Master's thesis

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Optimization of Safety and Costs in Hydrogen Delivery

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Reliability, Availability, Maintainability and Safety (RAMS)
Submission date: January 2020
Supervisor: Nicola Paltrinieri

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Preface

My master thesis is a focus on hydrogen as fuel of the future. Since it is a new source, knowledge about it is still limited and I would to take into account safety and cost problems to figure out the best solution during delivering phase. My work was carried out during the period between August and December of 2019 in RAMS of NTNU in Trondheim, where I cooperated with Safetec looking for management choices for delivery handling, and it was completed in Rome in chemical, materials and environment engineering department. The idea for the topic was brought up turning my attention on the accident happened next to Oslo in June 2019. My safety background made me curious about causes and consequences of the accident, not only in the direct meaning of material consequences but also on economical investment level. After the accident, authorities decided to close all Norwegian hydrogen stations, then I decided to study on the one hand the impact on the new fuel economy searching for proper ways to transport the fuel and on the other hand the safety that concerns the hydrogen delivery and the refuelling stations. This report is made to be discussed and criticized by students that are interested as me on the topic.

My hope is to add piece by piece a good knowledge regarding this resource and to demonstrate to my colleagues, who I'm writing for, that together we can build a "green" future.

Trondheim 2019-12-18

Aknowledgement

I would like to thank the following persons for their great help during these months of hard and rewarding work. First of all thank to my external partner Safetec company. They give me the possibility to see how wonderful could be working in an ambient where people are satisfied of their job, and especially to Mahdi Ghane, Stefan Isaksen and the principal safety engineer Ranveig Niemi. A huge "thank you" is for my supervisor Nicola Paltrinieri, who was following me step by step during my research period in Norway and afterwards. He had for me always good tips without forcing a way to solve my problems, he left me settle them using my mind-made methods.My goal is to met all of you with my final work, and I hope I made it.

G.C.

Abstract:
In the recent decades, attention has been paid to the improvement of hydrogen technologies as replacement of electric and/or hybrid cars. This can be defined as a green solution as the main product of hydrogen combustion is water. However, it is important to assess the related safety and costs, and reassure public opinion after the accident occurred in Kjørbo, municipality of Bærum (Sandvika), on 10th of June 2019.

The object of this study is to demonstrate that hydrogen fuel stations are safe and convenient if appropriate measures are taken. The Norwegian district of Østlandet (which is the district involved in the accident) and the nearby areas are taken into account. In the work, the position of the station involved in the accident is examined in order to optimize the transport of raw materials and be cost-effective and efficient in terms of safety and performances. It is therefore necessary to diversify the supplying for station typology and study the transport and fuel station risks according to the position and the exposure of the public in different scenarios.

A set of methods is used for the optimization. Quantitative risk assessment of potential accident scenarios is performed by means of the software DNV-GL Safeti 8.22. Economic assessment is performed using the software Exstendsim. The results are compared to appropriate acceptability ranges and used to identify the most important factors to consider for the optimization of hydrogen delivery.

Chapter 1

Introduction

1.1 Why hydrogen?

1.1.1 Development

Why hydrogen? In recent decades the demand for a better life, thanks to the reduction of air pollution, the increasing of population and the necessity to find a new energy source alternative to oil, that can cover the consumption of the twentieth century, have allowed to develop a rampant research.

To date, more than 90% of consumption is covered by fossil fuels, which however have polluting elements as combustion products. (Chiaramonti et al., 2005) Over the years many alternatives have been floated on how to overcome the current deadlock: among all these, hydrogen seems to be the favourite one. Criteria of decision were its vast range of supply typologies and zero harmful emissions(Barthelemy, Weber, & Barbier, 2017)

Hydrogen is the lightest and the most abundant gaseous substance in the universe. It is the fuel for shining stars and galaxies, why couldn't it be Earth fuel too?

In the atmosphere it is present as a molecule only for 50 volume ppm, because its weight as single element is not enough considerable to be retained by the Earth. Usually it is produced by decomposition of its chemical compounds, indeed it is available in large quantity inside water or organic matter as vegetables and hydrocarbons. In Kyoto Protocol view, which requires among the participating countries to reduce CO_2 emissions into the atmosphere, hydrogen seems to be an optimal solution. It has water as combustion product only and zero emissions if the production system, usually implemented from the water itself, it is powered by renewable energy.

Looking at the Global Warming Index (GWI) graph, whose data are shown in figure number n°1, we can easily recognize a dramatic view of the temperature increasing due mostly to carbon dioxide. The latter is result of a stoichiometric and inevitable combustion of carbon in an oxygenated environment. By now it is therefore known carbon is the main polluter in air and in the same time, together with hydrogen, it is one of main components in traditional fuels. Its combustion involves generation of partially oxygenated and other uncooled organic products. They are recognizable by the type of chemical structure C_mH_n and usually they are accompanied by the creation of oil-based fine powders PM10 classified as highly harmful and regulated by anti-human pollution.

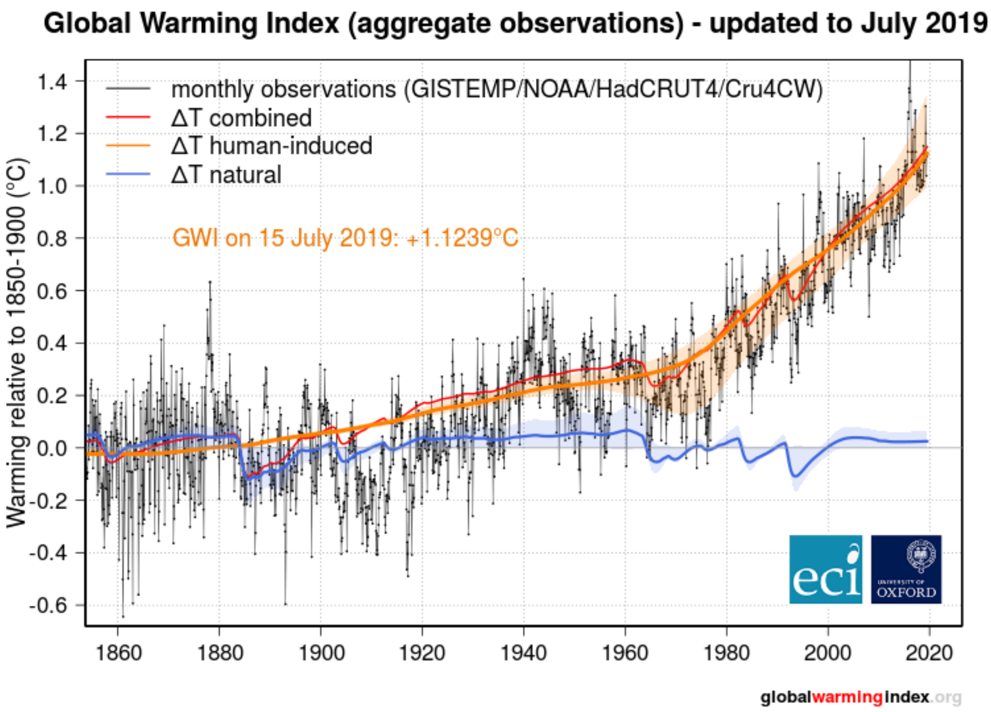


Figure 1: GWI (Oxford University Environmental Change Institute, n.d.)

Oxford University in collaboration with University of Bristol and Victoria University of Wellington is studying climate changes removing the natural influences from the results.

- Black line: temperatures provided every month by UK Met Office, Cowtan and Way, NOAA and NASA research centres.
- Orange line: human-induced drivers.
- Blue line: natural drivers.

Their index calculation method makes possible to estimate which one is the answer to the human behaviour and which one is the natural fluctuations year to year. Thereby they are questioning the position of many who justify the increasing of temperatures with a normal alternation between warm ages and glacial ages.

1.1.2 Environmental aspects

The new fuels search and the analysis of the various substances now considered to take the place of oil focus on well-defined characteristics such as:

- Availability
- Knowledge
- Cleanliness
- Convenience
- Independence from countries control

Those last appear to be wholly owned by hydrogen.

About availability, hydrogen can be considered inexhaustible in nature because usually its combustion starts from water through an electrolysis process and returns to the water itself after the generation of motion via fuel cell. Even in the case of element generation starts from the reformation of natural gas, then with combustion water would be got back.

Another fundamental characteristic is knowledge. Hydrogen is an element that has now been explored in all its forms and compositions because it has long been used in the oil and heavy industry. Moreover, since the second half of the twentieth century, studies on it have been encouraged by the desire to convert to nuclear power, in fact, hydrogen is the protagonist in the phases of nuclear fusion. In spite of this, hydrogen was still used in the following years.

At the same time, hydrogen is a clean source. Countries have as their purpose using fuels whose carbon content is reduced until minimum. To best analyse its quantity the C / H ratio is usually chosen to explain the carbon amount present with respect to hydrogen in different types of fuels. In the figure n°2 taken by the article "Technologies and regulations for hydrogen systems and vehicles" by Aldo Bassi, the C/H ratio demonstrates that hydrogen is the one with the lowest amount of carbon.

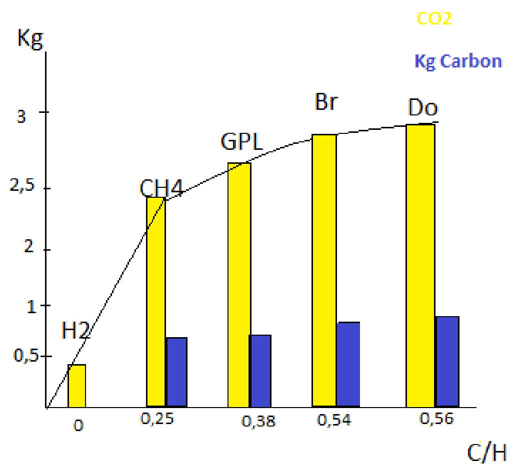


Figure 2: CO2 emissions to generate 10000 Kcal versus fuel ratio C/H (Bassi, 2004)

The carbon content is represented as C / H ratio and related emissions of CO2, coming from the generation of an equal quantity of thermal energy 10,000 Kcal or 41.8 MJ. Figure highlights as best fuels in ecological viewpoint hydrogen, methane and the LPG, instead of traditional petrol and diesel fuels. Unfortunately, to date, the better one is still resulted by fossil fuels for the most important part and this does not make it 100% green. In fact, in this case its use for transports would eliminate only one problem, namely the unloading from vehicles, but not the production, now known in the refinery industry.(Bassi, 2004)

Regarding the economic convenience of hydrogen on other alternative sources, it is necessary to make an excursus on the fact: it is economic if it is produced by petrol sources. Still it has not been possible to bring hydrogen at the same cost as gasoline or diesel if produced with renewable sources. To give a precise picture about the price of the hydrogen we should wait market develops in this transport orientation, but we can see some studies about production and selling of it depending of the plan sizes, electricity and/or natural gas costs and delivering. Cost of hydrogen is not only the element itself. Every step has its own cost in the supply chain and the distribution. Leaving out the design and preliminary analysis costs, next step is the production. Its cost depends to which type of production is considered and where the factory is located. Place is important for environmental aspects, strong price influencers. Usually, factories are already built. Hydrogen, indeed, is a common element in chemical industries, but to reduce the price we should think about bigger plants than an ammonia one. Time ago in Norway were located two of biggest electrolyzer plants in the world, then closed around 1970 for the changing of the distribution of methane. (Langås, 2015)

After producing, hydrogen is stocked in tanks. This stage has a cost itself depending by where, how long and how they decided to stock hydrogen. Storage can be cryogenic if we are storing liquid or at different pressures if we are storing gaseous hydrogen. While the first one is expensive for the heat insulation to maintain temperature around 20 K (-252 °C), the second one costs as well because of the compressor presence. This element allows you to get hydrogen compressed with a ratio that it is usually decided in design phase. Between low and high pressure, the price will grow more than double.

The phase which more than the others suffers dependence of external aspects is the delivering. Demand, route and weather are only few of factors in the middle of the study when delivering is planning. Then, it is really difficult to fix a distribution price valid for every place, but we can imagine that it should be composed by type of vehicles, salary of operators, energies spent and eventual street fee.

Last step is the cost for consumer and, at the moment, hydrogen final price is not comparable to other fuels.

Hydrogen fuel is recommended thanks to clean emissions for environmental aspects. In addition to that it cannot be overlooked the independence of hydrogen production in each country, a least on the paper. Every continent, every nation and every city can produce hydrogen through investment in renewable energy, nuclear, biomass, water or natural gas because its presence is everywhere, it has no deposits like oil. It would be enough to power the transport market and also other applications of stationary fuel cells such as energy backup in large data processing and telecommunications industries. Linked with the political aspect, hydrogen might be a solution of the “black gold" war. Our society is walking around oil mining, but if hydrogen technologies will spread in few years, that could be stopped by the national source variety. Every country, indeed, has the possibility to produce its fuel needed quantity, but I am not so positive on this aspect because there will be some countries, more rich right now, that could build plants and an elaborate distribution system, and others, poorer today, that will be oppressed again because they have no money to build an own hydrogen net.

1.2 Hydrogen regulation, standards and code

As soon as hydrogen will be used as fuel, it needs a regulation about the right way to take advantage of the new resource. Hydrogen itself already has some codes to manage it because it has been exploited for long time, but now it is necessary to add some of them to handle the fuel part. First of all, we should divide the gaseous standards to liquid ones. Most of the codes that are running them came from the International Organization for Standardization (ISO). Table 1 shows how the governing body wants to control all the stages between production and delivery.

Table 1: Regulations("ISO," n.d.)(Interno, 2018)

STANDARDS BY ISO/TC 197 Hydrogen technologies			
• **ISO 14687:2019** **Hydrogen fuel quality — Product specification** • **ISO 26142:2010** **Hydrogen detection apparatus — Stationary applications** • **ISO/TR 15916:2015** **Basic considerations for the safety of hydrogen systems** • **ISO 16110-1:2007** **Hydrogen generators using fuel processing technologies — Part 1: Safety** • **ISO 16110-2:2010** **Hydrogen generators using fuel processing technologies — Part 2: Test methods for performance** • **ISO/TS 19883:2017** **Safety of pressure swing adsorption systems for hydrogen separation and purification**			
PRODUCTION	**STORAGE**	**DISTRIBUTION**	**BUNKERING**
GASEOUS HYDROGEN			
ISO 22734:2019 Hydrogen generators using	ISO 19881:2018	ISO 16111:2018 Transportable gas storage devices —	ISO 17268:2012 Gaseous hydrogen land vehicle

water electrolysis — Industrial, commercial, and residential applications	Gaseous hydrogen — Land vehicle fuel containers	Hydrogen absorbed in reversible metal hydride	refuelling connection devices
	ISO 19882:2018 Gaseous hydrogen — Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers		ISO 19880-5:2019 Gaseous hydrogen — Fuelling stations — Part 5: Dispenser hoses and hose assemblies
	ISO TC 50 SC 4 Compressed gaseous cylinder standards.		ISO 19880-8:2019 Gaseous hydrogen — Fuelling stations — Part 8: Fuel quality control
	ISO DIS 19078 Standard for checking of methane cylinders used also for hydrogen ones.		ISO/FDIS 19880-1 Gaseous hydrogen — Fuelling stations — Part 1: General requirements
	ISO TC 58 SC 3 Compressed gaseous cylinder standards for designing.		ISO/TS 19880-1:2016 Gaseous hydrogen — Fuelling stations — Part 1: General requirements
			ISO 19880-3:2018

			Gaseous hydrogen — Fuelling stations — Part 3: Valves
			ISO/FDIS 17268 Gaseous hydrogen land vehicle refuelling connection devices
LIQUID HYDROGEN			
• **International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code)**			
PRODUCTION	**STORAGE**	**DISTRIBUTION**	**BUNKERING**
ISO/TC 197 (gaseous) **• CEN-CLC/JTC 6 (under establishment)**	ISO 13985:2006 Liquid hydrogen — Land vehicle fuel tanks	International Gas Carrier Code (IGC Code)	ISO 13984:1999 Liquid hydrogen — Land vehicle fuelling system interface
	CEN/TC 268: see website for several standards	IMO: IGC and IMDG codes	
	ISO/TC 220: Cryogenic Vessel	IMO: Resolution MSC. 420(97)	
	EIGA: Documents 06/19, 114/09, 119/04, Technical Bulletin 27/18	CEN/TC 268: see website for several standards	

and 11/14	
	EIGA Documents 06/19, 41/18
	ECE Regulation 67 rev.2, 110 rev. 12, 115 or 79/20094 or 406/20105 (container systems)
	CEN/TC 268: see website for several standards
	EIGA 06/19
	UNECE ADR

1.3 Differences between fuels

To understand which characteristics should be supposed to reach during the age when hydrogen will be the fuel of the future, it is necessary to know which ones characterize fuels of the present. To start it is fundamental to know which user we are involving. The carpool in Norway in 2018, as the table n°2 shows, was divided in petrol, diesel, paraffin, hydrogen and electrical cars.

Table 2: Norwegian carpool("Statistics Norway," n.d.)

