Economic feasibility of green hydrogen in transportation sector

University of Groningen

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ABSTRACT

This report analyses the potential ability of green hydrogen to emerge as a fuel in various modes of transportation. We find that for wheeled vehicles hydrogen can be a viable alternative for electricity or biofuels only if substantial investment in infrastructure is made. In the aviation industry our finding is that hydrogen seems to be the most effective fuel to help the industry to switch to no emission businesses, yet a transition period of 25-30 years is needed. Ships might also become hydrogen-fueled, yet given little research on that matter it is difficult to determine to what extent. The underlying assumption in research was that there is or will be developed infrastructure for hydrogen. As we prove in the last part of the research, without considerable investment in hydrogen transportation and storage facilities, one cannot expect the transportation sector to become hydrogen-powered.

Course: Learning Community Energy Transition

Authors:
Sjoerd Beltman S3387569
Karol Czaja S3167097
Lilly Lanio S3456390
Jasper Morsink S2909898
Yvette Soesbergen S4479742

Supervisor: Peter Perey, MSc

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1. Introduction

Since 1950 our fossil fuel consumption (gas, oil and coal) has exponentially increased from 20,139 TWh to 136,761 TWh in 2019. If the consumption continues to grow at this rate, it is expected that all the fossil fuel reserves will be depleted by 2060. While we will probably find new reserves before that point, the depletion will be extended. What will be a bigger problem is global warming. According to NASA since the pre-industrial period (1750-1850) Earth's global average temperature has increased by over 0.2 degree Celsius every decade. Most of this trend is extremely likely (> 95% probability) due to human activity since the 1950's and is proceeding at an increasing rate.

The term Hydrogen Economy was first proposed in 1970 by John Bockris during a talk he gave at General Motors, but didn't start gaining momentum until the early 2010's which caused the forming of the Hydrogen Council in 2017. Since both Japanese and Chinese auto and energy firms have committed to designing and building hydrogen vehicles and hydrogen stations.

In 2015 at the COP21 Paris agreement, 195 countries agreed to limit global warming to 2 degrees celsius above pre-industrial levels to fight the climate crisis. To reach this target, the world must cut 60% of its carbon dioxide (CO2) emission by 2050, even with the ongoing population growth of an estimated extra 2 billion by 2050 (Nicholas Lepan, 2020). In order to achieve this, new solutions need to be implemented into the daily lives of people. In September 2020 a plan was proposed by the European Union to reduce EU greenhouse gas (GHG) emissions by at least 55% in 2030, compared to the 1990 levels. And be completely climate neutral by 2050.

According to the European Commission, the transportation sector is responsible for almost 24% of the yearly CO2-emissions in Europe, which has also increased the most since 1990, when 14.8% of the emissions were from the transportation sector. Out of the different transport forms, the aviation sector is the most polluting per, but air traffic represents less than 3% of the global CO2 emissions, while road traffic is responsible for around 10% of the emissions.

In this paper we will focus on a more sustainable usage of trains, ships, cars, trucks, aviation and furthermore an aiding infrastructure to enhance the use of hydrogen in these industries.

1.1 Central research question

To further specify our research direction, we looked more closely at the available information. We found that much research was focused on the available options of the hydrogen economy and transportation. However, we found that not much research has been done on providing a clear overview of the economic feasibility of (green) hydrogen in the transportation sector. Therefore, we came up with the central research question to further analyse this gap: “What is the economic feasibility of hydrogen in the transportation sector?”.

2. Hydrogen implementation in the transportation sector

In this section we will further discuss the micro environment of the green hydrogen economy. We will look specifically at the automotive sector, the aviation sector, and the maritime sector.

2.1 Automotive sector

2.1.1 Passenger cars

2.1.1.1 Market economy and competitors/substitutes to hydrogen

There are 1.5 million new passenger cars built every week. Adding up to a total of 1.4 billion cars on the road worldwide. This delivers a vehicle saturation of 18 % (Toyota, 2020). Hence the demand for driving clearly is tremendous and we need a more sustainable solution to fight climate change. The car market consists nowadays of three sophisticated sustainable ways to conquer the increasing CO2 emissions, bio fuels, hydrogen and electric vehicles. There are other ways investigated constantly but most of them haven't made it to the market yet.

Bio-fuels are made from organics or wastes and are therefore a renewable energy source. They are the largest source of renewable energy used in the transportation sector. This is mostly due to its easy usage. One can use the car as it was before and simply fill it with bio-fuels. In most cases bio-fuels are blended with petroleum fuel. This is reasoned by bio-fuels being one and a half times more expensive than petroleum and as well can it not be to 100% be used in winter, since it becomes too thick when the temperature sinks. Bio-diesel is one form of a bio-fuel. It is a clean alternative fuel that is as well produced from renewable sources. 85% of bio-diesel production comes from the European Union (Britannica, 2019). It is arguable if bio-fuels make a net contribution to global warming. The plant-based biofuels can result in additional emissions of greenhouse gases that may offset the benefits of using renewable fuel. Additionally will erosion increase and biodiversity of wildlife areas decrease. Hence biofuels are easy to produce and implement but in the long term not an optimal solution and as well a little costlier than fossil fuels.

Hydrogen is basically produced by “splitting water” which can be carbon-free provided and the electricity used in the production process can as well be renewable sources like wind or solar power (Futurebridge, 2020). The problem with hydrogen in passenger cars is that very pure hydrogen is needed and therefore the natural pipelines are not an option. This is a massive logistical problem in the implementation of passenger cars. Furthermore is the safety and cost factor more difficult. Hence the environmental perspective is very appealing but the implementation offers some obstacles to overcome.

The last solution is electric cars. The development of electric cars is by far the furthest and serves already a big market. This is due to the easier implementation of electric cars. Only charging stations where needed either at homes or on road sideways. Possible downsides of electric cars are the charging time and the distance they can put behind.

We believe that the electric car is the biggest competitor to hydrogen cars. This is due to their already established market economy and the long-term more sustainable perspective than biofuels. Both vehicles have the same goal, ro reduce environmental impact of oil consumption, therefore an in-depth comparison will distinguish them in more detail.

2.1.1.2 Hydrogen-powered and electric vehicles compared

Hydrogen-powered fuel cell passenger cars and battery electric vehicles are the only zero-emission alternative to driving with oil for cars (Toyota, 2020).

From a consumer perspective the hydrogen car is by far the most expensive one. They start at 60,000 Euros which is in comparison to 21,000 for an electric car, a lot more and compared to an oil driven car that can be bought at around 8,000 Euros immense high. These prices are averages of medium-sized vehicles (Toyota, 2020). One can derive that the capital costs for choosing hydrogen are higher than for other vehicles. The running costs are roughly speaking the same for all of these, however lower for electric cars at the given moment. This is largely due to the not yet established infrastructure of hydrogen, which will in turn lower the prices for hydrogen due to economies of scale.

