UNIVERSITA' POLITECNICA DELLE MARCHE
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Analisi di letteratura in merito alla sostenibilità ambientale dei processi di produzione di idrogeno "green"

Literature review on the environmental sustainability of "green" hydrogen production processes.

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1) Introduction

The main objective of this thesis is to bring to light and investigate what appears to be one of the major energy sources of the future, Green Hydrogen. We will therefore present in the beginning of the thesis the reasons beyond the need to change the modern and actual situation, improving and reducing global gasses emissions and creating a self-sustainable economy. In fact, we will deal with the Green Hydrogen through what impact it can have in the everyday sphere, concerning trivially our needs, and in the industrial sphere, both with one goal: the reduction of emitted carbon dioxide and an environmentally sustainable future. To make the reading enjoyable and not boring, I will make use of sources carefully selected. Since this is a scientific thesis, the articles analyzed are almost all taken from scientific journals that can be easily found on Sciencedirect.com or journals of this kind. The few sources that are not part of this are, however, articles from the world's largest organizations, such as the International Energy Agency or well-known global groups. The main search engine is therefore the one mentioned above. The selection we have made is therefore intended to present those technologies that are most widely used today for green hydrogen, carefully explaining the production processes. Although this is a scientific thesis, we will not go too deeply into the regions from a chemical or engineering point of view, or rather yes, but our focus will be on the environmental impact they have. This will be followed in subsequent chapters by LCA: Life Cycle Assessment. These studies in fact aim to highlight the impact of this new technology from production to disposal, passing through each stage of the process. We can therefore preannounce that the aim of this thesis is to inform and summarize the main innovations that this technology introduces, specifying its potential and how it can lead to a green future. The central part of the thesis is aimed at differentiating the various methods of producing green hydrogen, while in the final part we can find conclusions that summarize everything and suggest the best paths to take towards the great desirable goal of global zero emissions. It is also extremely important to consider that the main topic of this thesis, Green Hydrogen, is highly topical and very promising for the future.

2) What are Fossil Fuels?

Since the first Industrial revolution man has always used coal as their main source of power for heating and producing energy. But what is coal? Coal is a fossil fuel that is a substance formed millions of years ago from carbon-rich remains of animals and plants, as they decomposed and were compressed and heated underground. When fossil fuels are burned the stoned carbon and other greenhouse gases are released into the atmosphere. Later during the years, many fossil fuels have been discovered and man has evolved towards new and very sophisticated forms of energy. But is it really like this? Abraham Pineo Gesner was a Canadian physician and geologist who invented Kerosene, his discoveries changed the way the world moves and how industries produce nowadays. He found in coal a way to synthesize a refine liquid fuel that burned more cleanly and cheaper than whale oil. Since the start of the nineteenth century many petroleum industries started growing all over the world. This new modern enlightenment is based on research and belief in science. One would think that this era would lead to a lush and revolutionary world, but like all life-changing discoveries in human life, they harbor pitfalls. In 2023 we could think that man has so far evolved from primitive source of energy leading to new and sustainable ways, but it’s not like this. That’s were the main problem resides at.

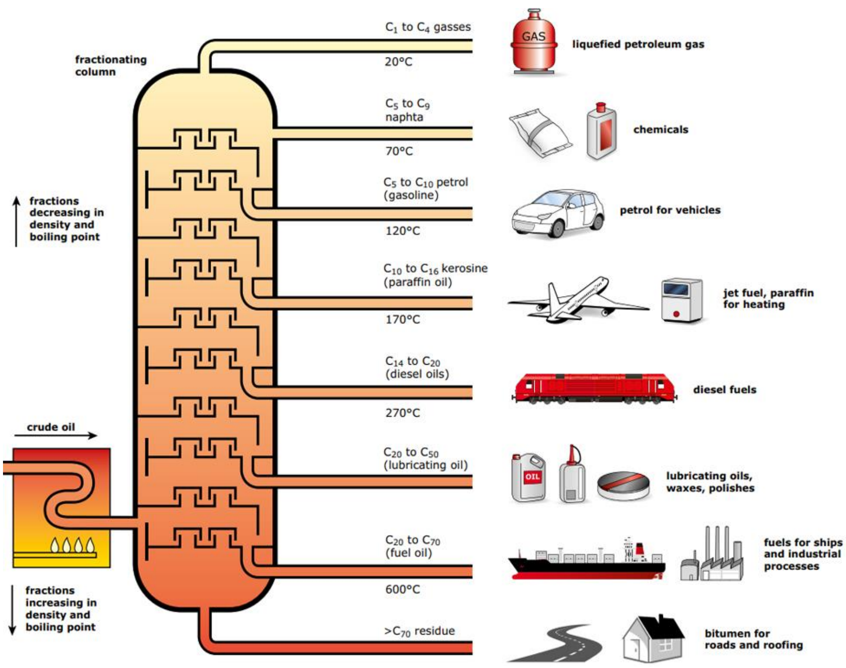


Figure 1 Fossil Fuels

The International Energy Agency (IEA) gives us an idea of the main source of global energy situation .

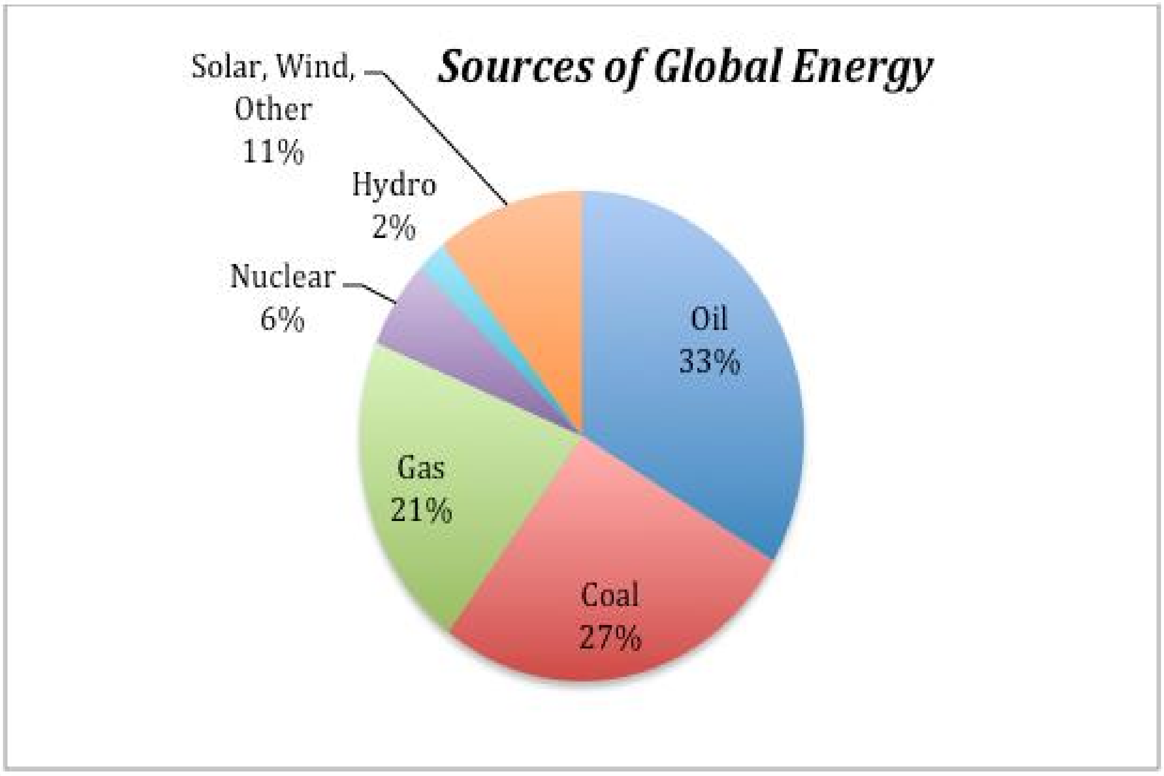


Figure 2 Energy Source

Major world powers such as the U.S., China, etc. still rely on non-renewable energy sources for the production of the latter as we saw in the graph. The use of internal combustion engine for auto vehicles, the replacement of steam engine with diesel has been a turning point in history with petroleum being a status of strength for nations. But what’s the problem with this liquid? In the 2000s this new demand and other politic reasons led to an energy crisis which saw his peak in 2008 with the price of oil reaching $147.30 per barrel and the most important consequence is the impact it had in world’s environment.

3) Why renewable and sustainable sources of energy are necessary?

The increasing demand of energy during the last fifty years is leading industries all over the world to an abuse of fossil fuels to satisfy these needs. World's pollution is drastically increasing and is no longer sustainable. According to World Health Organization every year seven million people die from air pollution due to inflammation and severe diseases. High level of particulate pollution reduces the amount of sunlight that reaches the surface of earth. It impacts the photosynthesis and contributes to a bigger hole in the Ozone Layer caused by Chlorine atoms released by chlorofluorocarbons (CFCs).

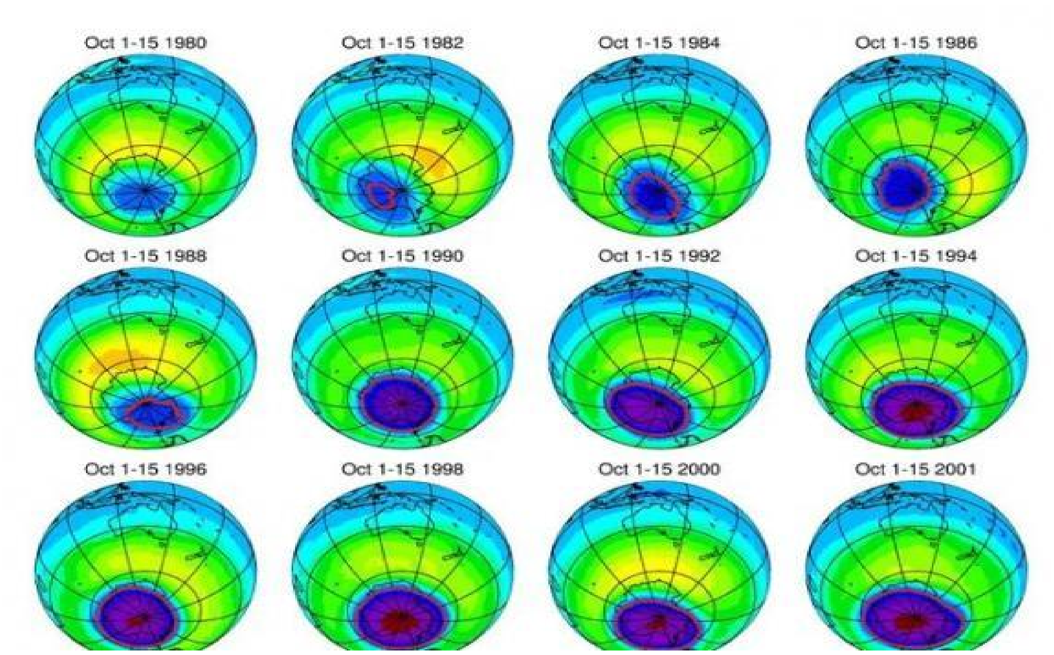


Figure 3 bigger hole in the Ozone Layer

Once free, chlorine is able to react with ozone (O_3), subtracting one molecule of oxygen (O) from it and thus forming chlorine monoxide (ClO) with release of oxygen (O_2)

$$CI + O_3 = ClO + O_2$$

The chlorine monoxide molecule (ClO) when it encounters another oxygen molecule (O) splits, again releasing chlorine (Cl), which is free to "destroy" another ozone molecule (O_3) thus realizing the chlorine catalytic cycle.

$$Cl + O = Cl + O_2$$

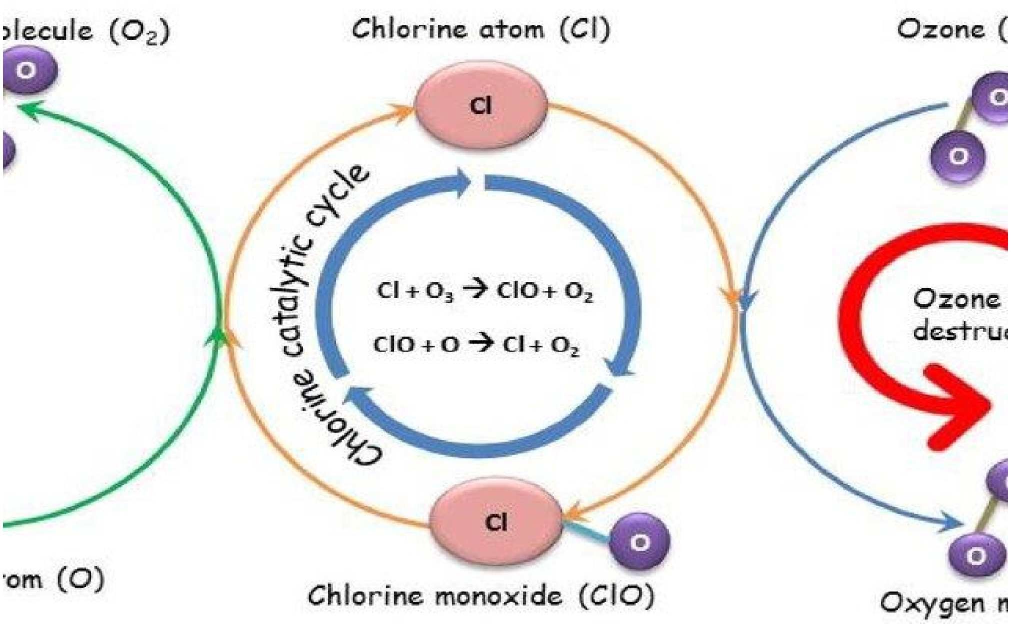


Figure 4 chlorofluoroncarbons

Industrial production of CFCs began in the 1920s, and the perpetuation of this cycle over the years has resulted in an average 3% reduction in ozone that protects us from ultraviolet-B radiation and conduces an important raise in temperature. This climate change leads to a range of consequences to our ecosystem that we cannot afford with a projected temperature increase of 4 Celsius degrees in the coming decades. The consequences to this outcome are dramatic with sea level rise, abnormal heat waves, drought and proliferation of viruses and diseases worldwide. These mentioned are just some of the consequences we are going to face if action is not taken. But this is not the only problem. Fossil fuels are running out. Millions of years to form and hundreds of years to consume them. According to IEA within 50 years many energy sources we are using will no longer be available. As we can see in the graph oil gas and coal will have this trend in the future

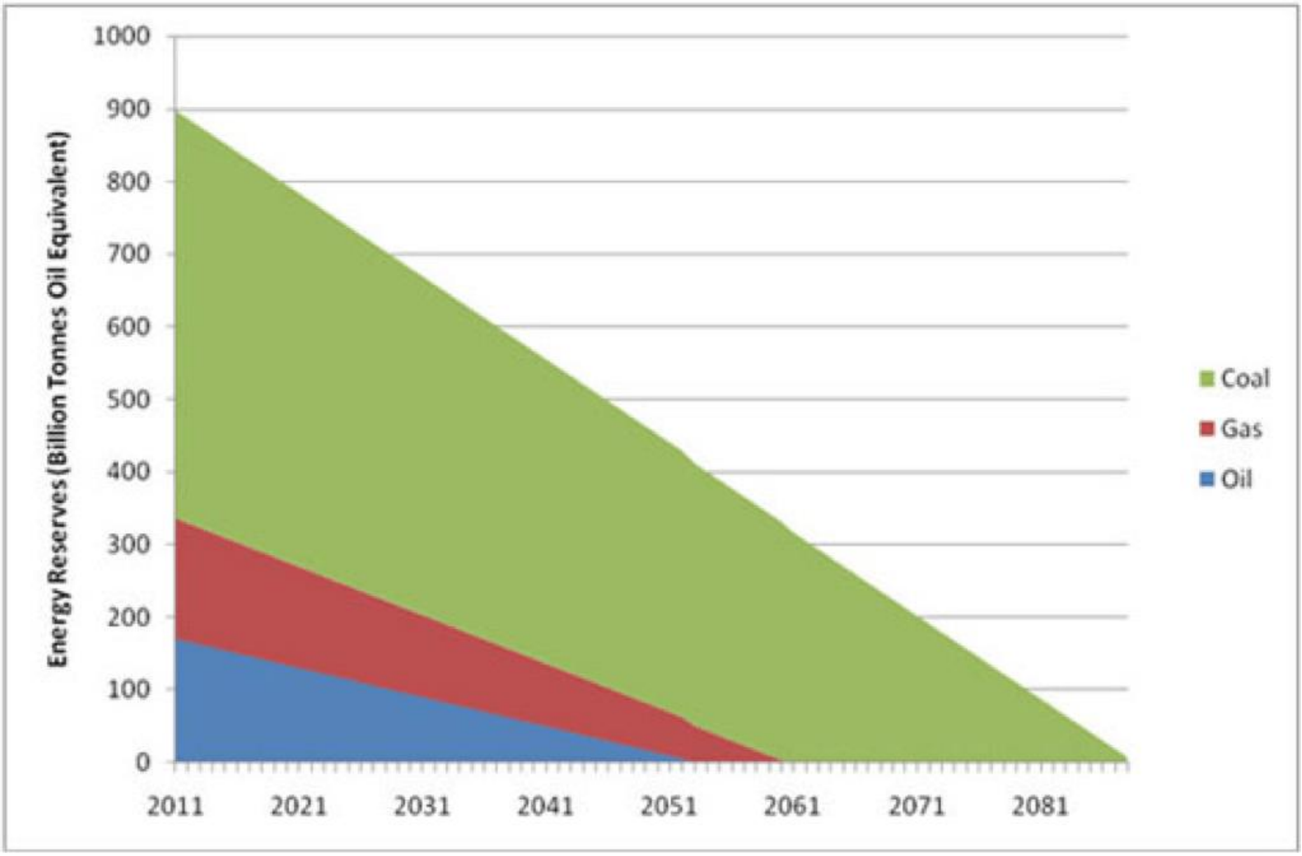


Figure 5 Oil is running out.

4) What can we do?

Well, all world's major governments are working to try to reverse this trend. The g20 met in Glasgow in 2021 to try to limit the temperature increase to 1.5 degrees. In this sense, this thesis is not about politics, but the preamble was necessary to explain why we are introducing a new form of energy that is still not very common but has enormous potential and with current technologies could greatly reduce global CO_2emissions by reversing the trend that has only increased over the past decades. This source of energy is hydrogen.

5) What's Hydrogen?