	Private cars
	2018
Petrol	1 075 179
Diesel	1 290 442
Paraffin	11
Gas	223
Electricity	195 351
Hydrogen	140
Petrol hybrid, chargeable	89 657
Petrol hybrid, non-chargeable	92 144
Diesel hybrid, chargeable	6 476
Diesel hybrid, non-chargeable	1 192
Other fuel	41

Majority of internal combustion vehicles are powered by petrol and diesel. The first is defined as a mixture of light hydrocarbons whose boiling temperature is usually between 50 and 200 degrees. It has high thermal potential, high volatility and octane number, but it depends to the type of mixture. It is known that there are various kind of gasoline, such as light gasoline, normal, heavy and for paints, but in the latter case it is used as a solvent. Gasoline must be pure in order to be used as a fuel. It must not contain water or any kind of residues as volatile polluting components, it must be colourless, clear and with a neutral reaction, obtained from oil and then treated through numerous processes. Most important ones are cracking and reforming serving to improve the characteristics of primary gasoline, the newly distilled. The process of evolution towards innovative fuels is slowly moving consumers away from buying fossil fuel cars, but as it can be seen from reported data, they are still the most widespread. This departure is mainly due to the environmental factor, because petrol is the fuel with the highest ratio C/H=0.54 from which pollution comes from. Unlike hydrogen, however, it has a narrow flammability range, which is 1%-7.6% in volume and both liquid and gaseous forms with their very high density, in the event of release, are not subjected to dispersion in air. No instantaneous vaporization and consequent dispersion for gasoline, but a possible pool fire. The boiling point is higher than 100°, however reachable in case of external fire or parts of the system overheated. Even though its auto-ignition temperature is higher than 300°, it is highest one among the examined fuels. The most common engines in Norway are powered by diesel fuel. Like the petrol, it is a hydrocarbons mixture too. They are obtained by fractionating the distillation of crude oil with some more constituents contained in it like aliphatic or cyclic parts, usually composed of 13 to 18 atoms of carbon and paraffin. Once again in common with gasoline it has a clear appearance, but its colour comes down to the production process and to the presence of yellowish dyes, but it must not be opalescent. In this case it could present anomalies, impurities or presence of unstable compounds. At atmospheric temperature it is in the liquid state, but it vaporises in a very wide temperature range, depending on its nature, between 141°C and 462°C. It is considered intrinsically safer than petrol, even if it has a self-ignition point at 225°C, because the flame point is higher and corresponds to 56°C. The flame point is the lowest temperature at which vapours are formed in such a quantity which is enough for combustion possible in presence of oxygen and ignition. LPG is the acronym for liquefied petroleum gas, although sometimes it is used as acronym for liquefied propane gas for its presence in percentage. They belong largely to propane, but is not the only component of the mixture. It is created by mixing alkaline low molecular weight hydrocarbons (propane, butane and hexane) to a small extent and, sometimes, even unsaturated hydrocarbons such as ethylene and butylene. The compression of these types of hydrocarbons occurs at low pressures around 2-8 bar, one of the reasons for choosing it. Together with the ease of transport at high density and low pressure, another reason is the low environmental impact in high energy yield. It is often preferred to methane for sizing and transport aspect and for the higher calorific value emitted at the same weight. As the regulations about hydrogen will require, LPG is odorized by ethanol being odourless and so dangerous in case of leak. In Italy, a lot of attention is paid to it after the accident in 2009 in Viareggio, where a freight train derailed after an external impact and caused the loss from a created hole. Following the wind, the leakage spreads and the explosion was fatal for 32 people and extremely incisive for other 50 who were seriously injured. Methane seems to be the closer solution to find a fuel environmental-friendly and easily usable in the same time, but the ratio C/H it's still 0,25. Hydrogen is the only element whit 0 as emissions ratio, but as mentioned above, it is still not competitive on the market for its price. To operate with hydrogen we will go against its physical characteristics. Conversely of other fuels that vary on the same orders of magnitude, hydrogen has a high calorific value of less than 120 Mj/kg, almost 3 times of gasoline, methane and LPG ones. Combustion speed can reach 200 cm/sec depending on the agent in which it expands against a really slow one of the rest of the fuels, it is counted around 30 cm/sec. At very low density at ambient pressure, hydrogen is considered a dangerous element especially for its wide flammability range from 4% (LFL) by volume to 72.5% (UFL) by volume. It is very volatile in addition and this characteristic makes it worse because of increasing the impact area in case of accident.

Table 3:Differences between fuels (Bassi, 2004)

Parameter	Gasoline	GPL	Methane	Hydrogen
lower heating value	44,4 MJ/Kg	46-45,4 MJ/Kg	50 MJ/Kg	120 MJ/Kg
octane	90-98	100	120	130
ratio C/H	0,54	0,38-0,4	0,25	0
heat hue	3,65 MJ/m3	3,48 MJ/m3	3,18 MJ/m3	2,97 MJ/m3
rate of combustion	23-27 cm/sec	23-27 cm/sec	30-35 cm/sec	200-40 cm/sec

lower limit flammability at ambient pressure	1% vol.	2,1-1,5% vol.	5% vol.	4,1% vol.
upper limit of flammability at ambient pressure	7,6% vol.	9,5-8,5% vol.	15% vol.	72,5% vol.
vapour density at 1 bar	4,75 Kg/m3	1,83-2,42 Kg/m3	0,67	0,08989 Kg/m3
vapour/air density	3,9	1,5-2	0,56	0,070
liquid density at 15°C	740 Kg/m3	585-573 Kg/m3	423 Kg/m3(-161°C)	70 Kg/m3 (-252 °C)
self-ignition temperature	320 °C	465°C	540 °C	560 °C
boiling temperature at 1 bar	125 °C	-42 °C - -1°C	-161 °C	-252 °C
REID vapour pressure (100 F)	0,25-0,45 bar (abs)	10-2,5 bar (abs) propane-butane	-	-

Differences with other fuels are seen when we are speaking about energetic density in different storage technologies. In every its forms, compressed or liquid ones, the quantity of energy emitted by 1 kg of hydrogen is higher than the one generated by natural gas, GPL, methanol, gasoline or diesel. The energetic density is 33,3 KWh/Kg, but it is reduced if it is considered the litre. Best compromise is the liquid phase at -252°C with an energetic density of 2,36 KWh/l, still less than metalhydrides with 3,18 KWh/l, natural compressed gas with 2,58 KWh/l, 3,01 KWh/l, 3,38 KWh/l for 200,248 and 300 bar respectively.

Table 4: Energetic density of fuels versus storage technologies(Bassi, 2004)

Fuel	form of accumulation	Energy for Kg	Energy for litre
Hydrogen	Compressed 200 bar	33,3	0,53
	Compressed 248 bar	33,3	0,64
	Compressed 300 bar	33,3	0,75
	Compressed 700 bar	33,3	1,46

	Liquid -252°C	33,3	2,36
	Metalhydride	0,58	3,18
Natural gas	Compressed 200 bar	13,9	2,58
	Compressed 248 bar	13,9	3,01
	Compressed 300 bar	13,9	3,38
	Liquid -162°C	13,9	5,8
GPL	Liquid	12,9	7,5
Methanol	Liquid	5,6	4,42
Gasoline	Liquid	12,7	8,76
Diesel	Liquid	11,6	9,7
Electric energy	Pb battery	0,03	0,09

Definitely Diesel and Gasoline are better solution for this aspect with 9,7 and 8,76 KWh/l, but their impact on global warming is greater. The graph in the figure n°3 makes the meaning clear. Diesel and gasoline cars have the index of Co2 equivalent kilograms for each kilometre exactly 4,4 and 6 times bigger than hydrogen one.(Bassi, 2004)

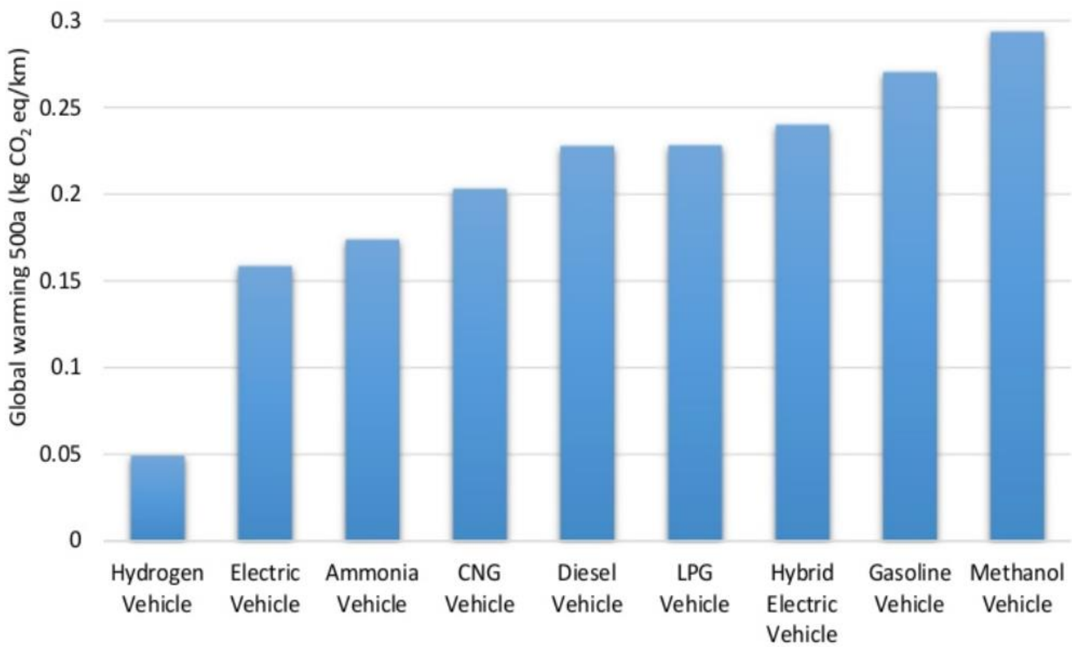


Figure 3: Impact of vehicles on environment(Bassi, 2004)

1.4 Power chain

Common denominator in every fields is low carbon emissions mission. At the base of hydrogen economy is present the growth of renewable energies. With the development of resources such as geothermal, wind, solar, hydraulic and the beginning of hydrogen manufacturing from CO2 including also biogas and methanol, clean energy could be produced to power the production of hydrogen fuel. This could be carried out in factories by electrolysis or by gas reforming. Industrial applications could be directly related to reheating as fuel cell forklift, hydrogen gas burner or fired industrial furnace. At the same time the hydrogen itself could be a primary resource for energy production from thermal power stations mixed hydrogen or ammonia combustion. They could be fed with an efficient distribution network which is expanding in these years with:

- transportation by pipelines
- liquified and organic hydride
- ammonia trailers
- it is beginning its flooding with overseas tankers
- hydrogen for domestic areas renewable energy-based.

The electrical grids are fundamental for large scale energy centres in the industrial side, but in the other side regarding the aspect in direct contact with the consumer. They can supply buses, bicycles, scooter, cars, trucks by refuelling stations, heating and trains. This hydrogen-renewable coupling could solve the problem that does not allow them to develop at 100%: the failure in storing big quantity of energy and transporting the amount for long distances. The combination with hydrogen, which is on the contrary capable to store electricity longer and to transport it in larger amounts, would be the ideal solution for the optimization and efficiency of green energies. This view is a link that binds with the generation of electricity in a series, a circular trend that has the potential to eliminate fossil fuels from trade and thus improve the condition of our planet, to date, won by pollution.

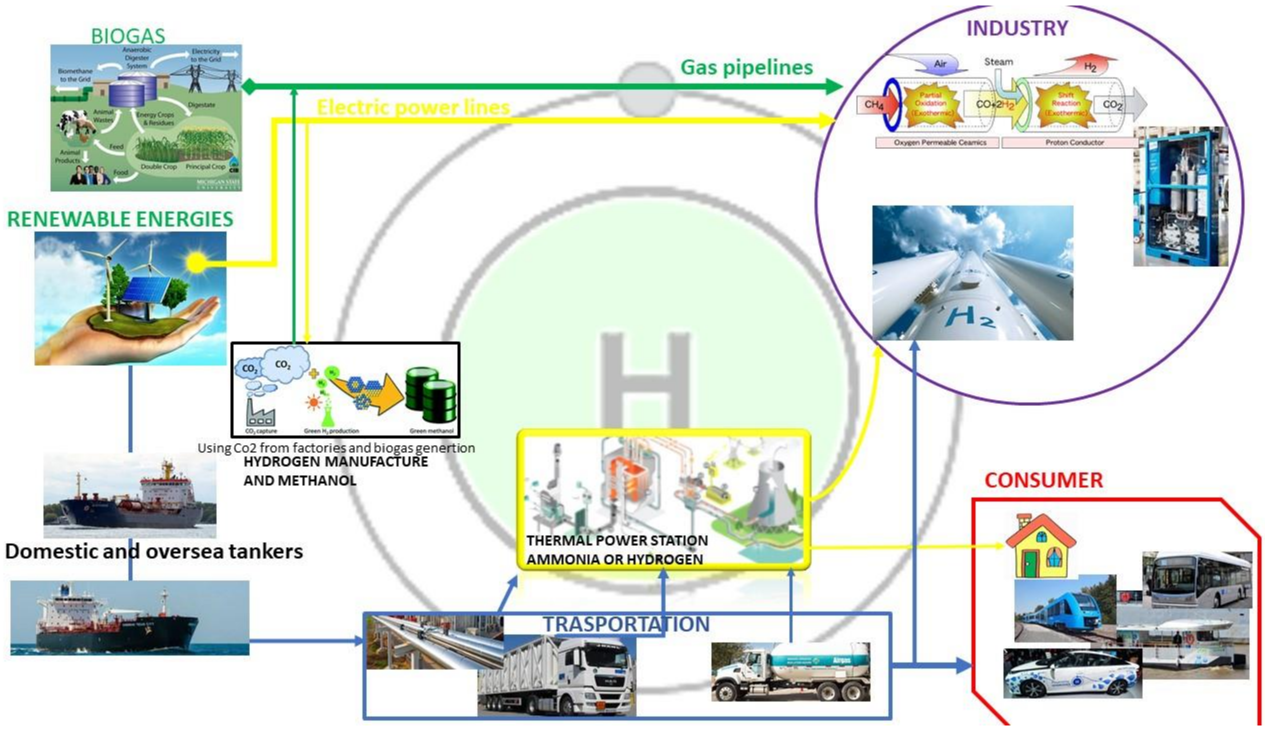


Figure 4: Power chain image Inspirated to (Toyota, n.d.)

1.5 Hydrogen delivery state of art

Distribution system is not only composed by transport and delivery, but also by storage, compression and hydrogen fuel stations for refilling. Best option for delivering is liquid and gaseous trucks or pipeline where the gas flows. Today is still early to speak about a commercial hydrogen car sector because the technologies should be grown up during this switchover phase to elicit a real market of hydrogen fuel. The goal of this chapter is to put forward which steps the source needs to follow to be used by the consumer.

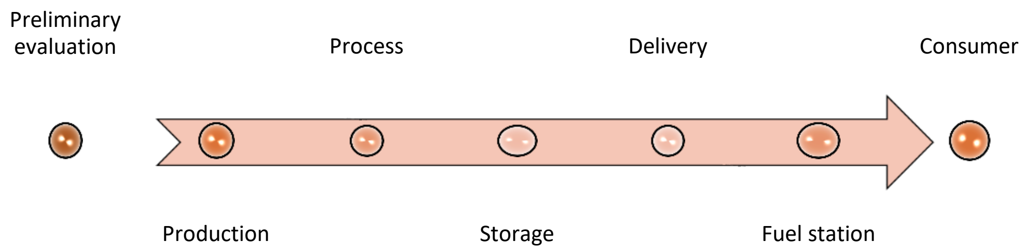


Figure 5:Step by step

1.5.1 Preliminary evaluation

Treating hydrogen is not only about producing it. The hydrogen economy is developing a variety of transport systems based on several predominant factors. Most of them are interlinked geographical and market characteristics such as:

- Target population
- Consuming behaviours
- Population density
- Size of refueling stations
- Market penetration of fuel cell vehicles
- Other Hydrogen consuming units

Distributionmethods take its root typically on the various physical states in which hydrogen can be distributed. The three primary hydrogen distribution transports are:

1. Gaseous hydrogen delivery

2. Liquid hydrogen delivery
3. A spectrum of possible vectors of solid or liquid hydrogen.

(DOE, 2015)The first two mentioned above are currently the most common types of transport and as a molecular element, hydrogen is uslly delivered by trucks, railways or barges. As far as the third mode is concerned, which is not common yet, it utilises other chemical materials to transport hydrogen. In this case, it is not present in molecular form, but in composition with liquid hydrocarbons, sorbents, metal hydrides, chemical hydrides or other rich compounds. However, transport by materials is not ideal for those expensive prices because they have not simple and inexpensive treatment processes or a reasonable price comparable with other fuels in origin which allows them to be competitive .

The aim in those years is exactly to get hydrogen comparable in the marketplace with other fuels and its delivery is one of key about cost and safety parts as it contains many components within it. On the way from the moment of production to the delivery one, you can meet in the street compressors, pipes, liquefiers, pipe trailers for gaseous, trucks for cryogenic liquids, storage containers, terminals and distributors. Therefore it is essential to analyse in detail the routes in order to optimise the transport of the new fuel. It is well known that we are now in a period of transition which sees hydrogen economy constantly growing even if its nature is known It will take some more time to get the full deployment of hydrogen-based transport technologies and infrastructures, but the world has taken this path. Main alternations will concern the needs and resources of distribution infrastructure. It will be several according to region and type of market (e.g. urban, inter-state or rural) and infrastructure options will also evolve as demand increases and distribution technologies mature.