However one has to take into account that the range from hydrogen cars is usually about the same as electric cars, but the charging time takes only 3-5 minutes whereby an electric car can take from 2 hours to 12 hours. As mentioned earlier are the fueling options for hydrogen limited. Shell has built a production and storage facility next to a gas station in London. This one is able to produce 80 Kg of hydrogen each day. The Toyota hydrogen car needs 5Kg to fill up and can then drive about 500 Km. They store the hydrogen in pressure tanks (Toyota, 2020). Meaning the hydrogen station can serve 16 customers per day. If there would be bigger hydrogen production centers on the countryside, which are then transported to the cities, it would be too costly and not competitive anymore on a large scale . In Table 1, one can see the above named comparison between the Tesla Model 3 and the Toyota Mirai. Therefore infrastructure is a big drawback for hydrogen cars. Electric cars had an easy start with that by implementing charging stations. This is even handy for the consumers to build into their homes

	Tesla Model 3	**Toyota Mirai**
Price to fully charge or fill	$10-$12	$85
Range	500 km	480 km
Price per km	2-2.4 cents	17.7 cents

Table 1: *Price & range of Tesla Model 3 and Toyota Mirai.*
Source: *RealEngineering.com, 23.11.2020*

As mentioned above, the infrastructure of hydrogen is more complicated than the one of electric cars. The consequence of this is that the initial infrastructure costs for electric cars are very low and for hydrogen cars very high. Once the infrastructure for hydrogen cars is established though, it will have low long term costs and economies of scale will boost the industry of hydrogen vehicles. There are already worldwide efforts to lay the foundations for a near-term development of hydrogen and fuel cells on the vehicle market. Several countries on the globe have announced plans to build 2800 hydrogen refueling stations by 2025 in Europe (McKinsey, 2019). Furthermore in 2017 the hydrogen council was founded with support of transportation and other industrial companies of 53 countries (McKinsey, 2019). Hence, once the infrastructure is built, hydrogen will have an advantage over electric vehicles due to economies of scale and as well the further usage in different car types. Usually electric cars are used for city vehicles, however once hydrogen is established it will be lucrative for every type of car.

Lastly, we want to address one more rumor that comes to place when hydrogen cars are a topic. Some people believe that they are not safe due to the pressure tanks where the hydrogen is stored. This is not the case! Since hydrogen is 14 times lighter than air, in case of an accident the hydrogen will disperse very quickly. In addition are the flames low radiant heat, meaning that there is a low risk of secondary or spreading fires. Lastly is hydrogen non-toxic. There is only pure water in the production process combined with oxygen in a fuel cell to produce electricity. (CHFCA, 2019). Hence, safety is not a concern that is relevant with hydrogen cars.

2.1.2 Trucks

The need for electrification of Truck transport is large. “Currently lorries produce about 2.5bn tonnes of CO2 a year out of an estimated total for all transport of about 9.5bn tonnes (not to mention the air pollution they generate).”

The structure of the Trucking industry calls for a decentralised solution. “Emission standards for trucks are rare, unlike those for cars, and it is a fragmented business with lots of owner-drivers who cannot easily be corralled into taking collective responsibility for tackling climate change.”

Needed distribution of refueling stations. Trucks often come across hubs in central locations which makes the need for a large refueling station feasible. Unlike cars, for which many drive from decentral locations to other decentral locations without coming through a hub, trucks commonly depart, arrive or come across a hub along their trajectory. Trucks drive from a distribution centre or industry parks to the consumer or vice versa, mostly over highways. Therefore, a fueling station close to the hubs or along highways allow for refueling quickly.

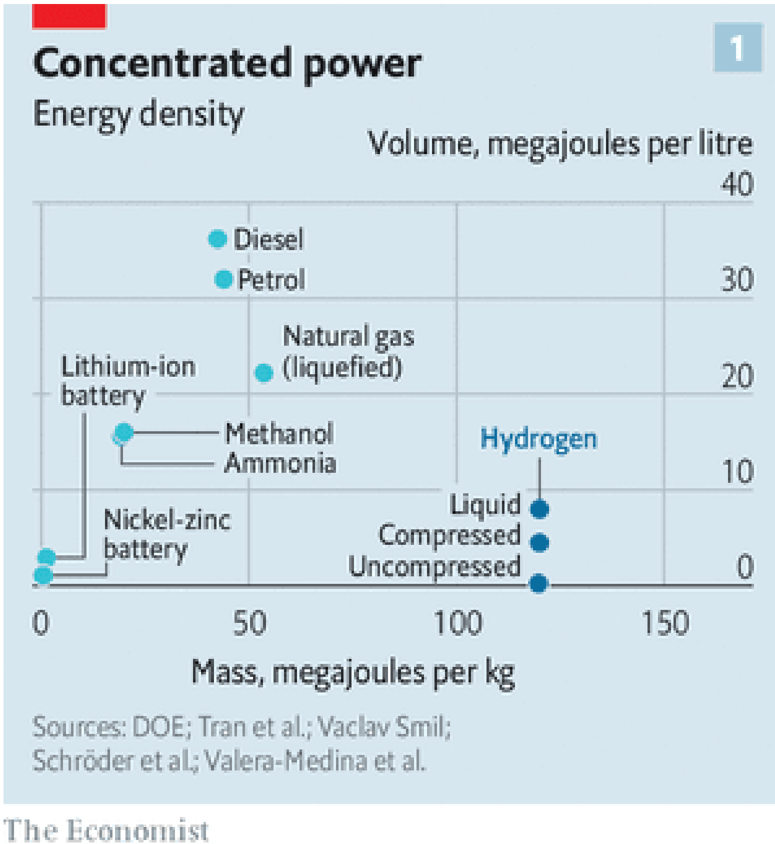


Table 2: *Concentrated power and energy density.*
Source: *TheEconomist.com, 18.11.2020*

Hydrogen has a benefit for trucks that electric trucks are missing and which are as well interesting in the implementation of passenger cars. Hydrogen is lighter than the batteries for electric cars and each kilogram of batteries to extend the driving range burdens on the cars material. These cars will need more sophisticated breaks, tires, etc. Figure 1, below, shows the relation of the driving range and vehicle weight for both hydrogen and electric cars. The same holds true for trucks, this being one of the reasons why electric trucks have not yet been established and electricity is rather used for smaller city cars. For hydrogen on the other side, it is not the case that the car gets heavier if one tries to extend the driving range of a hydrogen car. As an example, the battery of the Tesla 3 weighs 480 kg while the tank weight of the Toyota Mirai only weighs 88 kg. This makes hydrogen an ideal fuel for heavy transport where every kilogram costs extra money (Nicholas Lepen, 2020).

