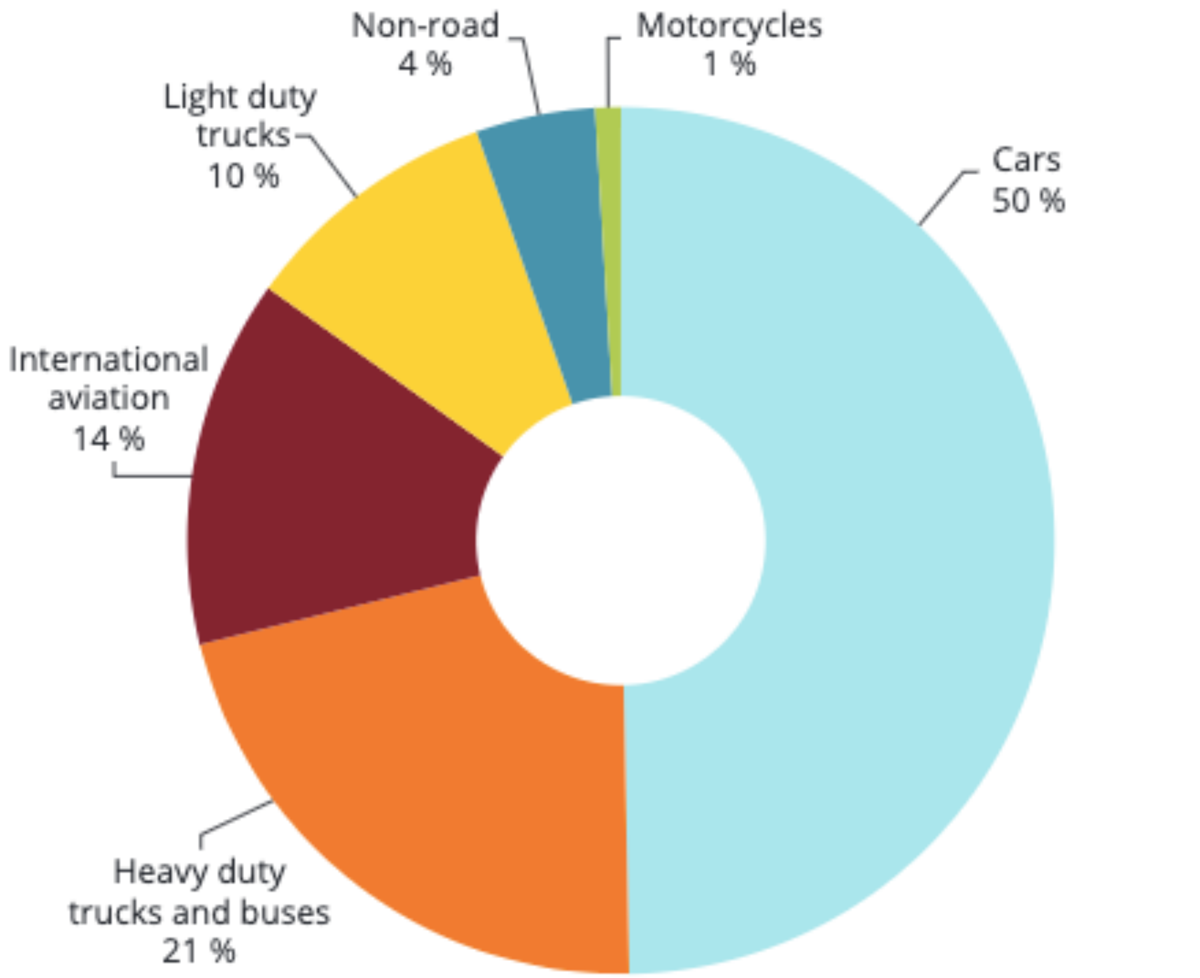

Figure 13. CO2 emissions by type of transport EU 2016.
Source: EEA Report No 15/2018. Monitoring CO2 emissions from new passenger cars and vans in 2017. p. 45. (EEA 2019)

One of the most significant advantages of hydrogen is that vehicles, in general, can quickly recharge. Generally speaking, cars, trucks, buses, trains could be easily fuelled in 5 minutes compared to the EV that take longer times, even though there are rapid storage stations.

4.2.1 CARS

In this section, we mention the uses of FC in cars. What this section will describe is the technology within the car, especially the case of the storage tanks from the FC cars. As H_2 storage tank technology has proven to be safe given the characteristics of H_2 as a debilitating agent of metals.

Many credit Karl Benz to have done the first car using the internal combustion engine (ICE) but this is not entirely true. Before that, there was a hydrogen-powered car. The first vehicle, a three-wheel car, used steam to move canons. Nicolas Cugnot created it in 1769. In 1807, François Isaac de Rivaz from Switzerland created the first internal combustion engine (ICE) using oxygen and hydrogen. Some years after in 1860, a French inventor Etienne Lenoir patented the “Hippomobile”, a gas fuelled ICE powered with H_2 gas, which worked with spark ignition and had one cylinder. That hydrogen was generated from the water via electrolysis. The Hippomobile top speed was from 3 km per hour. Afterwards, Lenoir adapted the technology to other gases like coal gas. Lenoir managed to be successful with his invention and sold around 350-400 gas motors. (Net inform s.f.) As well, there were electric vehicles. However, as the case with hydrogen cars, their inventors were not very persistent in their efforts, and the lack of infrastructure did not help that type of technology either.

Summed up the history is the same problem the FCEVs are facing at the moment: lack of infrastructure and not yet perfected fuel cell efficiency technology. Gasoline engines were in use and perfected. Infrastructure on gas station together with affordable units thanks to Ford assembly line made it easier for the general public to purchase this type of technology. In here we can see two main factors: persistence (from the inventors or their associates) and availability of infrastructure. A significant part of Benz and Daimler success was their continued efforts to popularize their inventions, so people could use them, and improvement in the ICE’s designs from Nikolaus Otto (the Otto engine patented in1867) and incorporating it to cars. Finally, Ford made gasoline powered cars cheaper and available by 1907 with the Model T. Roughly 30 years after, Daimler perfected the Otto engine in 1876. Then Karl Benz in 1879 did the same with a reliable two-stroke engine, continuous improvements followed after. By 1908 onwards, Ford, through the assembly line, made it possible to many not only in the US but also in Europe to have an affordable car.

FCEVs work very similarly as EV. Both EV and FCEV have electric motors and minimal pollutant emissions. The difference is how they store their potential energy. FCEV store energy in pressurized hydrogen gas (around 700 bar) which then will be converted to electricity through the FC.

It is worth to mention that both EVs and FCEVs produced minimal pollutant emissions. In the case of the FCEV, the only emission is water vapour and some ICE fuelled by gasoline or diesel and that their emissions on CO_2, NOx and other pollutants are minimal.

Concerning the options of FC cars, the first made was on from General Motors, GM Electrovan, made in 1966. As a fuel, the Electrovan used liquid hydrogen and liquid oxygen. What is worth to mention is that this car made by GM was made mainly as the automakers got inspired on the fuel cells used by NASA, especially those used in the Gemini's mission (NASA n.d.). GM only produced one and did not sell it as the materials used were very expensive, and there was no massive infrastructure to get hydrogen. (Hydrogen Cars Now s.f.) After that, FCEV research diminished. (GM Heritage Center 2019 s.f.)