With infrastructure it is meant not only stations and factories, where respectively hydrogen will delivery and produce, but also real pathway to bring the fuel and cover all the land in the countries, in our case, the whole Norwegian territory. The technologies for delivering could be classified by three sectors:

1. Production

   In this phase hydrogen is produced, but it needs also to be stored in some tanks waiting the moment when it will be sold. The type of the tanks depend on the element phase, the quantity and the pressure.
2. Terminal and trasmission

   The type of terminal and trasmission components are chosen for delivering according to selected route, quantities, conditions of the good and between different proposals. In the path to reach the statons we could meet geological storages, liquefiers, pipeline, trucks, railways, barges, terminals, liquid and gaseous tanks, compressors and pumps for liquid or gases. Every pathway has to be study as a single case.
3. Refeuling site

Components present in refuelling stations are designed based on their typology. If the station is a production one, we can have two situations. Production stations could use carrier or directly water by electrolysis to obtain hydrogen. First case, inside the HRS(Hydrogen refuelling station) you will have carrier processing parts and/or purification ones. Second one, it will be fitted with electrolysers. After these processes, product will be stored waiting for sales, so to keep it in high pressure will be necessary some compressors. This step is in common with the second type of HRS, the storage one. The latter is composed by more than one tank with different pressures. Right now, most of the cars powered by hydrogen have a compressed gaseous tank inside. That is why even if the delivery is liquid, sometimes HRS are equipped with heat exchanger associated with a vaporizer to distribute it to the customer through dispensers in gaseous form. (DOE, 2015)

One concept involves every type mentioned above, it is the health and the safety of workers and individuals who come into contact with the system belonging to every stage of it from production to consumers. It is also transversal to follow the standards and legislation in this regard, following in a particular way the procedures and implementing controls in multiple points of the supply chain.

In order to get an achievable optimisation, current and emerging technologies, systems and options for hydrogen supply need to be examined in order to decide which is the best compromise for distribution. The study is the basis of the design and allows researchers to identify areas that are most suitable for the establishment of a commercially viable hydrogen distribution infrastructure.

1.5.2 Required process to delivery

After doing the preliminary evaluations about factors which might be instruments to build the infrastructure and the structure around hydrogen, we need to focus on the process whose goal is spreading hydrogen economy. Making hydrogen available to the consumer depends on the source considered for production and consequently which conditions and which delivery stage are chosen. In the case of liquid hydrogen, after it is produced by gas reforming or electrolysing, it is transported and stored in cryogenic tanks usually around 3-5 bar of pressure. Then the liquid will pass through a pump that with its thrust directs it towards the vaporizer. The vaporization phase is very delicate and it is followed by high pressure storage. Then hydrogen will be distributed to buyers through dispensers and on average it takes 7.2 minutes to fill a 4.5 kg tank at 350 bar. As far as hydrogen in gaseous form is concerned, after being produced in liquid form or processed at room temperature in molecular gaseous form, it is usually compressed through a compressor.

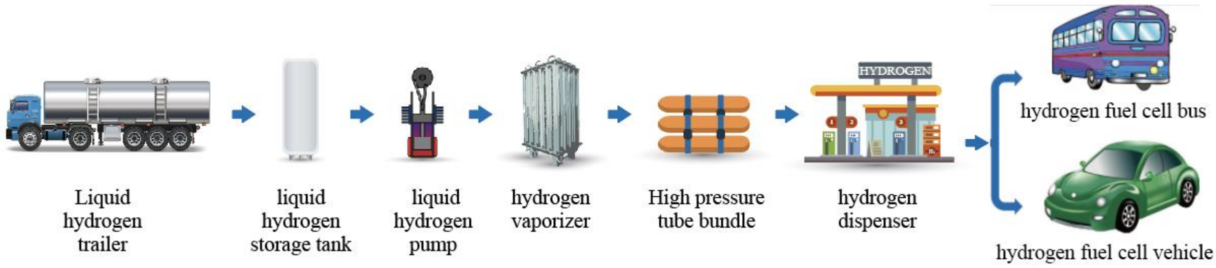


Figure 6: Liquid delivery steps (http://www.fuhaicryo.com/en/plus/list.php?tid=69)

Compressor will bring it to gradually higher pressure and will be stored differently in a low, medium or high-pressure tank if it respectively reaches the pressure ranges of 150-300, 200-500, 500-900 bar (DOE, 2015). These ranges are linked with structure and design of the plant. Right now, most of refuelling stations already built are made for gaseous distribution cause car tanks are designed for 300-350 bar. In the future vehicle brands are planning to sell cars with liquid tanks for hydrogen to obtain more fuel self-sufficiency with same volume.(Jenson, 1975)(US DRIVE, 2017)

1.5.2.1 Compression

As it had been specified in the previous paragraph, compression is fundamental for delivering hydrogen to consumer. Centre place of examined phase is occupied by mechanical compressor. Most famous types of it are volumetric and centrifuges compressors. The latter are currently used for treating natural gas during transportation and in circumstances where good results are required with a very modest compression ratio, between 1.1 and 2. Many of them utilize alternative technology and a high number of revolutions per minute in the range of 750-1800. To operate in stations, they are design with linear pistons or diaphragms whose aim is to contract gas with forward and to return movements: reason why they are called “positive displacement” compressors. These moving parts may cause destabilization or leakage, so checking valves are installed at inlet and outlet. Leaks, however, are not the only one problem for compression machine: they are subject to heavy contamination, noise and low reliability due to high centrifugal power despite the high capital costs. Many projects have proposed new compressor typologies called “intensifiers” present as solver of noise problems. Significant reduction in rpm and a different intrinsic design of the piston are the operation changes. The proposal compressors listed above is not satisfactory if you want to transport hydrogen in pipes. In fact, because of its very light molecular weight, hydrogen hampers machine dragging. Comparing with natural gas, the top speed will have to be designed about 3 times faster and it will be carried out on several stages. They are still at the design stage when selection of materials and efficient design of rotor are decided. Afterward reliability verification is following to increase performances and to reduce special seals, costs and mechanical complications such as vibration. For what it is so far has been derived from studies on the gas compression, the convenience lies in the amount in kg of treating hydrogen. If large quantities are processed, alternative piston compressors are the right choice. Contrary if volumes are smaller, membranes with different compression ratios are used according to required delivery. Stations usually require high compression, for example sometimes ratios could touch around 45 per 35 kg/h allowing pressure increasing from 20 bar to 950. However, HRS are designed for lower flow rates comparing them to a pipeline. Putting same initial conditions (20 bar), distributors amount is in order of 100 kg/h against 50- 200 tons/day through one pipe, but with extremely lower ratios from which pressures are obtained up to 70 bar. Flaw is no all the diameter measurements satisfied conditions for tube compressors. A lot of limitations for larger pipelines limited their use in the medium and long term, the need of advanced seals and tight leakage tolerances make leakage rates even better. As far as costs are concerned, in addition to high capital costs, it is necessary to add the amount of energy used for compression, which follows a logarithmic relation with pressure ratio. In the beginning a greater expenditure of energy will be spent and it will gradually decrease. High pressures are often chosen even inside vehicles, fuel is stored with a pressure of 700 bar at room temperature (950 bar at 80 ° C).

Compression is therefore a critical phase for plant in terms of both safety and cost. Many are investing in development of non-mechanical technologies, based on principles of molecular hydrogen separation by electricity and pressure differential drive with conductive membranes. Electrochemical compressors often can overcome problems related to other commonly present typologies, regularly due to intermittence. It causes valves and diaphragms unreliability and hydrogen seepage into the seals subjected to thermal stress.

Another possible compression kind recently has been studied is compression by metal hydrides. In some materials stasis phase is reached with a certain amount of hydrogen inside depending on the type of hydride. Machine operation is separated in two moments: first it absorbs hydrogen molecules at low pressure and low temperatures and then it releases same amount of it at high pressures wasting heat.(Baldwin & Investigator, 2012)(AA.VV., 2003)(US DRIVE, 2017)(US DRIVE, 2017)

As mentioned above, compressor is the element that mainly marks this phase, but it is certainly not the only one present.

Table 5: (US DRIVE, 2017)

Pipelines	*Refilling Sites*	*Terminals*
High throughput	Moderate throughput	Medium throughput
medium pressure (100 bar or 1,450 psi)	high pressure (950 bar or 14,000 psi)	high pressure (350-500 bar or 5,000-7,250 psi)
very high reliability	high reliability	high reliability

Generally, HFSs for generating hydrogen utilise PEM electrolysers with a diaphragm hydrogen compressor. This approach is in line with high safety level quests, no contamination, and low leakage rate. Some other stations use piston compressors. Most of them opt for ionic compression that has less electrical expenditure and require less maintenance. Linde is the most used for fuel stations and it works with five stages of pistons compressor, moving hydraulically up and down. Above them, an ionic liquid is deployed by pistons and compressed with hydrogen. Last step is hydrogen division from the ionic liquid over the separator, where the second one returns in the cycle system while the first one becomes pure.

In the hydrogen gas compression journey from production to delivery and delivery to the customer, different states are crossed with different characteristics. After manufacture, molecules pass through piping to be placed in heavy transport vehicles or to be transported directly by pipeline. In this case, its typical characteristics are high throughput, medium pressure ranging between 100 and 150 bar and very high reliability, due to of flanges presence, possible worn areas or material embrittlement. The latter is the cause of the high cost of materials. They are subject of research for continuous improvement from design and materials point of view and lowering of maintenance costs. The presence of numerous moving parts at higher peak speeds than those faced in natural gas compressors and production, which could be reduced by scale production increasing, make this stage expensive. (NCE MARITIME CLEANTECH, 2019)(Cardella, Decker, & Klein, 2017)

1.5.2.2 Liquefaction

At present, the main problem for high cost of hydrogen is due to liquefaction. It is a multi-stage process with high energy consumption that allows change of phase thank to numerous expansion and compression stages in an atmospheric or refrigerated environment. At room temperature and pressure, hydrogen is in a gaseous state: its boiling point at -253°C, corresponding to 20 K, is the second lowest after helium. To be liquefied and compressed it follows:

1. isentalpic expansion (through a Joule-Thomson valve)

2. expansion of cooling through a turbine

3. cooling with liquid nitrogen by means of a brazed aluminium heat exchanger

At point 3 we find the source of most efficiency and cost problems, cycle compressors and liquid nitrogen refrigeration. Within these occurs the modification process of the atom H structure, in fact a molecule of hydrogen can exist in two states of spin orbital electron: ortho and para. (Jenson, 1975)

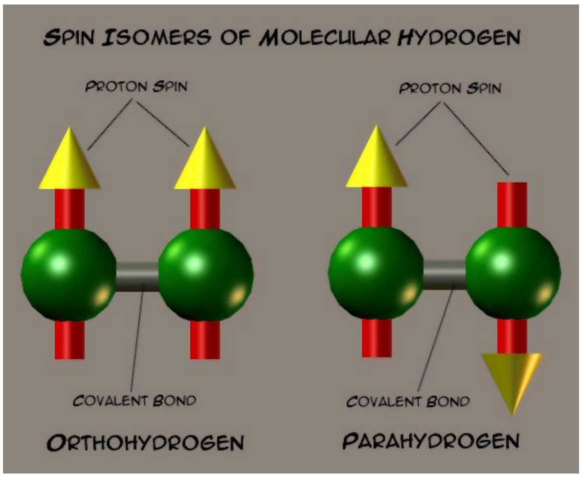


Figure 7: Spin of electrons in H atom(Timothy Wogan, n.d.)

If it is in liquid phase, atoms should be as close as possible to the composition homogeneity of 100% parahydrogen. To obtain this condition, conversion catalytic beds are used requiring a huge amount of energy. Indeed, heat exchangers have not been improved yet, even though they are being developed with combined aluminium exchangers with gas compressors and/or turboexpanders compatible with refrigerant mixtures. Preference for parahydrogen is due to the low temperatures at which ortho-hydrogen would tend to change spin. Bringing a heat loss, it would cause liquid hydrogen vaporization that would be added to additional large losses, still present in the storage and transport phases. About 35% of the energy contained in liquid hydrogen is spent on liquefaction processes. Currently used by suppliers of ~ 33kWh / kg, it is the lowest heating value, while about 10% is thermodynamically required to cool the hydrogen and to achieve transition to ortho/para. This phase brings at least $1 to the cost for each kg of produced fuel which grows so dramatically with lack of cheap materials with cryogenic resistance. In addition, capital cost to invest in liquefaction plants is high although it is reducible, as in the case of LNG, with large-scale plants. Scale economy leads to standard plant design and improved thermal management, but it is not applicable yet missing a developed market. Acoustic or magneto-caloric liquefaction, combined with new catalysts development to handle the conversion of hydrogen from vegetable to paraffin, has been thought as a cost solution, but research does not develop yet results that can be applied on large production scales.(AA.VV., 2003) (Jenson, 1975)(US DRIVE, 2017)(DOE, 2015)

1.5.3 Storage

As mentioned above, storage is always present in production sites and service stations that will have to supply cars parterre in picked area. Its main purpose is to let process to continue even during stop phase of the generating industry, regardless of stop reason. Stored quantity is subject of study during design phase and will depend on countless factors such as:

- Production

- External environment (spaces, population, proximity to residential areas...)
- Customer request
- Average product availability

While type of storage is dependent mainly on decisions taken in the design phase, which often call on the same factors as previous analysis to get the right quantity. Especially regarding it and volumes needed and occupied by the respective phases, liquid and gaseous, experts normally calculate a cost-benefit ratio. Gas storage is precisely the most widely used today for stations, which through a vaporizer, even if they receive liquid fuel, they store it in gaseous form sometimes. Storage step can also take place in the middle of the transport section. During a very long journey could be necessary a break or, in case of operating pipelines could be possible the presence of underground tanks, so-called "geological tanks".(Paper & Limitations, 2019)

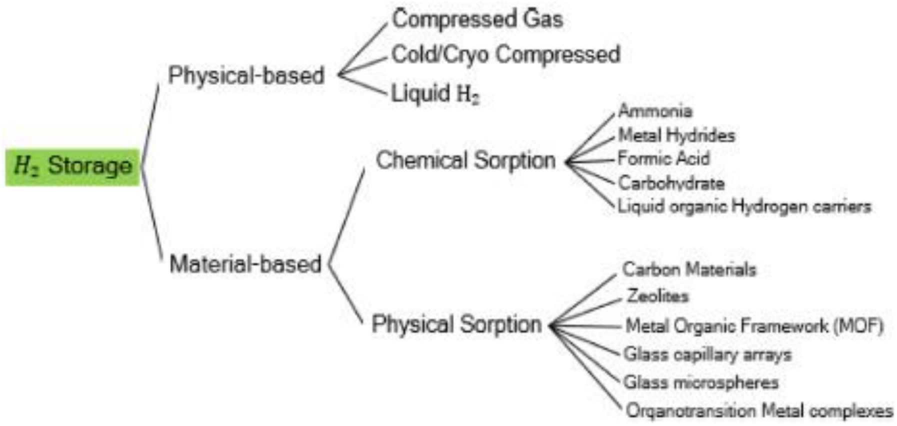


Figure 8: Hydrogen storage(Moradi & Groth, 2019)

Teams of engineers including mechanics, chemists and materials are always looking for structures and designs that can improve tank performances, which are subject to:

- Environmental effects: heat and humidity can alter their efficiency and reliability. Heat involves an effective materials study, shapes and thicknesses that lead to higher prices.
- Mechanical effects: they are mainly created by high pressure charging and discharging cycles. Result is weakening and fatigue on joints and mechanical parts, usually fragile parts of the system.
- Effects due to cycle depth

These effects are directly related to marketing of tanks that meet safety standards with respect to their useful life and asset capital cost depreciation. In the first moment of hydrogen economy development, i.e. in recent years, this phase will be an important discussion topic as it significantly increases delivery cost of fuel thus bringing it to a state not competitive with the currents. Recently, studies for storing have gone beyond looking for solid supports. These would have as long-term aim reducing costs and increasing volumetric efficiency because they have characteristics or particular absorbing abilities in their nanometric structures.

Cost reduction methods mainly concern:

- structural materials
- standard sizes for a small number of production volumes
- and development of low error rate non-destructive evaluation (NDE) technologies.

Arguments around materials are restrictive requirements regarding embrittlement, fatigue and the difficulty of maintaining structural integrity at cryogenic temperatures. For example, it has been proposed to add nanotubes or metal hydrides inside containers. Store density will increase, consequently decreasing of pressures could be available and to store hydrogen then will be possible in low-cost tanks. Research also focuses on the thermodynamics of the phenomenon that sees hydrogen absorption in low temperature conditions and their heating for release. This is a problem happening in tanks for cars too. However, they have limitations in terms of weight and volume and therefore often some systems are possible only for situations of stationary storage.(Barthelemy et al., 2017)

Station service tanks for reasons of public safety are usually confiscated inside high estate buildings. This precaution brings additional costs to structures. In order to reduce them and at the same time to meet level of public safety required by legislation and/or by acceptable social risk concept in service stations, some designers have proposed underground tanks construction or increasing of transport density through carriers. For the first solution, risk assessments are still open concerning corrosion, possible underground leaks, ground freezing, seismic stress and infiltration from outside. The vectors, on the other hand, could also be useful in overcoming daily liquid loss by boiling. A loss which has a considerable weight, especially in early stages of fuel development.(NCE MARITIME CLEANTECH, 2019)(US DRIVE, 2017)

1.5.3.1 Gas storage

The state of the art recognizes gas tanks as best way to store hydrogen in stations, but they are also part of truck for transportation. Depending on typologies, they are approved for different pressure ranges:

- Low pressure from 135 bar (~ 2,000 psi)
- Medium pressure from 350 bar
- High pressure from 500 to 930 bar (~ 13,500 psi)

Sometimes inside plants three previous devices are connected by a collector. It allows employee to draw from different increasing storage volumes and availability, not forgetting safety with alarm devices and valves present around.