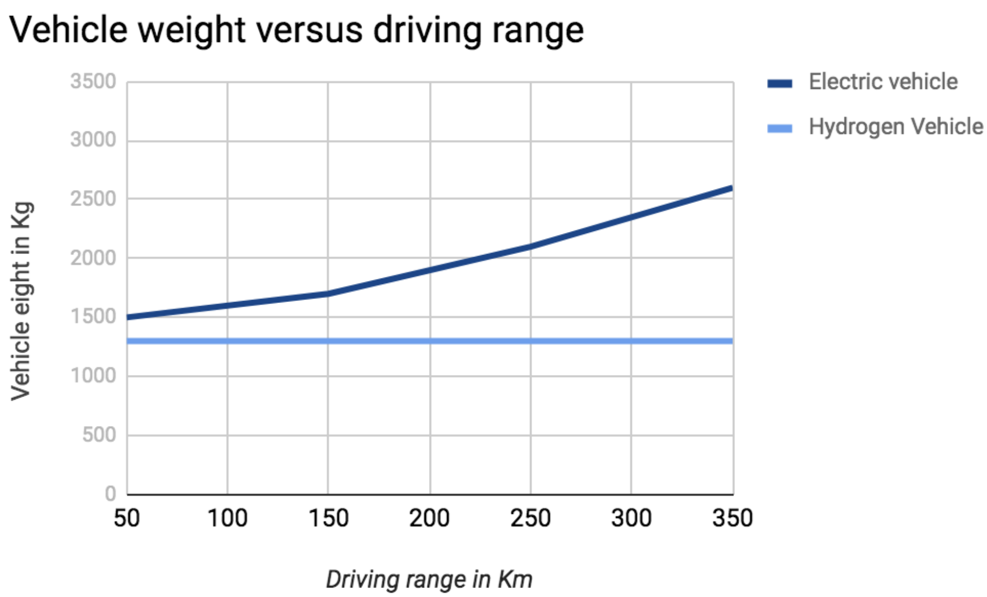


Figure 1: *vehicle weight versus driving range.*
Source: *RealEngineering.com, 20.11.2020*

After weighing the advantages and disadvantages of the usage for green hydrogen in passenger cars and trucks, we can summarize that hydrogen can be the best solution in the future, once the infrastructure is well established and initial investments have been made there. Green hydrogen offers advantages especially for heavier vehicles and as well in terms of the fueling time. With the given infrastructure it could as well profit from economies of scale and have therefore an advantage over electric vehicles in terms of safety, range and price.

2.2 Aviation sector

It has been more than 100 years since Wright brothers made a first successful flight with their Wright flyer which is considered a cornerstone for the aviation industry. Since 1903 this sector has gradually evolved and has become one of the most important means of transport. Surely, it changed the way different parts of continents, and the world, are connected. However, as much as it helped humanity to break distance barriers, it also speeded up the process which is now threatening a very wellbeing of our planet and societies - anthropogenic climate change. No wonder, then, that the energy transition in the transportation does include changes in the aviation sector.

First subsection discusses how the industry looks like today. We focus on the specifics of the aviation industry and how it contributes to global CO2 emissions. In this part, the economic feasibility of (green) hydrogen is also talked through. Afterwards, we discuss, what are the possible developments for (green) hydrogen to become a fuel for the aircraft industry and what challenges are to be overcome.

2.2.1 State of the world

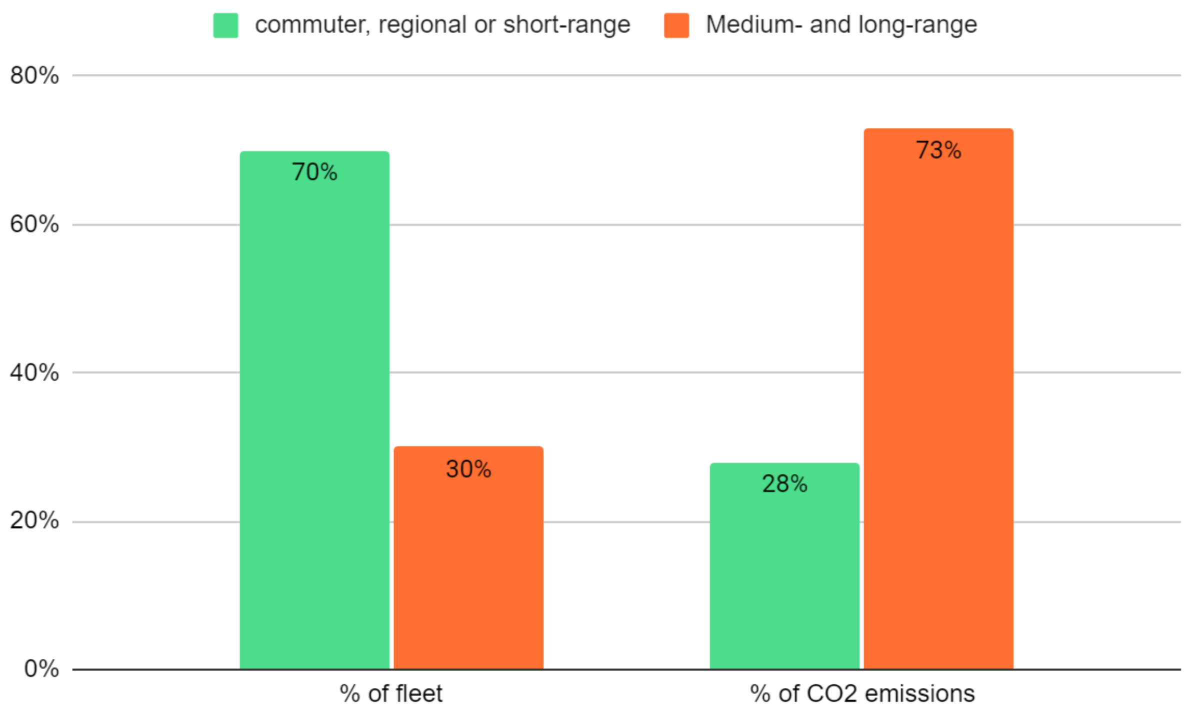


Figure 2: *Percent of fleet and percent of CO2 emissions by type of aircraft (Clean Sky 2 JU, 2020, p. 16)*

Aviation industry has some specific characteristics which are worth mentioning before moving on further. Firstly, even though the majority of global fleet is commuter, regional or short-range[1] (4%, 13%, 53%, respectively) most of CO2 emissions are made by medium-range or long-range aircrafts. Just those two categories account for 73% of total CO2 emissions of the aviation

[1] short-range flights are up to 4,500 km so in many regions, like in Europe, they are also international flights

industry. Aviation is, thus, a global market and should be analysed as such. Secondly, it is also a market which, due to the significant barriers of entry, represents a very limited number of products available. In other words, the number of aircrafts manufactures are very limited and products and technologies they offer are somewhat similar. In this section, we focus on civil aviation and abstract from jets used in cargo or militaries.

The discussed sector accounts for around 3% of global emissions (Thomson et al., 2020, p. 5). European Environment Agency looked at the different transport modes and checked how many grams of CO2 per passenger kilometer is emitted by each (2013). This was estimated by the average number of passengers per vehicle. The results are summarized in table 2 below:

Mode of transport	**Average number of passengers**	**Grams of CO2 per passenger kilometer**
Train	156	14
Small car	4	42
Big car	4	68
Plane	88	285

Table 2: *Average number of passenger per vehicles (European Environment Agency, 2013, p. 104)*

In the table above, one can notice a significant difference in the number of grams of CO2 per passenger kilometer. Clearly, planes produce around 20 times grams of CO2 more than trains. They also emit more CO2 than either of small or big types of cars.

A vast majority of aircrafts is fueled with kerosene, a product of petroleum. In the last decades a lot has been done to improve energy use efficiency in the sector. Thanks to design improvements, new technologies of turbines and operational changes, the aircraft fuel burn per seat decreased by as much as 82% between late 50’s and 2010 (The World Bank, 2012, p. 5). This does not change, though, that due to the increasing number of passengers, total CO2 emissions increased significantly over time (Thomson et al., 2020, p. 5). Thomson et al. (2020, p. 5) also predicts that if current developments are continued, by 2050 the industry may be responsible for up to 24% of global emissions. With the technology becoming around 2.5% more efficient year-on-year this number could decrease to 19%. Clean Sky 2 JU suggests that assuming industry growth of 3-4% a year and constant efficiency improvement of 2%, in 2050 we would see emissions doubled.