Nowadays, few options are entering the market for the FCEV. The firsts FCEV commercially sold, were the HYUNDAI SANTA FE in 2000 (Business Korea 2013), then the TOYOTA MIRAI in 2015 and the HONDA CLARITY. Practically most automakers have produced car concepts, and prototypes of FCs versions such as Mercedes Benz, BMW, GM, Ford, Nissan, VW and the list goes on. However, most of the refrain is that some companies mention there is no customer interest and little infrastructure. In the state of California, USA, there are more cars than fuelling stations, and in Germany, there are more filling stations than cars. In any case, still, the ICEs, hybrid and EV cars are the majority in the market.

The case of the TOYOTA MIRAI (which means future in Japanese) is worth mentioning. Toyota is the only car manufacturer who besides their ICE fuel operated and hybrid cars only offers FCEV as an alternative environmentally friendly car, in comparison to other car manufacturers who offer EV to sell to their customers. In California, USA, Toyota offers the MIRAI in a leasing contract, totalling the price in California of USD 59,464, where hydrogen fuel is provided for free for three years (Toyota Motor Sales, USA, Inc. 2019). Additionally, FCEVs have the characteristic that they can also work as mobile power plants and provide electrical energy, for example, to campers or soldiers; however, this is not the case compared to EVs. (Toyota 2014)

When talking about FCEVs, it is necessary to talk about its efficiency compared to electric cars and gasoline/diesel cars. The following table shows the efficiency percentages. In the next table, we can see the comparison of efficiencies between these technologies.

For more information compared to EV and FCEV and hybrid FCEV there is a study from Offer et al. In their comparative analysis one crucial fact has to be taken into account, there is a great electrical price sensitivity for both EV and FCEV. Additionally, FCEV are sensitive to hydrogen cost. What is essential to take into account is the drive patterns as EV could be suitable for a small range of driving, while FCEV are suitable for longer ranges, preferably from 100 km and beyond. (Offer, et al. 2010)

According to Fig. 14 done by ENAPTER during their recent presentation in Thailand, trying to create a sustainable environment with the use of FC cars. (ENAPTER 2018)

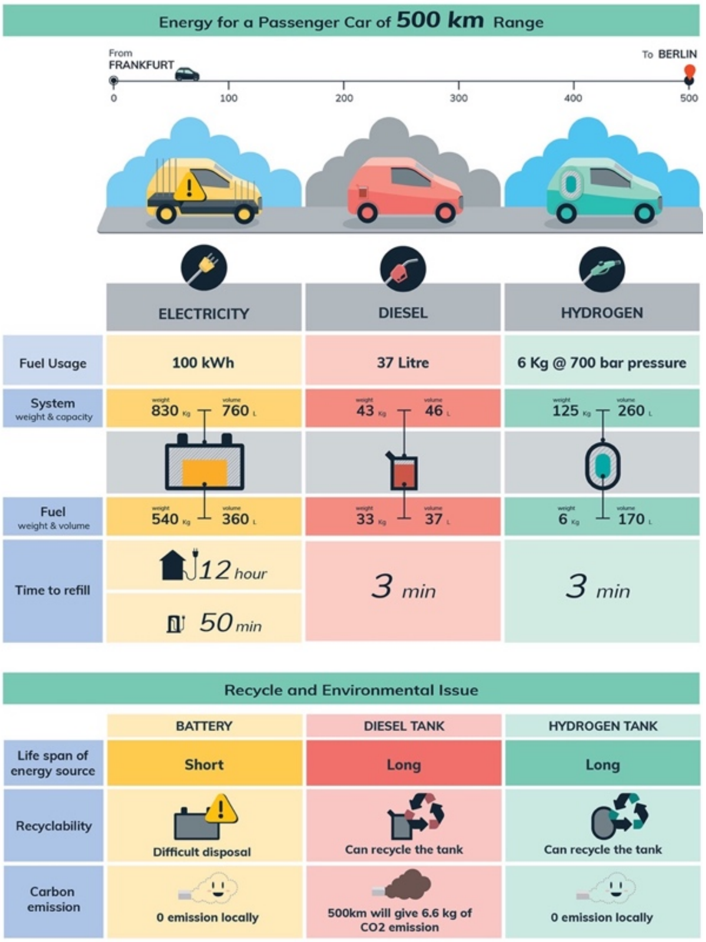

Figure 14. Vehicle comparison for 500 km distance.
Source: (ENAPTER 2018)

It is worth to mention why EVs are dominating the market. First, EVs use the infrastructure from the electrical grid that only needs to be plugged in. The second, TESLA's effort to put EVs in the car consumption spotlight and investing in supercharging stations.

What it is worth to remember is that still there is a lot of carbon footprint behind the usage of lithium batteries used in electric cars and their disposal after their life cycle. Another critical observation on EV is that they have an advantage over FCEV as they do not need to build an infrastructure as they are already profiting and building just a small connection of electrical connections for the superchargers. The already built infrastructure give the EV a massive advantage over other technologies.

New technology always faces the problem of the “chicken or egg” paradox, meaning the question of what has to happen first. Should investment come first to improve efficiency in technology or technology should come first to make technology available and then companies and organisations invest in them? Nobody is entirely sure, and through time, these two forces between investment and research and technology happen at different moments. Hydrogen is a particular case as it has been an intermittent technology. It has had three-momentum. First when it was discovered through the iron gases, then named a water constructor. A second period when NASA needed a powerful fuel for their rockets, and now that oil, coal and gas are running short and becoming expensive, alternative methods to harness technology are being resurrected.

EVs is an energy-intensive technology, and the future looks like the demand for energy will increase instead of saving energy. Some scientists are against the proposition of international organisations such as the UN to promoting electrification as a way to a sustainable economy. Let us bear in mind which primary energy sources are supplying the electricity markets at the moment as coal, fossil fuels, nuclear or renewables. Other sources complementing and aiding the RES could help the electrification process, supporting the primary sources of energy on the mind.

EVs and FCEV should not be seen as separate or rival technologies, but cooperative forces. As mentioned before, FCEV and EV depend on the driving range. Some integrative forces can be joined to make a sustainable solution. FCEV have longer ranges and are perfect for heavy truckloads or where routes can be heavily forecasted. EV could be used for more private and smaller routes. The hydrogen economy could benefit both solutions.

4.2.2 TRAINS

Trains are also big emitters of CO_2, and little is being said about what can be done about limiting their emissions. The case of hydrogen could show how CO_2 reduction in transportation is possible. In the last paragraph, an actual case, connecting a small unelectrified corridor, will be described.

Trains can be a solution for many rail types of transports, ranging from passenger trains like light and rapid transit trains to industrial trains such as freight, mine trains and even to special train in amusement parks. They can also connect remote and inner-city locations where no gas or low electricity infrastructure is available to connect small villages and then limit CO_2 emissions or with high electrification.