Hydrogen was discovered by the English physicist Henry Cavendish in 1766. Scientists had been producing hydrogen for years before it was recognized as an element. Hydrogen and energy have a long-shared history – powering the first internal combustion engines over 200 years ago to becoming an integral part of the modern refining industry. It is light, storable, energy-dense, and produces no direct emissions of pollutants or greenhouse gases. But for hydrogen to make a significant contribution to clean energy transitions, it needs to be adopted in sectors where it is almost completely absent, such as transport, buildings, and power generation. Although it may seem like a new form of energy, the demand for hydrogen over the past 50 years is described in the following graph:

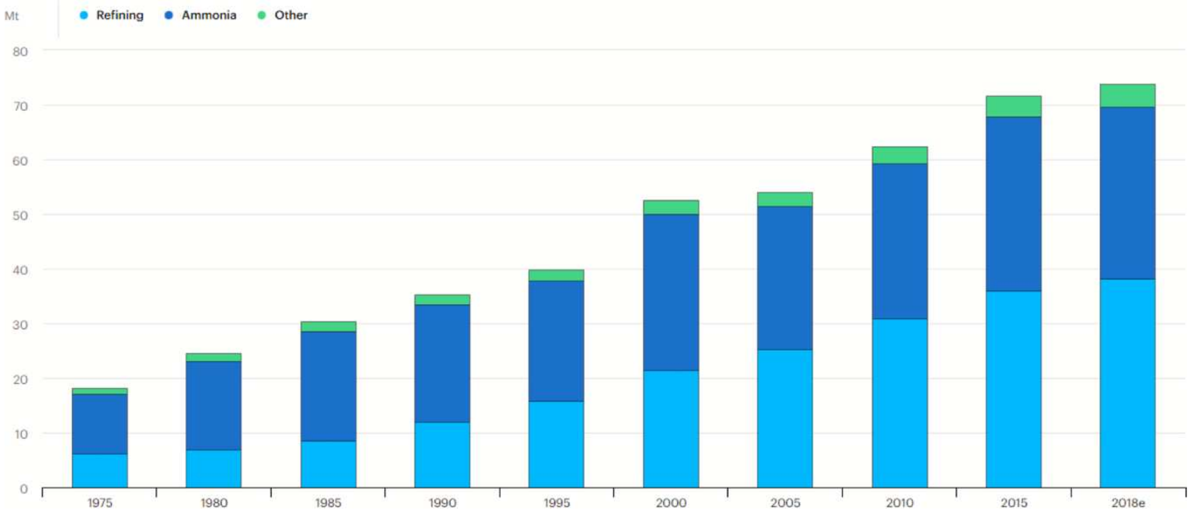


Figure 6 Hydrogen demand

As two-thirds of the total emissions come from the energy sector, the implementation of hydrogen can contribute to reducing the greenhouse effect in the coming decades. The first solar-powered hydrogen generator was built in Germany in 1990. Analysis by the International Energy Agency shows that hydrogen will contribute 6% of the world's total energy needs, while the Hydrogen Council estimates the same at 18%. Almost 120 million tons of hydrogen are produced annually of which two thirds is pure hydrogen and one third is mixed with other gases. Approximately 5 % of hydrogen is produced from natural gas and coal, and another 5 % is produced as an electrolysis byproduct. At the moment, there is no appreciable amount of hydrogen that is produced from renewable sources. On the other hand, this pattern will soon shift. Since hydrogen is always found together with other elements, it must be separated from hydrocarbons such as methane or water to be used as an energy carrier. Currently, approximately 95 % of hydrogen generation worldwide comes from fossil fuels .

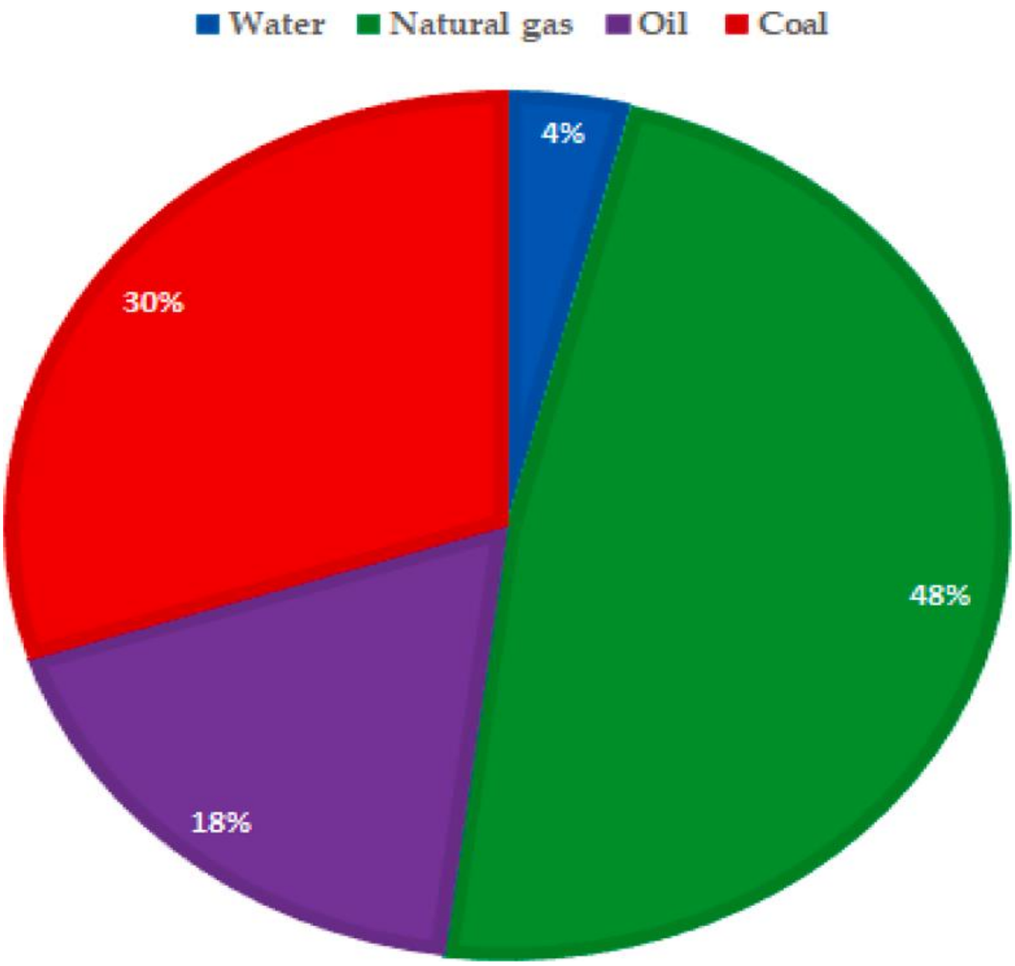


Figure 7 Energy sources

Among the global goals, as mentioned above, is to introduce hydrogen in an attempt to replace classical fossil fuel-based energy sources. By 2050, in fact, as we will discuss later, we should be moving towards a zero-emission future. The role of hydrogen will in fact be fundamental if used in the way we will explain in the following paragraphs. **Error! Reference source not found.**

6) Types of Hydrogen

-Grey hydrogen

Grey hydrogen is produced from fossil fuel and commonly uses steam methane reforming (SMR) method. During this process, CO2 is produced and eventually released to the atmosphere. It's the most straightforward method for producing hydrogen; however, it is not sustainable. Gray hydrogen is obtained by producing greenhouse gases higher than 36.4 gr of carbon dioxide per MJ, from renewable or non-renewable sources. Currently, natural gas and coal are the primary sources of hydrogen supply.**Error! Reference source not found.**

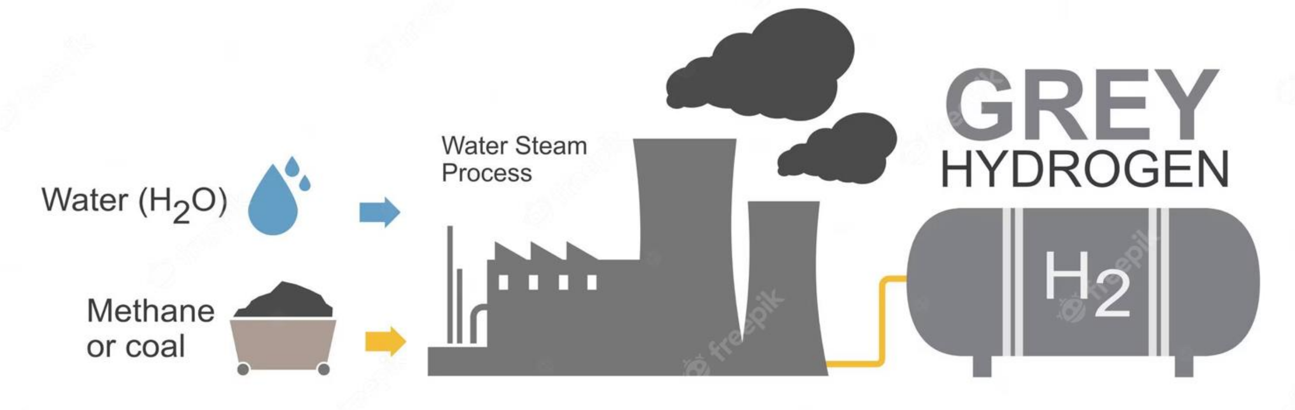


Figure 8 Grey Hydrogen

In reality, there are many other colors that characterize the different types of hydrogen, but in this thesis ,we will only analyze the most important ones and especially those that in the future may replace current energy carriers that are no longer environmentally friendly. Starting with grey hydrogen, we will move towards increasingly cleaner and more environmentally sustainable types, thus introducing the subject of the next section.

-Blue Hydrogen

The second type of Hydrogen energy is the blue one, more sustainable then the grey one but still not the cleaner yet.

Figure 9 Blue Hydrogen

Blue hydrogen comes from the use of natural gas, which is a fossil fuel, and the carbon dioxide generated is almost all captured and stored underground or confined and reused. One way to apply this is Steam Methane Reforming which mix natural gas with hot steam and a catalyst, producing hydrogen, carbon dioxide and carbon monoxide.

Green Hydrogen

Green hydrogen is the pivotal topic of this thesis, aimed at showing the ecological advantage of using this fuel. This new technology, not yet perfected, and we will see later how and where it can evolve, has great potential and with scientific research can lead to zero-emission energy production. The advantage is the use of all-natural inputs from sustainable emission sources.

7) How does it work?

Green hydrogen production methods are numerous, and we will explain the most important and efficient ones below:

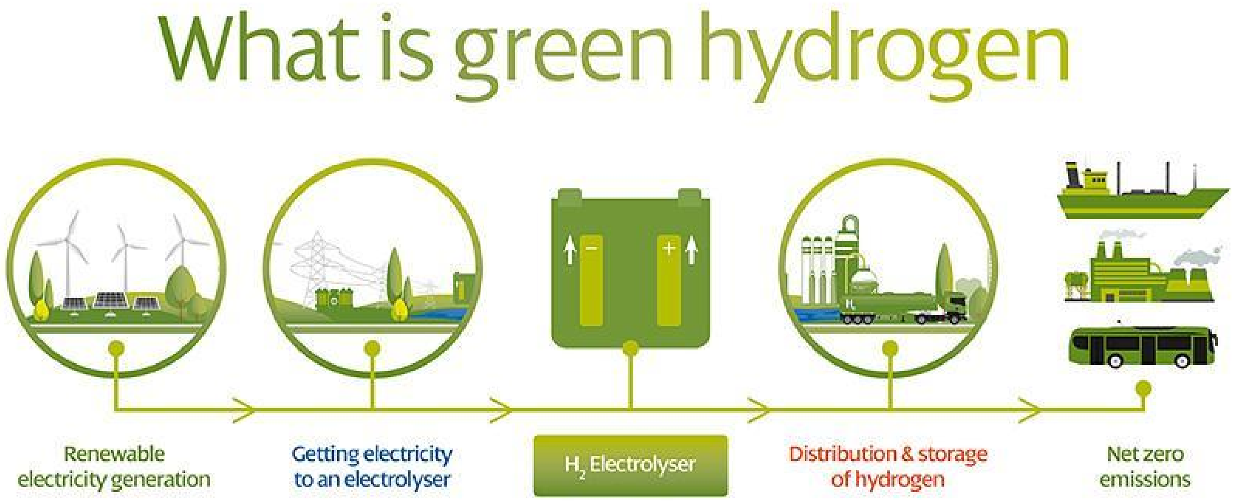


Figure 10 Green Hydrogen

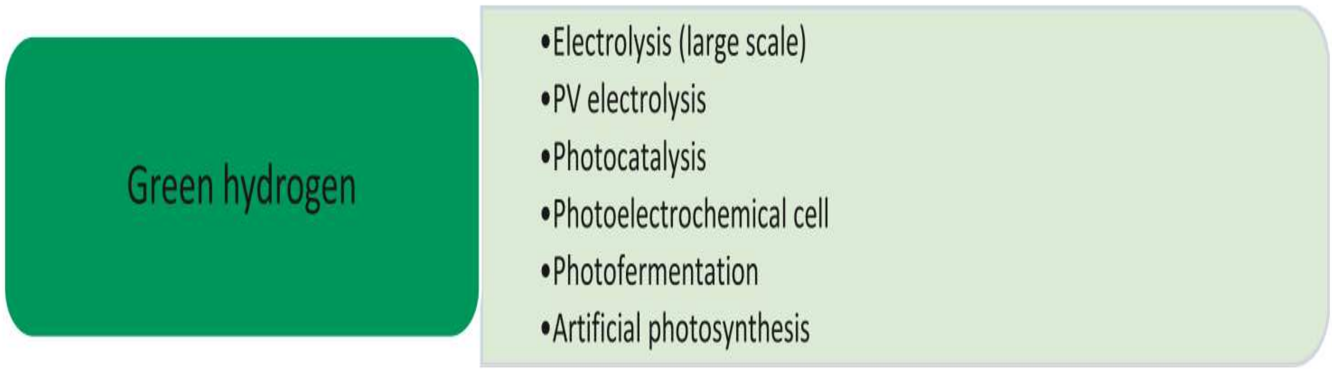


Figure 11 Green Hydrogen methods

8) Electrolysis

-PEM.

Electrolysis is one of the main ways to produce green hydrogen from renewable and nuclear resources. It uses electricity to split water into hydrogen and oxygen. The place where it takes place this reaction is called electrolyze. Electrolyzers can be of various shapes and sizes to suit small, medium, and large-scale requirements.

But how does it work? Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte. Different electrolyzers function in different ways, mainly due to the different type of electrolyte material involved and the ionic species it conducts.

In a polymer electrolyte membrane (PEM) electrolyzer, the electrolyte is a solid specialty plastic material. Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode. At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas. Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H_2$.Although the advantages of the PEM method are undisputed, with 99% pure hydrogen production.

and a compact design, there are some disadvantages that lower the efficiency of the process to 62-85%. This is due to the high cost of manufacturing polymer membranes and the use of noble metals.

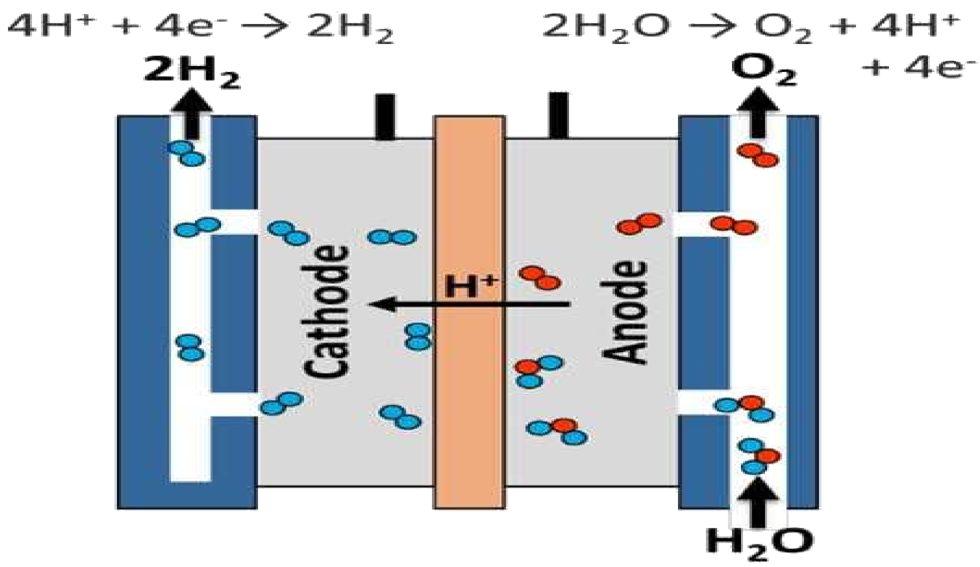


Figure 12 PEM

-ALK

Alkaline electrolyzers are another method that exploits electrolysis by transporting hydroxide ions (OH) from the cathode to the anode with hydrogen production in the cathode. Transport takes place via an electrolyte, an alkaline liquid solution consisting of sodium and potassium hydroxide.

-SOE

Solid oxide electrolyzers uses a ceramic material as electrolyte that conducts negatively charged oxygen ions (O_2^-)at high temperature generating hydrogen. Steam at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions. The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit. For the process to take place correctly and the solid membrane to function, the temperature must reach 700-800 degrees. Recent studies claim that the use of a proton-conducting electrolyzer and ceramic electrolytes makes it possible to lower the temperature to 500-600 degrees. This would allow existing technologies such as nuclear and non-nuclear to be used to operate this circuit at these temperatures .**Error! Reference source not found.**

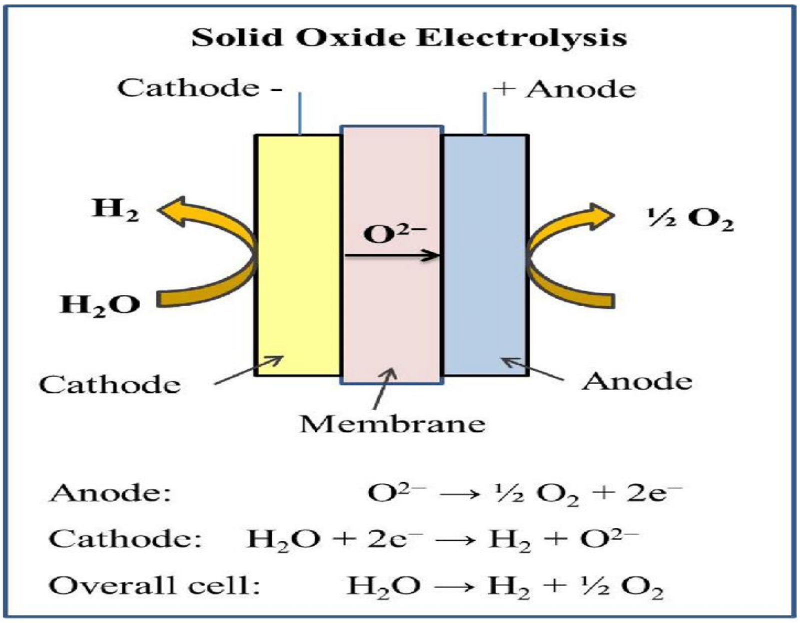


Figure 13 SOE

Photovoltaic Electrolysis

A promising alternative to the above systems is the use of photovoltaic cells coupled directly to electrolyzers. The energy produced by the photovoltaic system is used to power the electrolyzers and the circuit is called a solar-hydrogen-hybrid-system. The circuit consisting of photovoltaic (PV) panels, electrolyzers (EL) and the use of an accumulator such as a battery provides an alternative and, above all, clean way to produce hydrogen. The system thus composed has numerous advantages. For grid-connected systems, the energy from the grid is used to power the electrolyzer for longer and with greater continuity, thus avoiding frequent re-starts and shutdowns of the system. Another factor to consider is the safety of the system by being able to distribute excessive outputs in the external circuit beyond the maximum allowed and always give the system sufficient input for operation. For off-grid hybrid systems, the PV-ELs can be directly coupled to each other without intermediate elements, or we can use auxiliary devices such as maximum power point trackers (MPPT) or via short-term storage components. The accumulator or battery is used to counteract excessively variable inputs from the photovoltaic system. However, currently the efficiency of the solar-hydrogen hybrid system is too low to compete with fossil-fueled systems. he efficiency of this system can reach a maximum of 30% with high system degradation. Although the hybrid system's potential can reach 90%, we are currently

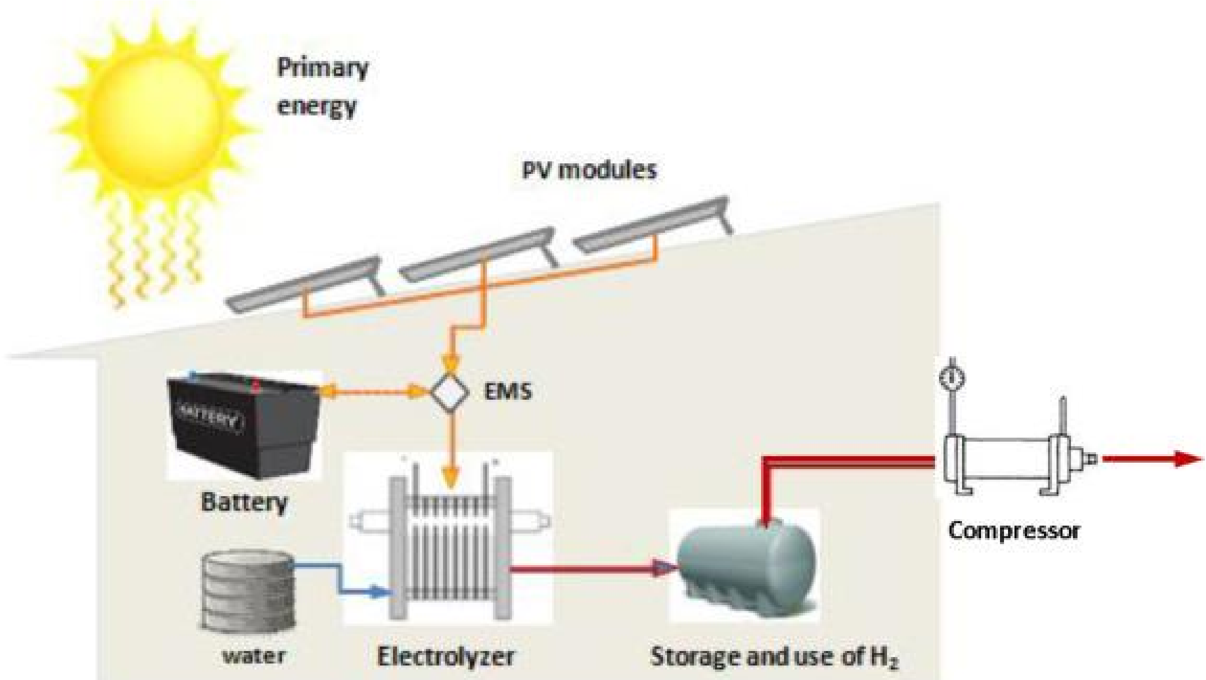


Figure 14 PV

unable to compete with fossil-fuel hydrogen. The fundamental problem is that the fluctuation of energy supplied to the electrolyzers greatly lowers its efficiency. At first glance, we could introduce, as in the system described above, an electrical circuit connected to the PVs in order to give a constant input to the electrolyzers, but this would greatly lower the efficiency of the solar panel system**Error! Reference source not found.**.