Each of these has in common with others shape and structure that constitute it. Pressure tanks, in fact, by designer are drown cylindrical and composed by a shell or a wall. All of them is covered by a coating area called membrane or permeation barrier. Recently shapes have been revised to make it easier to fill. Inside cars rectangular shape and cylinders are applied built with new materials. Material is, in fact, an active part of the research for device optimization and on it is based diversification in four types:

1. Fully metallic cylinder
2. Load-bearing metal liner hoopwrapped with resin-impregnated continuous filament

On site material which is one of main causes of facility cost, along with the gas terminals and other parts of delivery facility.

3. Non-load-bearing metal liner, axial and hoop-wrapped with resinimpregnated continuous filament
4. Non-load-bearing, non-metal liner, axial and hoop-wrapped with resinimpregnated continuous filament

(US DRIVE, 2017)

Usually a condition described in the following lines is preferred:

- Low pressure = 160 bar
- Average pressure = 430 bar
- High pressure = 860 bar

Current estimates about a initial investment speak of $600/kg for low pressure tank, $1,100/kg medium pressure one and $1,450/kg for the high pressure stock. For the difficulties in covering high costs during an early stage of development, researchers have recently experimented steel minimisation, especially for high pressure, through wrapping metal wires around structures. As previously mentioned, cost investment of tanks is also brought up by their useful life that represents their integrity and reliability. They demonstrate by undergoing mechanical phenomena due to cycles of charge and discharge, their depth and environmental factors such as heat and humidity. Therefore, new methodologies of storage are being experimented, not only stationary, but also for transport. Innovative cylinders have been put on market to solve problems as steel embrittlement and lightness. They replace steel with lighter materials such as aluminium or high-density polyethylene usually reinforced externally by composite materials and carbon or Kevlar fibres. Despite the best filling ratio and lower costs, in rectangular tanks and new studied cylinders, however, risks like resistive decay and fibres detachment of polymer matrix are frequent. They could be caused by the number of cycles at high pressure around or above 70 MPa which structures have to support.(Barthelemy et al., 2017)(US DRIVE, 2017)(Paper & Limitations, 2019)(Barthelemy et al., 2017)

1.5.3.2 Liquid storage

To date, liquid storage is unusual within stations built, but famous brands such as BMW have developed cars with liquid storage internal combustion engines. Car manufacturer has designed and built a liquid hydrogen station to fill prototype. However it detected problems in logistical management, despite being automatic, and economic. For these reasons, stations receive and store in liquid form, but they supply in gaseous form after processing the liquid through pumps, vaporizers and compressors. Taking advantage of the higher volumetric density, later hydrogen, being gaseous at atmospheric temperature, will be stored in cryogenic tanks whose materials require ultra-insulated steels through a double shell: the inner shell consists of stainless steel type INOX304 or similar and an outer shell of carbon steel, such as SA516 steel. The two layers are separated by an area which acts as an insulation and it is either empty or filled with perlite insulation. Despite this, boiling will be a budget problem especially during early stages of start-up because huge loss of weigh is heavy to support. For high percentage losses small tanks are the most prone with high A/V (area/volume) ratios. The ratio was calculated by "Hydrogen delivery technical team" one of thirteen teams that collaborated on hydrogen study "U.S. DRIVE Partnership" in July 2017. It has been discovered that for volumes of 50 m^3 the loss percentage is around 0.4% per day while it is reduced by more than 10^{-1}reaching percentages lower than 0.03% for volumes of 20000 m^3. These can be spherical or cylindrical and must withstand temperatures below 20 K (-253 ° C or -423 ° F) to keep the hydrogen in liquid phase. Typical tank pressures are around P<5 bar or 73 psig. Spherical shape is the best for leakage, reason why it is used by NASA in space application. In same condition of volume it uses less surface area. For more common uses such as gas stations you prefer to build cylindrical tanks. In order to reduce or avoid boiling, a small compression system in the tank has been thought of, its purpose would be storing evaporated product and taking it in another place.

They are also utilized in production to store large quantities such as 5,700-95,000 L (1,500-25,000 gallons or 400-6,700 kg) at an internal working pressure of 75-100 psi (5.2-6.9 bar). Research into underground storing places in liquid form is currently under development and it has led to innovative designs through multidisciplinary approaches in which teams of materials engineers work with thermal specialists. A complete liquid storage could provide incentives for above-ground footprint and higher storage capacities per volume unit than gaseous one, but still too expensive. The capital cost would be higher for metal materials, high-strength compounds and new insulators than for an entire pressure plant. Further studies are concentrated on underground storage vessels. In spite of above-ground vessels, these would require smaller stopping distances for station design codes than above-ground vessels.

(Paper & Limitations, 2019)(US DRIVE, 2017)(AA.VV., 2003)(Sdanghi, Maranzana, Celzard, & Fierro, 2019)

1.6 Hydrogen Transport

Route optimization is an important aspect to consider in terms of costs and safety to improve refilling of stations. The routes sensibly depend on national geography and practices. It is impossible to think that a route made for Norway could work as well in the USA. That means every time we need to optimize a zone, we should underline why a route is chosen. Nowadays, we can rely on the following ways of transport:

- Pipeline
- Pipe trailer

  Their name came from the structure they carry. Composed by pipes where inside is stored low pressure hydrogen in gaseous form, usually in normal conditions they stay at 250 bar (3626 psi) of pressure and their capacity is 800 kg. They are suggested for delivery in place located near to the production site or at least under 320 km far away.
- Cryogenic liquid truck

  The cryogenic trucks are state of art choice for a cheaper long distance delivery. They can cross a country for 960 km (600 miles) without problems. Normally they have a capacity around 4000 – 5000 kg, but their operation is inhibited by liquidation and isolation costs, boiling losses and stopping distances.
- Rails
- Barges
- Tanker

Recent studies from Japan and USA speak about them to transport hydrogen by carrier. Most of important solutions they found are around Methanol and Ammonia. Currently they are limited to tube trailers and liquid tankers.(Cardella et al., 2017)(Sdanghi et al., 2019)

Every way of transport has different characteristics that make it suitable for a certain purpose. The idea is to build a delivery infrastructure including more than only one type of route. A lot of proposals concern the use of pipeline, as used for natural gas, and road trucks to reach periphery areas and to cover populated ones. Hydrogen infrastructures today require public and private incentives, that is why right now rails and barges transport are still preferred. Pipeline are still too expensive, but they seem to be a great solution in terms of load capacities and weight limits.(Paper & Limitations, 2019)

1.6.1 Gas transport

Gasification process necessarily entails hydrogen. Gas distribution route includes compression, storage and transport by pipeline and/or tube trailer.

In this form, the element is mostly produced in some operations, like compression, which take place in several points between production plant and ending user. Another method to obtain it is choosing oil refineries and ammonia plants as seller because they are main users of industrial hydrogen.

1.6.1.1 Pipeline

To install pipelines served regions would have to:

- Have high concentrations of industrial hydrogen users

  Demand is significant about hundreds of thousands of kilograms per day
- remain stable for 15-30 years at least

Under these conditions, pipelines may be cheapest form of hydrogen distribution. A complete hydrogen pipeline infrastructure for supplying electric fuel cell vehicles would include both transmission and distribution pipelines to minimise overall costs. Transmission pipelines would be necessary to supply hydrogen over long distances, while distribution pipelines would be necessary for regional supply to end users. The capital cost of a hydrogen transmission pipeline is currently estimated about $1,000,000,000/million for an 8-inch line, including right of way. However, costs vary widely between regions of the country. It is also possible to convert existing natural gas or oil pipelines into hydrogen ones, in the moment within they will become available. This approach is currently challenged by risks of leaks due to obsolete infrastructure, contamination in converted pipelines and technical challenges in assessing risk of embrittlement for an existing pipeline with an unknown service history.

Main difference between hydrogen costs and natural gas pipelines should be cost of material, particularly for larger diameter pipelines, major than >12", where high-pressure hydrogen pipelines would be thicker than natural gas pipelines.

If we might make an accurate cost analysis, we will identify total making costs spread in labour costs as 50 % 20 % material costs and a transportation cost.

The methodology designed to reduce transport costs is its injection into existing natural gas infrastructures. It could seem a jump in the past because between 1800 and 1900 mixtures of hydrogen gas and methane were transported through same pipeline infrastructure. It is not an avant-garde present in the sector already both in Europe and in the United States for coal gasification. Taken from Californian "power-to-gas" project, the idea is to mix up to 50% hydrogen with natural gas. In this methodology, however, volumes could be carried are limited, indeed energy density per unit volume is about 1/3 natural gas one. This ratio means mixing 12% of hydrogen in a volume of natural gas, results will be got in terms of energy are only 4% hydrogen in the mixture. Other problems could be corrosion possibility or other physical damages. Uncertainty about construction methods regard materials and manufacturing techniques that have not been designed to ensure compatibility with hydrogen and post-manufacturing inspection techniques have to be applicated to build constructions. Further problems concern required pressure considerably higher than natural gas one. This would lead to additional compression need followed by a necessary purification to eliminate associated contaminants of natural gas, which could affect both operation and life expectancy of fuel cells.

While new materials are capital costs solution of construction. Consisting mainly of reinforced fiber polymers or high-strength steels, researchers have focused on X52 - X80 strength steel range. It has proven to be good at constant pressure, but still it has same resistance against hydrogen embrittlement. Tests on X-70 type showed costs reduction possibility by up to 30 % for wall thickness needed. Thus, focus was on X-100 or more welds and various high-strength base metal microstructures, which would show an acceptable embrittlement resistance for recognized certification bodies like American Society of Mechanical Engineers (ASME) code B31.12 of the American Society of Mechanical Engineers (ASME). Polymer-reinforced fibre (FRP) piping is not a pioneer in transportation industry, indeed it is already used in oil and gas operations. In 2016 tests led to significant changes in ASME B31.12 Hydrogen Piping and Pipelines Code. Lawer added burst pressure, compatibility with hydrogen environments, tolerance to defects, leakage rates and fatigue resistance tests. FRP are preferred to steels for delivery in coils of about 0.5 miles or even can be produced on site in lengths of 2-3 miles. Typologies reduce joints numbers and thus the release likelihood and decreasing installation costs by at least 25% for pipelines at 130 bar and 1 inch in diameter. Another branch of materials research is focusing on physical predictive models of hydrogen embrittlement to manage integrity of steelmaking equipment in general, along with the new steel development.(US DRIVE, 2017)

To avoid this huge price a possible short-term approach could be:

- FSW: The stir welding differs from conventional arc welding because it melts parts through substantial heating generated by friction of a rotating pin. This type of welding is better for microstructural defects minimizing, often present in mass fusion. Furthermore this welding is faster, energy efficiency holder and these cost-saving properties are more accentuated if they are working on large diameter pipes.
- FRP: Greater diffusion of fiber-reinforced polymer in industrial environments will require verification of performance in relevant environments, but they can cut around 25% the cost of labour. Conventional steels have been accepted in ASME code B31.12 for transmission of high-pressure hydrogen, contrary to modern high-strength steels (eg X100) which are not admitted yet for hydrogen embrittlement problems. It is necessary to evaluate resistance of modern high yield strength steels and to develop new ones reducing material costs, maintaining an acceptable resistance to embrittlement. Conventional models based on expected operating conditions of a pipeline are not sufficient. ASME code B31.12 for pipeline design reports stress-based models, but they aren’t able to predict performances if the history of a conduct is unknown or if the conduct undergoes unexpected solicitations, such as an event of overload or damage to third parties.

The development of models based on deformation could allow development of more accurate integrity management plans for pipelines, along with conversion of current pipelines for hydrogen service. In order to minimize costs, they would be designed at floor load so that they can serve a mature market, but at the same time, under these conditions, they undergo cyclical fluctuations in pressure, which in jargon is called "fatigue" load.(NCE MARITIME CLEANTECH, 2019)

When demand is less or less stable, it is generally met by on-site hydrogen systems, gaseous hydrogen tube trailers or liquid hydrogen trucks.

(US DRIVE, 2017)(Stiller et al., 2010)(Moradi & Groth, 2019)

1.6.1.2 Tube trailer

As previously seen, if we had completed developed market, pipeline would be the solution best suited for huge demand and the need to keep the new fuel price at competitive levels. Today, however, with a growing market, but not yet within everyone's reach, other solutions need to be found. One of these is road transport via tube trailers. They can transport up to 800 kg of hydrogen at a pressure of 250 bar over distances of 320 km.

In Norway there are no limits on the transport of hydrogen, but the size of the trucks is limited. The latter are the best solution for refuelling service stations because in them the hydrogen supply is at 875 bar. Energy required to fill is reduced thank to under pressure transport. These kind of trucks still are affected by leak problem whose detection of the odourless and colourless element makes it worse. It cannot be detected by human senses so authorities decide to add the rule as well as natural gas about adding odorizers. If might be not enough mobile devices could eliminate human error with direct or indirect measures. In addition to these pressures, it is necessary to define methods to control deformations on site that could be cause of noise control emissions and integrity loss.(Mori & Nomura, 2013)

1.6.2. Liquid transport

Another method of hydrogen delivery is liquid transport. Hydrogen at room temperature and atmospheric pressure, however, is in gaseous form, so it is necessary to implement a process of liquefaction. This process is now standardized and known, but at the same time very expensive in terms of energy and capital investment. The liquefaction process consists in cooling hydrogen gas to less than -253°C (-423°F) using liquid nitrogen and a series of compression and expansion phases, processes for which about 35% of the energy content of the hydrogen is consumed. As temperatures are so cold, storage requires strong insulation already in the liquefaction plant and then on trucks to keep liquid until the use points. Once arrived, liquefied litres will be stored in tanks with a vacuum jacket and usually vaporized when they need to fill cars. For hydrogen vehicle service stations, pressure is increased and then vaporised before being delivered to storage tank on application board. Conversion of liquid hydrogen into gas is done by passing liquid inside a room air bath or hot water vaporizer. Many have posed the problem of the most disparate environmental conditions for heat exchangers used in the latter vaporization process mentioned above, but so far research has come to devices that can ensure desired flow rates in the worst environmental conditions seasonal.

This type of distribution is the one most used nowadays because it is more competitive and can be moderated on demand. If the market requires a transport of more than 500 kg/day, tanker transport is preferable to gaseous road transport. This choice is due to a typical tanker truck can transport 5000 kg while a pressurized truck has an order of magnitude 5 times smaller. Typical steel tube gas trailer goes for a maximum of 1000 kg, without kilometres limitation. Existing liquefaction plants have a wide variety of production sizes ranging from 5,000 to 70,000 kg of hydrogen per day. It is clear liquefaction process has long since penetrated market, but now the challenge is applying it to the road distribution. Increasing hydrogen use as a fuel would justify the construction of new liquefaction plants with a larger scale factor or a new liquefaction technology such as magnetic or acoustic ones that can reduce future liquefaction costs.

The liquid transport takes place, therefore, on tanker trucks with a capacity ranging from 4000 kg to 5000 kg that move carrying the element for a maximum of 965.6 km (600 miles). However, transport is inhibited by problems such as:

- Cost of liquid hydrogen
- Losses due to boil-off
- Setback distances associated with liquid hydrogen storage at the point of use.
  (Moradi & Groth, 2019)(Chiaramonti et al., 2005)

1.6.2.1 Rail, ship, barges

In future supply chain, it is supposed to use also the rail, ships and bargues paths. These types of transport are already used to carry other materials, as well as them hydrogen will be delivered in cryogenic tanks incorporated in them. Cryogenic transports are built to carry up to 4000 kg of liquid hydrogen at almost atmospheric pressure, but, at the time of delivery during discharge phase, it is expected to boil. To optimize the delivery it is common between companies to:

- recovered hydrogen lost in discharging phase by carrying out a cost-benefit study in compressing it.
- Transport to multiple sites with a single tanker because in the costs must also add the distance from the source, the hours of the driver and losses.

To avoid losses has been developed long-distance vector method called LOHC. It is useful when we need to carry high quantity of element. However, it involves the resolution of numerous technical requirements such as the high pressures required for hydrogenation, high temperatures and catalyst poisoning required for dehydrogenation, product formation and reversibility. Detail which add some costs is the process of carrier hydrogenation/dehydrogenation about required capacity, quantity and type of catalyst.

(Pratt & Klebanoff, 2016)(Mori & Nomura, 2013)(US DRIVE, 2017)

1.6.3. Carrier transport

A new method to transport hydrogen for longer distances is carrier one. It may be the right solution to liquid boiling in tankers and for low density of gaseous tube trailers. Those are materials where hydrogen is not a free molecule, but it is bound with them, and they can transport, supply and storage it in any chemical state.

Researchers underline for their characteristics:

- metal hydrides
- chemical hydrides
- absorption materials
- liquid hydrocarbons

(Chiaramonti et al., 2005)

1.3.3.1 Metal hydrides

Metal hydridesfollow the van't Hoff equation, essentially hydrogenated alloys. The most promising as carrier are binary magnesium alloys and multinar alloys.