FC Trains have a sense when there is no or small electrical infrastructure in distant or small counties or towns. This is an excellent chance to show the potential of hydrogen as reliable, sure and adequate to passenger needs. Hydrogen trains have taken our days very recently. Some say, it was long ago that this should have happened. One of the possible reasons behind it, according to the Thompson study, is that the sector is technology averse. After all, the significant investment given not only in train racks but also in the train vehicles per se needs to bring back the amortization costs. We are at the brink of new investment in train infrastructure and old technology soon to be retired; train machinery will add new trains from different technologies that will be more efficient. Additionally, the European Union and the Horizon 2020 are investing heavily in the sector in order to reduce emissions. Hydrogen trains offer a high payback return and also offer the possibility to retrofit from very similar models running on Diesel.

First hydrogen train was demonstrated in a Canadian mine in 2002, done by a research by the Fuel Cell Propulsion Institute. It weighed 3.6 tonnes and had a built-in capacity of 17kW. Afterwards, in 2006 in Japan, the East Japan Railway Company together with the Railway Technical Research Institute of that country joined forces and created a design. (Thompson, Research 2019) The KuMoYa E995 FC battery hybrid car had a hydrogen tank capacity of 270 litres, run with lithium-ion batteries and had a storage capacity of 19 kWh, being capable of running at speeds up to 100 km/h and powered by two 95 kW traction motors.

Nonetheless, in March 2012 the programme ended. (Japan Railfan Magazine 2008) During this year and after the perception of the Coradia iLint in Germany and Japan’s Hydrogen Economy policy, this project may revive shortly.

China currently has two successful histories. There are two FC trams, one in Qingdao who began operations in 2015 and another tram in Tangshan in 2016. (Thompson, Two China Hydrail trams: The Mooresville connection 2018)

Nevertheless, not only trains exist, but there is also a significant amount of city rail transit being developed in Asian cities, mainly in China. Rail transit has a great advantage; as a part of the mobility sector, it can impact high-density residential areas with tramways and trolleys and decrease carbon dioxide and nitrogen oxide emissions. Now their efficiency is better, size of FCs is smaller than in the past, and its power has increased. It is easier to set up a Hydrogen Train as the kilometres they do each day are predictable and minimal infrastructure needs to be set up compared to highway systems.

Recently a new hydrogen train is running in Germany. The idea is not new. In his article “Why are hydrail trains running so late”, Stan Thompson mentions that around 1999 it was Dr

Holger Bursche who propose commuter trains in Northern Germany. Those trains could be powered by wind turbine electricity, that electricity could be carried as hydrogen and converted through FC. (Thompson, Research 2019) In a presentation of Dr Bursche, he was proposing to use and decarbonize the train lines. In Fig. 15 there is an extract of Dr Bursche's presentation done in 2006.

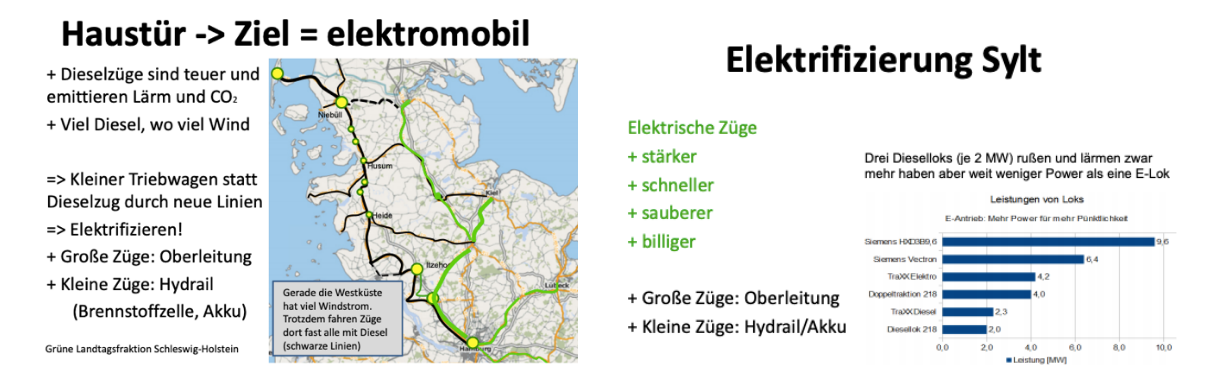

Figure 15. Energiewende auf der Schiene [Energy transition by rail]
Source: (Busche 2016)

It is the Coradia iLint train made by Alstom, a French rail vehicle manufacturer (Fig. 16). The iLint is the FC version of the Diesel Coradia. In a certain extent, the iLint could be considered a "retrofitted" Coradia. In the way that the iLint is very much similar to its Diesel brother. The high technological advancements in power to traction and in the high technology and security of hydrogen storage and fuel cell make it one of a kind. The Coradia iLint runs in the Elbe-Weser network since September 2018. There are plans from the German Local government to use 14 Coradia iLints in the extended route from Cuxhaven, Bremerhaven, Bremervörde and Buxtehude in Lower Saxony, Germany. The iLint produces electrical power for traction and is powered by a hydrogen FC. The energy produced is stored in the lithium batteries. The battery stores energy from the FC conversion when not needed or from kinetic energy when braking; this also allows boosting the train energy when acceleration is needed. These kinds of trains are very suited for non-electrified lines or corridors. The trains have the same performance as its Diesel model: 140 km/h as well as the same acceleration, braking performance and passenger capacity (160 seats per vehicle). The iLint can travel 600–800 kilometres on a full tank of hydrogen. The emissions are only water vapour. An additional advantage is that these trains are quieter due to the electric drive, which is a relief for people living near the train lines.

The train unit cost per se is expensive, compared to other types of train technologies, but its maintenance is cheaper. The public does not worry about the train and has had, so far, a positive experience. In the inside, the train has similar characteristics to regular trains. The difference is the lack of CO_2 emissions, and the absence of electricity to power it. Additionally,

CO_2 emissions have diminished in that corridor. Finally, the refuelling of the train takes little time, around 10 min as a train operated with Diesel would. The refuelling station is at Bremervörde station. (Alstom 2019)

In the following image, there is a sketch of how the train looks. The essential features of the train are the hydrogen, the FC, the lithium batteries and the auxiliary converter that takes energy when the train needs to brake contributing to generating braking and reusing that energy.

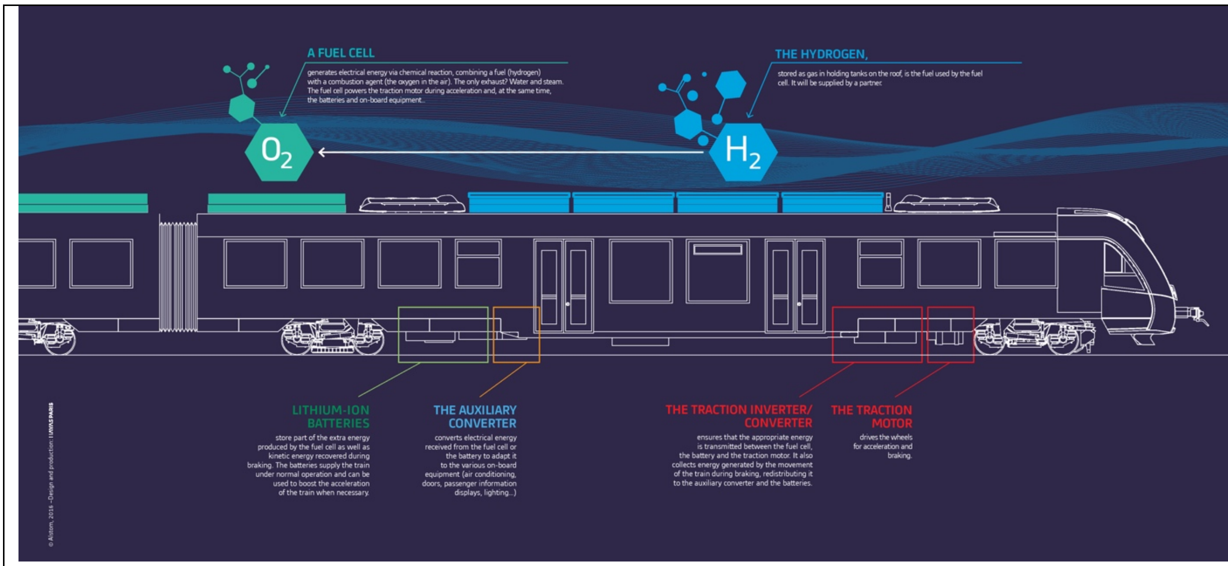

Figure 16. iLint Coradia Train.
Source: (Alstom 2019)