Photocatalysis

Hydrogen production by solar water splitting is one of the most promising methodologies in the future to overcome the problems mentioned above. In recent years, photocatalytic water splitting has attracted many scientists, given the potential, to build an efficient system. Why use solar energy for water splitting? Solar energy itself is inexhaustible striking the earth's surface at any instant generating an energy equivalent of 130 million 550 MW power plants. The process of capturing solar energy underlies the photosynthesis processes of plants which makes anthropological use desirable. In the photosynthesis system, water splitting is the main process in which the generated holes are captured by the oxygen-enveloping complex Mn4CaO5 to oxidize water into oxygen and protons. Thus, photocatalytic cleavage is considered an artificial photosynthesis. Thermodynamically, the reaction is uphill endothermic with Gibbs energy release of 237 KJ/mol.

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

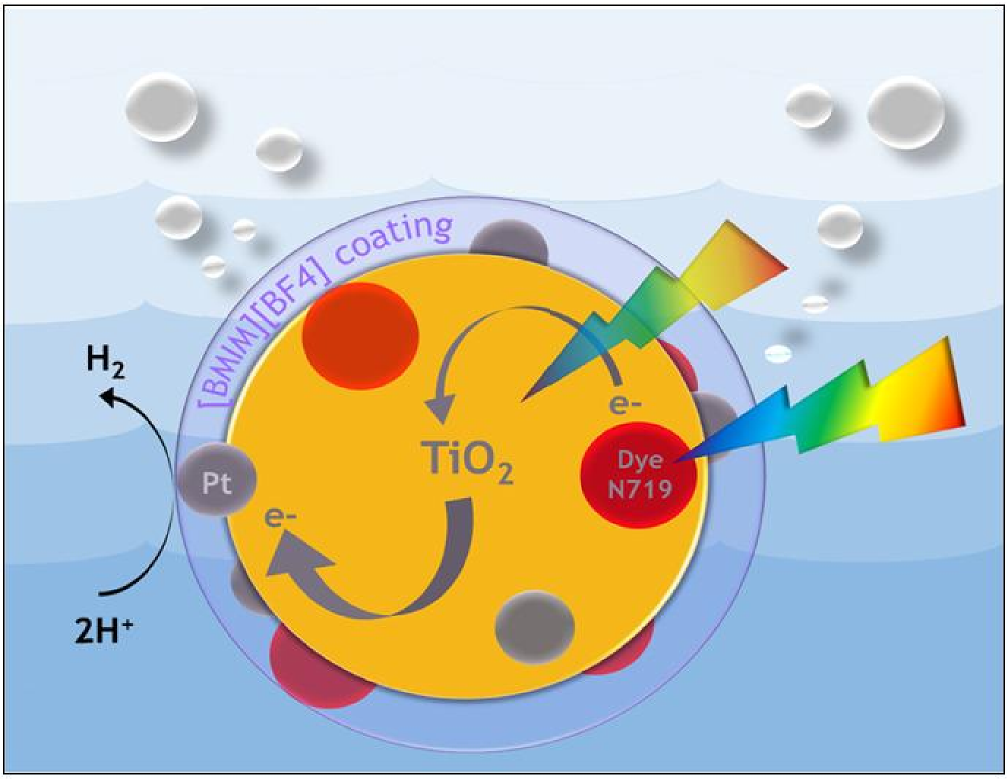


Figure 15 Photocatalysis

Photocatalytic water splitting reaction has three main steps.

-photocatalysts are excited by light to generate electrons and holes.
-The electrons and holes generated are separated and transferred to the surface of the photocatalysts
- the separation relationship occurs through solar energy.
The mechanism beyond this is that semiconductor materials are used for their special band structure.
The valence and conduction bands are separated by a forbidden band, called band gap, where electrons cannot be. When the semiconductor is irradiated with light at equal or higher energy than the band gap, one electron can absorb the energy and move forward to the conduction band creating a hole in the valence band. The holes and electrons can migrate to the semiconductor's surface and reacts with adsorbed speces creating free radicals which are highly reactive and typically then go on to attack other components of the system, such as pollutants. To maximize the photocatalysis reaction, it is necessary to act on the surface area by maximizing the surface area/volume ratio. The use of nanometer powders is optimal for a choice of surface area as the surface/volume ratio is inversely proportional to particle size. The reason behind this choice is that surfaces can contain lattice defects that powders do not. The materials used are: ,TiO_2,ZnO,CeO_2**Error! Reference source not found.**

Artificial Photosynthesis

The nuclear fusion of hydrogen in the sun produces light and heat that irradiates our earth with about 100-TW of solar energy. This energy is captured annually by the natural process of photosynthesis in biomass on land with an efficiency of 0.1%, which is about six times our annual world demand. Photosynthesis transforms energy from the sun into oxygen, which creates oxygen and fuels its vital functions. Chemists, biologists and physicists are collaborating together to try to recreate the natural reaction in the laboratory. The aim is therefore to find a catalyst to make the reaction happen. Photocathodes and catalysts can drive water splitting inspired by natural photosynthesis. The process converts the available solar flux, $H_2O$and CO_2 into O_2 and CH_2O.Artificial photosynthesis therefore attempts to convert H2O and CO_2 into liquids such as methanol and gases such as hydrogen. Scientists are therefore looking for a substance as a catalyst to convert water and CO_2 using solar or artificial UV light. Available catalysts are capable of converting carbon dioxide into carbon monoxide (fuel) but are inefficient and very slow due to the solvents used. It is therefore necessary to try to eliminate the toxicity of the solvents by heating and compressing the carbon dioxide to criticality at around 35 degrees. Natural light absorbers can capture most of the light available to them, unlike the semiconductors available in solar cells, which only capture some of the fringes and types of waves. The difficulties encountered are also not negligible. Contrary to what happens in natural where the reaction is continuous and uninterrupted, this is not the case in the laboratory. In fact, the reaction is continuously interrupted, burning chemicals although producing hydrogen and oxygen.
The process described so far can be summarized in 3 steps.

1)The separation of water into oxygen and hydrogen using light and a photocatalyst.
2)The use of a membrane to separate hydrogen from the produced gaseous isle also containing oxygen.
3)The use of a catalyst to create the reaction between hydrogen and $CO_2$to produce olefin.

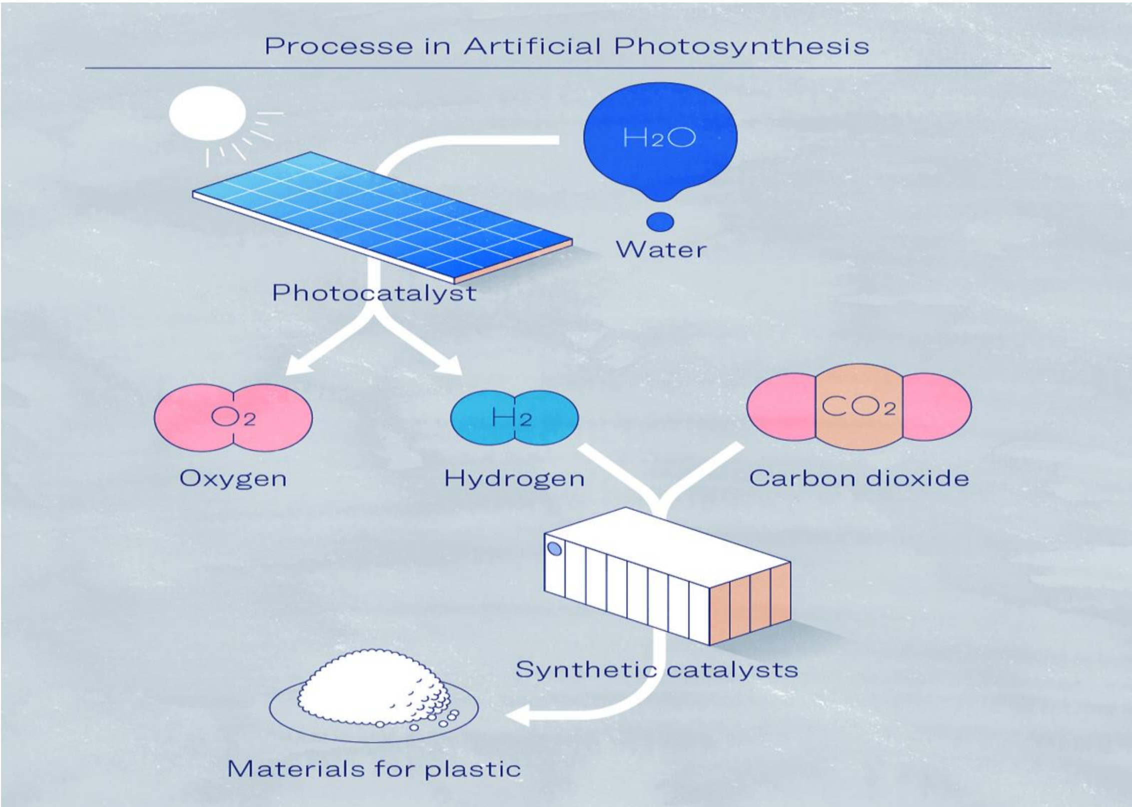
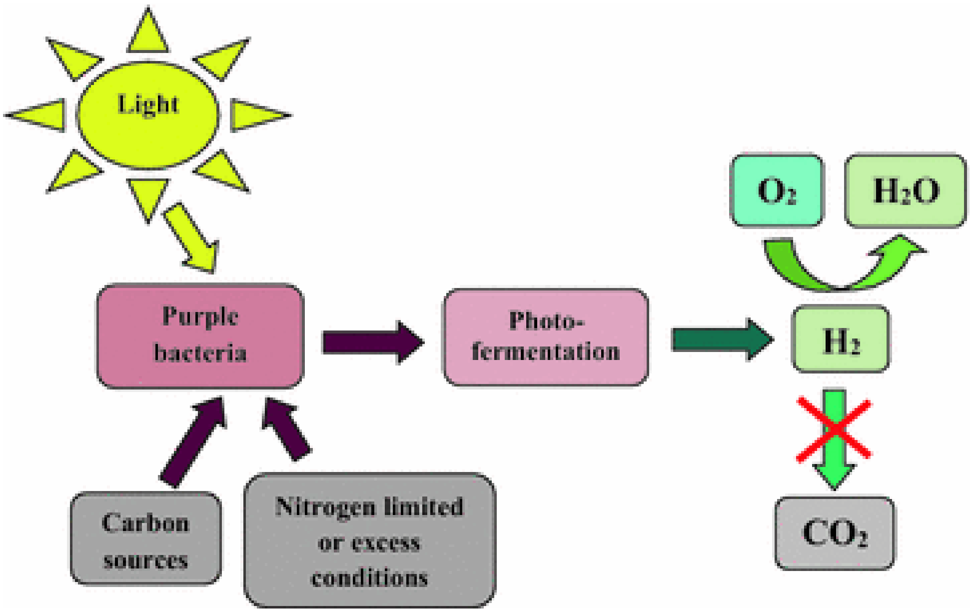


Figure 16 artificial photosynthesis

One of the advantages of this process is the recycling of waste material. In fact, the New Energy and Industrial Technology Development Organization (NEDO) has listed artificial photosynthesis as one of the most promising methods for the future, because in addition to supplying any engine or industry with hydrogen, it allows waste materials to be recycled. The olefine produced at the end of the process is in fact reusable to produce plastics, thus avoiding on the one hand the disposal of the substances, which is highly polluting, and on the other hand the use of further oil for the production of new plastics. There are, however, other complications. Hydrogen and oxygen mixed in gas are a very explosive compound, which is why it is essential to construct a high-performance membrane to quickly separate the two elements. It is obvious that all these investments have an initial cost, and economists and politicians are very critical of these new technologies that do not immediately show excellent results. What is equally obvious is that scientific research must continue uninterruptedly so that the results will arrive, but this takes time and maybe there are yet better methods for producing green hydrogen at the moment**Error! Reference source not found.**

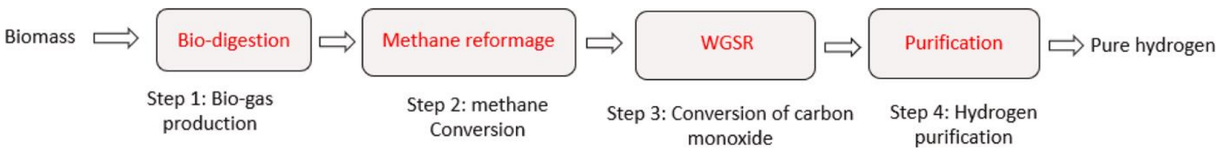
Photo-fermentation

Another method used in the green hydrogen industry is photo fermentation. We must always remember that the processes studied so far are still in the developmental stage, but in the coming decades they will surely be able to achieve such efficiency that they can replace fossil fuels and their use in hydrogen production. In photo fermentation, anoxygens and photosynthetic bacteria especially PNS are used. But what are PNS? Purple non sulfur bacteria are able to reduce H^+ ions into H_2 gas, using the reducing power from the oxidation of organic compounds such as low molecular weight fatty acids, and energy from the sun. This process is considered promising because of the high substrate conversion yields and the possibility of using a large spectrum of light derived from the sun. In nature, the elements that are capable of performing this process are, for example, algae. In fact, in the early 1990s it was discovered that by depriving algae of sulfur, they stopped producing oxygen by performing normal photosynthesis and began to produce hydrogen. The term biohydrogen therefore refers to the hydrogen produced by these processes. But what future does this technology have?. At the economic level an algae culture of the size of 700 thousand km2 would be able to satisfy the entire world by replacing gasoline. **Error! Reference source not found.**



Biomass

Biomass is always a clean energy source in hydrogen production. In this thesis we are showing many effective methods to synthesize green hydrogen but according to the needs and use they differ and prefer production routes. Neutrality towards pollution and its large availability in the environment make it the most used and especially less expensive and clean process in the 'large-scale industrial environment. The approach for the production of green hydrogen consists in the use in the use of biogas produced by an "anaerobic digestion" of biomass called methanization instead of the classic use of methane. The basis of the mechanism is the direct conversion of biomass into hydrogen and methane. The compound thus created is called biohythane where hydrogen is 10 percent of the total, methane 60 percent and the remainder is CO_2. At first glance it would seem to be a rather polluting process with high CO_2 production but with the purification process shown below, pure hydrogen can be produced. The production process can then be grouped into 2 steps: The production of biogas and the conversion of biogas into hydrogen.
The above processes unlike those based on solar energy are not completely zero-emission in that for decarbonization and for the production of 100% pure hydrogen an amount of $CO_2$is produced, about 13.7 kg per kg of H_2Which still makes the process competitive**Error!**



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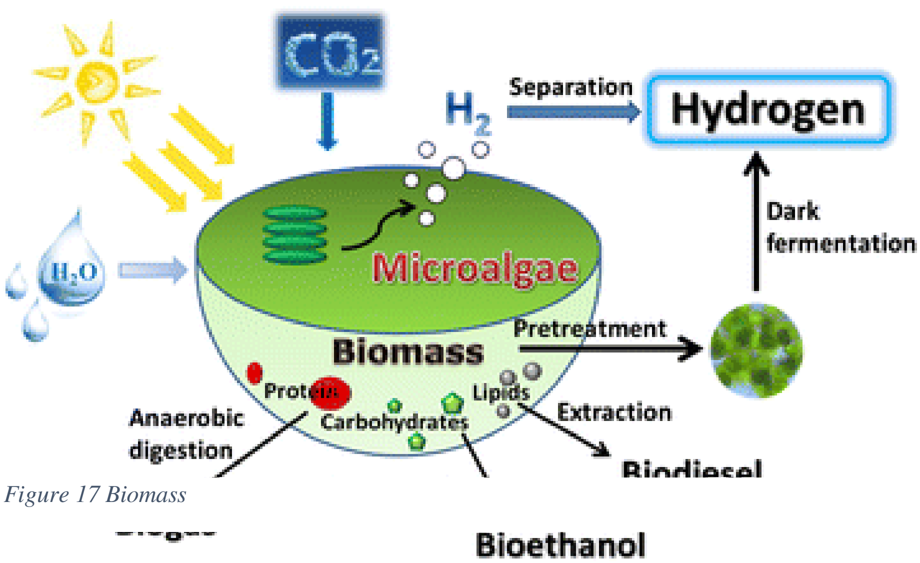


Figure 17 Biomass

9) Life Cycle assessment

The question we now ask ourselves is, with all the information given so far, how do we choose the best methodology for the climate? Which methods can we use to make the most sustainable choice?
Life Cycle Assessment (LCA) is the analysis of the impact an object has on the world.

Figure 18 LCA

In this section we will explain who may be interested in this, how it works and who benefits from it. The objective of LCA is not to create new data but to make decisions easier. In 2023, the main goal is to reduce the environmental impact of a product or process. To the question of who LCA is aimed at, the answer is everyone .From an industrial point of view, the LCA is fundamental because, on the one hand, industries have to comply with environmental laws and regulations, and therefore doing an LCA for products is fundamental to comply with anti-pollution regulations. On the other hand, investing in new products must always go through sustainability. The LCA impact on the market is much more important than people think. Nowadays, more than 50 per cent of consumers and potential customers support and believe that companies should improve and save the environment. LCA is therefore essential to get an inside view of the path a product takes, from its production to its end-of-life, going through each step and analyzing their impact on the outside world. Sustainable can sometimes sound like an abstract word, but in reality it is much more concrete than we think. Being sustainable means using less energy, recycling materials, etc., which makes a huge difference on an economic, environmental and consumer level.