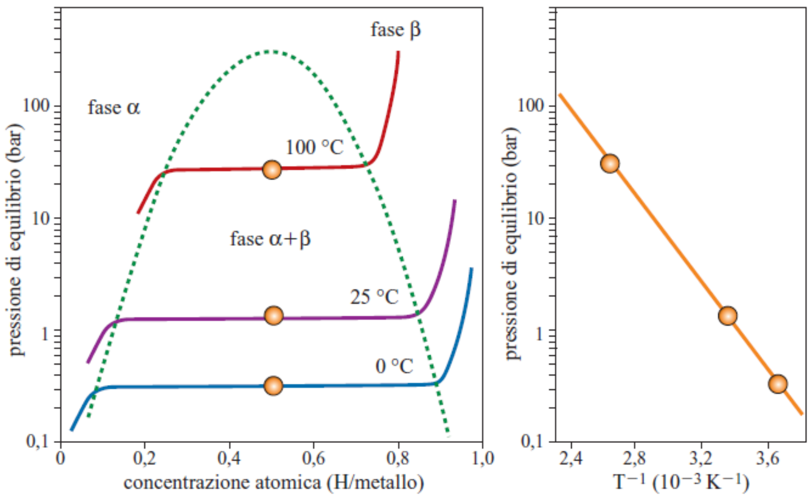


Figure 9: phases diagram and van't Hoff function for $LaNi_5$(AA.VV., 2003)

Hydrogenation goes through three phases. They will be faster if it occurs with porous and powdered metals.

1. Alpha phase: In this phase metal begins to change to a solid solution as the hydrogen molecule breaks down on its surface
2. Alpha-beta phase: intermediate phase in which pressure is constant up to 90% in solution of hydrogen concentration
3. Beta phase: The pressure rises dramatically and it is a hydride

For the transport of hydrogen is a recommended solution because, while the formation of hydride is an exothermic process, release is endothermic and occurs by lowering the pressure.

(Chiaramonti et al., 2005)(AA.VV., 2003)

1.3.3.2 Chemical hydrides

Chemical hydrides are usually delivered to fuel station with on-site production and once dehydrogenated, they must be sent to a plant to be hydrogenated again. This returning in factory when product is out of stock makes the system more complex and, therefore, more expensive. In the same time, those systems are handled and carriers are good solutions for massive local storage and seasonal periods countries, that have some difficulties with surplus of hydroelectric power during summer because they don't manage to conserve it for winter. In this kind of transport, the infrastructures are already built and their technologies are commercial exploitable. Among most important, we find Alkaline hydrides, Methanol, Ammonia, Methylcyclohexane, Sodium and Borohydride. The first are used for their high ratio of hydrogen inside, it's enough to think about lithium hydride, transported in the form of a suspension in a light mineral oil named "hydride slurry" to protect it from humidity, that has 12% by weight of H2. But, as said above, recycling process adds some costs.

$$LiH \rightarrow H_2O = Li(OH) \rightarrow H_2$$

Better than lithium is Methanol (CH3OH). It can reach 18.75% by weight of hydrogen with two reactions:

1. Catalytic decomposition of methanol
   One molecule of CO and two of H2 can be obtained.
2. Water gas shift reaction
   With CO and water another molecule of H2 is obtained.
   (AA.VV., 2003)

Methanol is a component strongly used in industry as a product of oil or natural gas, but to make it "green" you need to introduce into production process a carbon neutral from biomass or green hydrogen. The main methanol advantage is C/H ratio of 1:3, which makes it best liquid fuel. In addition, its density is equal to biodiesel one, 780 kg/m3. Methanol is usually transported in tankers whose price varies in distance and size. Tanks have no insulation for cooling, such as those for transporting diesel, highly flammable hydrocarbons at atmospheric pressure and they are oil tanks twice large when you are considering a standard energy content. (Cárdenas Barrañon, 2006)

More countries are thinking about a "Methanol economy" for the double energy density, common transports and for production simplicity. It is by natural gas reforming product, or also by oxidation partial hydrocarbons, for gasification of hard coal, of peat and lignite, for gasification of residues heavy or coke from refining oil and for biomass gasification. In all of them it is industrially obtained by synthesis gas reaction (CO and H2).

To reduce energy costs associated with transportation and hydrogen storage, some studies propose an "Economics SLH" (Synthetic Liquid Hydrocarbon), which provides for the synthesis of hydrocarbons from CO2 and use of H2, obtained by electrolysis from renewable sources. Of recently methanol has been proposed as a hydrogen carrier because it is economically advantage if there are large capacities like 5000 ton/day.

(NCE MARITIME CLEANTECH, 2019)

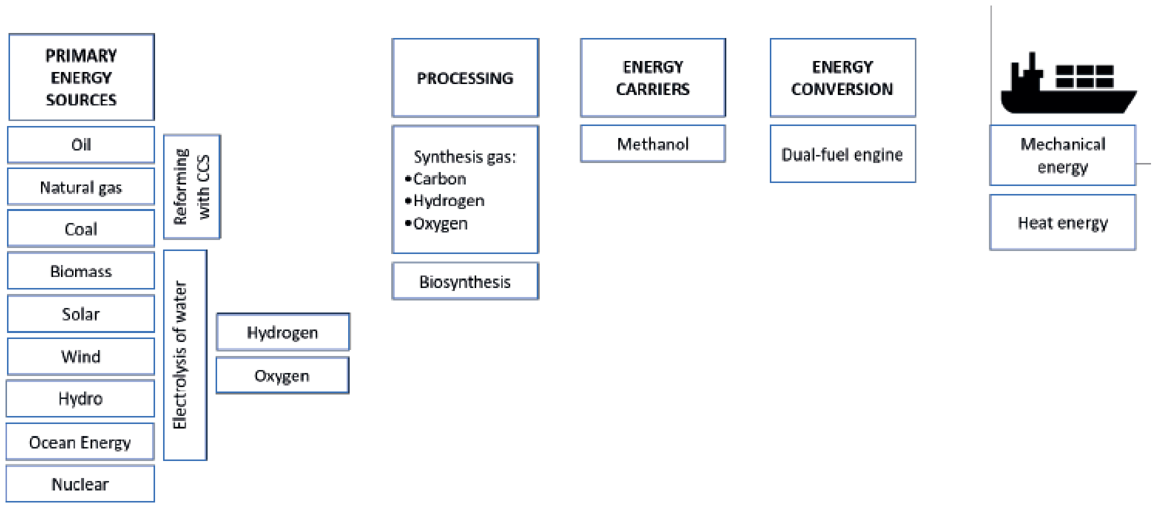


Figure 10: Methanol supply chain(NCE MARITIME CLEANTECH, 2019)

As shown in the previous picture, plans for methanol are made for long transportation like it could be sea one. Ships will carry around a big quantity of methanol in atmospheric conditions. Japan is already planning a crossing-route to reach American costs.

Sometimes safety is the dominant factor for choosing, as in the case of Ammonia: it is toxic and the lethal dose equal to 5000 ppm limits its use. Its properties are perfect to carry hydrogen inside itself, indeed, it is generated under high temperature and pressure reaction between H2 and N2. Convenience of Haber-Bosh process brings Ammonia to be blended with gasoline and biofuels in up to 70% quantity. Still, Ammonia is the best carrier of hydrogen as:

- it has already been in the hydrogen industry for years, in fact its industry uses half of the global production of hydrogen
- it contains 18% hydrogen by volume
- with its density of 653,1 kg/m3 under atmospheric conditions contains more hydrogen than one m3 of liquid hydrogen
- energy density 4.3 KWh/l

Ammonia is transported by truck, train or ship and limits are set on the basis of 36 tonnes weight. Mobile tanks therefore vary from 13 000 litres to 57 000 litres in capacity, but the most widely used have a quantity of ammonia inside of 30000/45000 litres. In rail transport, 70% of the pressure tankers of class DOT 105 or

112 are used. They have a capacity of 130 600 litres of anhydrous ammonia. For long journeys, sea transport is usually used on fully refrigerated vessels with a capacity of 15000 to 85000 m3 of gas or on LPG carriers. These have a capacity of 5000 m3 and differ from previous ones because they are partially refrigerated and lighter. it is also transported in pipes, it has an H2 content twice as much as liquid hydrogen and its use appears convenient even if the decomposition is endothermic, with 1kg of Ammonia you can provide H2 for 10 W FC for 40 hours.

(NCE MARITIME CLEANTECH, 2019)

While in Ammonia we have no waste products, in the use of methylcyclohexane (C_7H_{14}) the hydrogen is released in the dehydrogenation process of it from toluene at 500 ° C with a consumption of 20% energy contained in the obtained hydrogen. Also using sodium borohydride, reaction gives borax ($NaBO_2$) that must be turned back, but it is a really good solutions because in an aqueous solution at 50% by weight of $NaBH_4$ it provides, with a ruthenium catalyst, H2 with a ratio energy similar in volume to petrol. The negative aspects that bring it out of the market, are the low quantity of storage and metal sodium and hydrogen from natural gas costs.(Chiaramonti et al., 2005)

1.6.3.3 Absorption materials

To have advantages on the carrier material density and on the method of storage, reference is made to absorbent materials as they have a surface area and high porosity which allow a great dispersion. Best among all are carbonaceous materials, such as activated carbon (AC, Activated Carbon), zeolites, alumina (Al_2O_3) and silica (SiO_2).Among pores dimensions, micropores show better behaviour than medium and large ones, so some studies were focused on nanostructures such as fullerenes, single-walled and multiple-walled nanotubes, carbon graphite nanofibers and Metal-Organic Frameworks (MOF).They examined shaping pores at nanometeric size to take technical benefits from it.

(Chiaramonti et al., 2005)

1.7 Fuel stations

To analyse various issues regarding refilling of hydrogen cars we must know how is built a hydrogen fuel station, what kinds of machines work inside and specific vulnerabilities.

Fist diversification needs to be done is the typologies of Hydrogen procurement. We can recognize two different types:

1. *Storage*

   The hydrogen is made elsewhere, it is brought and stocked in the stations for local delivery.
2. *Production on-site and Storage*

The hydrogen is made directly in the station, which is produced and stored in the same place. It has dedicated a distribution zone to deliver the fuel giving it to customer hydrogen vehicle.

Combination of elements

Sometimes they use to build stations that are a combination of previous ones to be sure, in case of production decrease, that they can cover the demand of hydrogen fuel.

Today, as demonstrated in the table n°6 ,no predominance exists yet between the two of them. Germany and UK have completely balance with 11 and 2 spots, while in Norway and suspicious in Italy with 3 against 0 delivering stations, "on-site" predominates on the delivering.

Table 6: type of stations in UE countries*(Alazemi & Andrews, 2015)*

Station type	Country																
	Germany	Norway	UK	Italy	Denmark	Greece	Sweden	Iceland	France	Belgium	Czech Republic	The Nether-lands	Luxemburg	Portugal	Spain	Austria	Switzer-land	Total
On-site hydrogen production	11	2	2	3	3	1	1	1	2	2	1	1	0	0	1	0	0	31
Stations with hydrogen delivery	11	1	2	0	0	0	1	0	1	0	0	1	1	2	0	2	0	22
Total	22	3	4	3	3	1	2	1	3	2	1	2	1	2	1	2	0	53

To be true this table is updated on the 2015, so we should remember that until 2020 in Norway they sponsor the projects "NorWays"for spreading HRS.

1.4.1 Storage stations

First type of stations consist only storage sites where customer can stock up for his vehicle. The hydrogen is produced by an industrial facility, most of the times petrochemical, and transported by ship, road or rail tanker, or by pipeline. The decision regarding which type of transport is taken based on evaluations of distance and parameters seen in previous paragraphs. To cover short distances, compressed hydrogen gas transportation is preferred and may be done by truck, rail or short pipelines using containers. They are resistant to hydrogen embrittlement and certified by authorised authorities. For longer routes, they usually choose liquid transportation by road, rail or ship tanker with cryogenic storages (about 20K to keep the hydrogen liquid) or compressed gaseous hydrogen because it's so important to underline pipeline delivery could be long as one hundred and more kilometres.

Station structure is composed by nine main elements:

- *Energy sources*
- *Control system*

It manages all transfers and storage of hydrogen. overall safety is monitored by checking pneumatic valves, pumps, sensors and some others system devices.

- *Receiving port*

  It is used to receive hydrogen in all its form, like compressed or liquid, from a tanker or pipeline.

- *Liquid hydrogen reservoir*

  It's necessary if the delivery is liquid.

- *Heat exchangers*.

  Before compressing, hydrogen is usually transformed from liquid to gas by overheating system that is composed by valves, pipes, gauges and pressure relief devices.

- *Low-pressure hydrogen storage*

  Its need is to stock up hydrogen gas after the phase passage.

- *Compressor or air booster*

  To reduce gas volume bringing it up to 850 bar and to be able to stock it between 350 bar to 700 bar.

- *high-pressure hydrogen storage tanks,*

  Typically around 700 bar, they are better than several types because they allow customers to refuel their car tanks in few minutes as the gasoline refilling.

- *Dispensers*

  They are used to transfer the gas from high pressure tanks to the car ones.

  (Alazemi & Andrews, 2015)

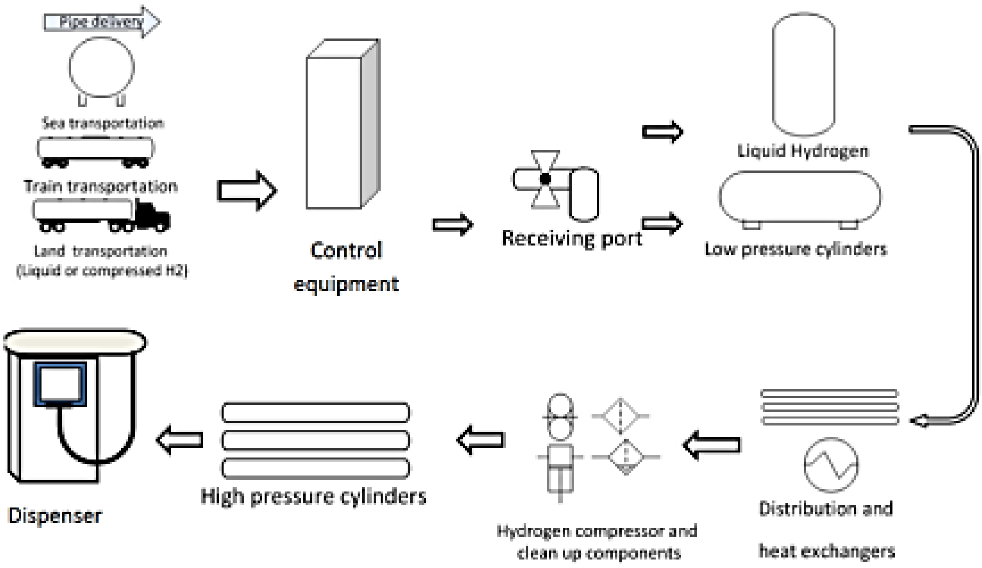


Figure 11:Storage station structure(Alazemi & Andrews, 2015)

1.7.2 Production and storage

The second type of hydrogen fuel station is different because the element is produced on -site. For that aspect more than precedence HFS, the structure presents the production process, in which hydrogen is made as in a petrochemical industry.

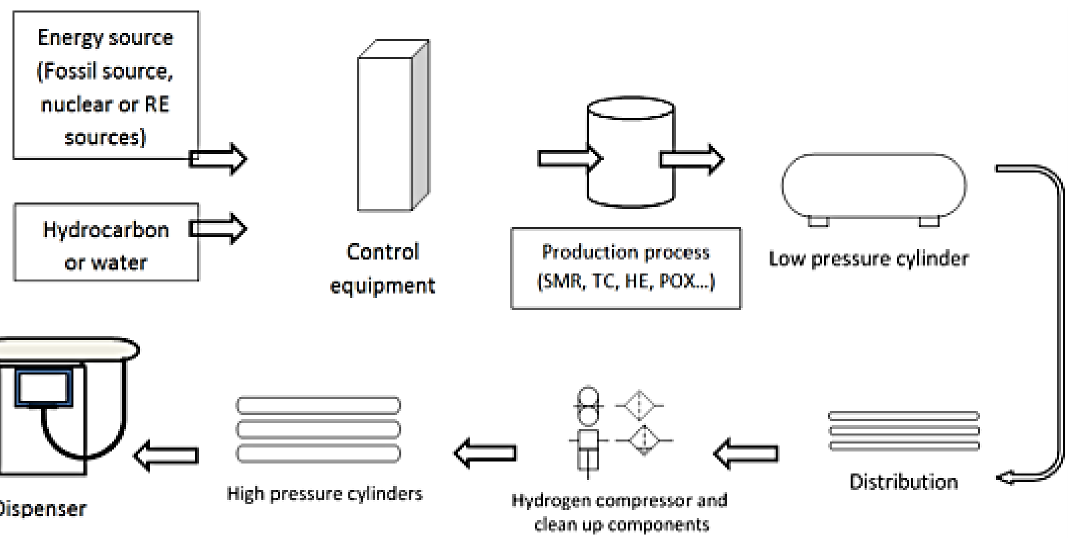


Figure 12: Production and storage station structure(Alazemi & Andrews, 2015)

Further details about production are listed below and they are divided based on resource from which hydrogen is extracted.