It is clear that, given the combating climate change goals and growing numbers of passengers, the aviation industry should either be curbed (the analysis of this is not a part of this report) or move to other energy sources. Some options are summarized in table 3 below.

	Kerosene	**Sustainable Aviation Fuels (SAF)**	**Battery-electric**	**Hydrogen fuel cells**	**Hydrogen combustion**
Description	Major fuel for aviation industry nowadays	Fuels obtained in sustainable fashion. These biofuels, synfuels or waste-to-fuel.	All-electric system which enables aircraft to fly.	Liquid hydrogen is stored aboard and converted to electricity.	Hydrogen is used to directly power jet engines
CO2 emission	Very high	Limited	Provided electricity is green, this aircraft can have zero emissions	Provided hydrogen is green, aircraft can have zero emissions.	Provided hydrogen is green, aircraft can have zero emissions
Limitations		Net-zero CO2 emission, yet only when offsetting is applied. More importantly,	Low energy capacity of batteries. Solution potentially applicable only	Both solutions require significant changes in design of aircrafts. Due to very low volumetric density, some more space for hydrogen would be needed. Furthemore, only fuel-cell solution does provide a full	

		non-CO2 emissions are still relatively high (for instance NOx)	for up to short-hauls flights. Also, recharging batteries may be time-consuming. Also, new architecture would be required.	NOx emission reduction. Another drawback is that water vapor emission can increase by as much as 150%.

Table 3: *Sources of energy for aviation industry (Airbus, 2020; Thomson et al., 2020; Clean Sky 2 JU, 2020)*

This table enlists potential fuels for the aviation industry. Today, it is common to use kerosene in the aviation industry. It is still cheaper than other options and its high gravimetric energy density make it a reliable energy carrier for this sector. However, its obvious drawbacks are very high CO2 emissions which makes it impossible for the industry to meet climate targets. As mentioned before, even with the developments in usage efficiency, carbon capture and storage technologies or other novelties, this fuel cannot be considered in a longer perspective.
The other option is sustainable aviation fuels. Interestingly, as they are similar to standard fossil fuel they can be mixed with fuels that are commonly used today as no change in infrastructure is needed. The International Air Transport Association (IATA) claims that "over 250,000 flights have taken to the skies using SAF since 2016" (*Developing Sustainable Aviation Fuel (SAF),* n.d.). Interestingly, SAF's can significantly reduce emissions - even down to zero. This is, however, a net-zero emission (what is emitted is offset in the process of production). Once in the air, SAF's keep having some negative environmental impact. Also, even though the CO2 emissions are limited there is still a substantial amount of other greenhouse gases produced.

Before moving on to hydrogen it is worth to notice a solution which can provide industry with neither CO2 nor other GHG emissions - battery-electric engines. Given that electricity to charge batteries is produced in a green fashion, this might give a scenario when the industry is actually green. There is a significant barrier though, i.e., low energy capacity of current batteries. This makes batteries a viable alternative only for commuter or regional flights of rather small aircrafts. Also, recharging batteries takes quite some time during which the aircraft cannot be used to provide income. Finally, batteries would require some changes to current architecture of aircraft.

Hydrogen emerges here with some advantages that are not visible in other “not-kerosene” solutions. First of all, providing that it is produced in a green fashion and used in fuel cell technology, it does not have a negative impact on the environment - notably, it only reduces CO2 emissions to zero but also has no NOx emissions - it naturally makes it more environment friendly than SAF’s solution. Furthemore, its advantage over batteries is that it can be refilled quickly and has significantly higher gravimetric energy density (33 KWH/KG in comparison to 0.3 current batteries).

2.2.2 (Green) hydrogen possible developments

As mentioned earlier, (green) hydrogen clearly appears to be a solution for the aviation industry. There are some drawbacks, though, which makes it difficult to distinctly define economic feasibility of hydrogen. First of all, as it has 4 times lower volumetric density than kerosene some significant changes in architecture of aircrafts is needed. Changes in design of body shape or turbine engines are required. These changes are of very high complexity so a bunch of R&D activities is needed. Another problem is the cost of (liquid) hydrogen. In 2020 it is at least 4 times higher (per kilogram) than kerosene (Clean Sky 2 JU, 2020, p. 48). This undermines the idea of using it as an energy carrier on the aircraft. However, it is expected that by 2050 this cost will keep decreasing and will be of a similar value for both types of fuels.

The key question is where to expect the (green) hydrogen to be an economically feasible solution for the aviation industry. Clean Sky 2 JU suggests that to introduce larger new aircraft may take from 15 to 20 years (2020, p. 61). Fleet deployment and adjusting airports’ infrastructure is also a project which, assuming common effort, may take years. All in all, providing diminishing costs of liquid hydrogen one can expect the industry to switch to non-zero in late 40’s at the earliest.

Some developments are on the way. Airbus has already commenced R&D activities in order to build hydrogen-powered aircrafts (Airbus, 2020). In press releases Airbus says that it wants to release its zero-emission jets by 2035 (Airbus, n.d.). On the current aircraft manufacturers duopoly, Airbus interest in green aviation is higher than Boeing’s. The Economist suggests that European regulator’s interest in energy transition might be a trigger for French giant to invest more (2020). Public opinion and regulators' pressure might be necessary to induce some action from the industry’s side.

2.3 Maritime sector

2.3.1 Ships

In terms of emissions per weight transported, the maritime industry, especially overseas, is the most sustainable form of freight transport. However, it is also the most colossal form of transportation. To illustrate, ships did account for an annual 1 billion tonnes of GHG emission between 2007 and 2012, which equals a 3 percentage cut of total global emissions (Smith et al, 2015). Solely focussing on the transportation industry, it is stated that for Europe, maritime contributes 13,4% to the total GHG emissions (European Commission, 2015). Whereas globally, it accounted for 9,26% in 2010 (IPCC, 2018).

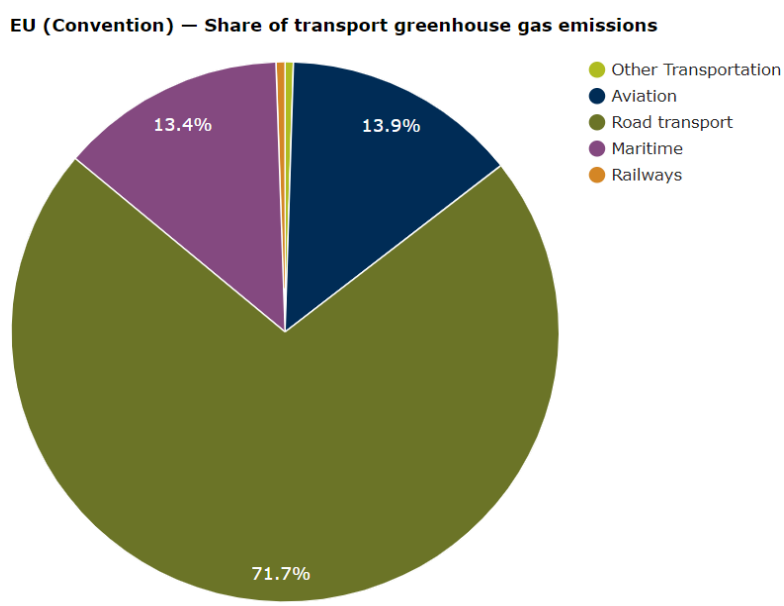


Figure 3*: composition of greenhouse gas emissions from transportation in 2018 (European environment agency, 2018).*

