# Risk assessment of potential leakage of hydrogen in the Netherlands

Bachelor thesis

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# Abstract

Hydrogen might be the energy carrier of the future. Before we repeat past mistakes, it is good to look at possible consequences for the climate. Hydrogen may leak at several points in a future hydrogen economy. In this report, these leakage points will be identified and the leakage rates will be used to model several possible scenarios. The found leakage rates are between 1.2% and 9.4% of the total amount of hydrogen used in a possible future system. These would cause 8.3% to 0.62% of a higher radiative forcing impact relative to what the stop of the use of natural gas in the Netherlands could decrease. With these found values a hydrogen economy would be beneficial towards combating climate change.

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# 1. Introduction

Hydrogen is now often introduced as the next big thing in fighting climate change. Since the emissions from our current fossil fuel based system started causing climate change, people have been looking at other options. Hydrogen is not an idea that only just emerged, although it gained a lot of attention in the media lately. Hydrogen was already viewed as a potential source of fuel since the 19th century, but as it is so flammable it was also seen as an unsafe option by the public for a long time (Bockris, 2013; North, 1992).

The need for alternative fuels is only rising. Especially for the Netherlands, which wants to get off of natural gas quickly and needs replacements. The government has set itself a deadline of 2050 to get of natural gas (The Oxford institute for energy studies, 2019). It is stimulating investments in hydrogen as one of the possible new energy carriers. In this report I will also consider 2050 as a likely starting point of a large hydrogen economy in the Netherlands. Hydrogen as an energy carrier would solve the emissions of greenhouse gasses as long as the hydrogen is produced in a sustainable manner. The burning of hydrogen results in water vapor which seems harmless.

However, large scale employment of hydrogen as an energy carrier may also have negative effects on global warming. Research done in the field of leaked hydrogen mostly focused on possible harm to the ozone layer. While some authors believe that the release of high amounts of water vapor into the atmosphere could be detrimental for the earth's ozone layer (Tromp et al., 2003), other authors conclude that leakages of hydrogen would not be harmful to the ozone layer (Warwick, 2004).

Another study contemplates the effects of a global hydrogen economy at different leakage rate values to compare effects on atmospheric chemistry (van Ruijven et al., 2011). It could either be negative or it could have no changing effect on the current situation. The tipping point according to van Ruijven et al. would be 10% leakage. Their model showed a higher Global warming potential at rates higher than 10%.

In this report, I will focus on another possible side effect, namely that the leaked hydrogen could possibly cause a higher global warming potential (GWP) and have a lower radiative forcing impact. I will first review leakage pathways in the different sectors of a hydrogen economy. These leakage rates, I then be applied to models of possible hydrogen systems in the Netherlands. The models that I made will show where and how much hydrogen could possibly leak. Finally, I calculated the total amount of leaked hydrogen and compared them to studies that model the effect of hydrogen on the GWP.

## 2. Leakage rates in all sectors of the hydrogen economy

There are several different predictions on what sectors would transition to the use of hydrogen. In the papers that I reviewed, the sectors production and import are almost always present. The transportation sector, either with or without ships and planes, is also always present. Other sectors considered are electricity plants, since hydrogen can be used to store energy, and households and buildings. Storage itself was also considered. The hydrogen needs to be transported and therefore hydrogen transported through pipelines or by trucks is investigated. Lastly, the industry sector is also considered.

### 2.1. Production of hydrogen

Nowadays, hydrogen is already produced in the Netherlands. This hydrogen is produced from natural gas and biogas (Weeda, Segers, 2021). It is mostly being used by the industry, that can use hydrogen in chemical processes or to become more sustainable.

The production of hydrogen in a future hydrogen economy would not be done by using natural gas. Instead, the European Union (EU) wants to switch to electrolysis with energy from renewable sources. So far, there hasn’t been a focus on leakage of hydrogen from this process. Further research in this sector would be recommended to know the exact total amount of hydrogen that would leak.

The expectation is that less hydrogen would leak during this production process than methane is leaking from the natural gas drilling now. This is the case, because hydrogen production would take place in a more controlled environment. In 2019, about 21,98 million kg of methane had leaked away during this drilling process (KVGN, 2020). For the leakage rate of hydrogen during electrolysis, no data is known yet, so it is likely that the leakage rate is low because I expect it to take place in a controlled environment. So, I will assume either 0% leakage or 0.5% leakage which would be a likely lower and upper limit.

## 2.2. Import

The Netherlands will likely not be able to produce enough hydrogen to be self-sufficient. Therefore, extra hydrogen would be imported for countries with a surplus. The EU wants to build a pipe network from country to country (Gas for climate, 2020). Besides this, global import can be done for example via ships that would arrive at Rotterdam harbor. The hydrogen that would arrive there would not necessarily be for the Netherlands, but could be further exported to other European countries.

The amount of import needed, depends on the production of hydrogen in the Netherlands, but also on how much hydrogen would be available for import from other countries. I expect the import to be quite high, as the production of hydrogen from renewable sources in the Netherlands would be limited to the amount of sun or wind and the available space.

Tanks on ships have leakage rates of less than 0.1%, and we know this since those tanks already exist and are being used by the National Aeronautics and Space Administration (NASA) (Barbir, 2013). It is likely that the technology of hydrogen tanks keeps developing and will be widespread once there is a full on hydrogen economy in place in 2050.

The leakage rate of import through the pipelines will be lower than tanks. It would be close to the leakage rate for the pipeline system inside the Netherlands. However, since hydrogen will have to travel great distances, the pressure will be higher and therefore the leakage would be higher. Still, it would be fairly low, in the region of 0.001% (Haeseldonckx, d'Haeseleer, 2007). Because import and export use the same process, the leakage rate for export should be the same.

## 2.3. Electricity and Plants

Hydrogen will most likely be produced with excess electricity from renewable sources. However, these sources are not reliable. During ‘dunkelflaute’, a period of time without sun or wind, there would not be enough electricity. Therefore, excess electricity should be stored as hydrogen and once needed, be used for the production of electricity. It should be stored as hydrogen, because batteries do not have a long enough life time (Steilen, Jörissen, 2015). The energy would need to be stored for months and not just days or weeks. In figure 1, the discharge time of several energy storage options are compared. As can be seen, batteries can store less energy and for a shorter amount of time than hydrogen.

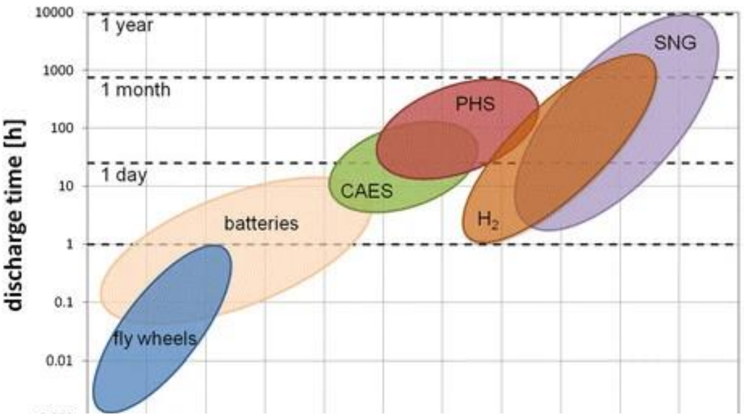

*Figure 1 : Graph showing the discharge time vs storage capacity for several energy storage options. (T. Schaaf et al, 2014)*

Turning hydrogen into electricity has a very low efficiency. This is the case in general, but conversion has many options to improve efficiency. It can be done by gas turbines, internal combustion engines and large scale combined cycle power plants. These processes have efficiencies of 30% for gas turbines and 60% for the large scale process (Steilen, Jörissen, 2015). The other option is the use of fuel cells. Fuel cells are still under development and there are a lot of varieties being developed with varying efficiency. The average efficiency now is 65% (Edwards et al., 2008).