The infrastructure was easy to implement as the train has already a set route and is easy to calculate the fuel it will consume, so there was less cost to develop infrastructure to deliver hydrogen. The federal government provided a grant of € 8.4 million, as the facility cost around € 10 million. Linde, a natural gas company, will supply the hydrogen gas. The trains will refuel in the Bremervörde depot, the first hydrogen train refuelling facility. At a later stage, it is planned to produced hydrogen by a wind turbine. (Shirres 2018)

According to the study of Haseli et al. where hydrogen train gases were compared, the result is astounding in the way that "*on an average basis, only an electric car using renewable energy-based electricity that carries more than three people may be competitive with hydrogen trains*." (Haseli, Naterer and Dincer 2008) This study is a reference of 2008 that serves to make a positive point towards investing in hydrogen FC trains. From that study to nowadays FCs have improved as we mentioned before, and it looks like their price will continue dropping as well as the GHG emissions related to Diesel trains.

In addition, in another study from 2012, the research on transportation considered the tank-to-wheel performance. The study showed that the efficiency from the hydrogen gas compared to Diesel and electric technologies is similar. The research pointed out the benefits as lower CO_2 emission than diesel when hydrogen used in the FC train was used from renewables making it a very similar efficiency to electric when transported between 5,000 to 7,100 km and even higher. (Hoffrichter, et al. 2012)

After Alstom and the German Government of Lower Saxony have joined forces with the Coradia iLint, it looks like more joint undertaking with other governments will happen. Such is the case that recently Alstom and Eversholt in the UK announced a collaboration to lease the FC technology to Eversholt Rail, producing the Breeze Class 321 train and it looks like in the Occitanic region in France are also interested. (Wordsworth 2019)

The future looks bright for trains as they could help decarbonize the transport sector and bring more benefits to passengers, companies and governments.

4.2.3 HEAVY AND LIGHT LOAD TRUCKS

As a possibility to further continue decreasing GHG emissions is by using hydrogen in the mobility sector in the heavy and light load. With this in mind, many pollutant emissions could be decreased, allowing developed countries to meet the diminishing pollutant emissions according to the Kyoto protocol by 2050 (or even sooner as some believe if fast deployed).

According to Figure 13 on CO_2 emissions by type of transport EU 2016 of the EEA Report No 15/2018 both heavy and light load trucks account 31 %. However, the picture is promising in particular niches for hydrogen in the light load vehicles such as forklift trucks, and the availability of vehicles is becoming more a reality in the next coming years and a growing interest and policy support.

Fuel Cells are considered to be significant competitors of battery and internal combustion vehicles. Nevertheless, both FCEV and EV could together be a great possibility to decrease GHG emissions. According to the FC framework in their Hydrogen Roadmap mentions the significant cost benefits between battery operated EV to FCEV trucks. In summary, the FC trucks are more cost efficient when they travel more than 100 km range and have a set route. So, both of these technologies can help decrease pollutant emissions.

Here we can see the cost compared to the range:

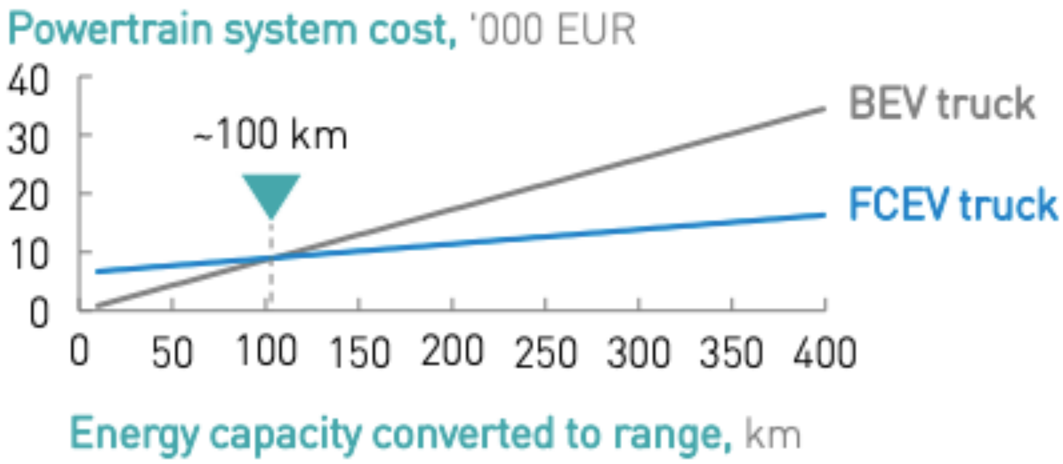

Figure 17. Powertrain system cost compared to range in FCEV trucks.
Source: Hydrogen roadmap (Fuel Cells and Hydrogen Joint Undertaking 2019)

A great way to decrease pollutant emissions is to apply less pollutant energy sources, storages and vehicles. Light-heavy trucks and utility vehicles used in intralogistics, inside logistics in the flow of material and goods inside the industry could decrease GHG emissions and push hydrogen and FC technology usage.

Forklifts are good examples in the hydrogen intralogistics solution, especially in warehouse logistics. As mentioned before, hydrogen forklifts have a niche in the market as their deployment FC technology and recharging stations are constantly improving. H2 and FC powered forklifts are preferred by companies to lead-acid batteries powered vehicles. The benefits the companies see on hydrogen was it behaved very much as petrol as it was easy and fast to refuel, compared to batteries electric vehicles (BEV) that lasted longer to repower. Therefore, the use of forklifts increased productivity, needed less maintenance, refuelled faster and reduced GHG emissions. Nearby power plants with renewable technology, such biomass and waste plants, wind turbines or solar panels, supply the hydrogen the forklifts use. Most of these interactions between power plants and industries using forklifts, happen in industrial parks. The case of hydrogen forklifts can be found in DB Schenker in Austria as mentions in the article from Beermann et al. 2013 and in Mercedes Benz in Germany. Nevertheless, they are being powered by hydrogen produced by OMV, an Austrian oil company and Linden, a German gas company. Still, this is a pioneering step towards a greener intralogistics and fewer pollutant emissions. The use of hydrogen in forklifts has become a mature technology as they are faster refuelled, have consistent performance, have a bigger lifetime span, are increasingly available, have reduced maintenance intervals. Additionally, they can operate at high temperatures. (Beermann, et al. 2014) Additionally, Beermann et al. make a comparison between the use of FCEV and BEV. The results on GHG-emissions can be reduced by about 10 % when FCEV are operated with biomass. Another depending factor is the composition of the country's biomass. In their study, the biomass composition was 85 % energy crops and 15 % livestock manure (most common biomass mix in Austria). The result led to a life-cycle GHG-emission of 414 g CO_2 eq/h (originally 460 with a 10 % reduction due to the potential increased lifetime of FC) vehicle operation when the hydrogen was produced from biomethane compared to the BEV with electricity from hydropower with 460 g CO2 eq/h. (Beermann, et al. 2014)