10) LCA steps and characteristics

Let us now analyze the real usefulness of Life cycle assessment and what are the critical and decisive steps in the creation of the most environmentally sustainable and low environmental impact product. There are essentially four phases of study and research as

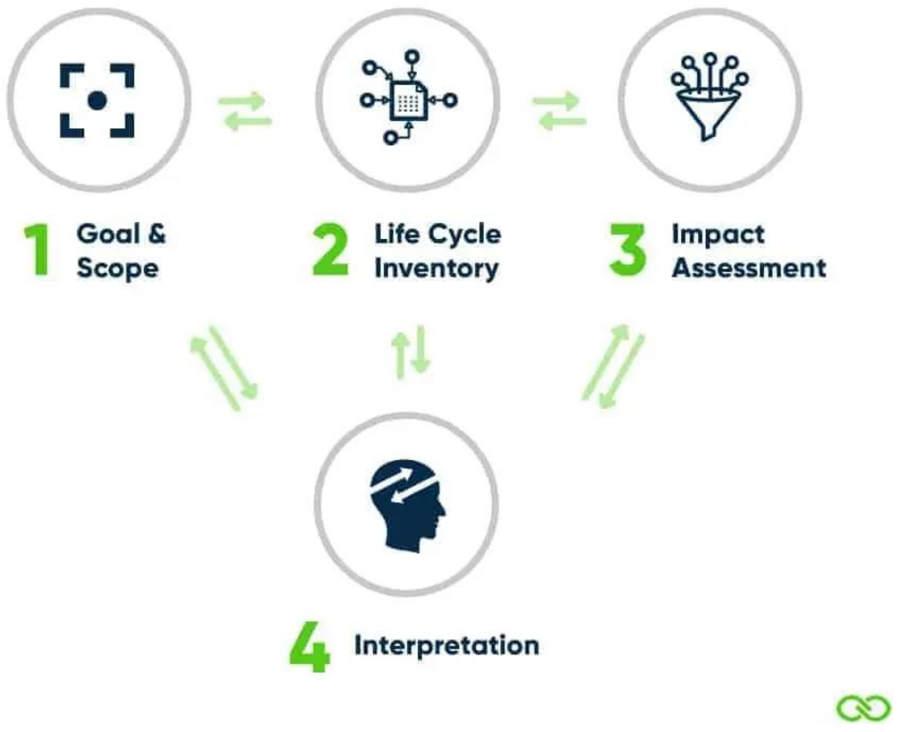


Figure 19 LCA steps

shown in the image below:
Cradle to grave: it is called this when the analysis is done in each of the 5 steps from the raw material to the end of the product. Cradle to gate: Only assesses a product until it is transported, eliminating the use phase of the object. Cradle to cradle is used in the circular

economy by involving a process of recycling the product and making it usable for another project. Gate to gate is sometimes used with products that have numerous processes in between to reduce complexity.

The aim and objective is normally the design and creation of an environmentally sustainable object considering that each product has a CO_2 emission that clearly depends on the processes one chooses to use. The second phase consists of the LCI, the inventory that we make of the inputs and outputs of a product or service, which is essentially the list of data we have. The data consists of raw material, water, type of energy, emissions to air, land and sea. This analysis can be very complex depending on the complexity of the production processes. The third step is the LCI, or life cycle impact. The most important categories are: human toxicity, global warming potential, ecotoxicity, acidification, eutrophication. One aspect to consider is that it is not only CO2 that contributes to global warming and pollution. other substances such as methane, nitrous oxide and other gases are also obvious, but for simplicity's sake we consider their CO_2 equivalent for their environmental toxicity. The last and perhaps most important part is the interpretation of the data. The final analysis should not only and exclusively be done by looking at the numbers and deciding based on the least amount of CO2 produced but take into account many other factors. A final aspect to consider is the use of software systems and tools for a more detailed LCA.[14]

Figure 20 LCA Grey hydrogen

Life Cycle assessment grey hydrogen

It is produced by steam reforming natural gas and coal without capturing CO2. More than 40% annually is produced by chemical processes. It finds its use in the petrochemical industry and for the production of ammonia. In the last 70 years, the demand for these two products has increased exponentially.

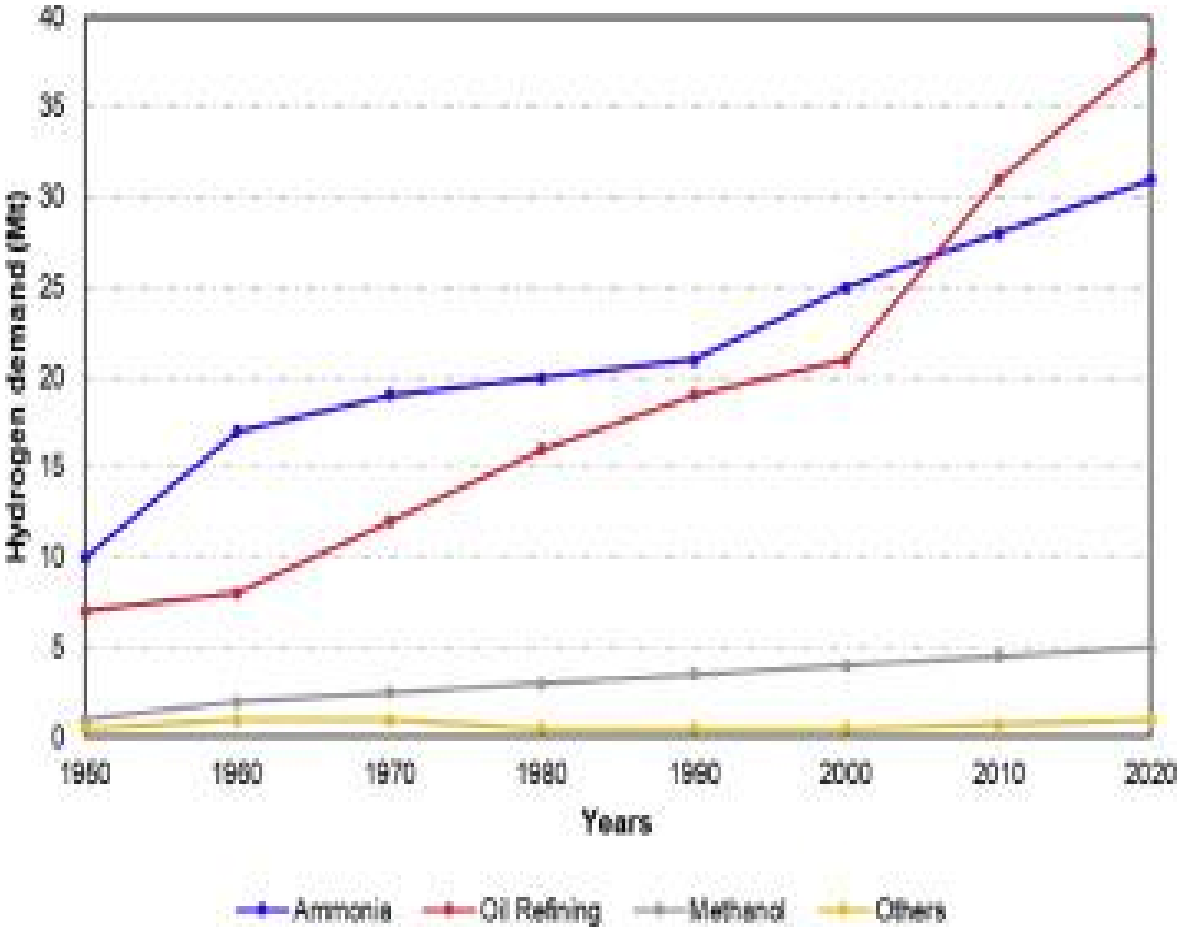


Figure 21 Grey Hydrogen demand

One method of producing grey hydrogen is goal gasification, which in some literature is also called brown hydrogen. Since coal is the most naturally occurring fossil, it is also the most widely used method. Especially China, being one of the largest coal producers in the world, exploits these resources for the production of grey hydrogen. Using fossil fuels, the LCA is completely unfavorable as we know as mentioned many times above the great danger to our planet. From the extraction of fossil fuels, which we know to be costly and polluting, to the transport, refining and endless use of them, the production of CO_2 is totally unavoidable. But why then is it so widely used? Grey hydrogen is cheaper than the others, at around $1/1.5 per kg, much less than the $2-2.5 of blue and the $4 of green. The life cycle assessment shows us that in spite of a usage of 45 million tons per year, it is not advisable to use it, preferring blue and especially green.

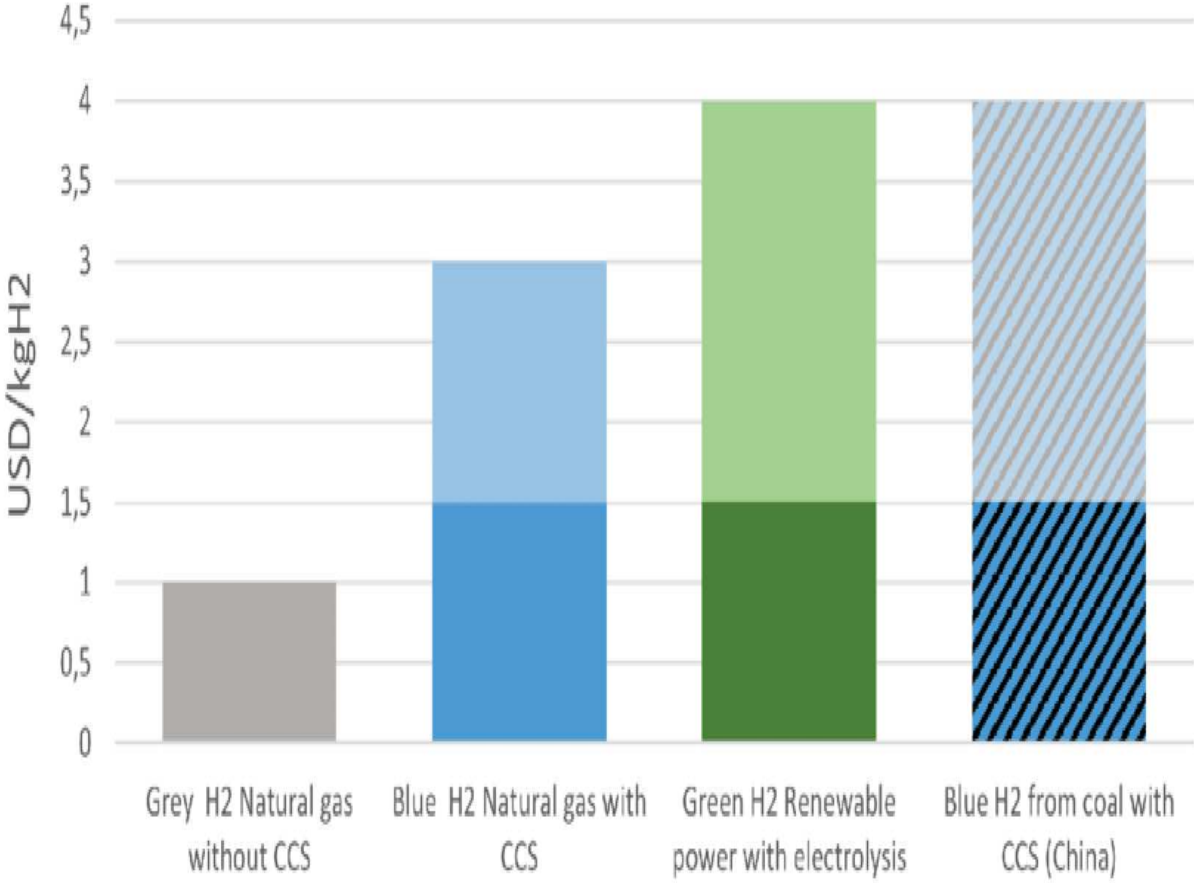


Figure 22 Hydrogen comparison

Life Cycle assessment for Blue Hydrogen

The LCA analysis carried out for hydrogen is useful to understand how and whether in the future the various types of hydrogen will help to avoid pollution. In 2020, a study was done in Europe on the life cycle impact of a blue hydrogen production system. The CO_2 -equivalent reductions per unit of hydrogen produced are in the order of 50-80% compared to non-green hydrogen production systems. The study used a possible global pollution in hundred year as a reference. These results confirm that although the production of blue hydrogen is not the cleanest, the use of the latter contributes to lower emissions. Although the difference compared to fossil fuels is enormous, in reality this type of energy fails to make a huge difference. The LCA method shows that blue is synonymous with low-emission hydrogen if two conditions are met. The first is that the associated natural gas must be as low emission as possible. This means that from the extraction of the methane and continuing its production chain including transport, storage must be minimized. This conclusion may seem trivial, but in countries like England, Norway or the Netherlands, this condition is met with 0.3-0.4 % pollution. In eastern countries such as Russia or even

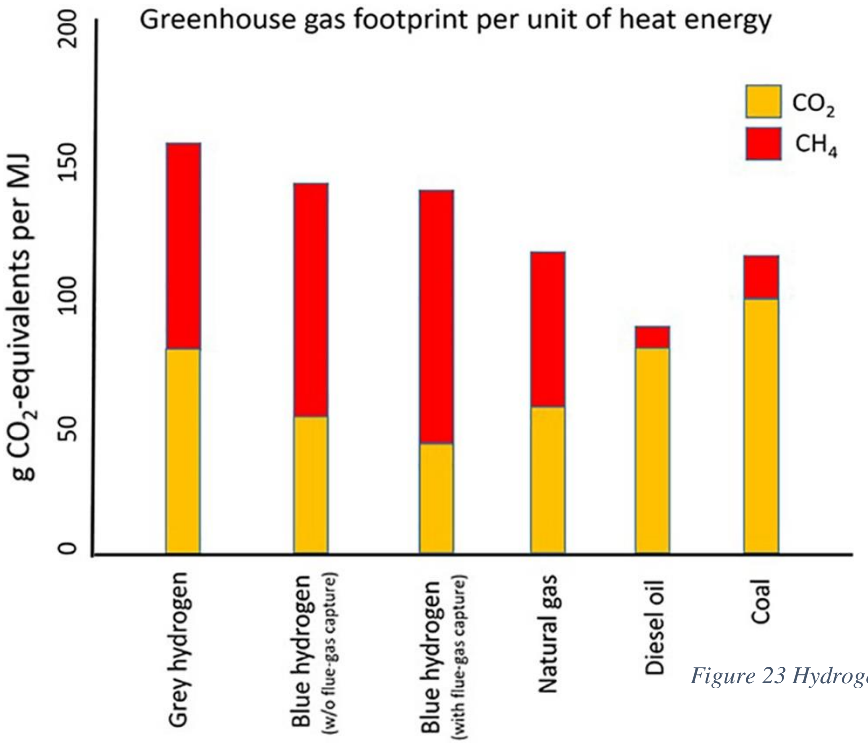


Figure 23 Hydrogen emissions

Libya, methane lifecycle emissions are more than ten votes higher at 2-3%. It is clear that this technology only makes sense if certain conditions are met. but this should include important investments in natural gas infrastructure to improve its efficiency and we know very well that the only interest is still profit. The second condition that would make sense in the use of blue hydrogen is an important capture of CO_2 in the processes. This should be around 90%.It is technically possible to go to 100%, but it would increase costs by a large margin and decrease energy efficiency. The above estimates bring blue hydrogen much closer to green hydrogen. It is clear, however, that no energy is totally zero impact, but the best compromise is achievable. In fact, I could contradict my last statement by introducing the argument of biomass hydrogen, which could be totally zero-emission, but because of its poor disponible, the impact is negligible. We then discussed how BH and GH can be equivalent. If this is not the case, then green hydrogen is preferable. To keep in mind is that these technologies are still under development. What seems like a discovery today, could be the engine of tomorrow's world. It is therefore crucial that the policies of the world invest in both BH and GH, developing and providing the world with new possibilities. As far as the cost of BH is concerned, it is almost entirely determined by the cost of producing methane. **Error! Reference source not found.**

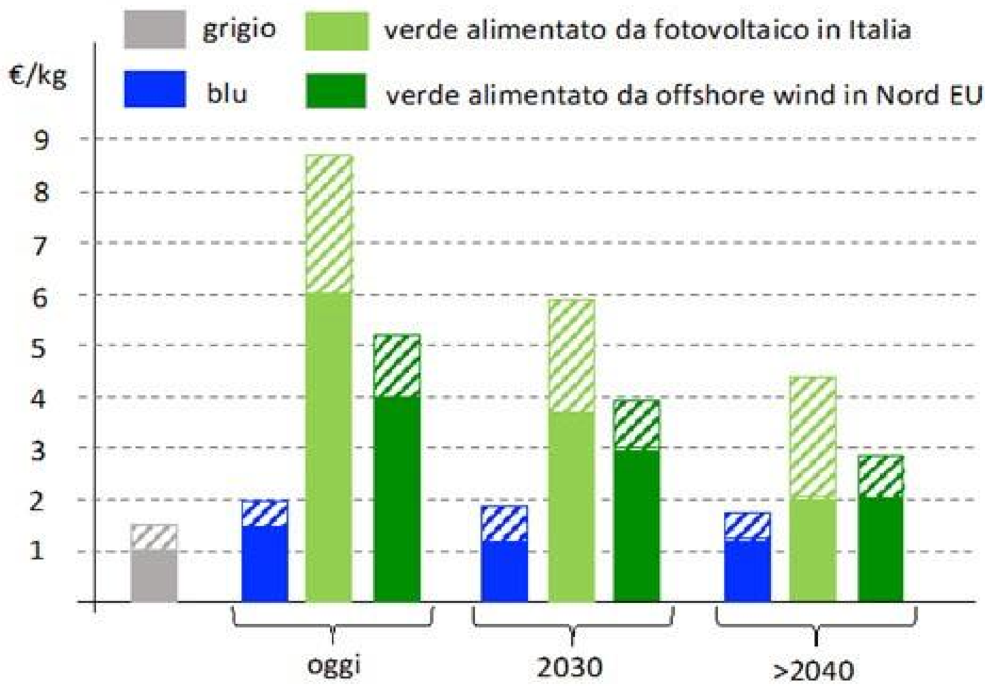


Figure 24 Price forcecast

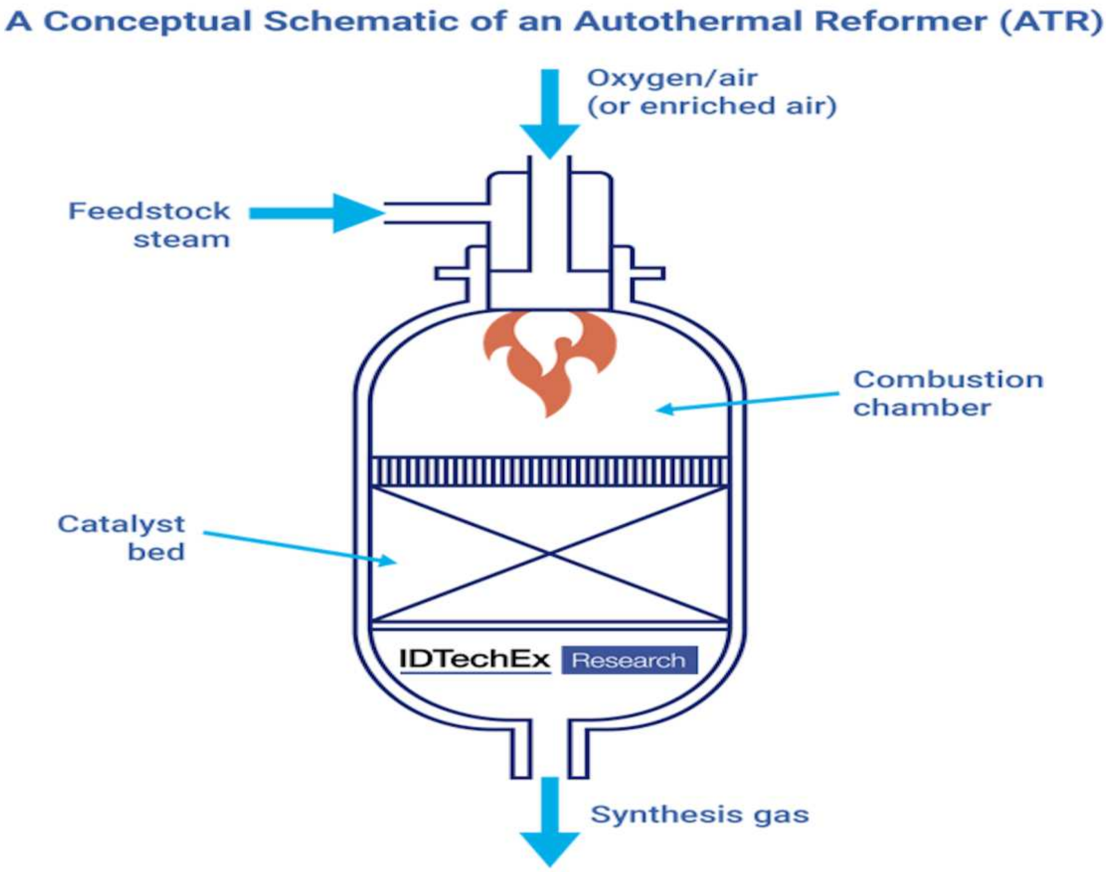


Figure 25 Autothermal Reformer

It is agreed that following the Life Cycle Assessment study hydrogen can have a decisive impact on climate change. This is true when produced from certain biological sources such as wood, agricultural residues etc. and using electrolysis from water and electricity with a low CO_2impact. However, it is less clear what the impact of hydrogen from NG (natural gas) and other fossil fuels with CO_2capture is. This is precisely what we have described above as so-called blue hydrogen. The production of hydrogen from NG is a well-established technology that has been used for decades in industries such as oil refining and ammonia production. Currently, the most widely used method is steam methane reforming (SMR) and air fed autothermal reformers (ATR). Partial oxidation of natural gas is commercially a usable operation for the production of hydrogen-blue. Common to both production methods is the creation of a synthetic gas called syngas from which it is easy to separate very pure H2 and CO2 molecules is the process in which the capture of carbon dioxide and its storage takes place. This characteristic is typified by the color of hydrogen. The percentage of hydrogen produced is very good at around 76-77% of the total energy produced by both processes. It is also easily noticeable that there is an excess amount of steam produced in the two processes that can be used for further energy production. This is the ultimate aim of the LCA, i.e. the study of the impact that processes or products have,

and in this sense the recycling of matter to produce energy is a point to make of blue hydrogen. The carbon dioxide from the syngas is separated from it using chemical solvents or physical methods. At this point, the CO_2 produced is transported to underground storage. The energy for this to happen is derived not from new sources, but from the use of hydrogen itself. This slightly lowers the efficiency of the process. The percentage of CO_2removed is 100% in SMR processes but in reality only reaches 50% of the total emsse because the process does not also cover the carbon dioxide resulting from combustion. It is fair to note, however, that many multinational companies are working to increase the efficiency of these processes as we shall see later. For LCA studies, the difficulties concern:
-Spatial and temporal uncertainty
-Lack of representational data
-Lack of metric quantities
- system boundaries.
The problem is therefore that the study of the environmental impact of hydrogen blue is not completely uniform and reliable in all parts of the world, leading to confusion and interpretation of the results. An international system for studying these aspects is therefore needed.