The amount of hydrogen in the sector electricity production would depend on the excess production, but also the need for seasonal storage. If it turns out that the economy can do without seasonal storage and has other means to bridge these periods, this could become a very small sector. However, the opposite can also be true, if the Netherlands would become more reliant on the sun and the wind for energy the amount of hydrogen would be higher.

Leakage in this process could happen everywhere, for example in the gas turbines or fuel cells. Because these technologies are being upscaled, there is no data available for possible leakage at the scale of an electricity plant run on hydrogen. The safety of the process is being thought through and research is being done into what would happen in case hydrogen leaks, just not into how much would leak. For now, I will assume a 0 - 0.5% leakage rate just like production.

## 2.4. Pipelines

The transport sector will be divided into two, first the transport by pipelines, second the transport by trucks. This is the case only for the transport of hydrogen inside the Netherlands.

For the transport of natural gas, there is already a complete pipe network available. Be that as it may, hydrogen is different to natural gas in its properties. So, the system would have to be tested and adjusted. Pilots are being done by adding hydrogen to natural gas till a certain volume percentage. This is not only done in the Netherlands, but all throughout Europe.

Still, the systems are all different in each country and therefore proper testing has to be done on each different aspect in the natural gas system. In the NL, most systems for natural gas are made out of API steel alloys that are not made for hydrogen. Therefore, there is a large chance of embrittlement (Dutch ministry of economic affairs, 2017). Germany, where similar systems and the same natural gas are used, hydrogen is already allowed up to 5% and in exception even 10 %. This is of however, still a far cry from the 100% the economy would need.

The current system exists out of a low pressure and a high pressure system. The low pressure system is used between the distribution points and households and the high pressure system is used from the production to the distribution point or industry. Recent research suggests that the low pressure system would not necessarily have to be replaced (Hormaza Mejia et al., 2020). Hydrogen would leak at the same rate as natural gas in existing low pressure systems. However, hydrogen could cause embrittlement to progress faster and therefore eventually leak faster.

In the high pressure system, changes would have to be made nonetheless. An option here is to treat the existing network to become hydrogen proof. This could be done by galvanizing the network (Gasunie, 2009; Mouli-Castillo et al., 2021). This could become very costly and time consuming but will be necessary. Another thing to consider besides the pipelines themselves, are the compressors that keep the pressure up. These are also not made or tested for hydrogen use. The compressor would be very important because hydrogen has a lower energy density than natural gas. Therefore, a higher volume of hydrogen would have to be transported to meet the same energy needs (Mouli-Castillo et al., 2021). It is believed that hydrogen could influence the materials in the commonly used centrifugal compressor, and cause them to fail. These compressors therefore need to be replaced, by piston compressors (Haeseldonckx, d'Haeseleer, 2007; Findlay, 2020).

For the low pressure grid, replacing the current pipes by polymer pipes could mitigate all risks. Polymer pipes would suffer less corrosion and have a better gas tightness at connecting points (Mouli-Castillo et al., 2021). They do suffer from less gas tightness overall. Taking this into account, calculations have shown that the leakage rate on an annual basis would be 0.0005-0.001% (Haeseldonckx, d'Haeseleer, 2007). This leakage rate would be for the low and high pressure systems.

## 2.5. Trucks

Pipelines would not be the only transportation method used. Where the pipes do not go, a truck could travel. Trucks would transport most hydrogen fuel to fueling stations of cars, planes and even ships. Trucks can also reach the places where the gas network might still have to be upgraded in 2050.

Trucks could work with two types of tanks, one in which hydrogen is stored as a liquid and another one in which the hydrogen gas is compressed. Modern automotive liquid hydrogen tanks can realize energy densities of 22 MJ/kg and evaporation rates of approximately 1% per day (Barbir, 2013). When hydrogen is compressed and transported that way, it costs energy to compress the hydrogen. However, trucks that transport compressed hydrogen do not have to deal with boil off losses that happen with liquid hydrogen transport, as was mentioned above. Still, gaseous hydrogen can leak away faster with a total leakage rate of about 0.5% (Wulf et al, 2018).

The most leakage of trucks occurs when a truck is being loaded or unloaded. Here 0 - 5% of the hydrogen could leak away, depending on the company and the phase the hydrogen is in (Reuß et al, 2017; Wulf et al, 2018). This leakage is taken into account at fueling stations. However, this technology is still being developed and has a high chance of reaching smaller leakage rates by 2050.

## 2.6. Storage

The storage of hydrogen could be very important. Hydrogen storage is needed for seasonal changes in production and usage, but also from a day to day basis.
Seasonal storage could be done in the same way as natural gas storage, by using caverns in the ground to store hydrogen and pumping it up when needed. Day to day hydrogen, that is transported through the pipelines, is also stored in these pipelines. The hydrogen that is moved by trucks will have to be stored in tanks on location. Therefore, more hydrogen will likely be stored in caverns or the pipeline system than in tanks.

At this moment, hydrogen is already stored in caverns across Europe. Even though in most instances the hydrogen stored here is still mixed with natural gas to form town gas, there are already three smaller caverns in the United Kingdom (UK) that hold only hydrogen, which shows potential for hydrogen caverns in the Netherlands (The Dutch ministry of economic affairs, 2017).

Caverns come in two types: caverns closed off by a clay layer and caverns closed off by a salt layer. Hydrogen could definitely be safely stored in salt caverns. It has already been done before with 100% hydrogen and therefore deemed safe. The leakage rate would be around 0% (The Dutch ministry of economic affairs, 2017). On the other hand, clay may not be as good a seal against hydrogen as it is against natural gas, because hydrogen is more volatile. This needs to be further investigated before 100% hydrogen can be stored here. For now, I will assume that hydrogen will be stored only in salt caverns and therefore only use the 0% leakage rate. Leakage in this sector will still occur from the pipelines to and from these storage locations.

Now, I will review the leakage from tanks. Liquid hydrogen tanks that are used now by for example NASA typically have losses of 0.1% per day (Barbir, 2013). Another source says that liquid hydrogen can be stored with losses of just 0.03% per day (Reuß et al, 2017). Hydrogen can be stored compressed as well. Then, leakage rates of 0% are expected (Reuß et al, 2017). Because it is unknown how much hydrogen will be stored liquid or compressed, I will use a leakage rate of 0.03% for all storage in tanks to assume maximum leakage.

## 2.7. Fueling stations & cars

Some car companies are already building cars that can drive on hydrogen. These cars would need to be fueled and this is why it is interesting to look into this category. The amount of hydrogen used in this sector would depend on how much hydrogen would fit in a car and how far the car could drive on it. If a car has a smaller range, it has to tank more often. This would mean fueling stations have to have a larger supply on hand. The phase of the needed hydrogen can also play a big part in causing hydrogen leakage. Cars could drive on hydrogen gas, but hydrogen can be transported as a liquid. So, hydrogen might have to be converted between the phases. Leakage could occur during this process.