Furthermore, the UN conference on trade and development estimates the maritime industry to grow at an annual rate of 3,4%, expanding the total GHG emissions stemming from shipping, and increasing the potential 'benefits' that can be gained in terms of GHG reduction. However, due to the economic incentives in the shipping industry, current literature mainly focuses on fuel efficiency, and marginal technological improvements, rather than deviating to alternative fuels to suppress emissions. Which is completely rational considering that the operating cost of shipping is determined for 50-60% by fuel consumption. Therefore, fuel minimization translates to a profit expansion, as well as a reduction in total emissions. Hence, much of the literature regarding the maritime industry therefore often focuses on the optimization of sailing speed, increasing profits, and decreasing total emissions. Even though these marginal improvements help to conserve emissions, it will not be enough to offset the market growth, let alone flattening the global warming trend to a significant extent. (Bouman, Lindstad, Rialland, & Stromman, 2017), for example states that emissions can be decreased by 4-6 percent due to optimization in regulations and policies. Additionally, (Crist, 2009), states that fuel consumption can be improved by at most 7 and 9 percent by using light weight construction materials, and optimizing hull dimensions of ships respectively.

In order to incentives the industry beyond the economic scope of fuel conservation, legislation and policies are essential. As a result, the landmark 2015 Paris agreements state that the maritime industry has to half its greenhouse-gas emissions by 2050. Including the expected growth of the sector into the equation, this translates to a 70% reduction of total emissions (Harvey, 2018). Therefore solely fuel conservation will not be sufficient in the long run, and alternative means of propulsion have to be sought, developed, and implemented. Some sources of energy that are in the race for emission reduction are Hydrogen, Biofuel, sustainable LNG, electricity, and wind energy as a hybrid addition.

Biofuel exists in many different forms and chemical structures, and is made from plant materials. Therefore, biofuels are arguably a viable alternative fuel to improve total emissions in the industry. The fuel is relatively easy to produce, and the production of the fuel is not dependent on the production of green electricity. However, the fabrication process is very labour intensive, and requires the exploitation of extensive quantities of farmland, potentially reducing biodiversity and suppressing the possibility of food production (Hellmann & Verburg, 2010). The production cost of biofuel per Kwh is estimated between $0.08 to $0.15 (U.S. Department of Energy, 2016).

Liquified natural gas (LNG) is the cleanest fossil fuel and is easy to transport, however it is still a fossil fuel and therefore still converts natural carbon storages into emissions. As a result, LNG produces 20% less carbon dioxide emissions than diesel, and entails a 90% reduction in nitrogen oxide emissions. Furthermore, natural gas is relatively economical, priced around $0.065 per KWh, (Greenstone & Looney, 2011). However, it must be noted the cooling process is very energy intensive, for which reason the actual sustainability is decisively dependent on the use of green electricity. Furthermore, the process of creating sustainable LNG demands the extraction of methanol from the gass, further accumulating the production costs.

With regards to electricity as a substitute in the maritime industry, it is tied to the limitations caused by the weight and energy density of battery technology. As a result, this technique is most promising for small boats and ships that have standard docking places. Think of short route ferries, that can charge whilst being docked. Even though electrifying this part of the maritime industry, it results in marginal emission reductions since short distance ferries and passengers transport only accounts for 0,6% of the total world fleet, and is therefore beyond the scope of this paper. However, one promising interim solution to mention is the use of plug-in electricity in ports to replace the ship's auxiliary engines during the docking process. This idea, called "cold-ironing', originated from the ports of Los Angeles (USA) and is expected to become the norm in most ports (Shah, 2020). Cold-ironing is a shore connection to the ship delivering electrical power for necessary equipment such as lightning, heating, and cooling. As a result, the ship can shut down it's combustion engine and use the electricity from the grid. Moreover, harbours can simultaneously decide to supply ships with clear energy sources to further suppress climate change.

Even though there is not a single full sized cargo ship powered by hydrogen sailing the seas today, (Mao, Rutherford, & Osipova, 2020) investigated the feasibility of replacing fossil fuels with hydrogen in the busiest container ship corridor, the connection between China (Shenzhen) and the United States (Los Angeles). This technical analysis, mainly focussed on the energy demand, and found that 43% of all cargo vessels sailing this route could be powered by hydrogen without substituting cargo space for fuel tanks, and 99% of the vessels could when either trading 5% of cargo space for hydrogen fuel cells, or adding an additional port along the voyage. The interesting result of the research is that medium sized ships, between 3 and 12 thousand container places (TEU's) have the highest attainment rate. This is due to the fact that these ships have respectively less space occupied by the fossil fuel tanks and their motor which can be used for the hydrogen drivetrain and its fuel storage.

Furthermore, (Horvath et al, 2018) conducted a techno-economic analysis on the potential fuels for decarbonization of the shipping industry by 2030 and 2040. They concluded that RE-LH2 (liquified hydrogen) is the most cost effective by both time periods based on its operating expense, investment expense, loss of cargo costs, and fuel costs. The main advantage of hydrogen was that the production cost per energy unit was the lowest, as shown in Figure 4. However, hydrogen was more expensive compared to the others in terms of it's capital expenditures for the transformation of the engines, and the fuel cells. The cost of installing hydrogen storage tanks for example is priced at 0.821[€/kWh], while it is only 0.305[€/kWh] and 0.138[€/kWh] for LNG, and MeOH[2] respectively. Moreover, as stated in the paper, and validated by (Mao et al., 2020), cargo space has to be abandoned and used for fuel cells. For deep sea vessels, this accounts for 3,5% to 4,1% in the case of hydrogen, whereas this is only between 0,6% and 0,7% for LNG, and between 1,4% and 1,6% for MeOH. This is graphically indicated in figure 4 below.

[2] CH3OH, also called Methanol, can be produced by biosynthesis.