Hydrogen, indeed, could be get from fossil fuel source too, with:

- *Steam methane reforming (SMR)*

- *Thermo cracking (TC)*
- *Partial oxidation (POX)*
- *Coal gasification (CG)*

Main processes for producing hydrogen from biomass are:

- *Biochemical*
- *Thermochemical (via gasification)*

It is common to obtain hydrogen dissociating water by:

- *Electrolysis (HE)*
- *Photoelectrolysis (PHE)*
- *Photolysis (also called photoelectrochemical or photocatalytic water splitting)*
- *Water thermolysis (WT) (also called thermochemical water splitting)*
- *Photobiological processes.*

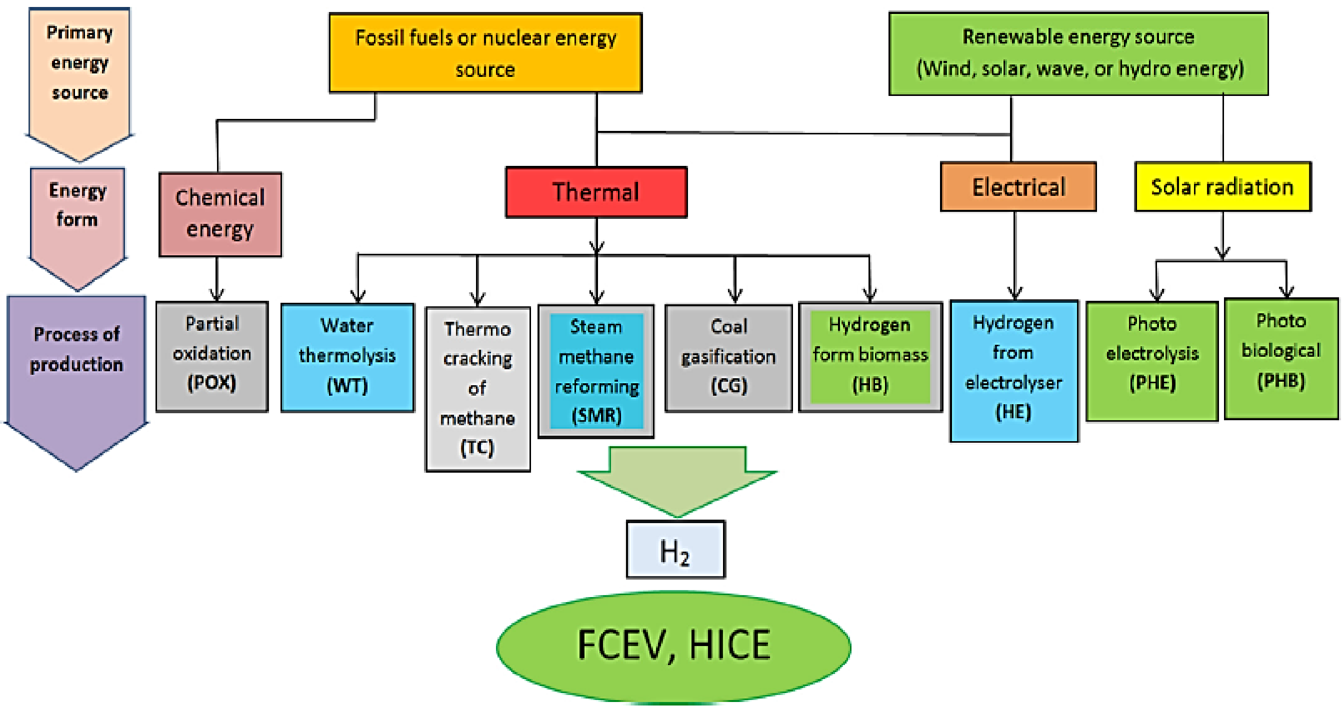


Figure 13: How to get hydrogen(Alazemi & Andrews, 2015)

Therefore a lot of now existing methods could be utilized to achieve hydrogen, but the only ones with zero greenhouse gas emission are renewable energy sources or nuclear power methods. In the Tables n° 6 data are relative to 2015 and show how hydrogen technologies have grown rapidly in last few years. Energy expenditure is divided in three categories depending on the amount of emission generated by production. As we can see, Germany is the country with the most elevated number of hydrogen dispensers, but it is still employing high emission methods for most of them. Actually only 5 on 22 are powered by renewable energies.(Alazemi & Andrews, 2015)

Table 7: Gas emission station types*(Alazemi & Andrews, 2015)*

Station type	Country																	
	Germany	Norway	UK	Italy	Denmark	Greece	Sweden	Iceland	France	Belgium	Czech Republic	The Netherlands	Luxemburg	Portugal	Spain	Austria	Switzerland	Total
RN energy	5	2	2	1	2	1	1	1	0	0	0	0	0	0	0	0	0	15
Low to medium GH emission	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High GH emission	17	1	2	2	1	0	1	0	3	2	1	2	1	2	1	2	0	38
Total	22	3	4	3	3	1	2	1	3	2	1	2	1	2	1	2	0	53

All processes require energy inputs and in Europe we are working to produce hydrogen completely "green "with stations powered only with renewable energies as solar, wind turbine or on-site made energy. Despite the considerable effort, common for delivering in stations is reling on grid energy sources. Out of Europe, preference about stations power supply seems to be different. In Asia most of production is made by reforming and then it is followed by delivery and not identified supplies. Crossing the ocean, in America we can see two different situations: North America with balance between not identified and on- site electrolyzer production and a bit less delivering, and South America with only a small presence of eletrolyzing sites. Probably detachment is caused by the political difference between the two parts.

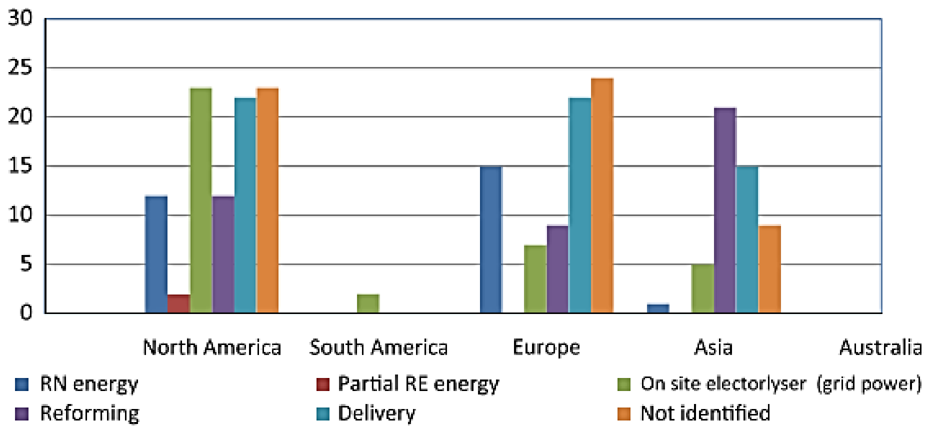


Figure 14: Production powering types(Alazemi & Andrews, 2015)

Daily hydrogen production rate and station storage capacity determine the number of FCEVs that can be served.

(Alazemi & Andrews, 2015)

Chapter 2

Problem statement

As showed by the previous chapter, experts' opinions on the best transportation route are still in contradiction with each other and the presence of a not yet developed hydrogen market does not allow a clear definition of prices. On the other side, the accident happened in Kjørbo in June caused almost a completely selling stop of hydrogen in Norway. The incident caused the closure of every Uno-X hydrogen station in the whole country, delaying the development of the new economy and making those who believed in the new fuel lose investment.

In recent increasing period, shutdowns mean:

- Loss of money
- Investment reduction
- Delay in development of infostructures
- Growth restriction of hydrogen car production
- Changing in public opinion

Listed factors are closely linked and all together can destroy the plan for the "green economy". It is enough to imagine if after the event people from Sandvika, region where is located the exploded fuel station, look at a tank as a bomb, or an investor who sees all his money turned into smoke. Sometimes public opinion could be a serious obstacle for growing something up and, of course, investors are fundamental to develop a net structured and stable. In Norway some stations were closed for missing of money by European companies that stopped inducements. Only 15 kilometres far from accidented station, in Sadvika as well, it's built another HRS. Located in Høvik, this station is part of Hyop circuit and it terminated its job after few months of work because of Europe investors did not give more money to keep it running. As soon as lot of station owners closed, most of car brands stopped the hydrogen car production.

A lot of parties are interested on the topic:

- Investor
- Car brands
- Consumer
- Population

All of them has some reasons to be interested. Hydrogen is a new market, full of economical risks, but in the same time full of possibilities. Car brands and investors are planning a strategy to use it and get some results from that. Population and consumer, in the other hand, are involved because every new technology, before being known, makes people curious and afraid. In the same time, a lot of people, in particular new generations are growing up with a different mind. Pollution, nature respect and for the environment that surrounds us, ozone hole and global warming are now rooted in the culture of today's young Europeans. Fortunately, awareness and sponsorship of these issues is raising people's awareness and, why not, also incentives from member states on ecological options are changing the average citizen's approach to the issue.

Following in Europe's wake, the aim of this work is to figure out which one is the best way concerning safety and cost for delivering of two stations in Sandvika fifteen kilometres far away from each other. Analysis of the problem will be taken into account this region and Oslo municipality where supply chain will describe which one is the most convenient solution by road routes. Found it, it will be compared if it is better to have a station delivered by road truck or an electrolyzer equipped station analysing differences round costs and safety.
By adopting a scientific approach to solve the problem, in this work results will be extrapolated on evaluations about selected zone set by the author. Touching parameters like weather conditions, population, number of hydrogen cars in 2050, statistic, estimated and literature data will be collected to re-build as close as possible the reality. Obtained all needed data, inserting them in Safeti DNV-GL program, it will be possible to figure out which one/ones will be the better combination/s to get all of people next to the chosen street safe. After this step, where32 cases (30 about combinations of parameters and 2 about the two considered stations) will be simulated, to understand which one is or which ones are the better option/s to have an efficient and economical delivery, simulation will run again on the 30 cases with Exstendensim v.10. This time the result will be a view on the number of trucks will be necessary to fill up the two stations every time they need to. In the sequent pages mean about the cost of transportation will be made considering all logical factors such as employee, distance and fuel costs and in the end a possibility which be suitable with Sandvika case will be found.

Finally, whit both groups of results, we will have an evidence about which one or how many possibilities in this condition we could choose and then we will compare that with the on-site exploded station.

Chapter 3

Methodology

Theorical studies

To optimize cost and at the same time safety aspects, the overall risk should be assessed. This process includes:

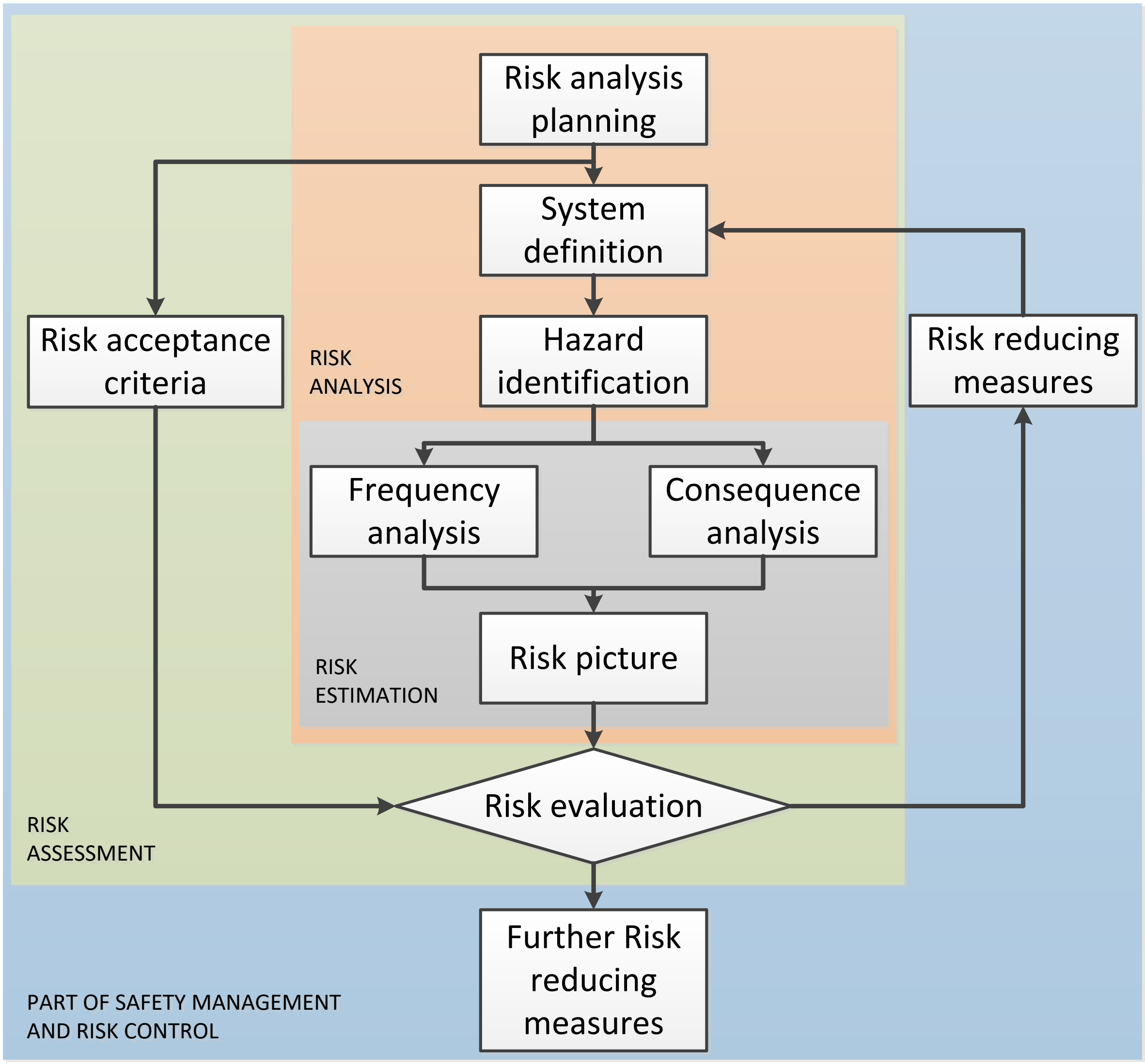


Figure 15: standard norsok z-013

1. System definition

   First of all to start a risk evaluation we need to find components that could be reason of the accident. Remembering the parts mentioned above, electrolyzer with its compressor, storage units and hydrogen refuelling station unit especially during loading seem to be pieces to take into account during report. Truth is that in literature is not present yet a big saved data collection about hydrogen station for obvious reason. Contrary its elements are already known because of the using time of hydrogen. A hazard is an internal characteristic of the object/system we are considering which has potential to cause damage. It can range from property damage to minor injuries and health problems to injuries that can lead to disability, illness or even death. Useful for identification is to remember near missing accidents and incidents occurred in the past. Missing old data, we should study on site:

- good and bad practices of your collaborators;
- safe and dangerous (maintenance-free) machinery and equipment;
- dangerous places;
- unstable or soft ground;
- holes and steep slopes of the ground;
- deficiencies or structural damage;
- access points for outsiders;
- risk exposure (employees, suppliers, outside workers, visitors, your family members);
- chemicals and the ways in which they are stored and handled;
- machines and their movement.

Hazards, then, could be grouped in categories to be analysed:

- human factor: lack of physical or mental capacity, lack of knowledge or skills, lack of skills, incorrect attitude or behaviour.
- Equipment: machinery, tools, software and hardware, tables or chairs.
- environment: light, noise, climate, temperature, vibration, air quality or dust.
- product: hazardous substances, heavy loads and sharp or hot objects.
- organisation: workplace layout, tasks, working hours, breaks, shifts, training, work systems, communication, teamwork, contact with visitors, social support or autonomy
  (European Agency for Safety and Health at Work).

2. Hazards identification

   Hazard developing and understanding are subjects belonging to this phase where we can also provide information to assess. Usually this step is managed by qualitative methods which take into account on the components, habits, places or steps underlined before in the identification. Appendix B in EN ISO 12100 speaks about:

- PHA

  Preliminar hazard analysis is focused on every life phase of the delineated system/components. This inductive method shows dangerous situations or events could bring you to the final event.
- WHAT-IF

  Used usually for simple application, reader has to answer to the question:” What could happen if….?”. The proposition “if” is the beginning of the condition during design or using phase. For harder application a check list is added to not forget anything necessary.
- FMEA

  For every component every way to fault is analysed.
- BREAKDOWN SIMULATION IN COMAND SYSEMS

  Technology and complexity are the criteria for this method and usually to demonstrate the theorical results are used practical evidences or hardware and software that simulate the behaviour or the commands.
- MOSAR

  Complex evaluation hazard method based on the idea to split the system in pieces where hazards are studied by a prospectus.
- DELPHI

  Expert limited, it is based on anonym questions whose agreed answer is known step by step.
- HAZOP
- SIX SIGMA

  The industry is addressed to continuing getting better. This is taked as a philosophy sometime, but it is guideline for companies.

In our case study Hazop will be chosen and explained below.

3. Frequency analysis

   Frequency analysis is an important step and often a source of error in risk analysis. In our case the Fault tree analysis (FTA) method is used, where the problematic events are retraced backwards until the primary causes of the problem occurred.
4. Consequence analysis and risk picture

   In order to outline consequences and have an image of the risk, in our case, a software will be used from which a FN curve will be obtained. The results will then be evaluated by comparing them to a predetermined threshold of tolerable risk.