First, the leakage at fueling stations starts when hydrogen is being brought to the fueling stations. While emptying trucks into the tanks at the fueling stations, between 0 - 5% already leaks away (Reuß et al, 2017; Wulf et al, 2018). Research was done at the then newly built hydrogen fueling station at Cal state in Los Angeles hydrogen research and fueling facility. It concluded when maintenance was not kept up, leakage reached 30 - 35%. Once they knew this and initiated proper maintenance protocols, leakage came down to 2 - 10% (Genovese et al., 2020). I assume that with further research into where hydrogen leaks, the leakage rate could end up between 0 - 2%.

Cars on hydrogen use fuel cells with varying efficiency and leakage rates. Right now, most of the hydrogen cars are still under development and a lot of research is looking into the possible dangers of hydrogen leakage caused by cars in a closed environment (Tang et al.,2020, Choi et al., 2013). While this is vital research to ensure the safe use of these cars, for this report, it would be interesting to know if and how much leakage occurs without damage and on a daily basis. Therefore, I have looked into research from Hao, *et al.* In this study, they looked at a hydrogen leakage while a car was driving and while it was parked. The results show that while driving there was 0.0004% of hydrogen around the car, but when a car is parked for eight hours during the day 1% of hydrogen leaked (Hao, et al., 2020). They also mentioned that there are rules and regulations future hydrogen cars must comply with. These rules indicate that only 0.5% of hydrogen may leak both if it is driving or parked (The Chinese standard, 2020). Therefore, a leakage rate of 0.5% will be used in the models.
The fuel sector is a sector with a lot of potential for leakage. Because of this, more research should be done on the why and the how this leakage occurs.

## 2.8. Households

Risks will be severely monitored before hydrogen will be used in households. Leaks would mostly occur around joints and valves. However, leak detection measures will be set in place to be safe from accidental leakage. It will take some further research as hydrogen is harder to pick up than gas (Dodds, Demoullin, 2013). Therefore, barely any leakage should come from households. If any, it would come from the pipeline system towards the buildings, which should have similar leakage rates as low pressure distribution pipelines. However, since hydrogen embrittles faster than natural gas, proper precautions have to be taken against potential damage.

Besides this, all household appliances are made for natural gas. If households would still use appliances based on methane, they should be replaced by appliances that can accommodate hydrogen.

## 2.9. Industry

The industry is one of the hardest sectors to make sustainable. It is highly reliant on natural gas and will probably not be able to electrify completely before 2050. Therefore, they will need a different gas. Here, hydrogen could play a big and important role. There is also a possibility that biogas will play a bigger role in this transition than hydrogen, as some predictions claim (Gasunie, 2018).

A sector within the industry that is already using hydrogen, is the agriculture sector. For high yields on land the Netherlands produces a lot of fertilizer, most of it is being exported after. For the production of ammonia a lot of hydrogen is needed. The total use in the Netherlands is around 59 PJ per year for the agriculture section (Weeda, Segers, 2021). Right now, no research has been done on hydrogen leakage during the production of ammonia yet.

In industry, more hydrogen is used for other chemical processes besides the production of ammonia. Research done for the Dutch government into how hydrogen is used in the Netherlands found that hydrogen rich residual gasses currently produced by the industry are redirected and not just released (Weeda, Segers, 2021). They are often transported and reused as fuel gas. I assume that once the industry is running on hydrogen, all industries will try to maximize retention of hydrogen and retrieve most, if not all, of the hydrogen that would be released. Considering all measures that would be taken, I assume that the leakage rate will be between 0.0% - 0.5%.

## 2.10. Ships and planes

This would be a potential hydrogen economy sector. Now no planes or ships that work on hydrogen as fuel work yet. If most ships and planes were to switch to hydrogen a lot of hydrogen would go into this sector. That would potentially make it the biggest hydrogen sector.

Although this sector would potentially be the largest, not so much is known yet. Therefore I will assume that planes and ships will have similar leakage rates to cars. Since all three of them will likely run on fuel cells and even though they might not be comparable in size, leakage rates may be similar or at least the regulations would be. So therefore the leakage rate for ships and planes would be 0.5%.

## 2.11. Summarized leakage rates

All leakage rates can be combined, which was done in table 1. What stands out when looking at this table is that fueling stations are now the biggest source of leaked hydrogen. This is mostly due to the inefficient way that tanks are being emptied out at the fueling stations. Other important categories are cars, ships and planes. Since these technologies are still under development, it will be interesting to see what will be done against leakages in these fuel cells.  The last column in this table includes predictions from me. If all technologies progress and more attention is given to potential leakage sources, all leakage rates should come down by 2050.

**Table 1 :** *Leakage rates and predicted leakage rates per sector*

| sector | Leakage rate | Average future leakage rate |
|---|---|---|
| Production | 0.0 - 0.5% | 0.05% |
| Import | 0.01 - 0.1% | 0.01% |
| Electricity and plants | 0.0 - 0.5% | 0.05% |
| Pipelines | 0.0005 - 0.001% | 0.0005% |
| Trucks | 0.0 - 1.0% | 0.05% |
| Storage | 0.0 - 0.03% | 0.005% |
| Fuel stations | 2.0 - 10% | 1% |
| Cars | 0.5% | 0.5% |
| Households | 0.0005 - 0.001% | 0.0005% |
| Industry | 0.0 - 0.5% | 0.05% |
| Ships and planes | 0.5% | 0.5% |

Table 1 will form the guideline to the calculations done for each model and shows a good overview of all the sectors.

# 3. Models

For each model, I considered a different prediction based on research that was done on a potential hydrogen economy in the Netherlands. For every model, there will first be given a specification of the predicted amount of hydrogen per sector in the economy. Reasons as to why was chosen for a high or low amount will be specified if known.

For models of the leakage that occurs per sector the highest leakage rates available will be taken. By assuming a worst case scenario of all the highest leakage rates the actual hydrogen leakage that occurs can only turn out better than expected.

No model specified what was transported by pipeline or truck. Research proves that transport by pipeline would be cheaper and better for the environment than by trucks (Wulf et al., 2018). This would at least be the case where pipelines are available. So, every sector where pipelines can go, such as households, industry and electricity were considered supplied by pipeline. For fueling stations, delivery by truck is more likely, at least for a large part, but probably not for shipping. Therefore, I decided to let 20% of this sector be transported by pipeline and 80% by truck.

The storage of hydrogen was not mentioned in any model specifically. There were no numbers given, even though it was mentioned, by the literature that I reviewed, that hydrogen should be used to keep up with seasonal changes in the energy demand (Berenschot and Kalavasta, 2020; Gasunie, 2018). Since the highest possible leakage effect this could have on an economy is 0.03%, it could be neglected, or at the end 0.03% could be added to get to the maximum leakage rate with storage leakage included. The models 1 and 2 had already taken a slight transport loss into account. These values have been ignored to calculate a new leakage rate with all leakage points taken into account.

## 3.1. Model 1

The first model I will base on research done by Berenschot and Kalavasta commissioned by the Dutch government (Berenschot, Kalavasta, 2020). They actually specified four scenarios: for regional, national, European and international involvement. Each scenario has different amounts of hydrogen. Since the Dutch government has already implemented some work a national approach is more likely, than a regional model. The Dutch government already has a cooperation with the EU as well, so an European approach is also more likely than an international one which would mean on a more global level than the EU (Netherlands enterprise agency, 2020).

The considered national model specifies expected transport losses. I have however acquired more information about other possible leakage points and should therefore get a higher loss number. This national model, which is shown in figure 2, expects that the most hydrogen is needed for industrial warmth. It is also expected that there will be high demand for hydrogen for the transport sector and that a lot of hydrogen will be used to produce electricity. Other sectors use less amounts of hydrogen but could still cause more leakage.