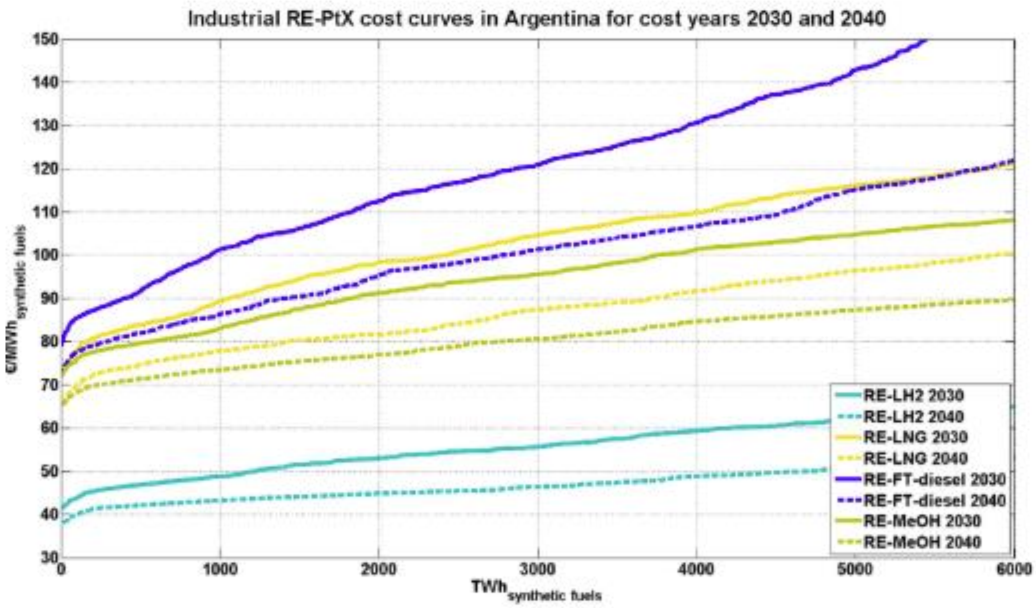


Figure 4: *industrial cost curves for synthetic fuel production in Argentina powered by hybrid PV-Wind power plants (Horvath et al., 2018).*

Besides that, (Horvath et al, 2018), sheds light on the difference between a combustion engine, and fuel cells, as well as the comparison with fossil fuels that are currently used. In figure 5 it can be seen that, once used in the configuration of fuel cells, hydrogen can almost equal the cost configuration of fossil diesel, and can even be less expensive once emission tax of fossil fuels are taken into account.

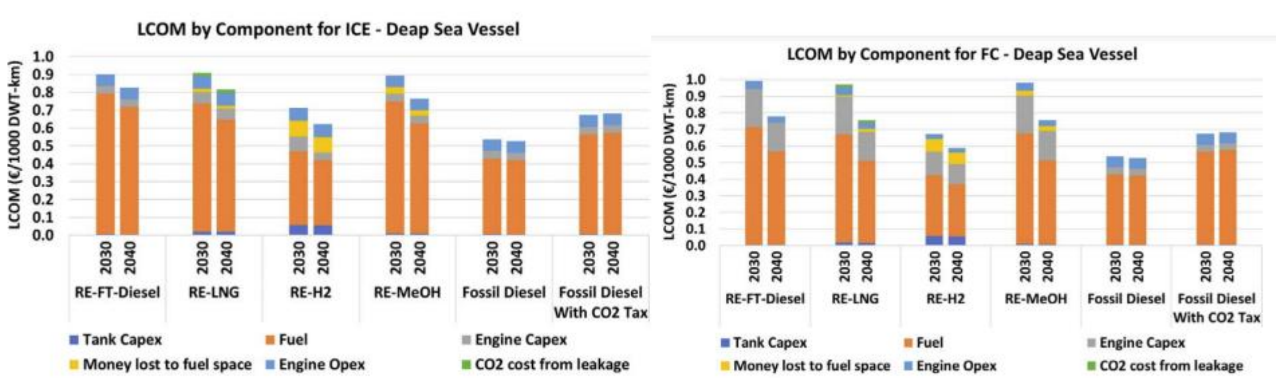


Figure 5: *the levelized cost of mobility for internal combustion engines and fuel cell technology in 2030 and 2040 (Harvath et al., 2018).*

Source:

However, it must be stated that the authors do not take into account the immense additional cost that the change in infrastructure imposes which could to a large extent change the results of the study with respect to fossil fuels. Furthermore, they do not account for the increase in demand for green hydrogen in case of a substantial drift towards hydrogen, which could alter the price of green hydrogen.

In conclusion, there has been limited to no practical research in hydrogen as a viable fuel for container ships. Nonetheless, theoretical research suggests that hydrogen is an economical viable source of energy in comparison to its competitors. It is relatively cheap to produce, assuming that it can be sustainably produced on a large scale. Moreover, it can even outperform fossil fuels and sustainable LNG in terms of production cost. However, LNG has the advantage of already being implemented, and accepted as a viable alternative fuel in terms of emission reduction. The main barrier for hydrogen is the lack of infrastructure, both in the transportation and the manufacturing of the product. Furthermore, the conversion to hydrogen requires vast amounts of investments by operators for fuel tank, and engine adjustments. In light of the Paris agreement targets, it is recommended that governments focus on the organization of a sufficient infrastructure for green hydrogen, such that operators are certain about the future use of hydrogen, and do not see their investments vaporize.

3. Hydrogen supply to transport sector

This section will look more closely at the macro environment of the green hydrogen economy. This section will further analyse and discuss the transport logistics and costs involved in transportation, the storage solutions that currently exist, and the options available regarding electrolysis.

3.1 Transport logistics and cost

To be able to run a green hydrogen energy, the hydrogen as energy carrier has to be transported from the production source to the end consumer. According to Hydrogen Europa the most common ways to transport and distribute hydrogen are:

- Compressed gas cylinders or cryogenic liquid tanks
- Blending with natural gas
- Pipelines

Blending natural gas with hydrogen is a proposed method by governments and utilities while striving to a low- and zero-carbon hydrogen injection into the existing Natural Gas (NG) grid to displace the traditional fossil fuels consumption and reduce carbon emissions. Since hydrogen has a much lower energy density than natural gas (0,033 MWh/Kg for hydrogen and 0,014 KWh/Kg for NG), end-users of the blended gas would require a higher volume of gas to achieve the same energy as pure neutral gas. This also means that, for example, a 5% blending of hydrogen by volume does not translate into a 5% decrease of fossil fuel consumption. In practice this means that a 5% blending of hydrogen volume would only displace about 1.6% of NG. Countries across the world have started various pilots to explore the impact of hydrogen blending, though different countries have set maximum blending limits, which are shown below in figure 6.