For the FC buses are attracting attention as diesel buses are considered big polluters. FC buses are considered to have a technology in development compared to conventional diesel technology according to the National Renewable Energy Laboratory (NREL) of the USA. (Eudy, Post and Jeffers 2017) Some of the greatest advantages are, as mentioned before, low refuelling time, low centre of gravity that means that they can brake faster and have more power in the well-to-wheel. FCEV buses are realistic zero-carbon vehicles that can help reduce urban air and noise pollution. Heavy deployment is seen in many countries like North America with 44 units, Europe with 83 units, Japan (through Toyota) will deploy 100 for the Tokyo 2020 Olympic Games, and China has 300 only in Foshan City. Buses are high on longevity prove of that in London have 18,00 hours, in California 12,000 hours. In Europe, FC buses have exceeded 90 %. (Stafell, et al. 2018) Recently the mayor of London, Sadiq Khan, mentioned that 20 double-decker FC buses will be in operation by 2020. This project is funded by the EU JIVE (Joint Initiative for Hydrogen Vehicles across Europe) project. Each bus will be able to carry up to 64 passengers and can cover 322 km. (Sustainable Bus 2019)

FC buses in China is of special interest as they are investing heavily in hydrogen vehicles and fuel stations as part of the program “Made in China 2025.” They have positively seen hydrogen technology to operate their heavy load trucks and passenger buses. According to the National Development and Reform Commissions, developing H2 is one of the 15 tasks to facilitate China’s energy transition. Chinese authorities in the town of Zhangjiakou in the northern province of Hebei decided to encourage hydrogen energy and Fuel Cell companies. The result has been a success. It is worth to mention that even though, fuel cell for domestic use in cars may not be competitive as previously mentions in charts and tables, it may be competitive in the passenger transport sector and intralogistics sector. As mentioned before, the main advantages are the fast fuel charge similar to those of gasoline or petrol (in 5 minutes), not waiting time as battery cars and longer km range. As well, the emissions are low on CO_2 and NOx. Let us remember that there is almost no CO_2 production only CO and HC from tube oil. In China, the industry of fuel cell is also receiving high amounts of subsidies just as other technologies like solar and wind did in the past. Zhangjiakou plans to build 16 hydrogen refuelling stations by 2022. The Wuhan capital of the Hubei province wants to home 100 FC automakers and build 20 fuelling stations to power their 3,00 FCEV. (FuelCellsWorks 2019) According to BloombergNEF China’s Joint Ventures with Foreign companies, like the case of Ballard Power Systems Inc. and Zhongshan Broad-Ocean Motor Co-investing in hydrogen and FC could drive costs down to an aggressive 50 – 70 %. Ballard, this Canadian FC company, previously had supplied 330 FC buses in Guangdong, Yunfu and Foshan provinces. The Chinese government believes that the next step is an economic impulse in the FC global market rather than research and development. (BloombergNEF 2017)

Concerning the Long-Haul Trucks (LHT) case, FC can meet the high energy requirements and high utilisation. Trucks could have a low investment concerning fuelling stations as mostly trucks need to return to their base. So, no need to install more refuelling stations as routes can be heavily forecasted. Also, it could be easy to deploy a refuelling network. The start-up Nikola developed a long-distance Heavy-Load Truck or Heavy Goods Vehicle (HLT or HGV) that uses hydrogen. Unfortunately, FCEV LHT have not been adopted as they are fuel price sensitive. (Stafell, et al. 2018) Recently Nikola published a press release where they signed an MOU with key industry group members (Hydrogen Suppliers & Fuel Cell Electric Vehicle (FCEV) Automakers, Air Liquide, Hyundai, NEL, Nikola Motor, Shell and Toyota) to develop hydrogen fuel hardware to standardization and increase market adaption for FC trucks. (Nikola Motor 2019)

In Fig. 18 the website Markets and markets mentions the Compound Annual Growth Rate (CAGR) to be of 8 % in 5 years from 2018 to 2023. The generation market is projected to hit a size of USD 199.1 billion by 2023. The CAGR describes the rate at which an investment could boost growth, even though it does not represent the risk on the investment. This 8 % means the growth to develop further the hydrogen market and mentions the main stakeholders and their countries. For purposes of this study the following are mentioned: in California, USA; HyGear, the Netherlands; Ballard and fuel cells FCgen-LCS forklifts; Iwatani in Japan through Japan’s New Energy and Industrial Technology Development Organization (NEDO), Toshiba Energy Systems & Solutions, and Tohoku Electric Power to construct Fukushima Hydrogen Energy Research Field (FH2R). The Asia Pacific region will be the largest market, according to the study from Markets and Markets. This investment is heavily related to the increasing pressure to diminish the sulphur, carbon dioxide and nitrogen oxide emissions generated by the industry and transport sector. China is expected to build a hydrogen city with an investment of 290 million and this Asian country will keep on its heavy investment in research and development on fuel cells and building hydrogen stations. As well Japan has plans to have 100 FC buses, 6,000 FCEV by 2020. (Markets and markets 2019)

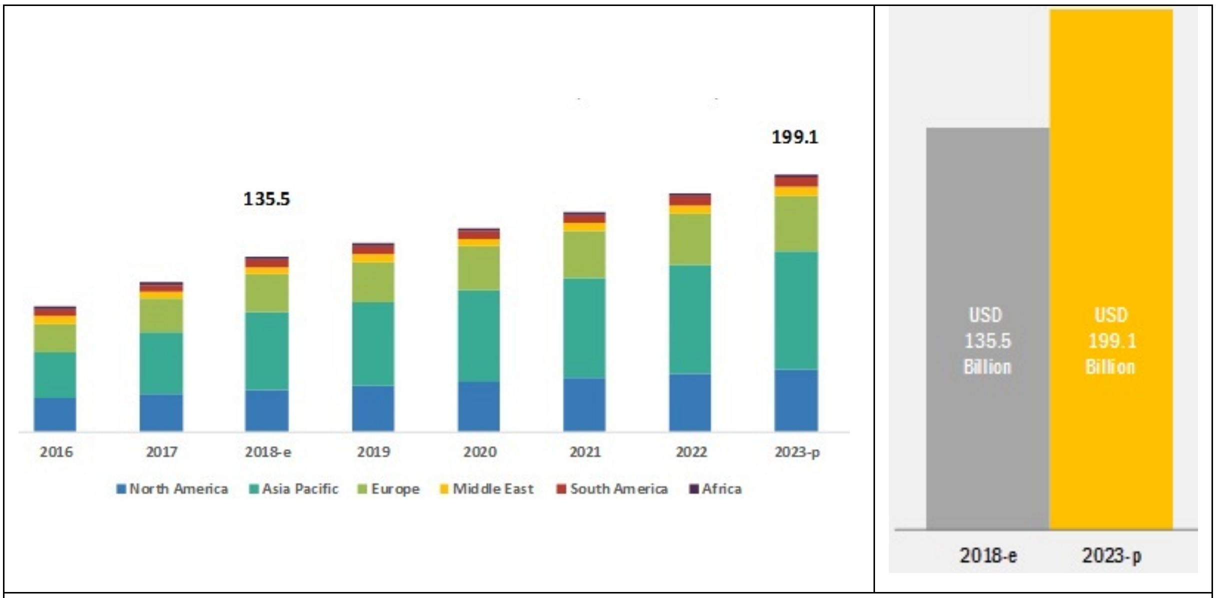

Figure 18. Hydrogen market generation.
Source: (Markets and markets 2019)

As previously stated, hydrogen could help cope with the energy demand from China and India as it looks like the generation market will continue growing steadily according to Markets and markets, IEA, EEA, OPEC and other international organisations.