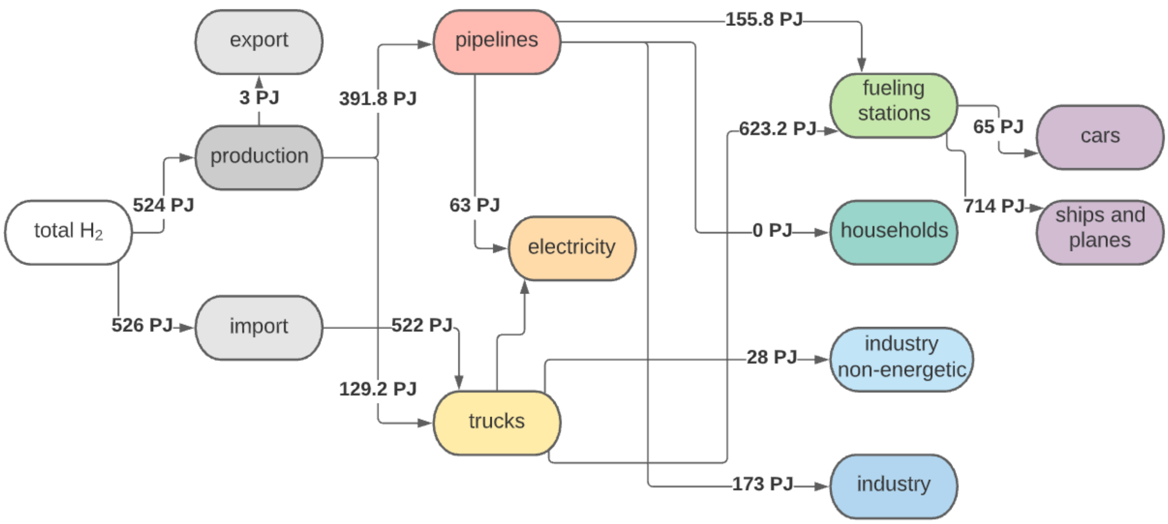


*Figure 2 : Hydrogen system based on the national prediction done by Berenschot and Kalavasta, 2020*

So, now that the amount of hydrogen per sector is known all leakage rates can be applied to each separate sector. Here, the fueling stations have the highest leakage rate and therefore cause the most leakage. The leakage model is shown in figure 3.

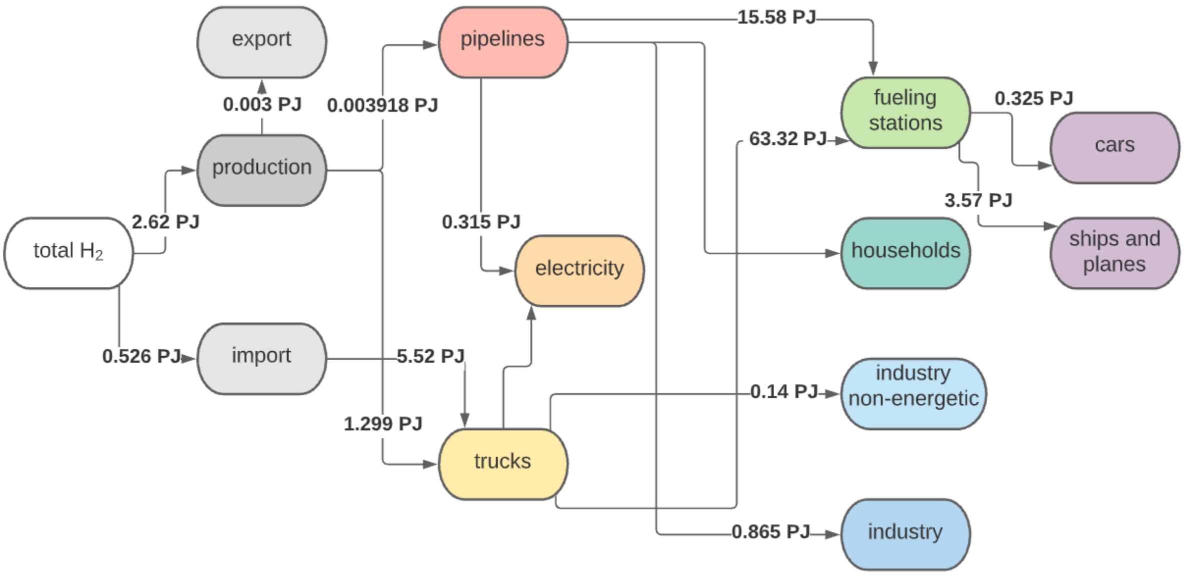


*Figure 3 : Hydrogen leakage model based on the system in figure 2*

Total leakage comes to 93.09 PJ or 8.9% of the total amount of hydrogen. This is a lot more than the 3 PJ of losses due to transportation the research suggested. However, if you would change the leakage rate for the fueling stations from 10% to 2%, the new total would come to 30.77 PJ. This is a lot more, but closer to what the paper suggested. This would be 2.9% of the total amount of hydrogen. In the discussion section of this report, the found leakage will be compared to other studies that looked at the impact hydrogen could have on the climate.

## 3.2. Model 2

Like the first model, this model was also based on the research from Berenschot and Kalavasta as commissioned by the Dutch government (Berenschot and Kalavasta, 2020). In the European scenario that was used for model 2, a lot of hydrogen is used for industrial warmth and the production of fertilizer. Besides this, a large amount of hydrogen goes to the transportation sector. What stands out is that in this scenario no hydrogen is used to produce electricity. To cover the seasonal demand changes, more or less hydrogen would be imported according to the demand of the market. This EU controlled model is shown in figure 4.

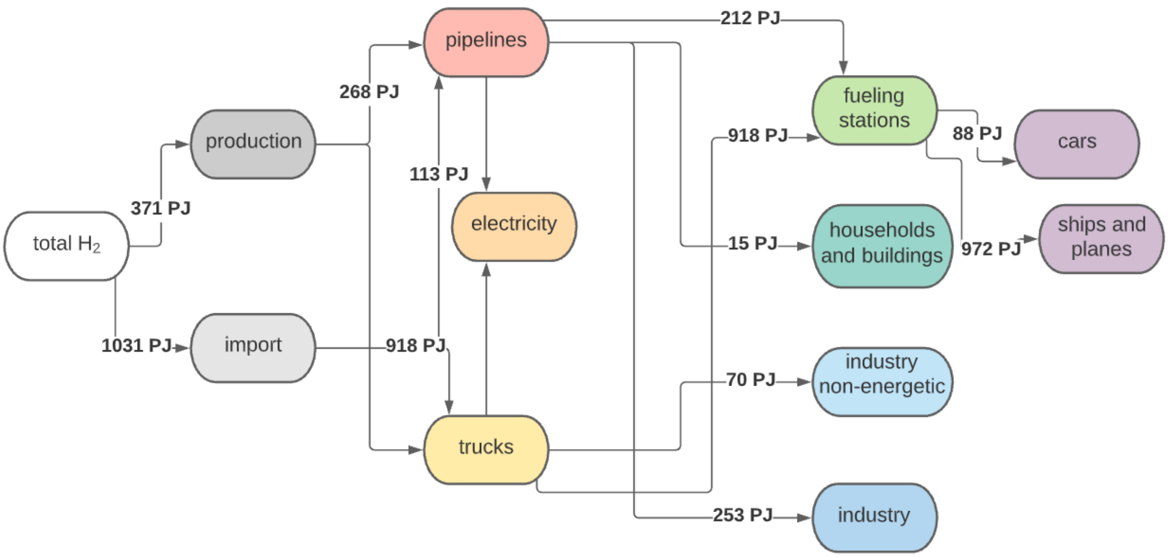


*Figure 4 : Hydrogen system based on the European prediction done by Berenschot and Kalavasta, 2020*

Here, the sector 'industry non-energetic' is new, since it was not discussed in the previous chapter. However, this was mentioned in the industry sector. The industry would not only use hydrogen as a source of energy but also use hydrogen for chemical reactions such as the one to produce ammonia. Especially in this chemical sector where the focus lies on the recovery of every last bit of product, so it can be reused, no losses of hydrogen are really expected. The leakage model of figure 4 is shown in figure 5.