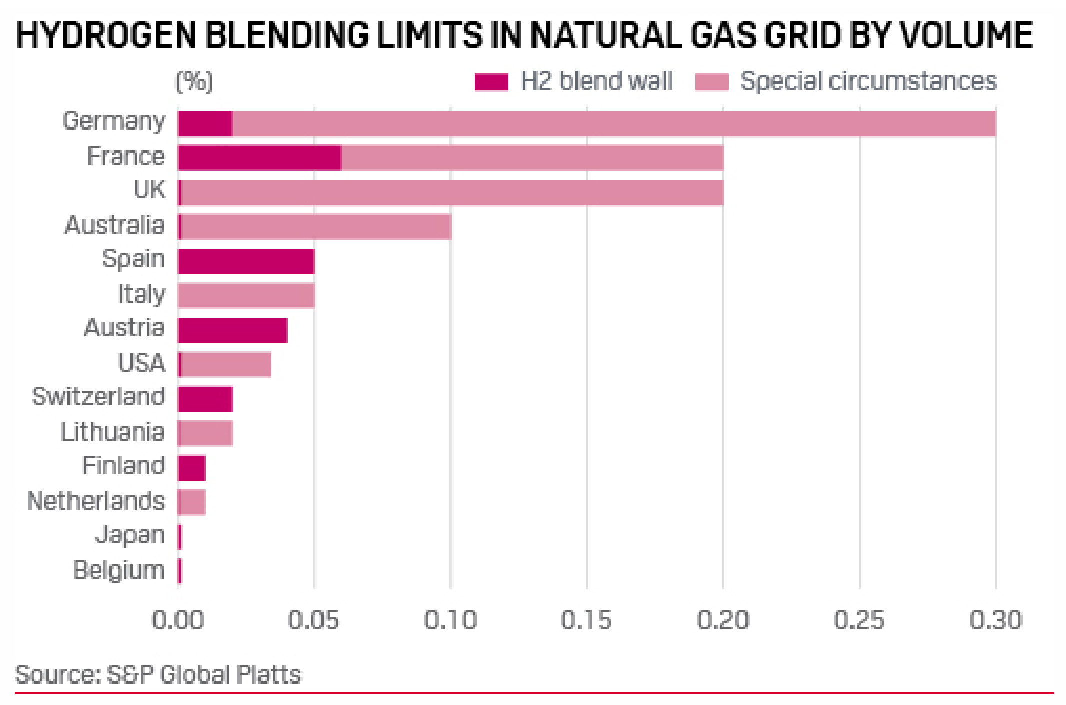


Figure 6: *hydrogen blending limits in NG grid.*

Source: S&P Global Platts

The last option, pipelines, would be considered the best option for a large-scale use of hydrogen as an energy carrier. Existing NG pipelines can be used to distribute the hydrogen, after some small changes. Research from Heaseldoncx and Dhaeseleer (2007, p. 1385) shows that, to satisfy the energy demand currently provided by Higher Heating Value (HHV) of NG is approximately 40 MJ/Nm3 (0,01 MWh/Nm3), whereas the HHV of hydrogen amounts to 13 MJ/Nm3 (0,004MWh/Nm3). This means that, to satisfy the same energy demand, the volume of hydrogen to be transported has to be three times that of NG.
However, the density of hydrogen is nine times smaller than that of NG. Furthermore, Heaseldoncx and Dhaeseleer (2007) state that, assuming an unchanged pipeline and pressure drop, hydrogen is able to transport 98% of the energy compared to lean NG and 80% when compared to rich NG.
Natural Gas pipelines use two types of compressors: centrifugal and piston. As far as piston compressors are concerned, the working gas that is used in the system is of no importance. But for centrifugal compressors, using hydrogen requires a larger compression of a volume as NG. To obtain this pressure a higher rotational force is needed (x 1.74). This rotational force is limited by the pipeline material strength, which is calculated for NG pressure's, not H2 pressure's, which can cause problems when hydrogen is transported through existing pipelines. The risk of problems that can occur with the NG pipelines differs per pipeline. It does not only depend on the material of the pipeline, but also on past pressure fluctuations. The risk of hydrogen leakage is the largest in cast iron and fibrous cement pipelines, however while the volume leakage of hydrogen will always be larger than NG, the energetic loss will be smaller. Though it is important that the pipeline network that is used to transport the hydrogen is being used anymore to transport natural gas and are only available to transport hydrogen.

Baufumé, Grüger, Grube, Krieg, Linssen, Weber, Hake & Stolten (2013, p. 3828) proposes not connecting these areas with a small demand to the network, as the high shares of fixed cost for this would not outweigh the benefits of being linked to the pipeline network. Instead they suggest on-site hydrogen production or trailer delivery. The advantage of on-site hydrogen production is that it can be produced with energy that can be brought to the site easily, such as solar power. The downside of on-site production is that the amount of equipment required for the amount of hydrogen produced is significantly higher than for large scale facilities, due to the economy of scale. At an extreme small scale, fossil fuels could be reformed to hydrogen on board a fuel cell vehicle, but the systems are complex and costly.

From several possible scenarios they have calculated in Germany that relying on the existing network of fuelling stations (for cars and trucks) and pipeline infrastructure would be the best option to facilitate a transformation from a NG depended economy to a hydrogen economy, as this decreases the upfront investments (€ 8.2 billion and network length of 12,997 km) and shortens the payback periods.

In the previous chapters different forms of transport have been discussed, the implementation and growth of implementing hydrogen driven alternatives are closely linked to the transportation network of hydrogen. An existing network is necessary for the purchasing of hydrogen-fuelled vehicles, but a network will not be built without investors. To build a viable network and have customers ready to use the network, supplier and manufacturing companies will have to work together. This collaboration will be key to create a positive investment and will have to be monitored by the government to ensure that there is no monopoly and everyone will have access to the grid.
A starting point to move vehicles from a fossil fuel based energy source towards a hydrogen based energy source would be the trucks. As they often move from one central location, a warehouse for example, to another set location, installing hydrogen production and storage sites to re-fuel the trucks. These storage locations can be used at a later moment to also refuel hydrogen passenger cars also.