Finally, Table 4 and 5 gives a comparison of the performance and efficiency between the ICE, BEV and FCEV and as well, the units sold in main leading countries.

Table 4. Comparative performance of primary drivetrains.

		ICE	FCEV	BEV
Lower is better	Current capital cost	$	$ $ $	$ $
	Fuel cost	$ $	$ $ $	$
	Maintenance costs	$ $ $	$	$
	Infrastructure needs	$	$ $ $	$ $
	Emissions	● ● ●	●	●
Higher is better	Efficiency	*	* *	* * *
	Range	* * *	* * *	*
	Refuelling speed	* * *	* * *	*
	Lifetime	* * *	* * *	* *
	Acceleration	* *	* * *	* * *

Symbols give a qualitative comparison between different performance metrics (low/medium/high).
Source: (Stafell, et al. 2018)

Additionally, Stafell et al. made a table comparing the current fuel cell station, forklifts and FEV in 2018.

Table 5. Summary of hydrogen and FCs as of 2018.

Country	CHP units	Fuel cell vehicles	Refuelling stations	Forklift trucks
Japan	223000	1800 cars	90	21
Germany	1200	467 cars, 14 buses	33	16
China	1	60 cars, 50 buses	36	N/A
US	225 MW	2750 cars, 33 buses	39 public, 70 totals	11600
South Korea	177 MW	100 cars	11	N/A
UK	10	42 cars, 18 buses	14	2

CHP = Combined Heat and Power
Source: (Stafell, et al. 2018)

4.3 INTERNATIONAL ORGANISATIONS

This section is dedicated to those organisations promoting hydrogen and FCs. Without promoting agents' new technologies, especially those that need infrastructure would not be able to bloom. In previous sections this study has mentioned that it is true that Oil and Gas is becoming scarce, it is also true that the energy demand will not decrease but increase in the immediate years. Therefore, some organisations and government agencies have realised on this and have join forces to promote sustainable solutions aligned to actual market conditions and preparing to the increment of oil prices by investing on hydrogen. In this section some will be briefly mentioned.

4.3.1 HYDROGEN COUNCIL

In this study it is worth mentioning the Hydrogen Council. This council was established on 2017 and is formed by industry and energy sector CEO's from influential companies from all over the world. The reason to add the council is that they are an essential factor promoting laws in developed countries and they are investing heavily in the hydrogen and FC sector. Most of them are oil and gas companies and automakers (like Shell, Air Liquide and Toyota). We go back to the end of 19^{th} century was the ICE was made and the importance of driving that technology back in that time was the importance and persistence of their developers like Daimler, Benz and Ford. Nowadays the only persistence maker has been Tesla pushing for EV. Maybe the next significant leap will be the Hydrogen Council pushing this technology forward.

They can be a potent force to drive electrolysers and gasification cost lower so they can be truly competitive. This efforts on trying to drive the process down could help decarbonize in the immediate and median future the economy and help reduce emissions. There is also something else to add. The demand of energy will not drop even though there are more efficient electrical appliances, hybrid cars and industries are using catalyst to reduce emissions. This so far has not proven effective. From what this study has described so far is that most of the demand will increase as the energetic needs of the world will increase. So far, the renewables will not be able to cope and deliver with that demand, no matter how efficient they become. What they need is an intermediate energy carrier that can help to cope and harvest the intermittent energy. Hydrogen has proven to be that element. There is still many research and development to do. However, the problem with new technology, it is necessary to plan in the introduction phase, so it can help to solve the decrease on CO_2 emissions and bring energy security with stable energy to the users. This investment can come from the Council to help improve the efficiency of the technology of nowadays and to promote further research with cheaper materials that can help drive the costs down.

4.3.2 FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a public-private partnership which until now has launched 246 projects in Europe established in May 2008. The three main members are the European Commission, Hydrogen Europe Research (research community) and Hydrogen Europe (fuel cell and hydrogen industries representative). They aim to support and promote the research and development as well as demonstration and application of hydrogen and fuel cells in Europe. Under the FCH JU, there is one project that is pushing to use the gas pipelines to conduct hydrogen. The current project wants to know the mix percentage that hydrogen and natural gas can be mixed without harming the existing pipelines; additionally, the project aims to know the current state of the pipelines and the cost of connecting fuelling stations to gas pipelines. (FCH JU 2019 s.f.).

4.3.3. ADDITIONAL ORGANISATIONS

The case of Japan is distinct. Japan government institutions and car dealer companies such as Toyota and Mitsubishi are leading Japan's goal to make Hydrogen Economy a reality by 2020. They are influencing the market heavily with Japan's great subsidies. Japan is impacting heavily Asian markets with his Hydrogen Economy program. Additionally, the high economic growth mainly in China and the research and development in South Korea have created extensive research and development of renewable technology in that part of the globe. These two last countries, China and South Korea, are supplying with research and development Japan's plan to decarbonise its economy. This great influence is driving the current price of hydrogen down, mainly because of the subsidies: "The retail price of hydrogen is currently around 100 yen per normal cubic meter (yen/Nm^3) (USD 90 ($)

cents/Nm^3), and the target is to reduce it to 30 yen/Nm^3 by 2030 and to 20 yen/Nm^3 (17 cents/Nm^3) in the long-term. (Nagashima 2018)"

Besides, NEDO, the New Energy and Industrial Technology Development Organization, promotes technology development and demonstration projects to problem-solving and support industrial, energy and environmental technologies. It was established originally as the Sunshine plan in 1974 only as an R&D long-term plan until formally established in 2003. NEDO has been actively using the Kyoto Carbon Credit mechanisms. (NEDO 2016) They are actively working in smart grid and alternative energy projects in New Mexico, Sandia National Laboratories and Los Alamos National Laboratory (LANL). For 2010, their budget was approximate of 209.7 billion yen (ca. USD 4,000 billion in 2010) (NEDO 2010) In their many projects they recently published a study where NEDO and Partner created a Solid Oxide Fuel Cell (SOFC) with the highest rate in industry: 52 %. (NEDO 2018)

Additionally, the FCEV and Hydrogen Station Network Development is mainly developing hydrogen fuel dispatches mainly in California, in the USA. In some cases hydrogen could be produced in the same places where oil is refined, like Lipman mentions on his report "An Overview of Hydrogen Production and Storage Systems with Renewable Hydrogen Case Studies" in 2011 most of the hydrogen production was mainly in the next three states in the USA: California, Louisiana, and Texas. (Lipman 2011) p.7"

For the International Energy Agency, there is one branch dedicated to promoting the research, development and technologies towards Hydrogen, the Hydrogen Technology Collaboration Programmes (Hydrogen TCP). The number of contracting parties is 24, one of them being the European Commission and has six sponsors, being the most important one: Hydrogen Council, Shell Global Solutions International BV but also UNIDO. Most of their research is concentrated on storage, biological hydrogen, renewable production, safety, life-cycle sustainability assessment and marine applications (International Energy Agency 2019).