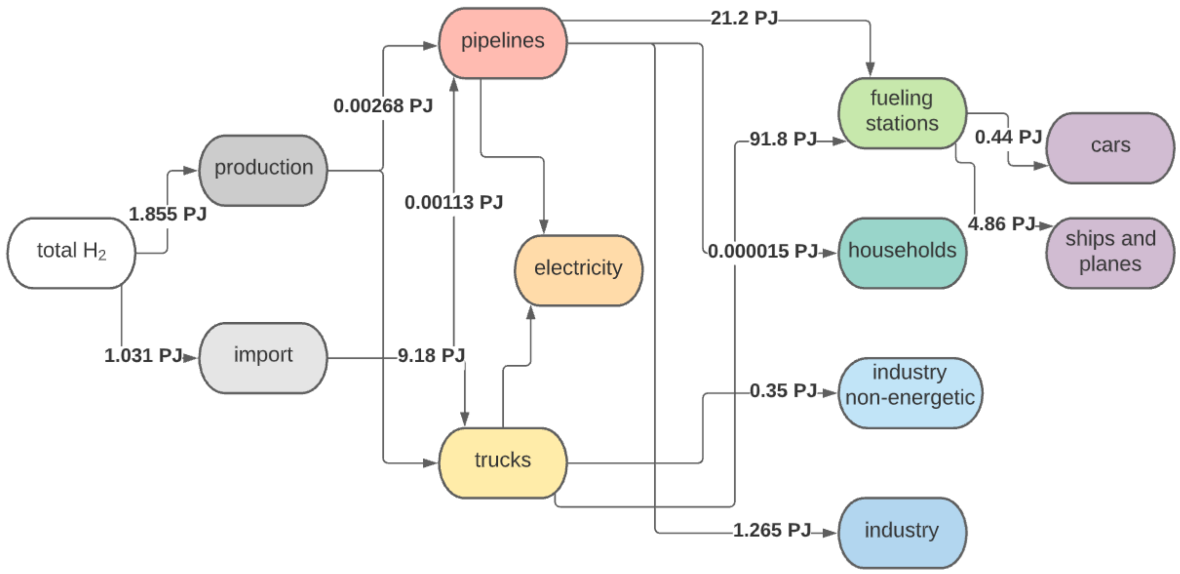


*Figure 5 : Hydrogen leakage model based on the system in figure 4*

The total leakage of this model comes to 132 PJ or 9.4% of the total amount of hydrogen. The fueling stations stand out again. If we were to use 2% as the leakage rate instead of 10% the leakage would be 22.6 PJ. The total would then amount to 41.6 PJ or 3.0% of the total amount to hydrogen.

## 3.3. Model 3

This model was based on research done by (Gasunie, 2018). To provide a sense of where the Netherlands might go in the future, they conducted research called 'Survey 2050'. Here, they first outlined a scenario for 2030 and then a scenario for 2050. Since they had specified different sectors, this model looks different to the last two models. The model is shown in figure 6.

Here a lot more energy is going to plants that would produce other sources of energy like electricity but also biogas. This was not further specified into how much would go into what type of plant. What was specified, was that an amount of hydrogen would be used to produce electricity for the industry, but that the heat produced during this production process would then also be used by industry. This would make the process of turning hydrogen into electricity more energy efficient, up to 85% (Edwards et al., 2008). The method is called combined heat and power (CHP) and it is already being implemented.

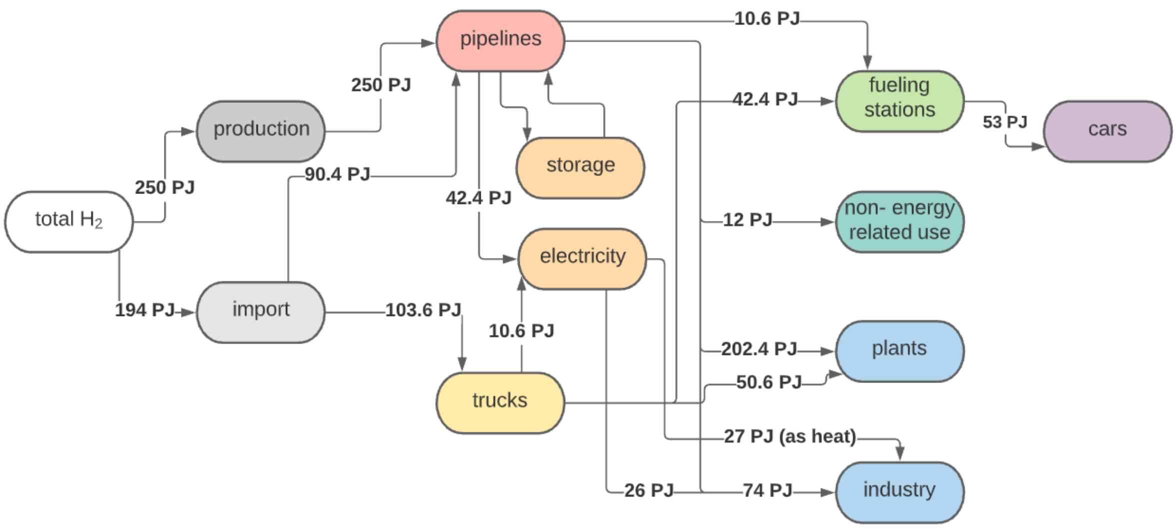


*Figure 6 : Hydrogen system based on the model done by the Gasunie*

The sectors plants and non-energy related use have not been specified in the earlier chapter. However, as mentioned by model 2, non-energy related use means the hydrogen is used for chemical reactions. Since the recovery of materials is one of the highest priorities in the chemical industry, it is expected that little hydrogen leakage would occur. As for plants, there are a lot of possible plants and so far none have been built and tested for leakage, so I will assume a leakage rate of 0.5%. The leakage model is shown in figure 7.