5. Risk evaluation

Predefined criteria are utilized to compare estimated risk levels and to define their importance. In this phase we decide whether it is necessary to address the hazard as well as the most appropriate strategies and methods of hazard treatment.

Its main aim is prevention and accidents mitigation in potentially hazardous facilities, but for the writing work it is supposed to be the basis of the choice between options which are comparable in terms of costs. Methodologies will be used for the study of the risks on the transport route and in the risks on site in the stations. You have chosen Hazop and Fault tree analysis to identify respectively top events that must to be studied and their probabilities. Sometimes to prioritize actions that it is necessary to mitigate, HAZOP is combined with other techniques. For that reason, FTA is used to reduce the uncertainty since it is quantitative techniques. Blending of them it can identify potential causes or ways of failure and assess quantitatively the probability of development of the accident. As far as probability of transport accidents is concerned, accident probability on the road in Norway for heavy transport will also have to be added to the failure probability of the tank allocated on vehicles.

3.1 Hazop

HAZOP is a qualitative technique that carries out a structured analysis of the process and allows identifying deviations that may take place with regard to the intended functioning, as well as their causes and consequences. Usually it is a technique used by multidisciplinary working groups because it is good to analyze systems from every point of view. Often areas and operations are defined by dividing process in influencing variables by sector. For reasons of time, lack of a team in the thesis project and the complex structure of the problem on road, in this work I will limit to show the structure of a hydrogen station similar to Kjørbo one with its possible deviations. Whenever a detailed study of the process and used substances, or in this case the station structure, is finished, method involves a review of scientific publications and literature to build an historical analysis of accidents quite similar to the case study identifying risks and causes by Hazop. After those sessions, it is possible to enumerate potential fault causes and consequences for every deviation from the design. The method is based on guide words that are selected and can be modified and added as needed.

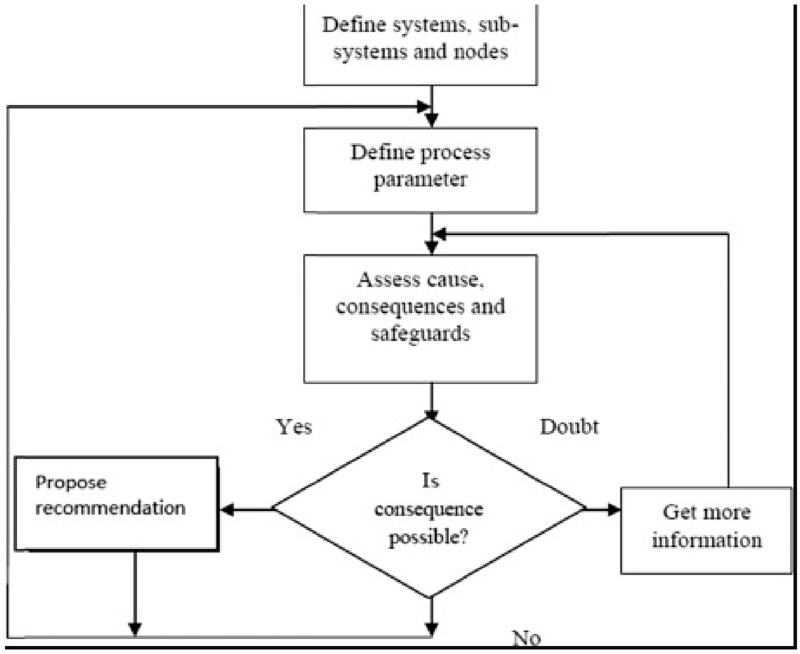


Figure 16: Hazop steps (DrEduardo Calixto, in Gas and Oil Reliability Engineering (Second Edition), 2016)

The main guide words for industrial processes or chemical structures, such as the concerned station, could be:

- NO
  It describes a situation of absence of the selected parameter
- LESS
  It describes a situation of quantitative reduction of the selected parameter
- MORE
  It describes a situation of quantitative increasing of the selected parameter
- OTHER
  It describes a situation of partial or total replacement of the selected parameter
- INVERSE
  It describes a situation of opposite function to design intention of the selected parameter
- PART OF
  It describes a situation of only a part of what should happen occurs
- IN ADDITON
  It describes a situation of quantitative increase in production of the selected parameter

Selected the parts, the guide words and the parameters, now it is enough to fill in the table. Usually it is built with in line:

Cause

Consequence

Protection

Comment

Top event

and column guide words and parameter to which the study is attributed.

3.2 Fault tree analysis method

To quantify probability of catastrophic loss and breakage identified by hazop, it is necessary to use a quantitative method and not a qualitative one like the one mentioned above. To do this, it was decided to use the Fault tree Analysis method. Structure of the tree is defined by a progressive process that investigates root causes of the event. Each branch is developed in such a way as to go back to the primary cause and then calculate the probability of the top event by associating each causing event with its own probability and adding or multiplying them according to whether the branch has an OR or AND door respectively.

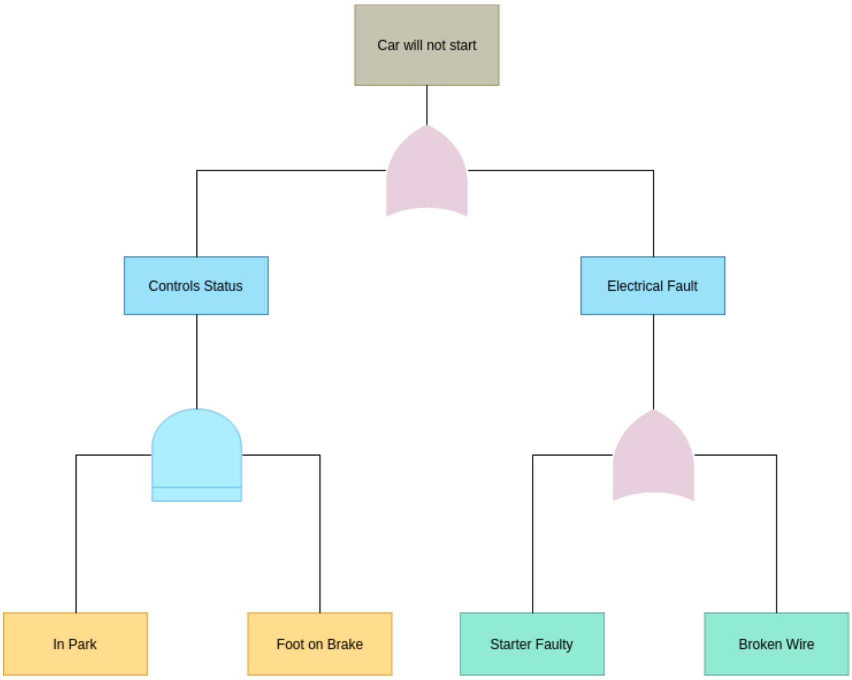


Figure 17: *Fta structure exemple* ("Fault Tree Analysis," n.d.)

3.3 Risk analysis method

To elaborate a risk analysis usually is chosen a method to calculate damage amount for every scenario could be caused by the top event. In this case, event tree analysis or the bow-tie analysis are the best solutions to consider every possible consequence. Both of them are based on a built graph where branches bring you to discover probability events. Event tree analysis is a top-down technique more often used after the fault tree one where with logical connections engineer can show risky paths. Success and failure of safety devices installed in the considered system are drawn by a Boolean logic graph. It starts with a single initiating event and lays a path for giving out probabilities of the outcomes and for identifying all consequences. In this report I will utilise Safeti software to be more accurate. It is a software sold by DNV-GL which helps user in QRA (Quantitative risk assessment). Specified for onshore processes, chemical and petrochemical facilities or analysis of chemical transport risk, with Safeti I built every case inserting probabilities, density, map, chemical elements, traffic on the road and every detail I need to model my specific case. Safeti analyses complex consequences from accident scenarios, taking account of local population and weather conditions, to quantify associated risks with the release of hazardous chemicals. It also underlines major risk contributors allowing you to take action to mitigate those aspects. Safeti has been chosen by many companies to design plants in a safe way thanks to decision support tool for strategic planning, facility siting and layout. It is not the only one, indeed software includes also tools available for assessing chemical and petrochemical process plant risks and shows them with risk contours, FN curves and rankings of risk contributors.

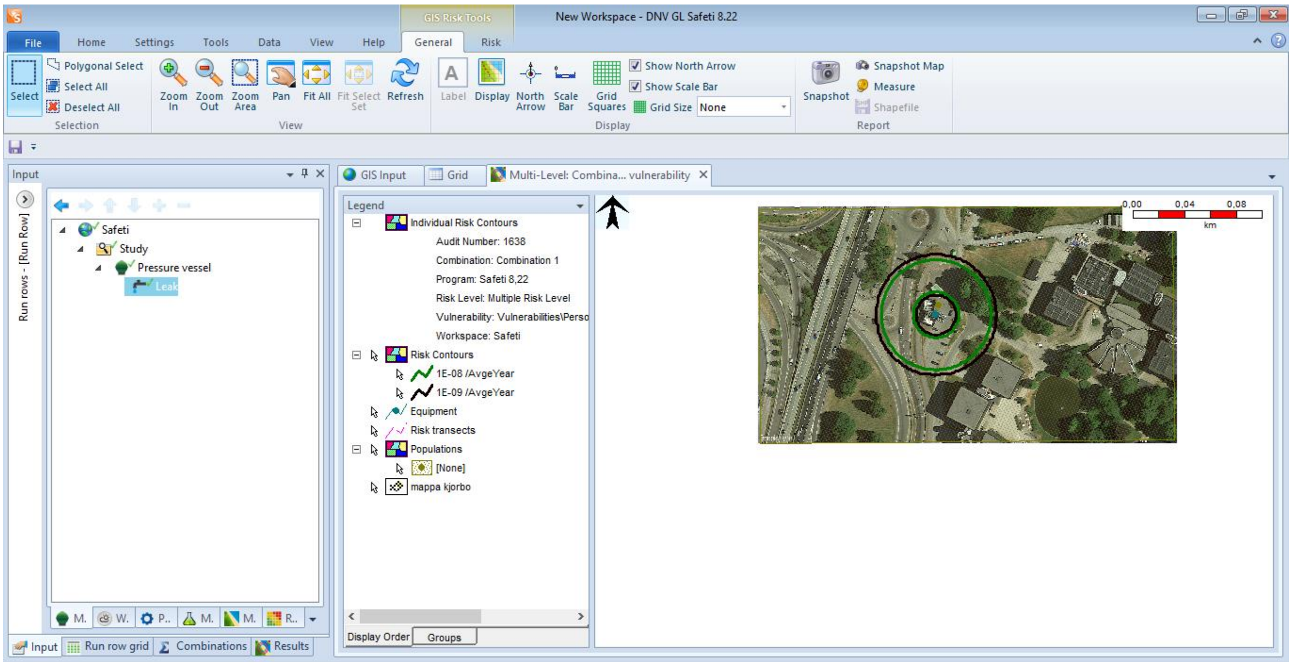


Figure 18: Safeti software

On the left the program presents a structuring sector where you can build your problem selecting every aspect showed down:

Model

Where your plant shows up

Weather

Section dedicated to select the intensity and the direction of the wind, temperature, humidity…

Parameter

General parameters valid for every run row

Material

Chemical materials or solution of them present in the system

Map

Section to insert map and scale with original dimensions, characteristics, buildings…

Risk

Important to model exposure, vulnerabilities…

Afterward having the model, you can run it and discover what could happen and for every range of probability the intensity of explosion or dispersion with risk contours and the FN curve to analyse the level of risk.

3.4 Cost analysis method

For each phase of the elaboration process to have a proper optimization we need to know the cost. In next chapters I will report some data about the amount of hydrogen fuel in different countries. The reason why it is not fixed yet is actually different costs of hydrogen processes between nations, costs of workers and progression of technologies presents in them. To obtain an accurate optimization on the transport of hydrogen considering all the factors I will use Exstendsim 10.

As you can read in the "Help", the program is a powerful tool to simulate logical links in simple or complex systems. It could make multi-purpose simulations with graphs to concentrate a complete framework of them, create a custom front and interfaces to show whenever the user wants the state of art and write all the data in some libraries adding them to the ones already present in it for every kind of event you would to model . Main modelling methodologies are the continuous process modelling, where the variables describing the program are fixed point by point and change with the passage of seconds, discrete event models, these types of events are characterised by a process punctuated by individual events. In the time between one event and the next nothing happens and often involve the appearance of queues. Third type is a mix of the two of them, as the first it describes the flows of stuff rather than items while as the second because it recalculates rates and values when an event occurs.

Factor	Continuous Process	Discrete Event	Discrete Rate
What is modeled	Generic "stuff", represented by values that change when the model changes state.	Distinct and identifiable entities ("items" or "things") that can be individually tracked.	Streams of homogeneous "stuff". Or bulk or high speed flows of otherwise distinct entities where sorting or separating is neither necessary nor wanted.
What causes a change in state	A time change	An event	An event
Time steps (see "How time is treated in the main modeling methodologies" on page 10)	Interval between time steps is constant. Model recalculations are sequential and time-dependent.	Interval between events is dependent on when events occur. Model only recalculates when events occur.	Interval between events is dependent on when events occur. Model only recalculates when events occur.

Figure 19:Models table (Help)

In order to develop in a strategy mode companies could simulate parts of them making some modifications before the investment and see a prospection in years of the cost amortization and the earnings. Exstendsim is not only a describer of real problems, but it tests various hypothesis and alternatives to find the best solution. Its principal characteristic is the possibility to improve the model starting from a simple one. This stepwise refinement allows the user to understand complex systems and to predict the developments. It is also useful to identify problem areas and potential improvements.

System operations are recreated with a mathematical model to solve any real problems or to explore something is not clear yet in the existing or simulating process. The parameters insert in the model are completely studied from the reality or from some others type of estimations and they can be direct or output parameters, the latter are calculated with operations on the input parameters.

The model I made to draw the situation in every case I would to study has this form.

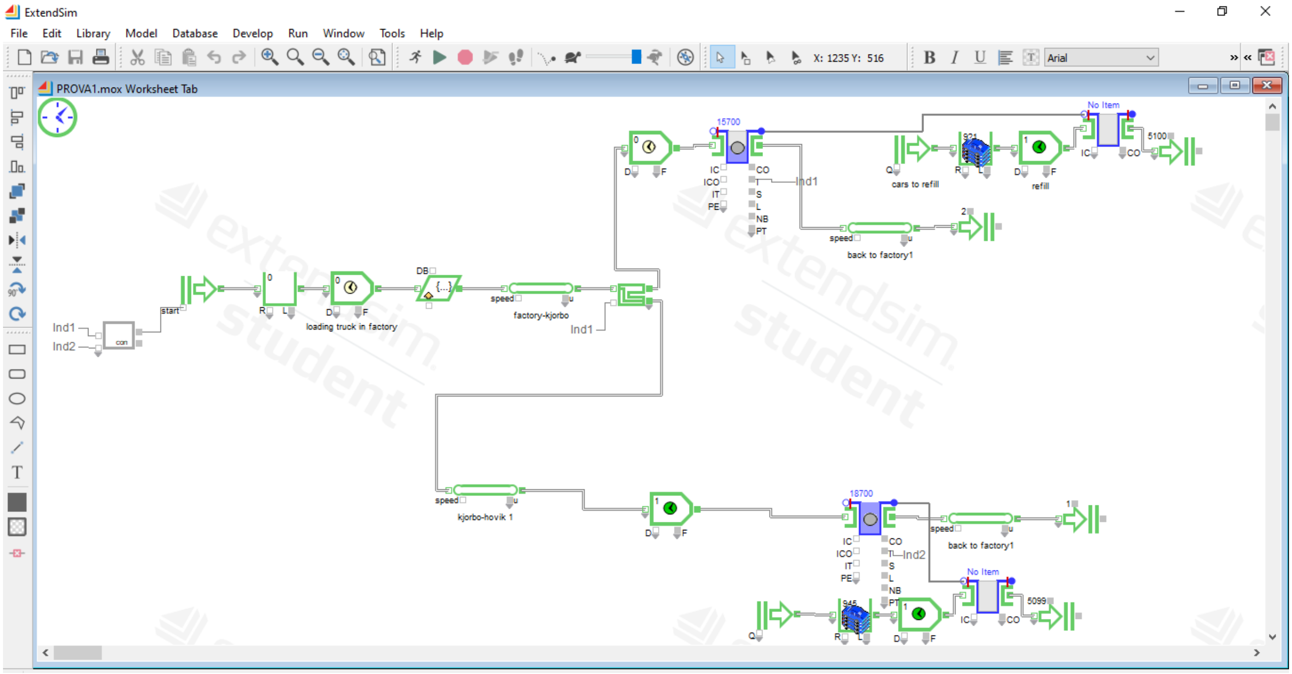


Figure 20:Exstendsim software

Starting the description on the left we will find:

1. “Max and min" block

   This block decides, linked with indicators 1 and 2, which station the truck will refill. It depends by the amount of fuel present in the tank. The threshold is 10000 kg in case of gaseous hydrogen and 10000 litres in case of liquid element.
2. “Create” block

   Task of it is to create a truck whenever the refuelling stations call with the indicators.
3. “Queue” block

   It is forced present before an activity because it could be occupied and without the model will be stopped.
4. “Activity” block

   The first activity block simulates the filling of the truck.
5. “Set” block

   Item passing through are loaded by hydrogen.
6. “Convey item” block

   This block is the route trucks follow, with speed and metres.
7. “Select item out” block

   Selection is the step where the truck is addressed to the first station or the second one.
8. “Activity” block

This activity is present in both of the line the truck could follow after the selection (only in the second one a "convey item" block appears to add 15 km between the two stations). It is a model of the tank refilling.