CHAPTER 5. CONCLUSION

5.1 SUMMARY

This study has demonstrated that although hydrogen is one of the most abundant molecules in the universe and our planet, in order to take its power, it requires some form of fuel or energy to extract it. Nowadays, H2 has many uses like for petroleum refineries, chemical plants, metal production, edible oils, and electronics manufacturing. The way it is delivered is via liquid or pressurised gas. Sometimes to decrease the cost of on-site hydrogen generation techniques are used for industrial plants or nearby refineries or nuclear plants. (Zohuri 2016)

Hydrogen is not a primary source of energy but an energy carrier, meaning that hydrogen can carry energy. This allows energy to save energy for long periods and then can be transformed and produce electricity and heat. As well, through this study, it has been shown that hydrogen and FCs can improve its efficiency and help diminish GHG, especially CO_2 emissions which is one of the emissions in the mobility, industry sector. It can also help renewables save their excess of energy in their intermittence periods.

There are several methods to produce hydrogen, that can be divided into non-renewable and renewable methods. So far, this study has explored two: electrolysis and pyrolysis and gasification.

According to the Hydrogen Council is also important to visualize how hydrogen technology can be deployed.

Regarding pyrolysis and gasification, the most important is the composition of biomass and the heterogeneity. Many new technologies for gasifiers are available but is being employed at a small scale. Another issue is that pyrolysis and gasifiers yield a broad mix of fuel gases and liquids (being bio-oils). This makes the possibility to adapt this technology to different types of crops, crop refuse and even waste. What needs to be taken into account to perfect it is to clean and decarbonize biomass or refuse before in order to have higher yield percentages volumes.

The following is a sketch in Fig. 19, done by the Hydrogen Council, summarizing the cases and proposing a route towards hydrogen economy for 2050. This describes a possible route towards a sustainable hydrogen economy in the sectors of mobility, industry and power generation.

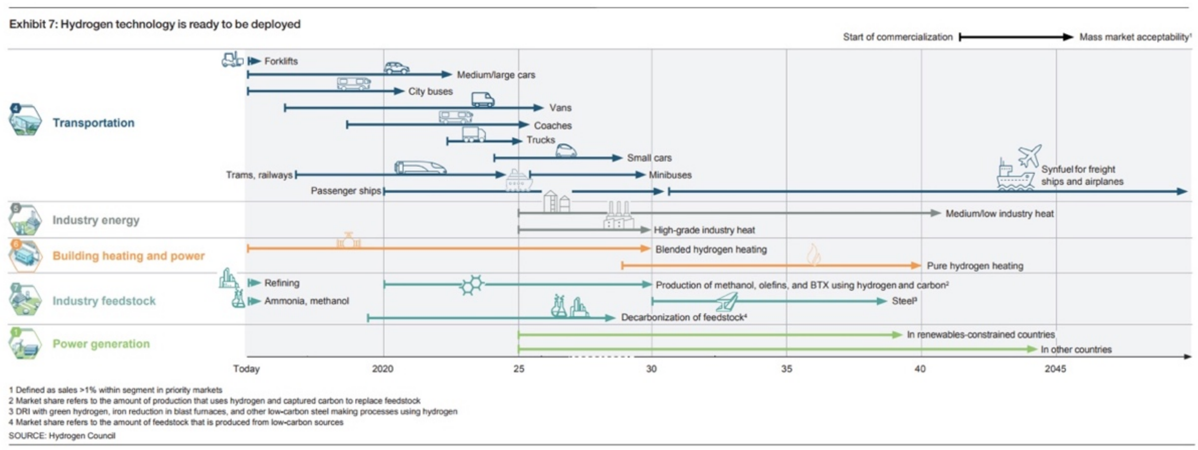

Figure 19. Hydrogen technology roadmap deployment.
Source: **(Hydrogen Council 2017)**

5.2 DISCUSSION OF RESULTS

This study would like to urge need to rethink the way is commonly produce energy. Hydrogen, as mentioned before, produces water when involved in the electrolyser reaction. The primary and newest concerns for hydrogen and FCs are their low efficiency concerning to EV battery cars, its high volatility and the possibility to drain clean water.

Also, there needs to be taken into account the carbon footprint from all the available technologies. All sources of energy emit pollutants into the environment. Even renewables pollute when considered the process of how they were made and when they will be disposed at the end of their lifetime. It is advisable to take all of this into account when choosing another method. What is certain is that renewables have a limited potential in the short-run to reduce carbon emissions by themselves. What is needed is efficient coupling to other energy sources, especially in the industry and transport sector, efficiency in the storage of energy and the end use, the emissions could decrease rapidly. Additionally, accelerated environmental policies could further reduce GHG as well as carbon tax policies or further adopting carbon emissions trading according to the Kyoto Protocol. As well, it is needed a precise and constant track on the environmental protection footprint.

The future of green or blue energy may not be only one primary source of energy. This study showed that through different sources, like MSR, Nuclear Power, Electrolysers and PEMs, gasification, pyrolysis, energy security may be possible but only through a change in the mindset of how actual energy is harnessed. Hydrogen economy makes us think in a better way to harness the energy that we need through the sources, existing infrastructure and the possibility to retrofit it we could sustain and still power the increasing demand of energy.

The main characteristic is the possibility of scalability, standardisation and high integration.

Hydrogen can link well with existing primary sources of energy and with existing power plants using oil/gas and nuclear power plants together with renewables, especially wind turbines.

Hydrogen must overcome two main restrictions from the industry: high cost from new technologies such as for the PEM electrolysers and the limited or non-existent infrastructure.

Hydrogen suffers from an efficiency and deployment paradox. According to an article from the Royal Society named Hydrogen: the future carrier by Zuettel et al., 2010, saying that energy savings may increase energy demand rather than decreasing it. (Zuettel, et al. 2010) This is also explained in the Jevons paradox, called rebound or take-back effect. Summarized, mentioning that when compared short and long periods of energy savings, in the long run, there exists a higher energy use. However, according to its magnitude, if lower than 100 % there are improvements, but if there are more significant improvements than 100 %, the consumption will be higher. (Herring 2015) According to Eurostat, the EU is expected to exceed its European 2020 target of GHG reduction by 20% in 2020. (Eurostat 2018) Nevertheless, according to the Energy Efficiency Directive of the European Commission, ambitious targets have been set for 2030 from 20 to 32.5 %. This will be achieved by yearly energy savings of 0.8 % of final consumption from 2021 to 2030. (European Commission 2019)

The current state of the technology is improving the PEM FC, driving their cost and their sizes by 50 %.