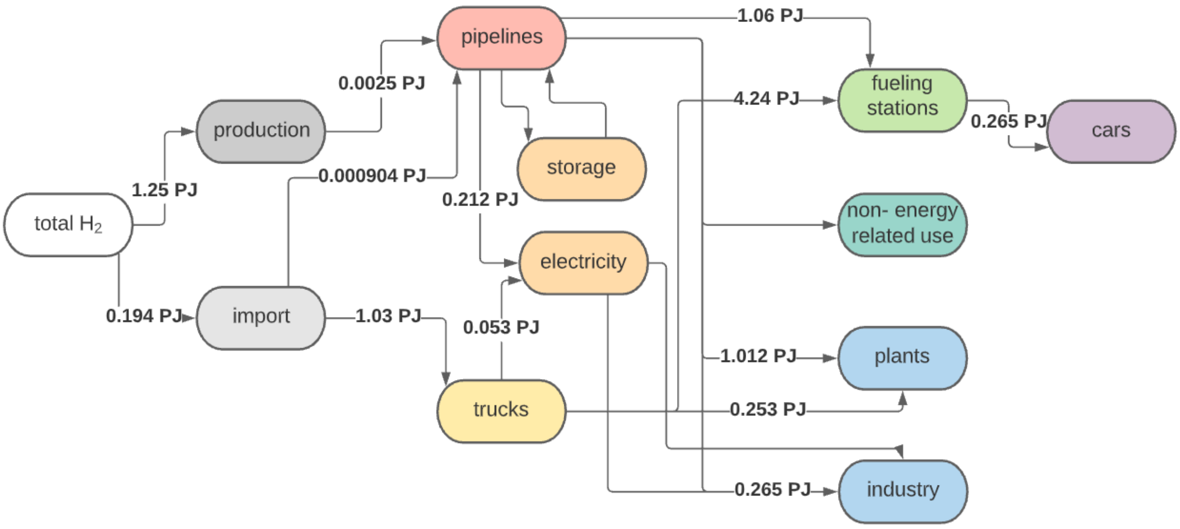


*Figure 7 : Hydrogen leakage model based on the system in figure 6*

The total amount of leakage would be 9.8 PJ, the lowest amount of leakage of the models so far. This would only be 2.2% of the total amount of hydrogen. If we were to assume a 2% leakage rate for fueling stations instead of 10%, the leaked amount would be 1.06 PJ. The total amount would then be 5.6 PJ or 1.3%. The low total leakage rate of this model is due to the fact that the conversion of ships and planes to hydrogen was seen as highly unlikely. The Gasunie assumes that ships and planes would still run on fossil fuels.

## 3.4. Combination

The combination of all 3 models is not straight forward. The biggest difference is the conversion of planes and ships to hydrogen. The easiest way to combine the models is to first make a model without considering the conversion for ships and planes.

By putting all 3 models next to each other in a table (see table 2) a clear overview can be made. Then, the averages can be calculated to form a new model. The sectors pipelines and trucks are not in the table because they only transport hydrogen and their average would not be of any significance. The amount transported by each option will be determined by how much the end-users of each sector use.

**Table 2 :** *Table showing the hydrogen specified per sector for all three models previously discussed. The last row shows the averages of the three models to form a combination.*

| Sectors | Model 1 | Model 2 | Model 3 | Average |
|---|---|---|---|---|
| Production | 332 PJ | 258 PJ | 250 PJ | 280 PJ |
| Import | - | 168 PJ | 195 PJ | 121 PJ |
| Export | 3 | - | - | 1 PJ |
| Electricity | 63 PJ | - | 53 PJ | 38.7 PJ |
| Storage | - | - | - | - |
| Fuel stations | 65 PJ | 88 PJ | 53 PJ | 68.7 PJ |
| Households | - | 15 PJ | - | 5 PJ |
| Industry | 201 PJ | 323 PJ | 86 PJ | 203.3 PJ |
| plants | - | - | 253 PJ | 84.3 PJ |
| Total | 332 PJ | 426 PJ | 445 PJ | 401 PJ |

The sector of ships and planes could be added, but could also possibly be omitted from the hydrogen economy, as the Gasunie has done. For ships and planes, model 1 had 714 PJ and model 2 had 972 PJ, now the average would be 843 PJ. This amount will likely be completely imported, as was done in models 1 and 2, and will be added as such to the model. Finally, this potential hydrogen economy is shown in figure 8.

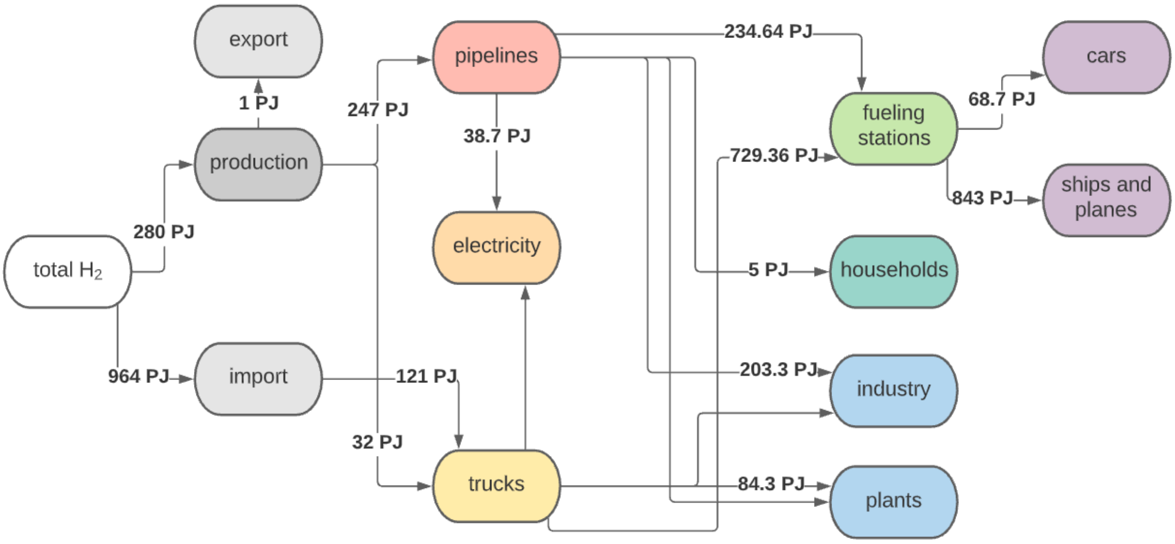


*Figure 8 : Hydrogen system based on the combination of all previously shown models*

As can be seen, a lot of hydrogen goes to the transport sector. This sector also has the highest leakage rate.  The most hydrogen comes from import and the leakage rate is higher here than at production. So, the more import, the more leakage occurs.

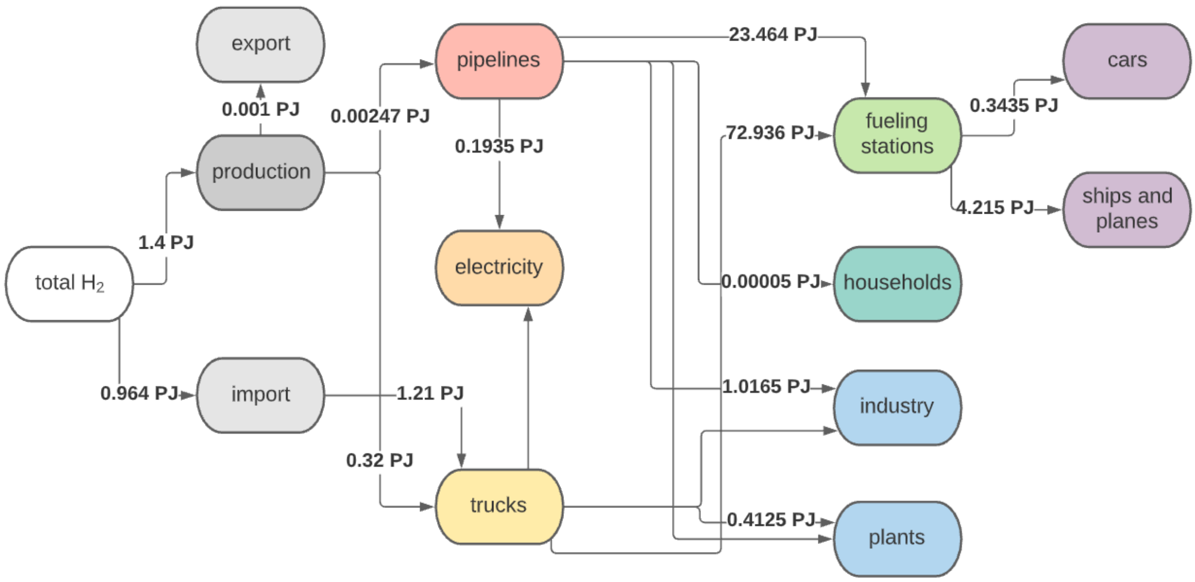


*Figure 9 : Hydrogen leakage model with the highest leakage rates based on figure 8*

In figure 9, the leakage model based on figure 8 was made with all the highest leakage rates. The total leakage is 106.5 PJ which is 8.6 % of the total amount of hydrogen. If the fueling stations would only leak 2% instead of 10% the total leakage for the whole system would be 29.36 PJ. This would be 2.4% on the total amount of hydrogen. Now to compare this worst case scenario to a more positive one, I will also make a model with all the lowest leakage rates and one with my predicted leakage rates.