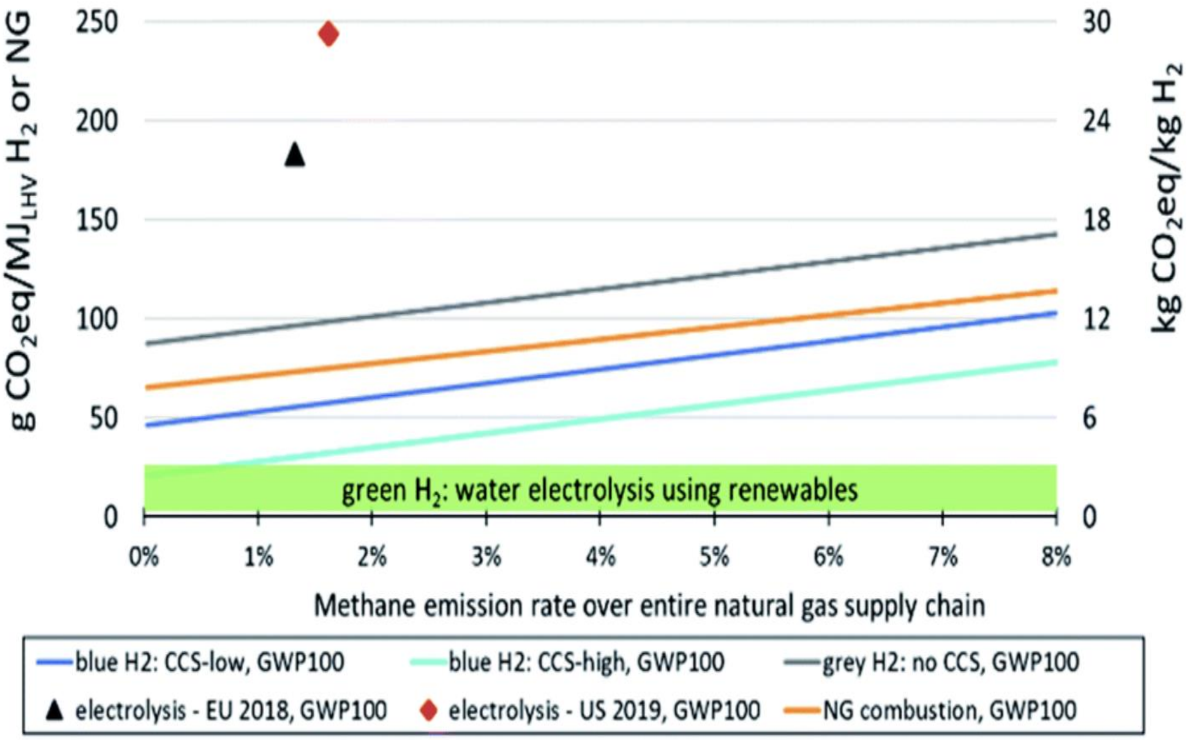


Figure 26 Emission comparison

11) Life Cycle assessment for green hydrogen

The life cycle assessment for green hydrogen, which is the one theoretically better because it is cleaner, analyses the environmental impact from production through transport to its use. Starting from the initial process, the production, the question we have to ask ourselves is the following. Where does the energy that powers the electrolyszers come from? The answer is not entirely trivial. We must say that if energy sources are not renewable and sustainable, hydrogen production technology would pollute more than fossil fuels. There are essentially two variabilities at stake, conversion efficiency and the ability to make up for the variability of renewables while not falling back on fossil fuels. For this reason, an LCA analysis is once again crucial. The European Commission's joint research center published a policy assessment, in which it states that large-scale production of green hydrogen, which is expensive in the short term, can be cost-effective in the long run. Another determining factor is clearly the transport, which can be more or less expensive depending on the distance and thus also have a greater impact on consumption and environmental pollution. Considering that green hydrogen or hydrogen in general has a very low volumetric density, transporting compressed hydrogen is the best ecological choice. all way liquefaction is the most widely used method, but it requires a 24-36. % of electrical energy.it is therefore a choice that has to be made, either to import green hydrogen produced abroad, or to produce it locally considering all the costs of an on and off grid impact, or to produce hydrogen using the grid and thus depend directly on the grid source. It is therefore not so simple to move towards a cleaner future, because we simply risk consuming and thus polluting more. Just think of the costs when renewable sources are not available, the costs of transport and compression, and also grid consumption. It is therefore clear that for every cost there is pollution. The higher the costs, the greater the environmental impact they correspond to.

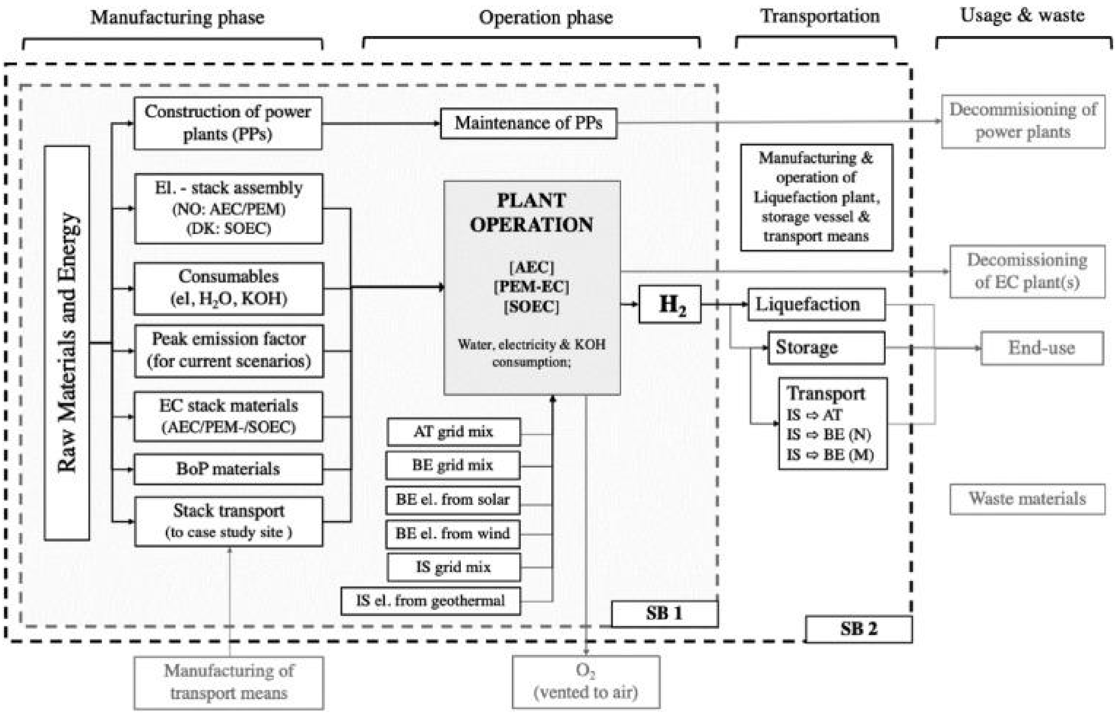


Figure 27 Green Hydrogen LCA

Studies conducted in Belgium show that of the three possibilities, the most expensive is certainly the one that does not use renewable energy sources such as sun and wind, while the most efficient currently uses part renewable energy and part electricity from external circuits. The currently highest cost for the overall use of green hydrogen is liquefaction, which puts the total pollution of the process at 80%. Transport is certainly the most difficult to judge, considering that shipping is done with large fossil fuel engines, which makes it ethically useless. Another important factor to consider is that as green hydrogen is almost always produced by electrolysers, the construction of these is very expensive. There are several criticisms to be made of green hydrogen as well. The first is the lack of clear data on the cost of electrolyzers from a manufacturing point of view. The second is the lack of responsiveness in providing data to agencies as technology and things change very quickly and so does the data they bring. The last analysis I would like to make is the following one shown in the next graph, which shows how transport and costs are distributed according to annual CO_2 emissions in 2020 and in the decades to follow. The results should be interpreted as follows. An initial investment in this clean energy will certainly have higher costs due to infrastructure and transport, but by investing now and producing the hydrogen locally, the cost per kg will be noticeably lower in the coming decades, thus reducing pollution. The last consideration we can make is that by taking countries that import and export, such as Iceland, for example, the latter's transport costs, and pollution are very high. By producing on their own, each country would also avoid creating monopolies around the world to dictate hydrogen prices, again not making the mistake of preferring profits over the future of our world**Error! Reference source not found.**

12) How storage impact environment

Why is storage important? As we know, green hydrogen is totally dependent on natural resources, especially solar energy. It is therefore not possible to ensure a constant and always equal flow of energy to the system. This is clearly due to the variability of weather and seasons. In fact, it is not possible to rely on green hydrogen for totally renewable and sustainable energy only when the sun is present. In the winter seasons, in fact, using classic fossil fuel systems would only further pollute, making the whole process futile. it is therefore essential to have a storage system. We have explained the storage methods above, and fortunately hydrogen is very flexible in this respect. In fact, there is no need for a complicated storage system, no need for a minimum height above ground and no need for a particular type of soil. By using an appropriate storage system, we make the system economically viable, especially for countries with different season as Italy or others, it makes the system worthy and sustainable**Error! Reference source not found.**

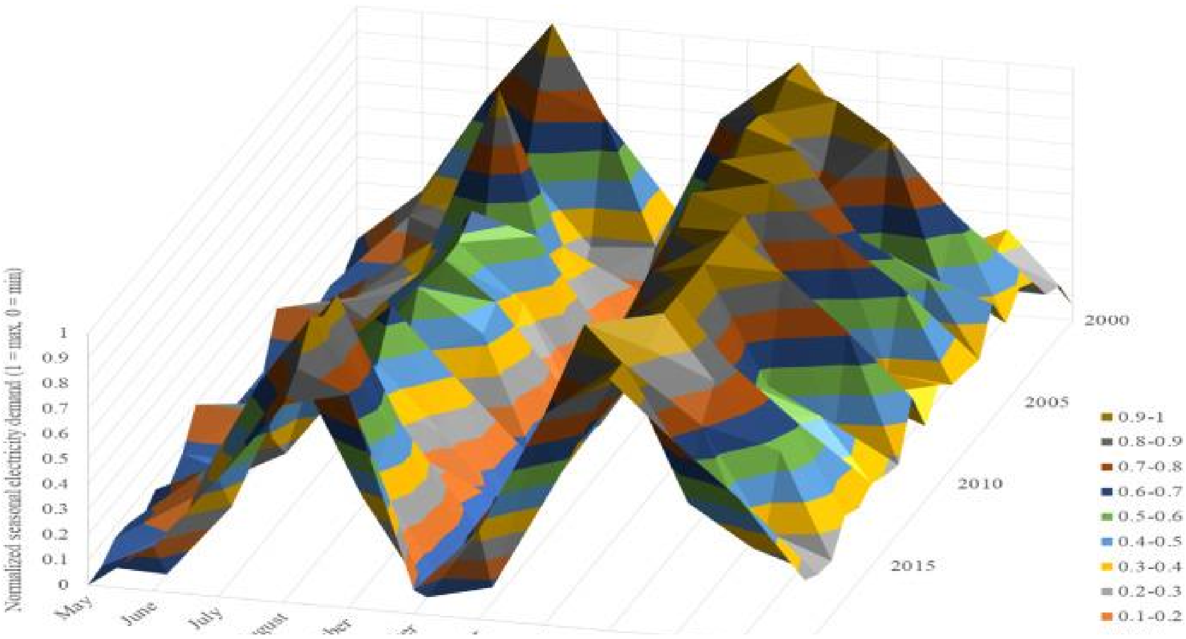


Figure 28 Hydrogen Storage

13) Hydrogen Storage

Having discussed how to produce green hydrogen and all the potential and problems associated with this new technology, we must also study how to use it. Once produced, hydrogen must somehow be optimally collected and stored. But how do these steps take place? Hydrogen can be collected as a gas or as a liquid. Storing hydrogen gas requires the use of high-pressure tanks, which reach approximately 350-700 bar. Liquid hydrogen, on the other hand, requires cryogenic temperatures to prevent boiling and ensure that the hydrogen does not turn back into gas at temperatures of around (-252.8). Hydrogen can also be stored on the surface (adsorption) or within solid materials (absorption).

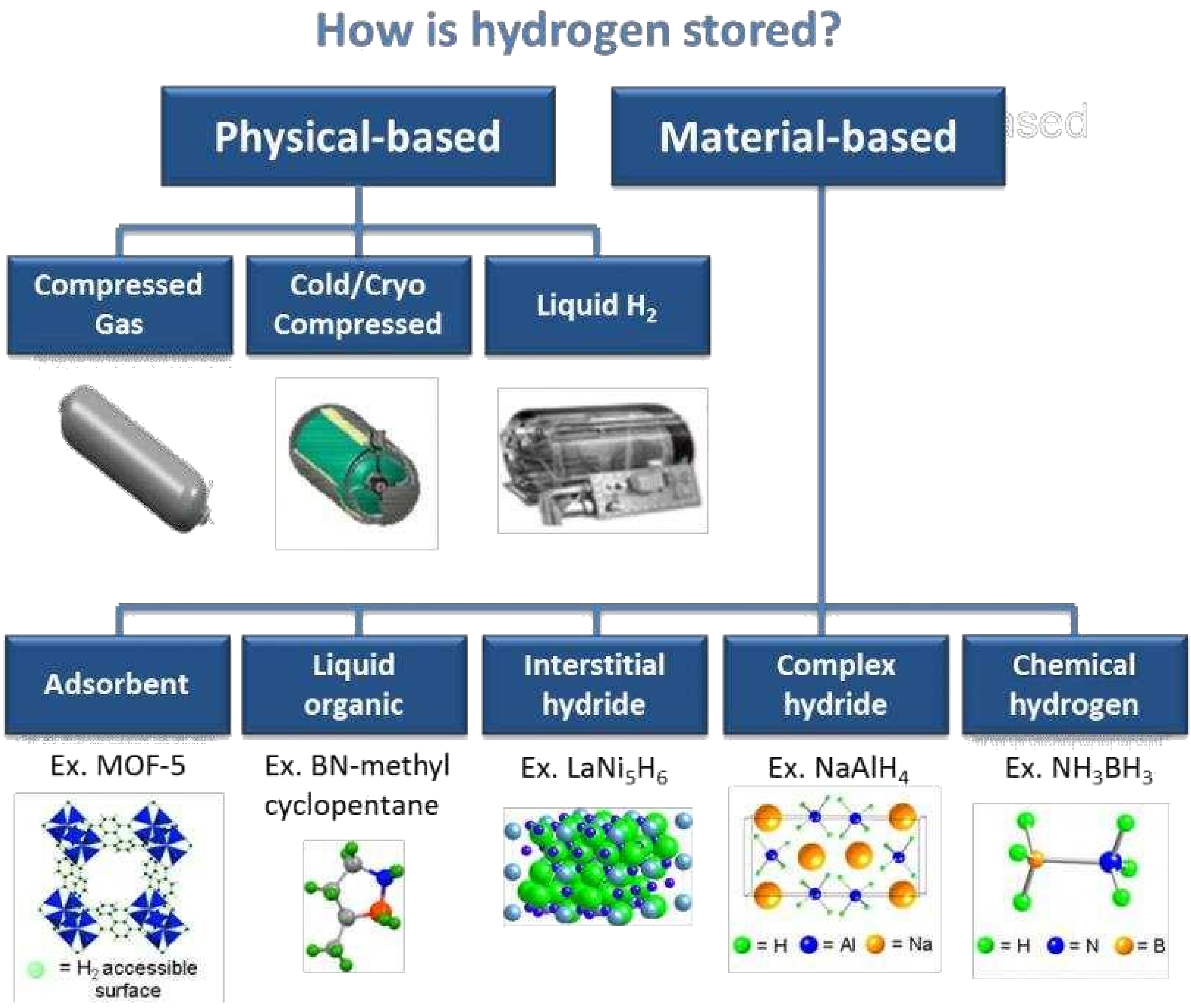


Figure 29 How Hydrogen in packed

Gas compression

The pressures at which hydrogen is produced are relatively low, around 20-30 bar. In order to be transported around the world, it must be brought to higher pressures and then compressed through various methods. These methods include mechanical compressors. There are essentially two types that are used, positive displacement compression or centrifugal compression. Alternative methods for compression are still mechanically based but exploit an electrochemical reaction in which hydrogen passes from a low-pressure anode to a cathode via a high-pressure proton membrane. However, this method is still in the experimental stage.

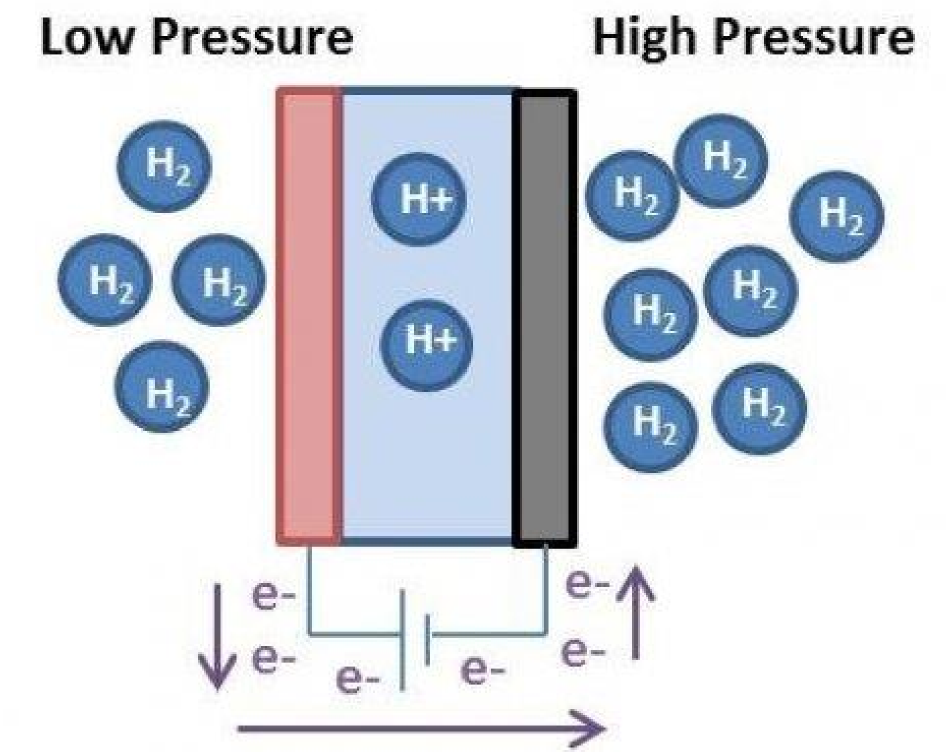


Figure 30 Gas Compression

Liquid Hydrogen

The liquid form of hydrogen is fomented by cooling hydrogen to -250 degrees Celsius. The liquid form of this gas is much more efficient as it has a much higher energy density, but this process can be very costly due to the low temperatures. In the midst of an LCA analysis, this factor is therefore an unfavorable point, as even in transport, the hydrogen transport trucks have to be very sophisticated in order not to evaporate the hydrogen and thus not to heat it up. All this attention is expensive and an LCA must be done to see if the benefits are worth.