Also, the hydrogen tanks have been improving since Toyota have been promoting their reduce in size, increase safety and lighter weight.

There is a particular situation with new technology, the so-called “the chicken and egg” problem. According to the IBM website, new technology has phases. The five stages can be summarised into the following: introduction, planning, deployment, maturity and retirement. The introduction is when a new technology is proposed to solve a problematic. The planning phase is the first part of how new technology can be produced to reach customers. The deployment puts available technology in the customer purchasing channels serving small business. In the maturity part, technology is used extensively by the public. The last stage, retirement is when the technology is taken over by new or improved technology and migrated to new processes. The main problem lays between introduction and planning (Tost 2010). If there is no infrastructure and support to deliver the technology, it will not grow and reach the public. Therefore, there must be a suitable process to make the technology affordable.

Mainly the efforts of their inventors and a push in the infrastructure help the technology. It is regarded as necessary in the case of new technologies to be supported by associations. Hydrogen so far has the support of councils, association, partnerships and joint ventures from public and private organisations like the Hydrogen Council, which has helped so far to reactivate the Hydrogen Economy. While sometimes the influence of these organisations can be darkened by their intentions or because of the nature of the leading companies, is still worth to mention that investment is vital so technologies can have funding for research, develop, adaptation, improvement and reach final customers. In order to disrupt the Chicken and Egg paradox on new technology, environmental policy can help promote new technology adoption and adaptability. Currently, Tokyo 2020, Made in China 2025 and the EU Energy Efficiency Program to decrease CO2 emissions by 2030 will help boost hydrogen by intensifying technology and making it more readily available and cost-efficient.

5.3 OUTLOOK

The future outlook looks bright in both ways of industry, research (technology development) and policies. There is a small niche, but it is growing. The beautiful thing on Hydrogen is the way it can be harvested. It is true it is one of the most abundant elements but to be harnessed takes somehow a large amount of energy, but it can also bring much energy into the energy system and can be coupled with the current infrastructure.

Possible future research should include more technology increasing the FC hydrogen production and efficiency and a possibility to recycle its components. As well, current policies look very promising for Hydrogen Economy. Especially in Japan, where substantial investment is being made to prepare the country for future events such as the 2020 Tokyo Olympic Games. In the case of the European Union, intensive research is in the gas pipelines to transport and store hydrogen and gas/hydrogen mix to power Heavy-Load Trucks (HLT) through the project supported by the European Commission.

Additionally, there are many more uses for hydrogen and FCs. More energy can be harnessed through domestic FCs that could also heat households. This domestic FCs could help decrease energy demand, giving it a small break to the whole infrastructure and diminishing GHG emissions. Also, it could be the right solution for supplying electrical energy, heat to households and long-term energy storage. A final advantage would be financial saving for the users. (Europen Comission 2017)

Japan is influencing other countries to produce hydrogen. Those countries are Norway and Australia. In an article from Reuters, it is mentioned Australian and Norway efforts to supply

Japan hydrogen with different methods. Both are on a race trying to make hydrogen affordable through different methods that include both renewables, the first, and non-renewables, the latter, with CCS. Norway will supply Japan with liquified hydrogen (LH2) produced by hydroelectric and wind farms supplied on tankers. Norway will try to deliver hydrogen to Japan by a price of 24 yen/Nm3. Australia will deliver hydrogen made through coal and use the CCS also in LH2 form with a price of 29.8 yen/Nm3. In both cases, this massive undertaking will decrease the cost of hydrogen production. There is an excellent investment as FCEV and FC powering industry in Japan want to show the world by 2020 that HE is possible. (Karagiannopoulos, Paul and Shel 2017)

Even though many scientist and researchers believe that hydrogen economy is far to become a reality in the immediate future, this study wants to show that there have been valuable additions to the current technology and some improvements in a small amount of time that prove that the change is coming maybe not fast but steady. For just a piece of example, fuel cells have become smaller and cheaper to the past. Recent events, namely Climate Change protesters all over the world, are pushing government and organisations to take action. Specifically, the actions of the young Swedish activist Greta Thunberg, protesting in her home country, Sweden, every Friday. This movement is taking its toll and is being replicated in more parts of the world, not only followed by students but also by adults. If this trend continues, there are high expectations that organisations will shift to other sources of technology to reverse climate change effects. Nowadays, more governments are banning the use of straws and plastic bags. These actions may seem small, but they carry much weight for making a significant change on how we will harness energy emitting less CO_2 and other GHG pollutant emissions.

5.4 RECOMMENDATIONS

Due to the constraints of time and format, further research on cost analysis from different sources to capture hydrogen is highly advised. Prices tend to vary quite a lot. Mostly because some are dependent on oil and gas sectors and those are subject to variability. Hydrogen is a new market, where new buyers and new technology is being created. Just as this study is written, Major Sadiq Khan announced that 20 double-decker FC buses fuelled with Hydrogen will circulate in London, Great Britain by October 2020 and 18 new trains in Germany are in operations, and the G20 will meet discussing the future of Hydrogen Economy in Japan. All these events may drive more costumers into the market and increase the demand for hydrogen, therefore an increase in scale economies and then diminishing the current price. As well, there are more and more electrolysers improving their efficiency, especially the membranes in the FCs are being more efficient and getting smaller. All this, increasing demand, efficiency improvement and decrease in size of FC and more interconnectedness from FC to renewables are affecting the actual price of H_2. Additionally, this will affect the production percentage this study described in the first section, where it showed that 96 % was produced through the SMR process and the rest through electrolysis. The future looks very promising for this technology that once was used to take a small car from Paris to Joinville-Le-Pont in 1863 then taking astronauts to the moon in the 1960s, to power electricity in small islands and far away shelters Hydrogen economy, an economy with less carbon, may be possible and able to linking renewable primary energy sources.

Additionally, CCS technology should also be researched as it would also help to keep reducing the CO_2 emissions from most of the factories that are in operation at the moment. A possibility is that H2, together with renewables and CCS, could diminish the GHG emission and power the increased demand for energy.

A note regarding pyrolysis and gasification, many energy producing technologies use those thermochemical processes. Research should be solely on this process as it continues. The problem is that pyrolysis and gasification yield many useful fuel gases and liquids (methane, hydrogen, biochar, bio-oil). According to the Bridgwater study of 2012, this technology holds a lot of potential according to its versatility, increased efficiency and environmental acceptance. As mentioned regarding FCs, there needs to be a comparison solely on the past literature review and the real-life conditions reactors. (A. Bridgwater 2012)

Finally, this study wanted to provide the actual state-of-the-art in two leading technologies to produce hydrogen, pyrolysis-gasification and electrolysis. This study showed that hydrogen applications have a high possibility, but there need to be more cases put on practice. As well, PEM efficiency can improve by the use of nanotechnology in the membranes. Nowadays, PEM cost due to the continued funding of Councils and Organisations all over the world is decreasing. As well, the case of pyrolysis and gasification is taking more importance. Through this, the cost of hydrogen production could decrease and be more consumer friendly. Some institutions have aimed to intralogistics to start building a market and have planned different strategies to improve the current technology of producing hydrogen with renewable technologies, especially photovoltaics and wind turbines, therefore address the problem of the intermittence.

Hydrogen Energy Systems have the best potential of becoming a viable possibility in the near future.

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