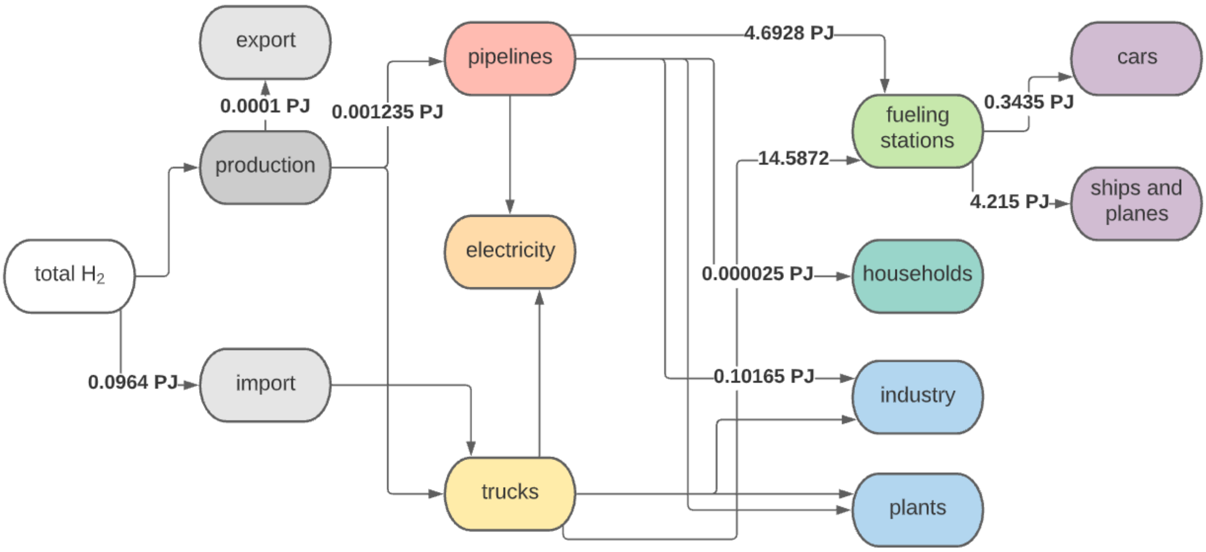


*Figure 10 : Hydrogen leakage model with the lowest leakage rates based on the system in figure 8*

In figure 10, the leakage model was also based on the system in figure 8, but here all the lowest leakage rates were applied. The total leakage is 23.95 PJ, which is 1.9% of the total amount of hydrogen. I do not expect that multiple sectors will get their leakage down to 0.0%, so this will be a very unlikely scenario.

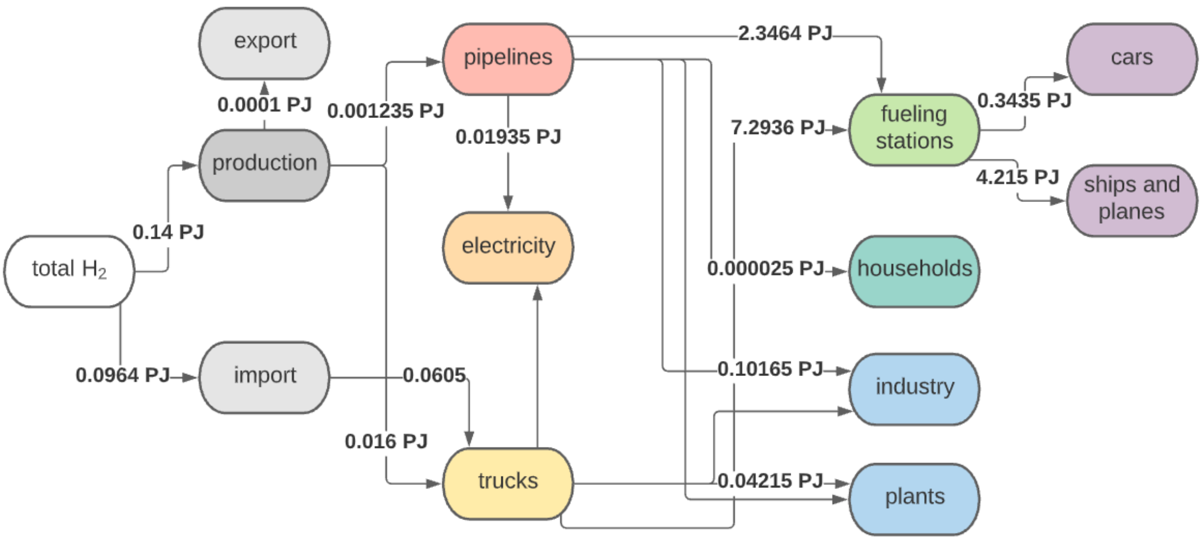


*Figure 11 : Hydrogen leakage model with the predicted future leakage rates based on the system in figure 8*

In figure 11, a leakage model is shown that was based on the system in figure 8 and the future leakage rates from table 1. Here, the total leakage is 14.68 PJ or 1.2%. The leakage rate in this system is lower than the leakage rate in the system of the lowest leakage rates. Therefore, the mitigation of leakage across all sectors could be more effective than reducing some leakage rates to 0%.

The most important sector keeps being the fueling stations. In the next chapter the consequences of each model will be discussed as compared to modelling studies done on the effect of hydrogen leakage on the climate. First, all models can be combined into one graph. In figure 12, the total amount of hydrogen for each model is shown next to their total amount of leaked hydrogen. This overview makes it clear that the amount of leaked hydrogen in 2050 will probably be small, compared to how much hydrogen the economy will use.