Combine cold and cryo-compressed hydrogen

Another solution for storing hydrogen is the combination of the two methods described above. This method has more energy than compression but also requires more energy to reach lower temperatures. The energy that is used is approximately 9-12% available for compression and approximately 30% for liquefaction. But which of these shown so far is the best?

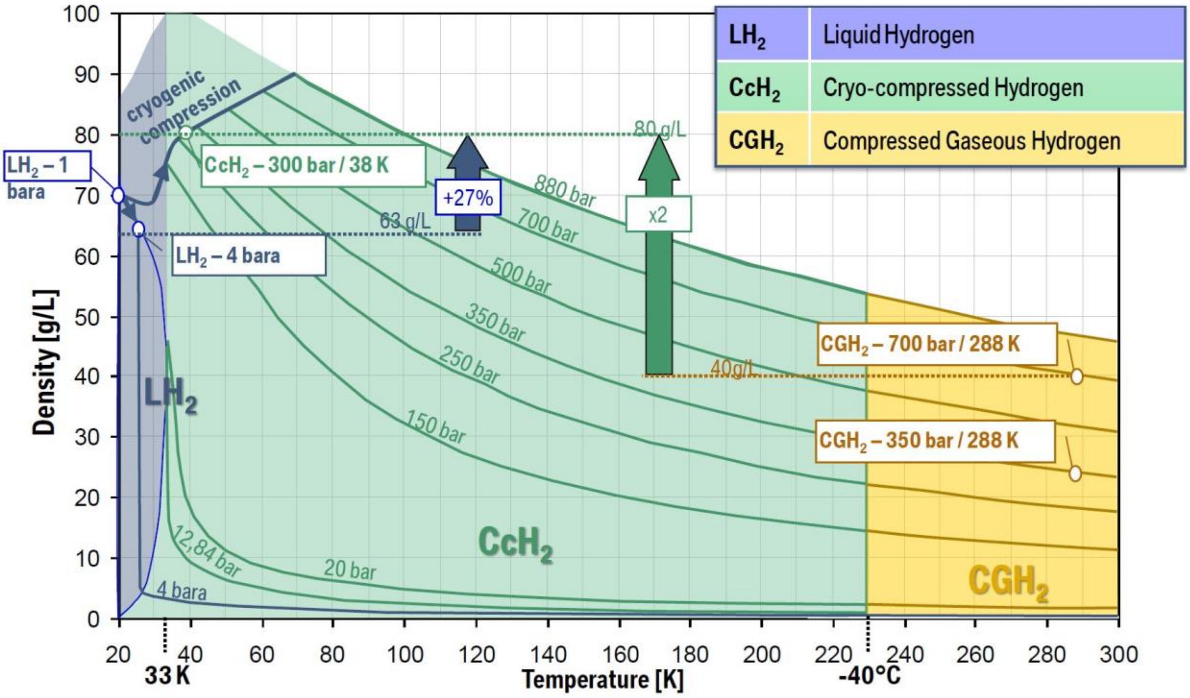


Figure 31 Mixed cold and gas

Material-based storage

Hydrogen can also be stored using materials. There are three possibilities: absorption to store hydrogen within the material, adsorption to store it on the surface of the material and hydride storage, which uses a combination of solid and liquid material. In adsorption, the hydrogen molecules attach to impurities on the surfaces of organometallic materials containing pores. or pores of aluminosilicate materials. This method has a high volumetric energy density due to the 'area' of the sorbent. In absorption, hydrogen splits into molecules that are trapped inside a material with a solid crystalline structure. The third method, hydride consists of trapping hydrogen molecules across the surface in metallic elements such as palladium, magnesium and lanthanum. Hydrogen can also be imaged in organic liquids such as toluene. The advantage of this method is the storage of hydrogen in smaller volumes at lower pressures and ambient temperatures.

Underground Hydrogen storage

In some parts of Europe and America, it is possible, as an alternative to the solutions we have listed so far, to store hydrogen in a different way. The proposed solution is underground storage. This type of solution has already been in place for natural gas and oil for several years. It is used when there is a particular abundance of the product, when there is a market fluctuation or a crisis. But what is meant by underground? The locations used are salt mines, depots of exhaust oil, natural gas or aquifers. These solutions are industrially preferable especially on a large scale and for very large numbers. It is clear, however, that the cost is not favorable as it is a very expensive solution.

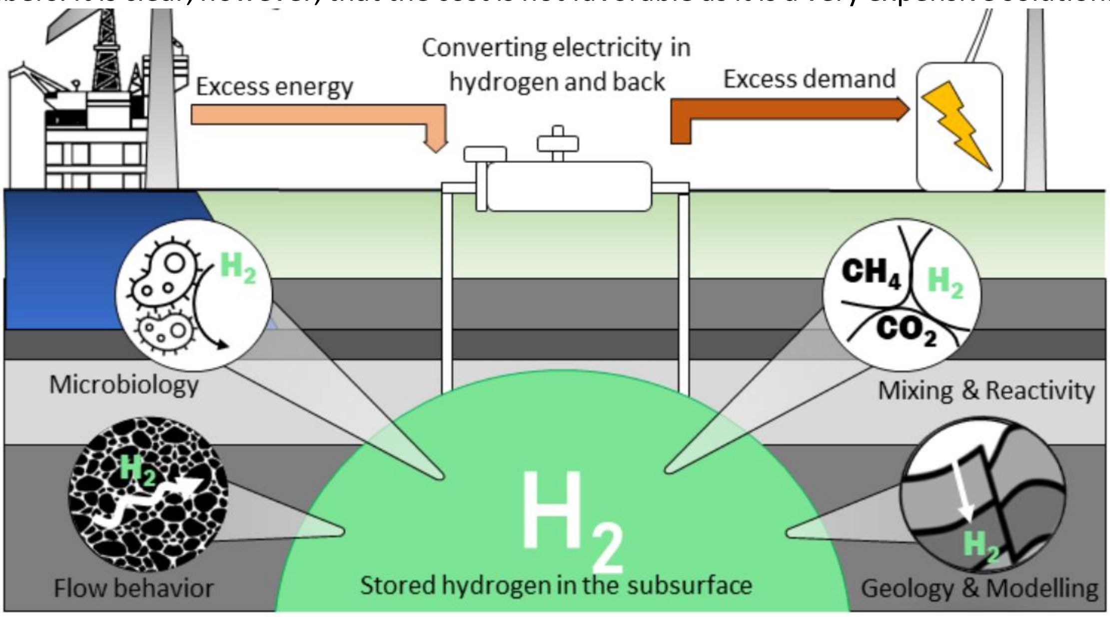


Figure 32 Underground storage

HENG

Another solution that has already been introduced is to feed hydrogen into the existing natural gas network. The compound thus formed is called HENG. Literally meaning Hydrogen Enriched Natural Gas. The percentage of hydrogen is approximately 50% of the total volume. This solution, which is usually used in case of excess, was first introduced in Germany, in USA and in England in the 20th century. However, recent studies have shown negative effects of introducing such high percentages of hydrogen into existing pipelines, showing that only 10 % of the total volume would be harmless. We will show later why and discuss the topic of transportation. **Error! Reference source not found.**

14) Hydrogen impact on environment from waste

Having all the prerequisites for analyzing the impact of green hydrogen on the environment, we can draw some interesting conclusions. We have already seen how the environmental impact of this new technology is essentially positive and promising. National, European and international authorities have come to terms by achieving a goal, however. Zero emissions in 2050.To achieve this sustainable model, scientists and politicians are working cooperatively on the development of alternative energy sources. One of these, which is objectively the most revolutionary and the most promising, has been the subject of this thesis so far, hydrogen. Specifically, green hydrogen. We have seen so far that in fact only green hydrogen has the ability to positively impact our environment by significantly reducing carbon dioxide emissions. We know that green hydrogen exploits the natural and renewable sources that the world makes available to us, and we use them for electrolysis and other methods mentioned above. All this said so far is true for heavy transport. But how can this technology further impact the environment? A new aspect to consider is the use of waste material. This is indeed a huge innovation. The use of waste material thus becomes our primary source of energy. This could have a very positive impact on the environment in the future. A similar type of plant is finding its way into Egypt.

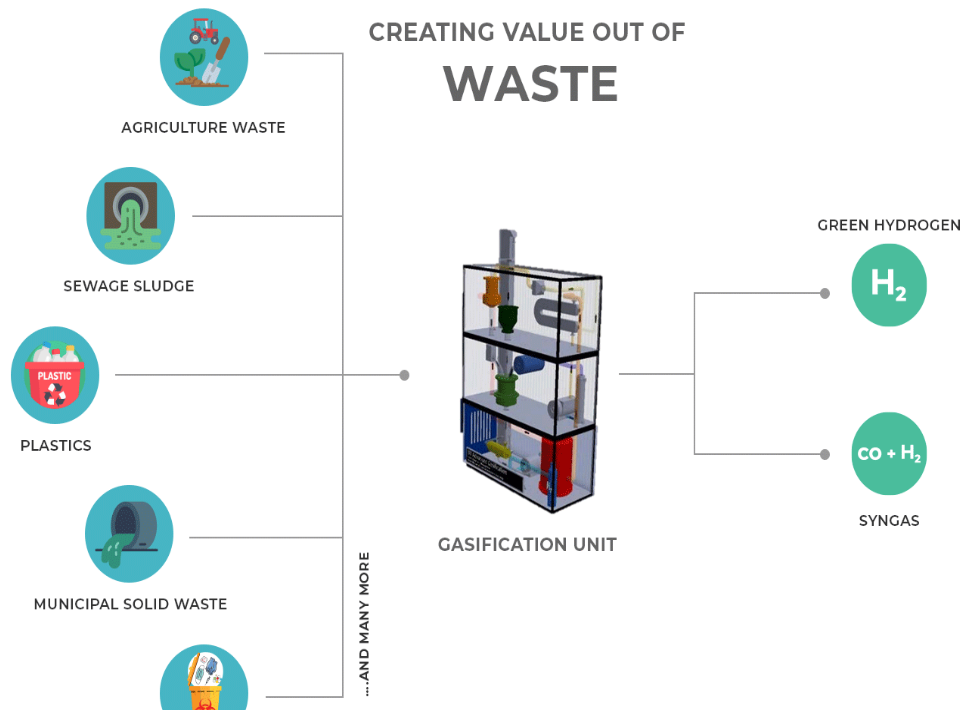


Figure 33 From Waste to Hydrogen

A well-known American company is in fact investing in Egypt on an advanced system that converts organic waste but also non-recyclable plastics into energy for hydrogen production. The capacity of this plant is to produce 300,000 tones of green hydrogen per year from 4 million tons of waste. It is therefore strange to think of green hydrogen and clean energy when it is produced from waste materials, but indeed it is. Not only then is green hydrogen a clean source, but it is produced from materials that would only pollute our planet more. The gain is therefore twofold, considering that the lung of our world is also ours. In fact, the incinerators of this waste do not disperse the gas content into the environment, but use the heat produced to drive turbines, create electricity, and thus create hydrogen using methods that we have seen so far. We can therefore consider almost everything we have seen so far as positive. But why almost? Are there any negative aspects that we have not seen? Of course, roses have thorns too, but the advantages we have seen are very important.**Error! Reference source not found.**.

15) Not all applications are impacting positively

However, there are small controversies in this energy. After a thorough analysis of the uses of hydrogen around the world, we can say that not all applications are optimal for it.

Domestic use

For example, hydrogen, although green, does not have a positive impact in domestic use, as we see that electrification is a better solution, obviously from solar energy or renewable sources. But why? Existing gas pipes can only support 5-20% hydrogen, as we have already seen, which severely limits emission reductions. Furthermore, for a real environmental benefit, control systems would have to be installed for each house and security systems, which are not economically viable and therefore have a negative environmental impact. Studies show that if we used hydrogen as a heating source in our homes, there would be four times as many accidents as today.

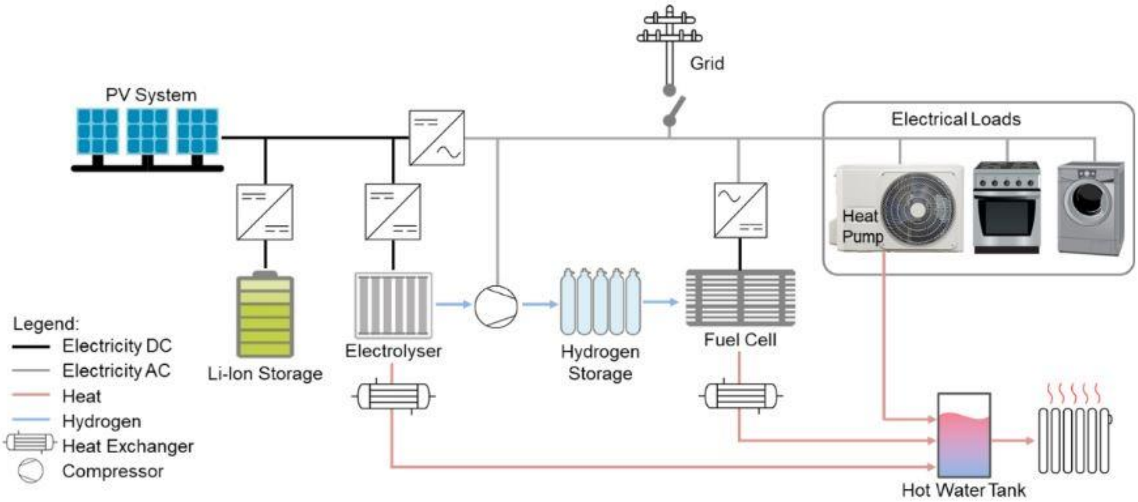


Figure 34 Domestic use of Hydrogen

Electricity

Hydrogen has no advantages in the electricity sector. In fact, the turbines used to produce electricity currently run on gas. By mixing gas with hydrogen (HENG), the emission reductions are very small, compared to cost and safety. In fact, only 5-20% of the hydrogen can be used. The reductions would be around 13%, very small and not very efficient. It is more effort than yield. There are in fact no plants capable of burning 100% hydrogen. Very toxic and harmful NOx residues would be created. It is to be considered that the hydrogen slaughter is not in fact able to provide a continuous and efficient service for the time being. In fact, we have seen that large quantities of hydrogen are available when there is an abundance of renewable energy such as sun, wind, water, etc.

Transport

Although many automotive industries are investing heavily in hydrogen, many scientists and politicians are skeptical about its use. In fact, it is perhaps the automotive sector that should be regarded as the one of most popular interest where everyone can talk. It is proven that if the energy produced is from renewable sources, all-electric cars are still ahead. This is true for small cars. For heavy transport such as trams and trains etc., they have a higher utilization. It is therefore clear that the environmental impact has a limited effect on road and car traffic. This is still due to the infrastructure still not being able to meet the demand, and the biggest criticism is as follows.

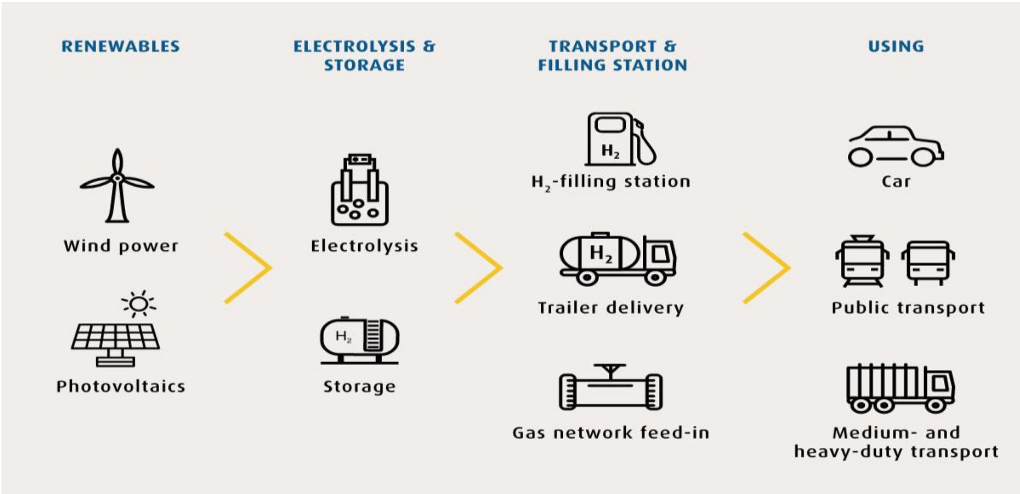
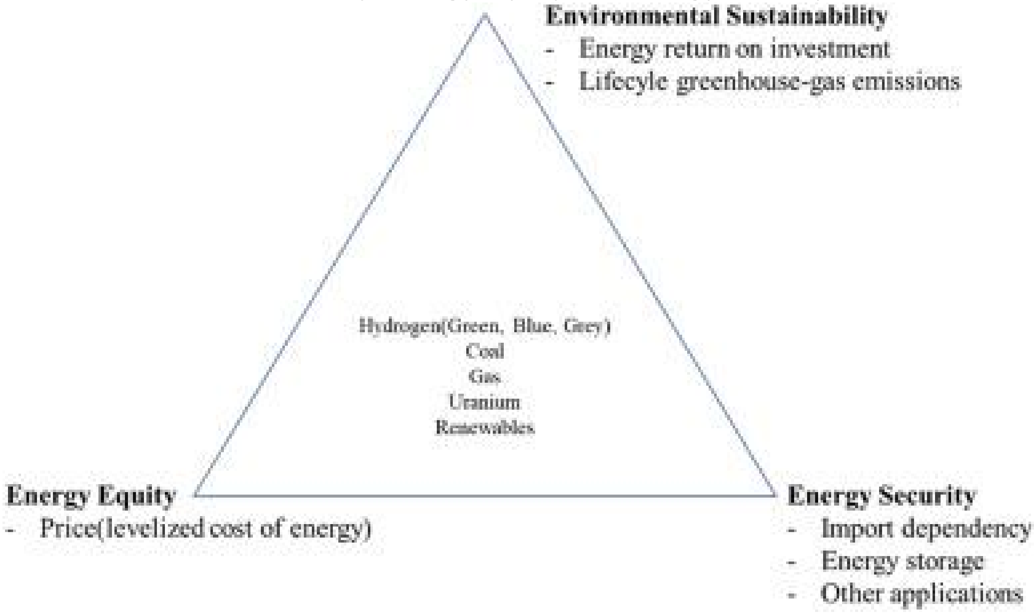


Figure 35 Hydrogen Transport

It is better to use energy as a direct energy source than to use energy to create hydrogen and then use it as a source of power. What is said here only applies to cars and transport.**Error! Reference source not found.**

16) Green hydrogen impact analysis

The environmental impact that hydrogen has on our world is, of course, a matter for different countries to assess. The Korea case is emblematic for what are the conclusive analyses and the LCA impact. As we can show, the World Energy Council has published three basic indices that must be analyzed to assess the impact an energy source has. Environmental sustainability, energy equity and energy security.