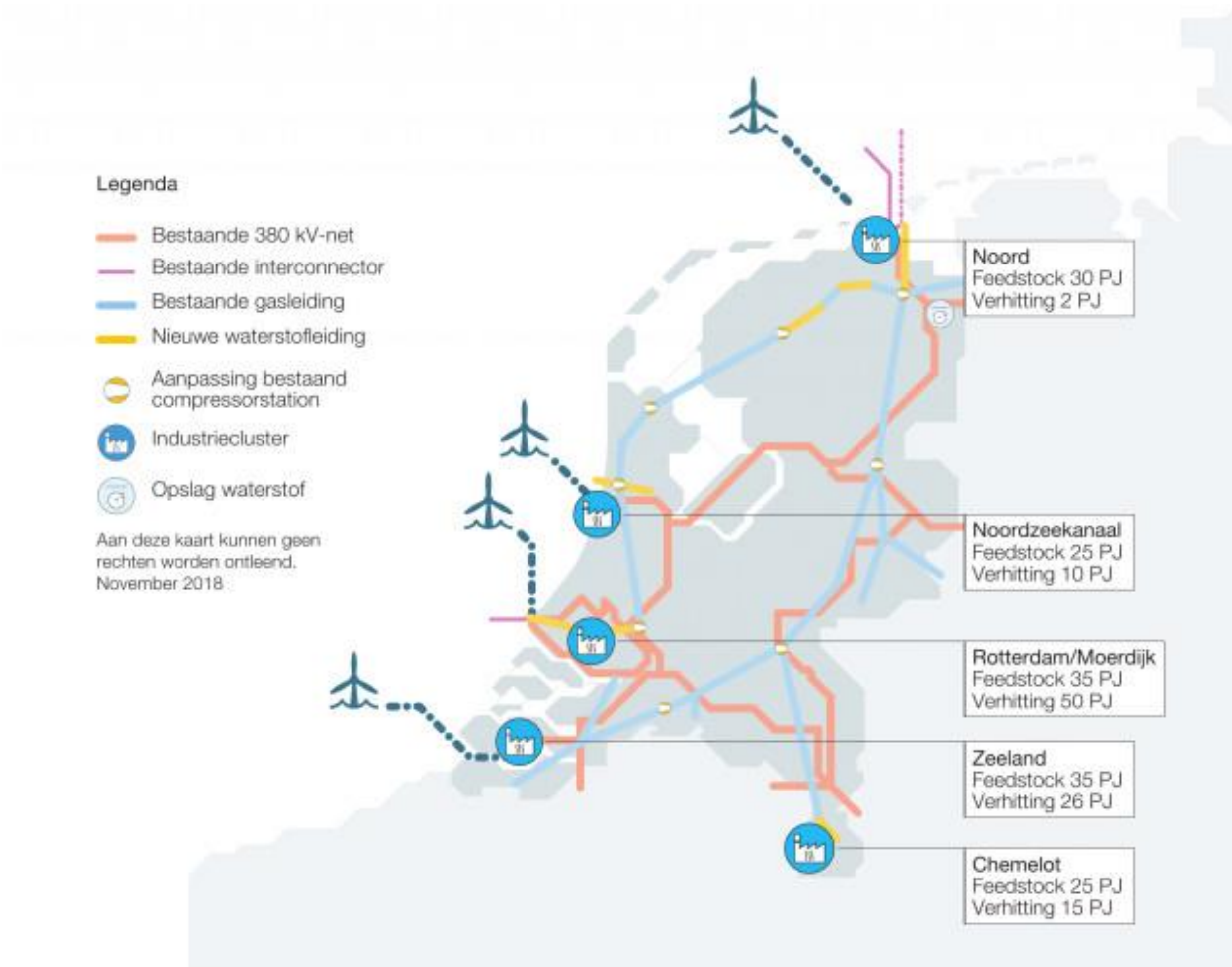
3.2 Hydrogen storage options

In this section we will elaborate further on the hydrogen storage options. In the previous section we focus mostly on the transportation of hydrogen, in this section we will take a broader look at the storage options. In the case of hydrogen, there are several different options that can be considered in order to store hydrogen. The method of storing hydrogen severely depends on the quantity of hydrogen that you would want to transport, the purpose of this hydrogen, the destination and the time on which the hydrogen is needed. Figure 7, below, shows us different options and measures their potential energy storage capabilities.

Figure 7: *Storage options for hydrogen*

Source: *dewereldvanwaterstof.nl*

In the future, if the demand for hydrogen rises, larger storage options would be needed. As previously stated, Baufumé et al. (2013) advise to not connect smaller service areas to a potential pipe network as the costs would outweigh the benefits. Therefore, trailer delivery can be used by filling a trailer with green hydrogen from a central location, such as a man made hydrogen storage, a storage within a salt cavern or a storage location in an empty gas field. In locations where there is a large demand that would not be able to be satisfied with trailer deliveries, storage options can be built. These locations would namely be industry clusters such as the port of Rotterdam. The following image shows a plan for a hydrogen backbone within the Netherlands made by Gasunie. However, we advise that independent research is done on this subject.



(Image from: https://www.gasunie.nl/nieuws/waterstof-coalitie-concrete-plannen-voor-een-vliegende-start-van-de-waterstofeconomie)

Figure 8: *Hydrogen backbone in the Netherlands.*

This figure shows the existing pipelines within the Netherlands and the pipelines that need to be created. Furthermore, it shows the compressor stations that need to be adjusted in order to handle the hydrogen transportation. Gasunie suggests that in order for the industries to switch to hydrogen, a large and stable supply is needed. Therefore, they suggest that most industry clusters in the Netherlands should have a direct connection to the hydrogen network. In addition, Gasunie suggests that the wind and solar farms should be used for electrolysis.

3.3 Electrolysis options

In order to have an efficient infrastructure, a stable electrolysis environment is needed. When running the electrolysis it is most important to have it run at a consistent rate, this is in order to have the costs as low as possible. In order to have it run at a consistent rate a stable energy supply is needed. The northern Netherlands is in a unique position to focus on electrolysis. Several large energy connections are available in the Eemshaven. The NorNed energy cable, which is an energy cable between Norway and the Netherlands, can supply around 700 MW. Furthermore, as Norway produces their energy mainly through hydro power which in general generates a stable supply of energy. In addition, the cable of offshore windfarm Gemini connects in the Eemshaven and supplies around 600MW. Lastly, in 2019 opened COBRAcable which connects the Dutch en Danish energy networks is connected in the Eemshaven and has a capacity of 700 MW.

In addition, we found that electrolysis can be performed on specially created islands near solar and wind farms in the sea's. These islands will get a supply of energy from these sustainable energy sources and directly create hydrogen. Gasunie suggests that directly transporting hydrogen is more efficient than transporting the energy through cables and creating hydrogen on the mainland. Thus, an opportunity is to develop infrastructure around already existing sustainable energy sources and use these sources of energy as a method of creating hydrogen from electrolysis. After that, the hydrogen is transported and stored on the mainland where it can be freely transported to industry clusters or other smaller areas. However, creating the infrastructure around these sources of energy might deem more costly than using the existing infrastructure. Thus, we suggest that more research is needed to be done on this opportunity.

4. Conclusion

In our paper we discussed in detail the economic feasibility of green hydrogen in the transportation sector. Therefore we distinguished between a micro analysis, including passenger cars, trucks, aviation and ships and a macro analysis discussing the storage options, transportation option and infrastructure.

Taking our findings from the passenger cars and trucks section into consideration, we can conclude that hydrogen is an option that can compete with electric cars and biofuels in the future, if initial investments are being made to construct an infrastructure. Especially for heavier vehicles hydrogen is a beneficial option since it is very light and therefore does not burden the car. In the aviation sector we can conclude that green hydrogen can be a solution, which is more economically feasible than kerosene or SAF's. Moreover, besides battery-electric engines, fuel cells powered with green hydrogen seems to be the only solution with no emissions of CO2 or other GHG. However, given the necessary changes in construction of aircrafts and current cost of hydrogen, which is expected to decline and costs around the same price as kerosene by 2050, we should not expect the industry to go green before late 2040's. Lastly shifting our minds to the transportation sector of ships, we can summarize that the industry needs to take into account the need to find an alternative fuel to realize the Paris climate agreements; operators of container ships are obligated to use alternative fuels. Theoretically, green hydrogen is expected to be the cheapest alternative due 2030. However, the literature does not take into account the massive obstruction captured in the logistical issues. Furthermore, sustainable LNG is seen as a valid competitor to Hydrogen, however LNG only reduces the amount of emissions by approximately 20%, as it is still a fossil fuel. Moreover, the production process of sustainable LNG is very energy intensive for which reason its sustainability is dependent on the use of sustainable electricity. Overall did we observe that the transportation sector has in common the need for an established infrastructure. Once this is achieved, all three sectors and the climate can benefit hugely from the usage of green hydrogen.

As mentioned above we see the need for a more structured analysis of the macro problems that might arise with the usage of green hydrogen. Our findings conclude that in order to further the adoption of hydrogen in the transportation sector, a stable supply and storage is needed. Furthermore, storage capacity is to be focused in industrial clusters as well as in smaller service areas where pipelines are not feasible. In addition, to create a stable supply of hydrogen, using solar and wind farms may use electrolysis to create green hydrogen. Furthermore, the current existing Natural Gas (NG) grid be used to transport hydrogen, however this infrastructure can only be used for hydrogen then. To either build or convert the current NG governments will need to monitor the investment and changes to ensure that there is no monopoly on the grid.

We believe that the future outlook for green hydrogen can be achieved in the next 20-40 years. However, tremendous initial investments need to be made in infrastructure and research and development to create a market that enables green hydrogen to make use of economies of scale and be therefore competitive to other green solutions on the market.

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