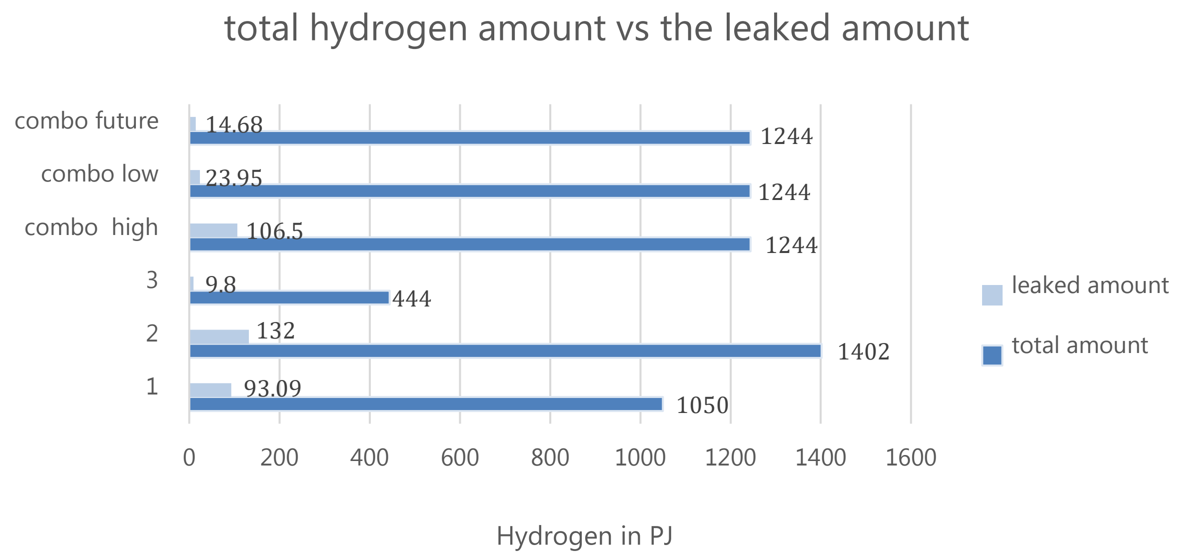


*Figure 12: A graph showing the total amount of hydrogen and the total leaked amount of hydrogen of each model.*

# 4. Discussion

A study into what the exact leakage will look like in a future hydrogen economy, has not been done yet. What has been done, is a modeling study that looks at what kind of impact leaked hydrogen might have on the environment. This study was done, because other studies had suggested that a hydrogen economy could lead to an increase in hydrogen in the atmosphere due to leakage. This leaked hydrogen could negatively influence the stratospheric ozone layer by depleting this protective layer around the earth due to reactions with the other atmospheric gasses (Tromp et al, 2013, Warwick et al., 2004, van Ruijven et al, 2011).

Another study came to the conclusion that the real impact of a hydrogen economy on the ozone layer would depend on when this economy would start (Tromp et al, 2013). If it were to start on a large scale in 2030, the ozone layer might not have recovered from the years in which chlorofluorocarbons were released. When the hydrogen economy would really start to gain traction in 2050, chlorofluorocarbon levels would be substantially lower and the ozone layer could have recovered. That would mean that the hydrogen economy would have less of a negative impact on the ozone layer. In the paper it was postulated that if the fuel cell industry were to grow in such a way that the impact on the ozone layer would be minimized, this new hydrogen economy might not be as harmful to the ozone layer as earlier research suggested.

I reviewed other research that looked at the impact of just the switch of cars to hydrogen (Schultz et al., 2003), because cars have a large impact on the emissions of the ozone precursors nitrogen oxide ($NO_x$) and carbon monoxide. Since cars powered by hydrogen would not emit these pollutants, the air quality will significantly improve. Up to 50% reduction of $NO_x$ emissions could decrease the OH levels in the atmosphere. This would cause a longer lifetime for methane, which is reliant on OH oxidation in its lifetime cycle. The impact on the climate due to a hydrogen economy would only depend on how this hydrogen is produced, since hydrogen can still be produced by natural gas. Hydrogen production could then release more methane and increase the greenhouse effect. Hydrogen in cars would have a positive impact on air quality but not necessarily on the climate.

Here, I will ignore the possible effects on the ozone layer and focus more on the greenhouse effect that the current fossil fuel industry is causing, as Derwent et al. did in 2020. In this study, they tried to prove that an earlier study done by Derwent et al in 2006 was accurate. This study claimed that a leakage of 1% of a possible hydrogen economy in the UK could cause 0.6% of the climate impact of the current fossil fuel industry. In 2020 they made a more accurate model of the then known effects of hydrogen in the atmosphere. They did specify that there is much more to learn in this field of atmospheric hydrogen and that it should definitely be further researched before we switch to a hydrogen economy.

From that model Derwent et al. made, they discovered that the indirect global warming potential (GWP) of a hydrogen economy in the UK could be 5 +/- 1 Tg over a 100 year period. This equals 5 +/- 1 Tg per year of CO2 integrated over a 100 year time period. On the basis of the model, made with STOCHEM-CRI, the conclusion is that 1% of leakage would cause 0.7% in radiative forcing (RF) impact, compared to the current system (Derwent et al., 2020). RF impact is the amount of energy the earth receives from sunlight compared to what the earth itself radiates back into space. A positive RF impact means the earth receives more than it sends out (Environmental protection agency, 2020). The more energy stays here, the warmer the earth gets.

On the basis of their report I could make a table with values I found to calculate RF impacts a possible Dutch hydrogen economy. Since the same GWP will apply I can use that to find comparative values for CO2 for the hydrogen leakage. Total CO2 emissions in the Netherlands now come to about 150 Tg per year (international energy agency, 2018). If you were to just look at emissions due to natural gas, it is about 66 Tg per year ( international energy agency, 2018). It is most likely that by 2050 the Netherlands has replaced the natural gas by hydrogen but is still reliant on the other fossil fuels (Berenschot, Kalavasta, 2020; Gasunie; 2018). Therefore, I will compare the effects of CO2 reduction to the emissions due to natural gas. So, the RF impact that the hydrogen economy would cause was calculated by comparing the effects of hydrogen in the atmosphere to the decrease in CO2 due to the stop of the use of natural gas. The results of my calculations are shown in table 3.

**Table 3:** *Leakage rates compared to the Co2 equivalents and the radiative forcing impact*

| Model | Leakage (PJ) | Leakage (Tg) | CO2 (Tg) | RF impact |
|---|---|---|---|---|
| 1 | 93.09 | 0.776 | 3.88 | 6.0% |
| 2 | 132 | 1.10 | 5.50 | 8.3% |
| 3 | 9.8 | 0.082 | 0.409 | 0.62% |
| Combo high | 106.5 | 0.888 | 4.44 | 6.7% |
| Combo low | 23.95 | 0.200 | 1.00 | 1.5% |
| Combo future | 14.68 | 0.122 | 0.610 | 0.92% |

The percentage in the last column of table 3 shows how much less the RF impact would go down due to the indirect effects of hydrogen on the RF impact. So, the result show that a hydrogen economy would not make the entire greenhouse effect go away. Since Leakage is likely to occur in some form the effect will stay, even if all fossil fuels would have been replaced by hydrogen.

In table 3 it can be seen that model 2 would cause the biggest impact on the difference the switch from natural gas to sustainable can make. The paper from Derwent et al. concluded that the leakage of hydrogen in a future hydrogen economy should be curtailed. They also mentioned the large uncertainty in there results due to a possible bias in their models. A bias could have been in their model because there is still not enough known about atmospheric hydrogen and its interaction with the other trace gasses in the atmosphere.

## 5. Conclusion

After modeling several scenarios, the found leakage rates are between 1.2% and 9.4% of the total amount of hydrogen. These would have RF impacts of 8.3% to 0.62% relative to the effects of no more use of natural gas in the Netherlands could have on the RF impact. With these found values, a hydrogen economy would be beneficial, and not detrimental, towards combating climate change.

Although a lot more research into leakages of several sectors would be important towards a better understanding of the consequences of a potential hydrogen economy. Sectors such as production, electricity, industry and ships and planes should be further investigated. Other future research should be done on the effects of atmospheric hydrogen. It is important that the definitive effects of hydrogen leakage on climate change be known.  Especially, since the whole world might switch to a hydrogen economy in the near future.

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