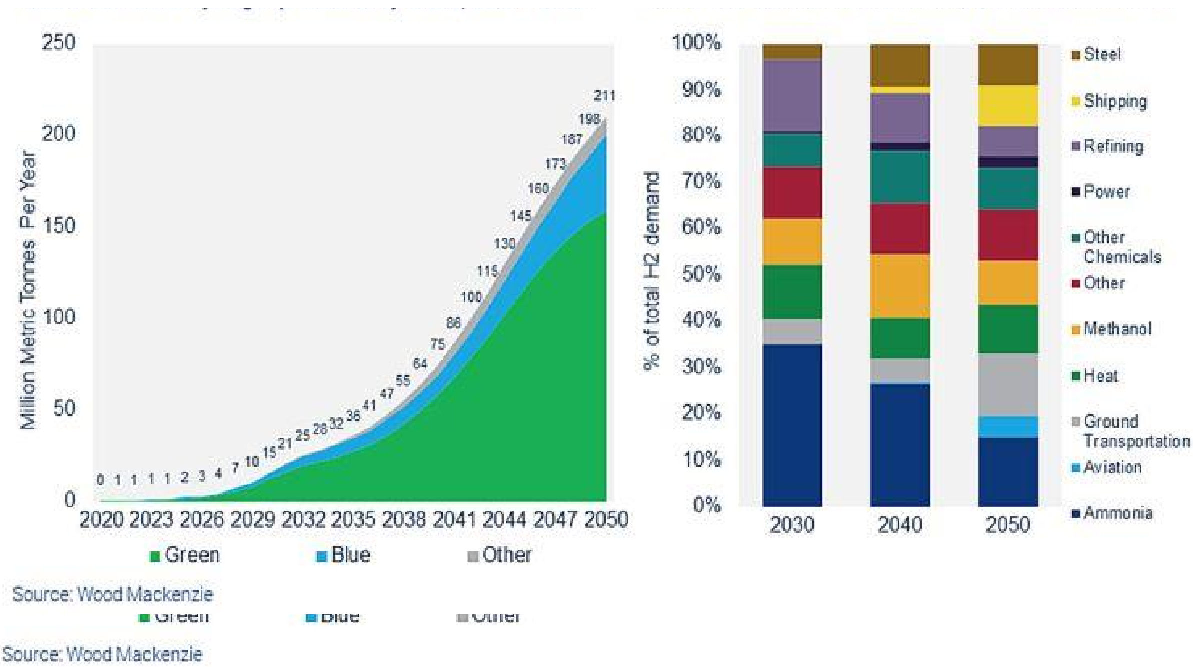


Green hydrogen is then compared to all other energy fomes such as coal and fossil fuel, analyzing these three categories. Energy return on investment is the ratio of the total amount of electricity generated divided by the total energy invested during the life cycle. As far as green hydrogen is concerned; its efficiency is still comparable to nuclear or other forms. However, economically it must be greater than three to be sustainable. The main result is that nowadays, the cost of green hydrogen is significantly higher than blue and grey hydrogen, which use oil and natural gas for production. And that's one important factor to consider for the sustainability of this energy.

Hydrogen[b]	4.2–7.8	PV HTSE
	4.0–6.3	CSP HTSE
	4.0	PV AE
	3.5	CSP AE
	1.1–2.8	PV, Low energy intensity material
	1.0–2.6	PV, Medium energy intensity material
	0.8–2.3	PV, High energy intensity material
	2.2–2.5	Steam Methane Reforming

Green hydrogen capacity takes off post-2030 (LHS) and starts to penetrate hard-to-abate sectors

Figure 36 Green hydrogen impact analysis



But dependence on what? How does this factor impact the environment? Taking Korea as an example, which has no possibility of producing hydrogen independently, it is forced to buy from outside.99.4 per cent of the hydrogen produced is imported, so it is not an environmentally and economically sustainable solution. From an environmental point of view, all the advantages of a zero km renewable source are lost, not using solar or wind energy, with zero local and non-local emissions. The problem is in fact that transporting hydrogen to the country of destination is certainly not zero-emission. Economically, it is completely disadvantageous for the country .The main reason is therefore the fact that the infrastructure is not yet ready for this change, but predictions of scientists and politicians say that by 2050 it will be the world's leading energy source, replacing all others, both blue and grey. **Error! Reference source not found.**.

17) Impact on land and animals

We have so far discussed the most positive aspects from both a social and environmental point of view. In fact, a major investment in this technology by all countries of the world, or those who have the possibility, leads to many opportunities. We create jobs for the locals and the impact on the environment is certainly very positive, and from a geopolitical point of view, independence from other countries. But to get a more complete view of green hydro or biohydrogen, let us look at further impacts it has on our earth. In fact, we have widely discussed that to produce green hydrogen, we need renewable energy. Whether the electricity is produced by solar or wind power matters little, what is important is its zero impact. Both humans and animals are impacted in certain ways by these energy sources. In fact, if we take electricity from windmills or wind turbines, they impact the lives of birds and bats, creating sound and visual pollution, impacting the local ecosystem, and creating magnetic fields that interfere with existing technologies. In fact, the scientist Erickson W.P., studied how the installation of wind-powered systems positively increases animal mortality by 3-14%. Speaking of solar energy, a poor installation or misuse of this technology has also shown significant impacts on our environment. In countries with high biodiversity such as South Asia or Africa, these systems can 'pollute' interfere with animal life. In addition, vegetation must be reduced and removed to allow the installation of solar panels or turbines, resulting in an ecological imbalance and the release of organic carbon through the soil.

Figure 37 Green hydrogen impact on environment

18) Impact on water

Desert areas offer plenty of solar and wind exposure but the water resources that would be needed for green hydrogen plants are limited. The needs of these systems are in fact very variable and sometimes insufficient in areas with a lot of solar exposure. Adding up the water needed for the actual production processes and the water needed for maintenance and cleaning of the machines, the amount of water consumed is about 3.7-5.2 tons per KWp.

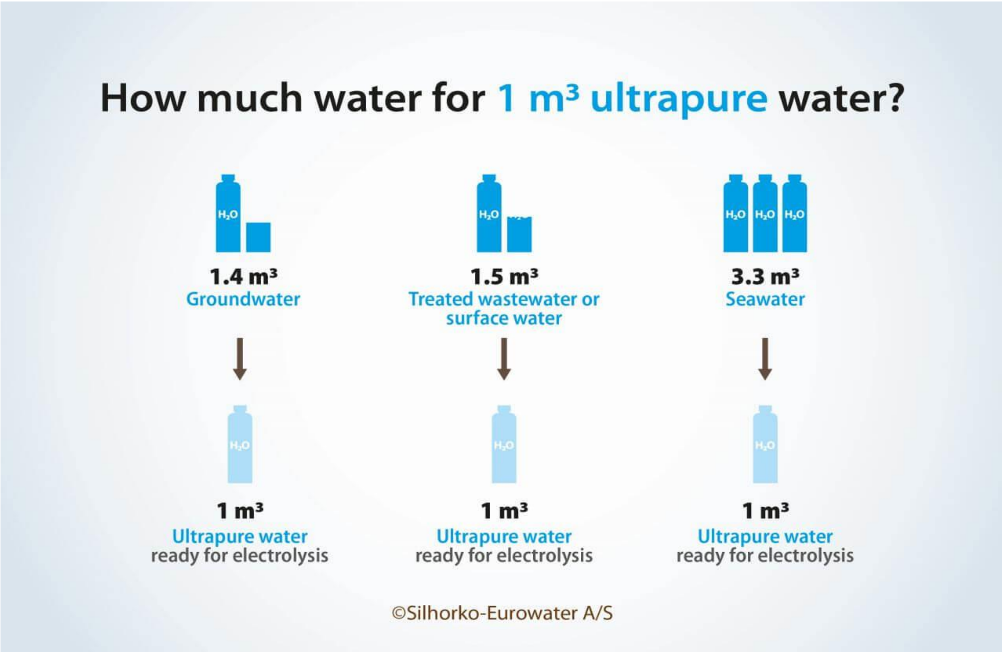


Figure 38 Green Hydrogen and water

In addition, commercially available electrolyzers require purified water. New technology emerging instead shows that even wastewater or salt water (without purification) is sufficient for operation. This aspect could in fact be very interesting because water would be recycled and not wasted. Currently, around 9 kg of water is required for the production of 1 kg of hydrogen by the SOE process and between 18-25 kg for PEM electrolyzers.

Heavy metals impact.

As far as the production of electrolyzers is concerned, they are produced from heavy and rare metals found in mines and mined for production. This means that an increase in mining non-renewable raw material to produce renewable energy increases the environmental impact. Unfortunately, the use of heavy metals is much greater than for fossil fuels. Once extracted, they must be purified and processed, and recycling is not possible. Only 1% of lithium is recycled. An increase in the use of electrolyzers would therefore increase mining and extraction of heavy metals. Of concern is the shortage of nickel, which has increased by 20% in recent years and is crucial for ALK processes. The Mineral World Bank Report is therefore concerned about the ecological balance and biodiversity if the search for heavy and rare metals continues to increase. But what is the problem with these heavy and rare metals? They are, as we have said, fundamental to the development of green technology, but for every ton of rare earth product, the mining process produces 13 kg of dust, 9600-12000 cubic meters of waste gas, 75 cubic meters of water and a ton of residual radioactive material.

19) Climate Impact

Sun and wind do not generate any harmful gases for our planet during the green hydrogen production processes. Therefore, the replacement of fossil fuels in the energy sector with renewable sources is crucial for the future. A simplified summary of this thesis is shown in the figure below where the current yes and no of this technology are analyzed.

Currently, the process of producing the necessary components and materials leads to polluting gas emissions. This can in time be improved or even eliminated by creating for examples wind turbines with eco-friendly metals and photovoltaic panels.**Error! Reference**

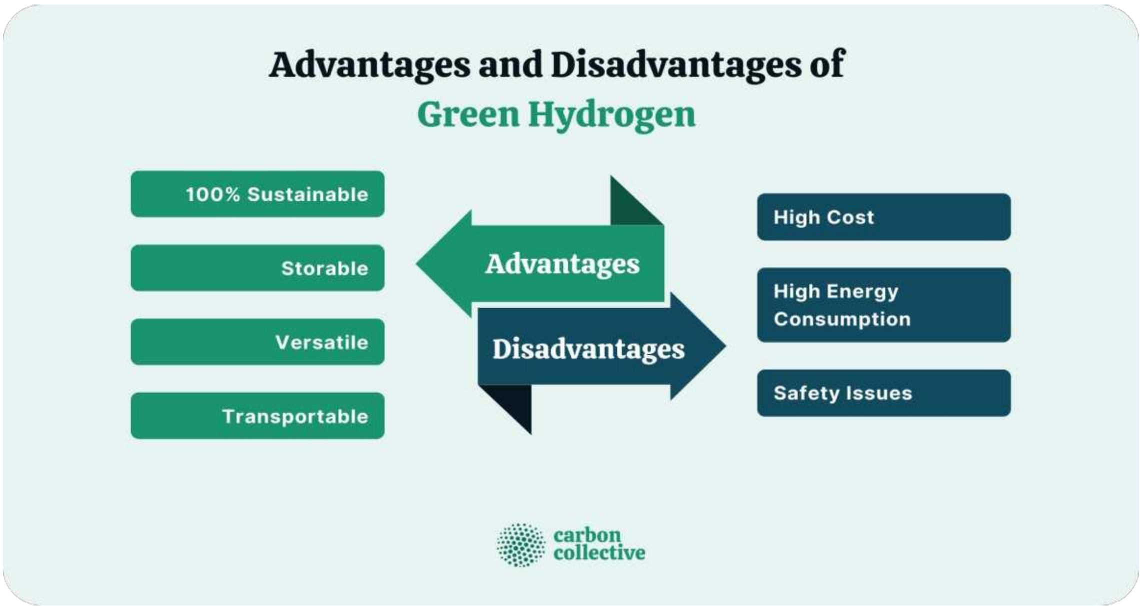


Figure 39 Climate impact

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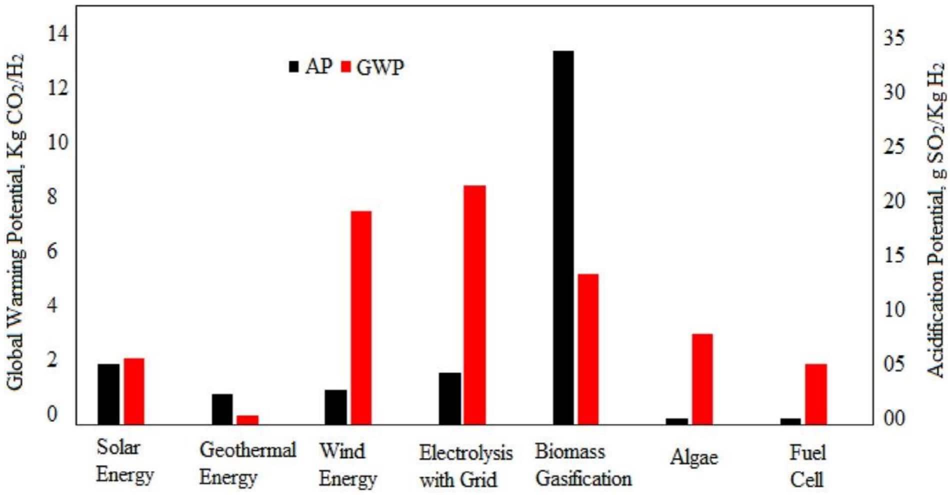
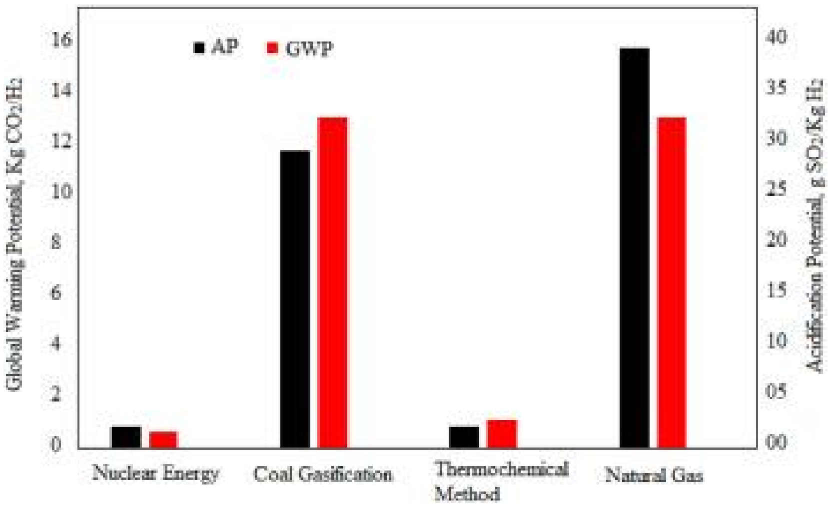
Having discursively seen the impacts that green hydrogen has on the environment, we can draw some conclusions and provide specific data. Currently, carbon dioxide production can be reduced through sequestering processes and technologies that we have seen. How can we estimate the impact of green hydrogen on our global health? The most widely used global indices are acidification potential (AP) and global warming potential (GWP). The data below essentially shows how these vary according to the technologies used, renewable and non-renewable.



As we can see, the methods with the lowest GWP are solar, geothermal and biomass.
The problem with biomass iNs the production of acidic residues that are then released into the soil and the sea. It is therefore clear that the factors to be considered are not only emissions into the air (GWP) but also emissions into the soil and sea (AP), which are not directly caused by man.



Generally speaking, therefore, we can say that any technology to create green hydrogen is in any case more ecologically sustainable.**Error! Reference source not found.**

Figure 40 Comparison on emissions

20) A study case

An interesting study conducted in recent years can serve as an example to show how technologies seen so far can influence future emissions. The study in question analyses three different countries, Austria, Belgium and Iceland. Each of these countries is subject to an analysis based on the geographical possibilities and hydrogen production facilities they have. For Austria, a mix energy system is analyzed, in Belgium, solar, wind and grid energy, for Iceland grid and geothermal power from Hellisheidi.Each scenario uses three different technologies, PEM, AEK,SOE for the current analysis (2020) and for 2030 and 2040.For Belgium, several IRES sub-scenarios are also considered, due to the inter-mixing of renewable resources. Results are expressed according to the GWP resulting from the LCA analysis of systems, AP and energy dependency. The results also show that wind power has the greatest reduction in carbon dioxide in 2020, while the Icelandic scenario is the best in 2030 due to rising carbon dioxide capture. The Austrian scenario, on the other hand, is the most promising based on the technology used in terms of GWP in the years 2020-2040 with a reduction of 96-97% of emissions.

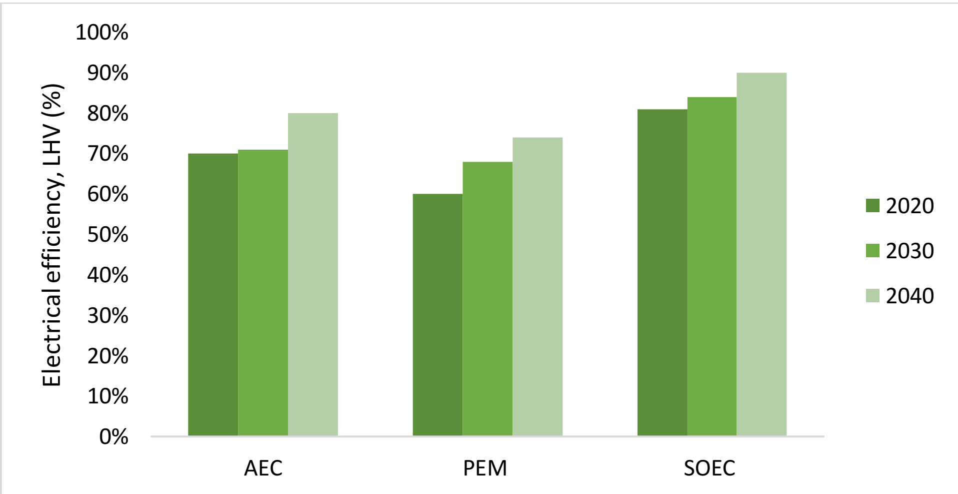
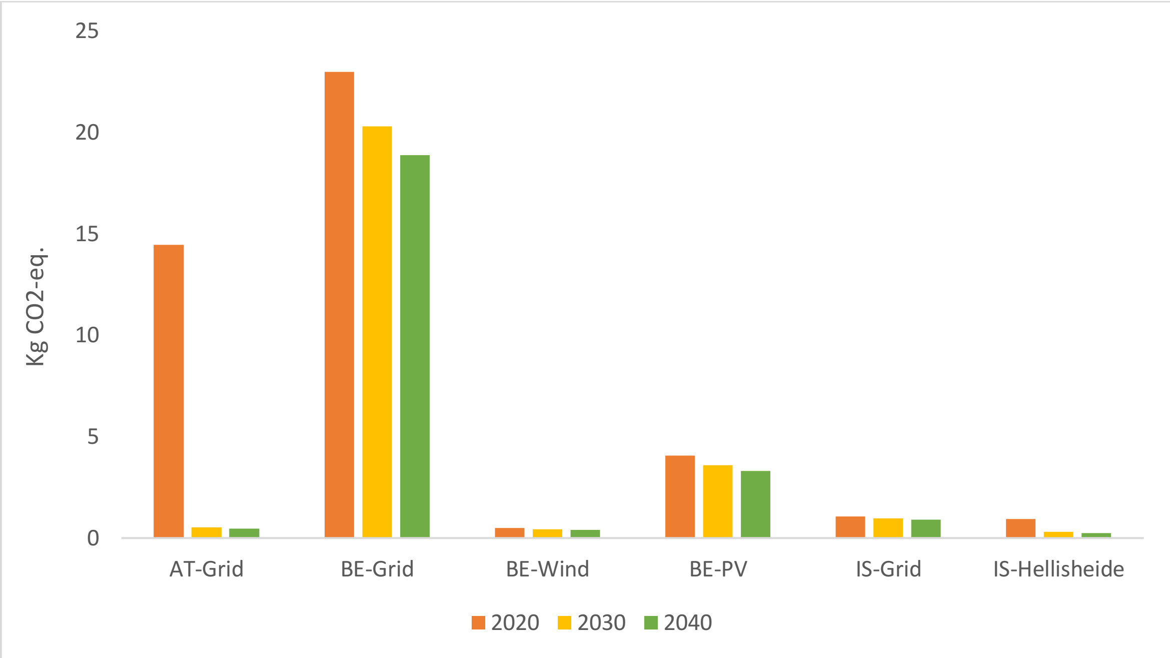


Figure 41 a case study

Figure 42 PEM system analysis



The GWP results show that water consumption and stack transport have little influence on emissions, whereas in the Icelandic scenario, liquid hydrogen transport has a significant impact on emissions as it is transported by heavy oil-fueled ships.

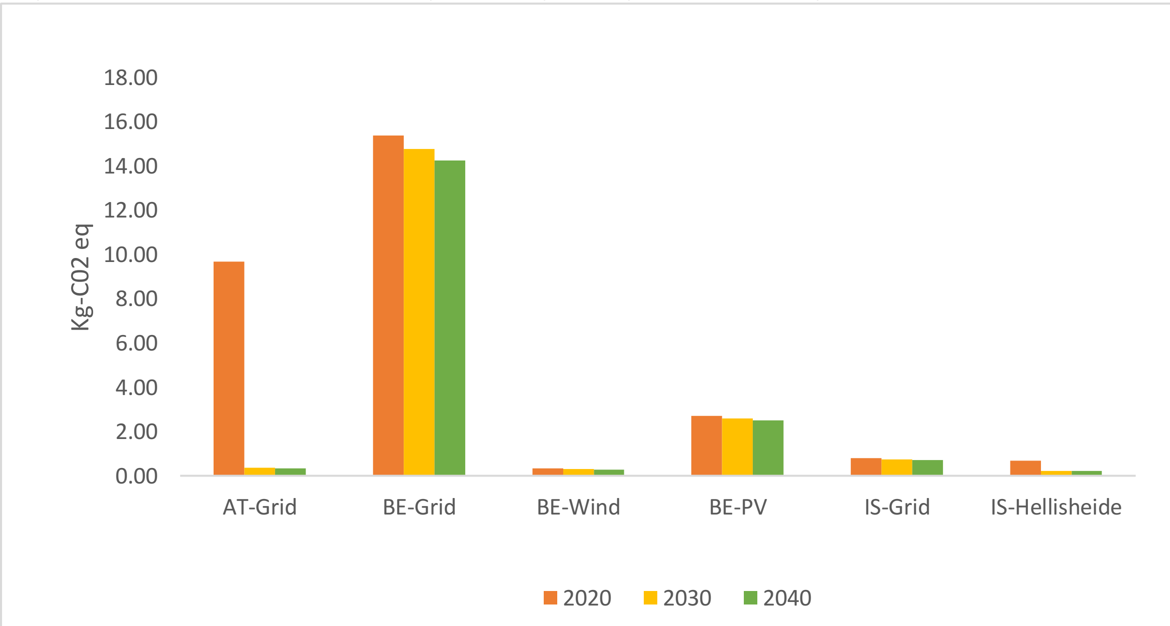


Figure 43 SOE siystem analysis

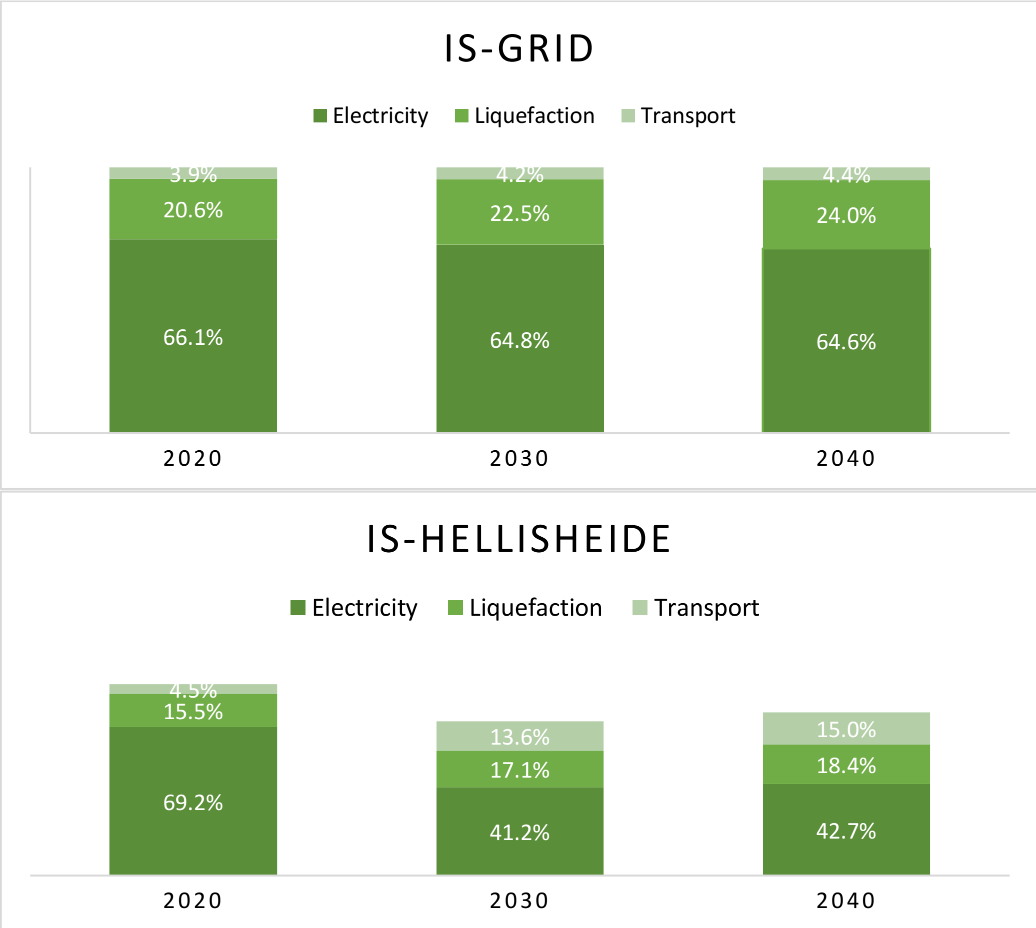


Figure 44 Systems comparison

It also emerges that the worst-case scenarios in each country are those whose systems are intermittently powered by electricity from the grid. The best results in terms of emissions are in fact based on the exclusive use of sun and wind to power the electrolyzers. Further, in general, it emerges that the SOEC system is the most sustainable and most productive method. **Error! Reference source not found.**

21) Netherland case

To complete this analysis we can take the Netherlands case. In this LCA study of the environmental impact green hydrogen has on the environment, the study goes into what the various aspects and characteristics of green hydrogen will be in the future. The two main scenarios presented are scenario A, "full hydrogen power "the most ambitious but also the most necessary scenario that the Netherlands must achieve to achieve zero emissions in 2050. The table below shows how green hydrogen is implemented in all regions of the country with suitable plants, where 1kg of H2 is produced by a 1GW plant powered by wind turbines. This scenario also includes an ambitious policy program to extend the technology to transport, and to create new offshore wind parks to power the already widely used electrolyzers.

Level of electrolysis implementation	Transport market penetration by H_2 (in % of car fleet)	Policy support	Technology development	Stakeholders involvement	Production/distribution framework	Technology promoted for H_2 production	Main origin of electricity (for electrolysis)
Implemented in all regions • National scale	70%	Strong policy support • R&D subsidised • Carbon tax • Laws adjusted for H_2	Strong development • Reduced noble metals consumption • Large-scale systems	Strong collaboration • Clusters, supply chain construction, coalitions	Mostly centralised	Electrolysis	Wind • Construction of large wind parks
Implemented in few regions (mostly North)	50%	Limited policy support (electrification, blue hydrogen)	Limited development	Limited collaboration	Mostly decentralised	Anion Exchange Membrane electrolyser	Solar
Not significantly implemented	30%	No support (electrification, blue hydrogen)	No significant change	Dispersed efforts	Parallel evolution • Backbone (1 GW) and decentralised frameworks	SMR (blue hydrogen)	Nuclear
	10%					Coal gasification (blue hydrogen)	

Figure 45 Scenario A and B

The least desirable scenario is scenario B, 'hydrogen not based on wind energy. In this scenario, none of the Dutch government's objectives and investments are successful. Only a few plants have been created with a capacity limited to 100MW. Hydrogen technology is not implemented in the transport sector, favoring battery technology. The most widely used technology will be blue hydrogen with non-negligible emissions and following capture, and electrolytes are powered by nuclear energy. In the table, scenario B is the one not emphasized, and is therefore the least favored for the future. It is also interesting to see how the various technologies proposed so far impact various environmental aspects. As we see in the graph below, in thirty years from now, compared to the black and white column, the technologies will pollute much less. In fact, we can see that ALK and PEM are polluting if we consider rare metals, while SMR (Steam Reforming Method). On the other hand, PEM and ALK methods are less polluting than carbon dioxide .Also to be considered. that between scenario A and B there is a difference in performance in favor of B, the more polluting one, but only 7%, a difference that on large numbers is not important **Error! Reference source not found.**

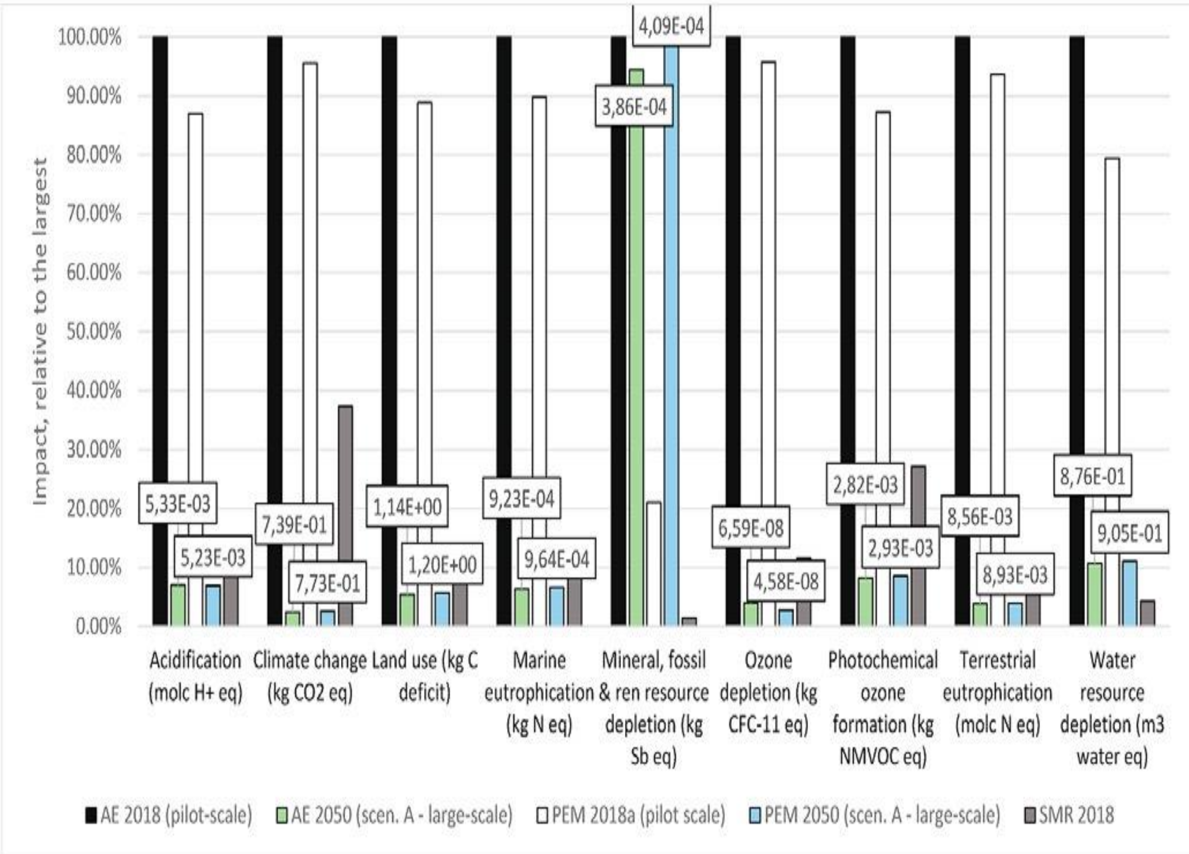


Figure 46 Different Forecasts

22) What will happen in the future?

That said, as far as the future is concerned, the most promising sources, as we have said, depend on location and exposure to natural energy supplies. Many countries will be able to harness more solar or wind energy depending on their geographical location. However, we can generally give some estimates, in kilo tones, of green hydrogen produced among the various energy sources. As we said before, solar energy is currently the most favorable and has the greatest potential, given the large amount of energy that is released every day.

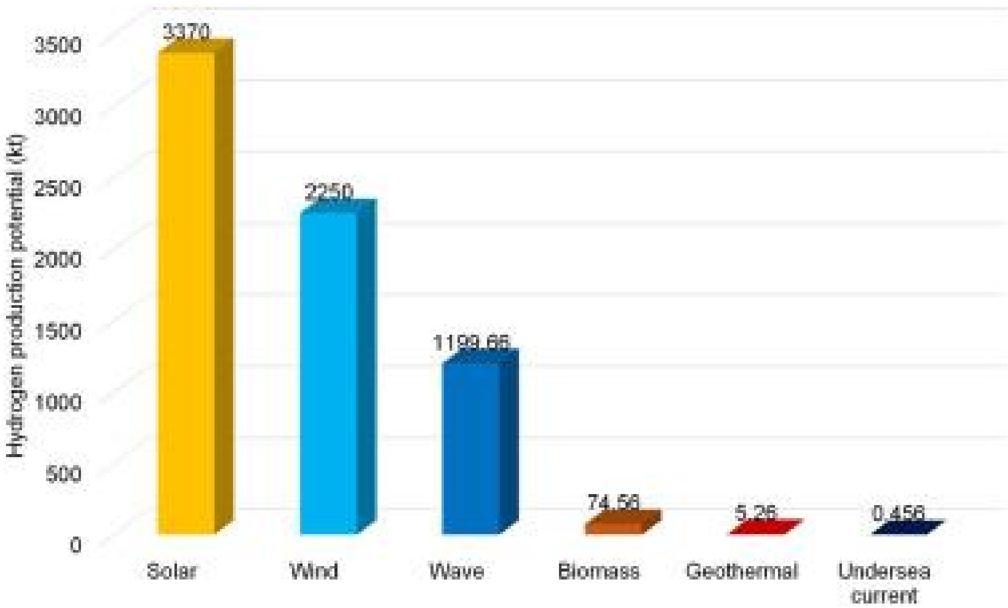


Figure 47 Hydrogen production potential

The results shown above should not come as a surprise at present, as the current technology enabling the production of green hydrogen is not entirely efficient, and the sun will remain the most widely used source in 2023. As the G20 has decided to achieve zero global emissions by 2050, investments are already being made in new forms of energy, and one of the most promising is green hydrogen, which is the subject of this thesis. Of course, one does not yet hear about green hydrogen nowadays since the cost of the latter is $3-8 per kg, which is still unfavorable in comparison to other cheaper forms. this trend is set to reverse, reaching just $1-1.5 per kg in the next thirty years, making this technology economically competitive and above all ecologically sustainable. Zero hydrogen emissions are not yet a certainty, but the desirable scenario is that of 85% use of renewable energies, leaving fossil fuels with a residual 10%. A trend that the world's nations therefore seek to reverse. The purpose of this thesis was not to convince people to use green hydrogen, but to raise awareness of the need for new forms of technology for a sustainable future.

Although this technology is still under development, it is equally true that the potential already seen in this thesis far exceeds our current forms of energy.

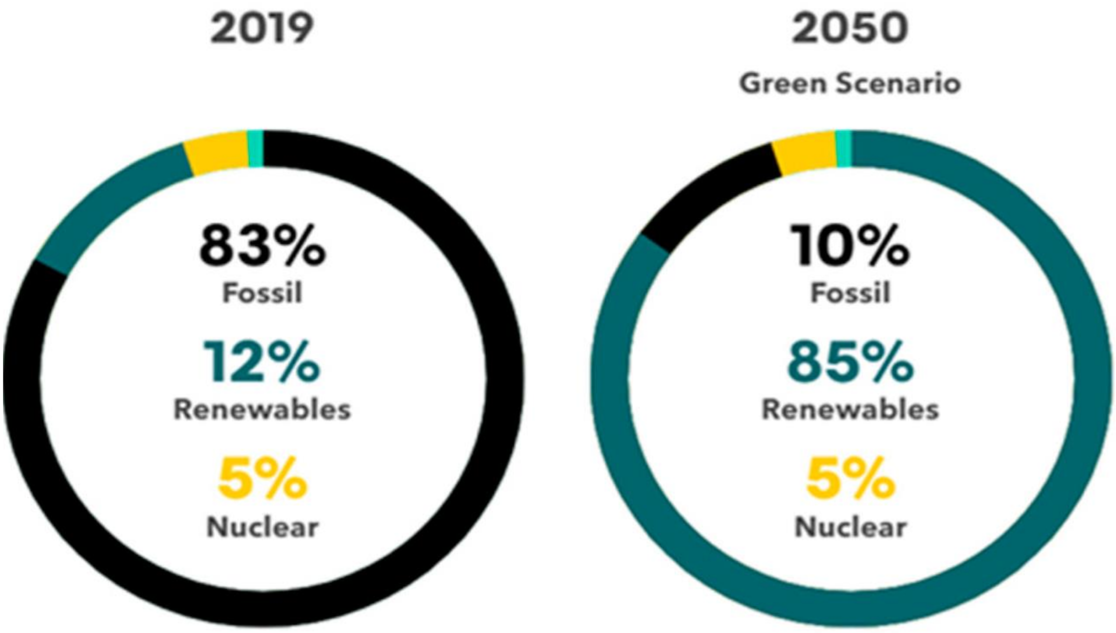


Figure 48 2050 scenario

The effort to be made, therefore, is to refine this technology in the still unresolved difficulties that have been listed in the previous sections of this thesis. This will only be possible with economic funding in scientific research and with faith in science. For science is our best source of energy, the motor of the world towards more evolved and more sustainable ways of living. Only then will mankind be better than yesterday and worse than tomorrow.

23) Conclusion

La fine di questa tesi ha lo scopo di riassumere quella che è stata una discussione dettagliata sulle maggiori possibilità per l'umanità di invertire la tendenza negativa delle emissioni globali di anidride carbonica, in questo caso attraverso l'idrogeno verde. Abbiamo ampiamente spiegato come i disastri naturali non siano casuali ma piuttosto una conseguenza dell'uso eccessivo di combustibili fossili. Abbiamo discusso di come l'idrogeno sia attualmente un'alternativa sostenibile solo se ricavato da fonti rinnovabili come il sole, il vento, eccetera, come esistano diversi modi per produrlo. Abbiamo poi spiegato come il ciclo di vita dell'idrogeno verde sia del tutto positivo, soprattutto dal punto di vista industriale, ma come non esistano attualmente le infrastrutture necessarie per il suo sfruttamento dal punto di vista domestico e non solo. La parte finale della tesi è stata inoltre riservata alla spiegazione di quali siano le tecnologie migliori. Per migliori intendiamo quelle che possono soddisfare i bisogni mondiali di miliardi di persone e soprattutto che hanno un impatto ambientale neutro, se non positivo. Inoltre, abbiamo scritto molto su un'opportunità che questa tecnologia ci offre, il riciclo dei materiali di scarto dei processi produttivi. Infine, abbiamo concluso che l'elettrolisi SOE (Solid Oxide Electrolyzers) è il metodo di produzione più efficace e meno inquinante, adatto a grandi numeri, insieme al PEM (Proton Exchange Membrane) e alla biomassa. Il primo ha il limite di dipendere da metalli nobili. rari, mentre la seconda tipologia, quella delle biomasse è ancora in via di miglioramento. Andiamo quindi a concludere dicendo che i tre metodi elencati sopra sono già sufficientemente sviluppati per poter condurre un'economia eco-sostenibile. Abbiamo quindi terminato con successo il nostro compito di studio dell'idrogeno verde.

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