9. "Interchange" block

   Both of interchange blocks represent the tank in the station, in the line between the activity and the convey the tank will be filled by the truck while the interchange in the station on the right before the exit is got empty by the cars which want to refill in the HRS.

10. "Convey item"

    This is the way back to the factory.

11. "Exit"

    The amount on the block is the number of cars and trucks arrived after the way.

This model will be run for 518400 minutes, ones present in one year composed by 360 days, with the arrival of the car described by an exponential distribution with 6 as mean. Data were taken from the Hyundai study about 2050 and papers where is written a sequence of 10 cars per hour.

Every case I will find in following chapters will be run in same condition of time and with the same structure of the model. The route I will draw are made to pass first by Kjørbo Station and then Høvik Station. If the first one does not need refilling so the truck will continue for 15 km to refill the second one because trucks are created only in case one of them needs.

Chapter 4

Case study

After analysing the main aspects necessary to have a complete picture of the context in which hydrogen has to be inserted, I need to define possible transport and storage scenarios in the two stations types. Time restriction required for the work allows me to analyze only one region of Norway chosen as a case study. My choice was directed on it because of the recent accident occurred in June 2019.

	Østlandet (*Austlandet*)			• Akershus • Buskerud • Hedmark • Oppland • Oslo • Østfold • Telemark • Vestfold

Figure 21: Region of the case ("Regioni_della_Norvegia," n.d.)

The treated region is Østlandet to which the county of Akershus and Oslo belong. Specifically, the case study reported in this work will be the accident that occurred in the municipality of Bærum with capital Sandvika in Kjørbo.

Figure 22: Kjørbo location in map ("Google earth," n.d.)

In that region we can take attention on two stations with different technologies:

- Kjørbo station:

  Named in the previous line for the event, it is a production and storage station.

- Høvik station:

  the second one is a storage station. Afterwards Hyop decided to add a track with an energy generator which makes it production and storage. We can use it as part of case study for storage station because it has same structure.

4.1 Development

During the afternoon of the 10th of June 2019 there was a hydrogen explosion in an Uno-X hydrogen station in Sandvika in Bærum run by Nel.

Figure 23: Photos from Kjørbo station(“Immagine incidente,” n.d.)(“accident images,” n.d.)

The runner was warned with a report of an incident involving a fire at 17:40 p.m. and it immediately mobilized its crisis response team in Norway and Denmark coordinated with Uno-X team. Thanks to the prompt actions of them and technical support for emergency response services, the fire was contained some minutes after 20:00 p.m. The cause is still unknown, but the police identified the leak of fuel from the high- pressure storage unit.

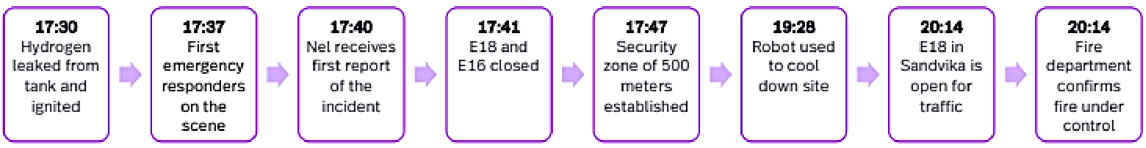


Figure 24: Timing of the accident(Relations, 2019)

Nobody was harmed, although in proximity there was a lot of traffic probably due to a return from a long weekend and the glasses of some windows belonged the nearest building were ruined. Only two people received minor injuries when their car airbags deployed, possibly triggered by the blast. To protect customers, Nel technical experts recommended the temporary closing of same family stations. Production by Nel is present in Norway, Korea and US with same typologies of stations.

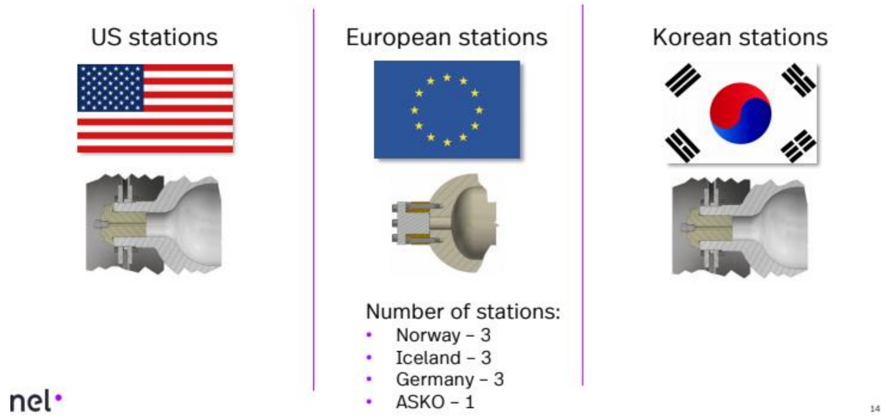


Figure 25: Differences between plugs in Korea, US and Europe(Relations, 2019)

The US and Korean stations were soon reopened because their plug structures are different for regulatory reasons and this kind of incident cannot occurred. As showed in the picture n°19, Europe plugs have the locker in orizontal position inserted in the fixed part of the connection contrary the others are stopped in vertical by a clamping device.

Nel is qualified expert for hydrogen technology sector. It counts more than 3500 units where convert water and electricity to hydrogen and oxygen in industrial processes. These are scattered in 80 countries or more adding to the primacy of largest electrolyzer manufacturer in the world. Nel would like to become leader in hydrogen fuel station manufacturing, today it has 50 HFS in 9 countries. An accident like this occurred could affect the company image. For this aspect it wants to be in a close cooperation with authorities and quite clear with customers, suppliers, car vendors, business partners and other stakeholders taking short-term and long-term decisions quikly.

The company decided to task the Gexcon AS to investigate on the roof explosion cause. Mentioned company is a world-leading one in safety and risk management field for its advanced dispersion, explosion and fire modelling. Along with Bureau Veritas and SINTEF, they probably found the cause in an assembly error of a specific plug in a hydrogen tank in the high-pressure storage unit. Gexcon on its website in June wrote that the Vice President Consulting, Geirmund Vislie, will expose himself about “Key Learning Points from Recent Hydrogen incident in Norway” during the conference of Maritime Hydrogen and Marine Energy. This year, the 4th conference took place on 18-19 September in Florø.

4.2 Kjørbo Hydrogen fuel station structure

The hydrogen station was opened in 2016 by Uno-X Hydrogen and registered as Nel H2 station with on-site production from electrolysis. Localized in 1 Kjørboveien, Sandvika, Akershus in Kjørbo the hydrogen fuel station is composed by:

- the electrolyzer
- the dispenser used by customers
- stationary low-pressure storage unit
- a low-pressure transport unit
- stationary high-pressure storage unit
- various valve pane
- hydrogen refuelling station unit

The picture presented by Nel in the report about the accident shows the positions of the components.

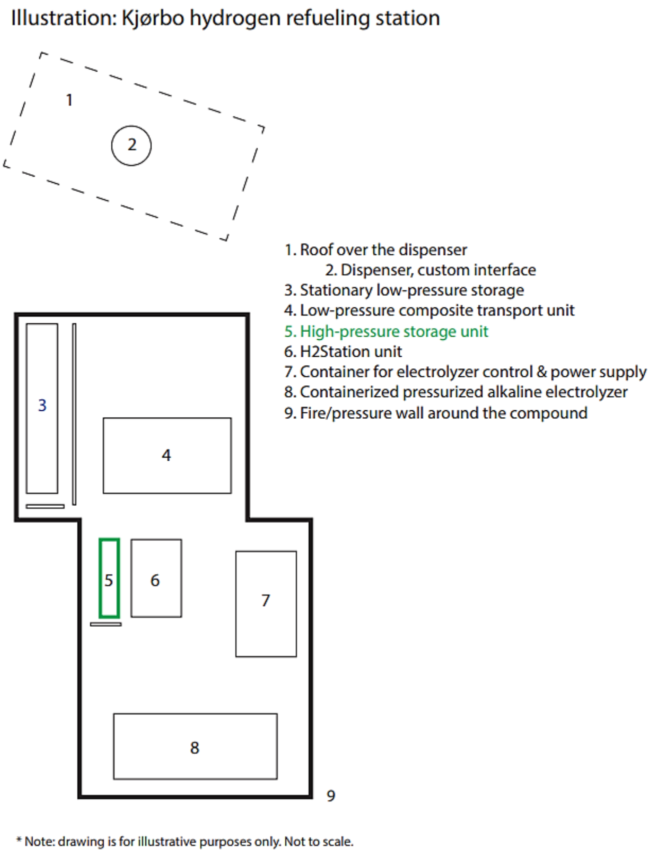


Figure 26: Structure of Uno-X H2 station(Relations, 2019)

Moreover the site also includes a containerized, pressurized alkaline electrolyzer that produces hydrogen in part from solar power. This is delivered by Nel Hydrogen Electrolyser division. Unit n°5 consists of steel tanks and other components by third parties, some of which are designed by Nel.

Figure 27: unit n°5 (Relations, 2019)

During the inspections after accident, Nel, finding the root cause, made safe the stations. The head ordered to check all components and their materials with a magnetic particle inspection, a penetrant testing and some other verifications. All of these had positive results. Check-up on the design was also positive, passing the 1000000 cycles accelerated test. Contrary assembly was not successful because it didn't pass the tests of bolt analysis, physical gap and opening torque.

A second image, posted by Nel in the reportage of Kjørbo incident, gets clear the root cause: an assembly error in high-pressure storage unit. The accident was caused by a leak in the red sealing area that started to spread. Wear on the seals and increased leakage pressure from the hole led to a pressure level that the blue bolts could not counteract because they were not properly tightened before. Their pre-tension was insufficient and it leaded to lift of the plug. The blue sealing failed immediately and the leak was not controlled.

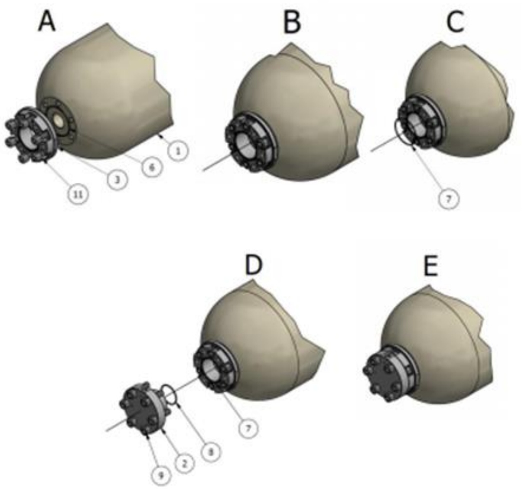


Figure 28: Lockers (Relations, 2019)

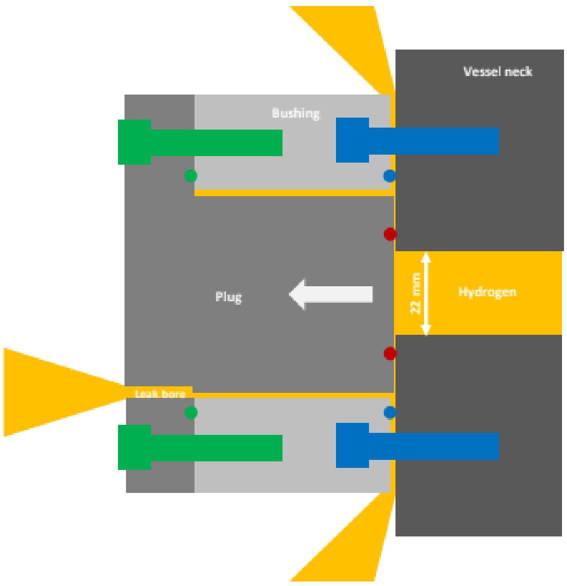


Figure 29: High pressure storage failure plug(Relations, 2019)

4.3 Integrity verification program

Nel has initiated an inspection and an integrity verification program for the high-pressure storage units with similar plugs. The company would to give green light to operators in July or first half of July for other countries. While Europe and Norway, they have to update components to correct the individuated root cause structure. Experts have proposed and operated an update and check of the sites and replacement of all common elements present in.

It could be summarized in 4 main points (Relations, 2019):

1. Verified plug solution
   - Inspect all high-pressure storage units in Europe
   - Check/re-torque all plugs
2. Updated routines for assembly of high-pressure storage units
   - Introduce new safety system/routines (aerospace standard)
   - Torque verification, double witness and documentation/marking
3. Improved leak detection
   - Software update to increase leak detection frequency
   - Consider additional detection hardware/modifications
4. Ignition control measures (site dependent)
   - Smooth surface/no gravel around high-pressure storage unit
   - Additional ventilation in compound & higher extent of EX-equipment.

Chapter 5

Analysis

5.1 Analysis methods

In order to carry out this thesis, a resolution method has been devised that integrates the economic part of hydrogen transport and the safety part in Akershus and Oslo. Once scenarios had been identified, with the relative hypotheses mentioned above, two different routes were analysed for each defined starting point, north, south and west: the first is usually faster and passes through main streets, unhabited centres and highly trafficked areas. These reduce transport costs due to shorter distances, but at the same time this choice entails the exposure of the population and the fee for private lines. The second one is longer and therefore with higher costs in terms of consumption and delivery time, even if there is no tax because it is pubblic and it crosses roads with less traffic and places where the population density is obviously lower. These routes show the needed number of trucks to reach the monthly quantity defined as the estimated demand for each station. This will depend on external parameters due to the area and in our case we will have two different questions, one per station. Finally, once the number of trucks has been identified, the cost of each scenario will be obtained. From the point of view of safety, instead, we will analyze the route, for length, average traffic and population density, and intrinsic hazard of transported substance. The aim is to obtain for each scenario, like small loss, medium or catastrophic breakage, a level of risk which could be included in the general curve F-N. In it intervals are mapped for the acceptability based on probabilities and damage scheme for which we will have a safe area defined in green and a red area of unacceptable scenarios. At this point, we can decide which scenarios suit for the transport of hydrogen related to the case study, as they meet the level of safety required and the monthly demand for the stations.

5.2 Applied hazard identification

The place is still closed for inspection, so it is not possible to study the on-site procedures could cause damages.

5.3 Applied Hazop

For privacy reasons on the accident being not solved yet, it is not possible to access the structure of the involved station, but referring to a classic hydrogen station with on-site production by electrolyzer and with 3 stages of compression, it is possible to pinpoint hazards. The picture shows the structure composed by compressor, valves, pipeline and tanks.

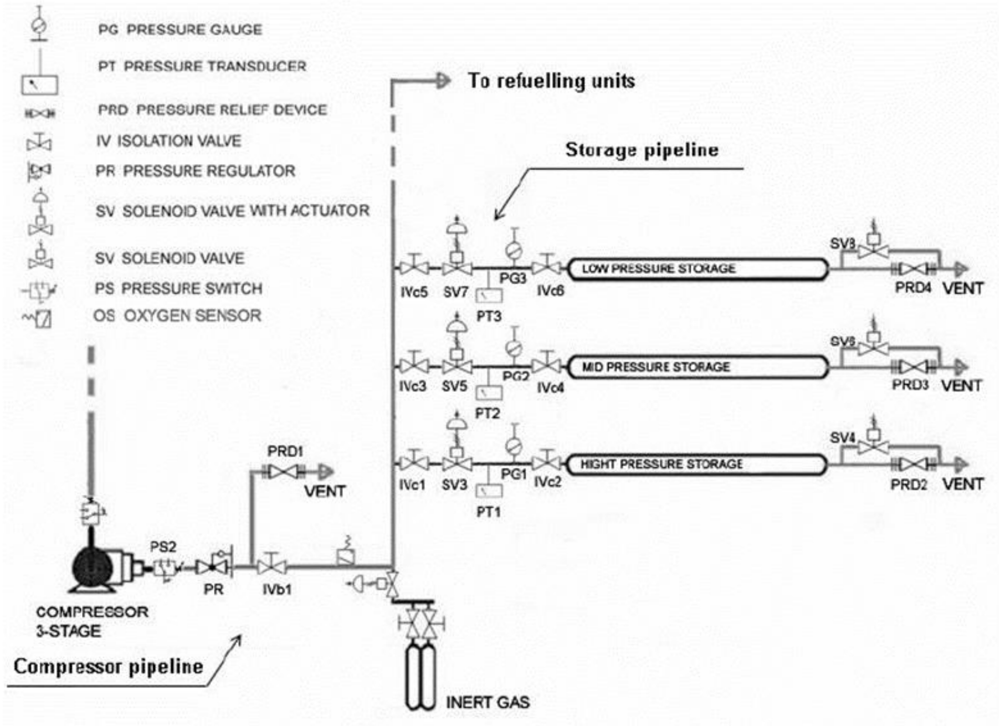


Figure 30: Compressor scheme(Casamirra, Castiglia, Giardina, & Lombardo, 2009)

Hydrogen is produced on site and stored in form of compressed gas by a three-stage compressor. It is sent to three storage vessels, respectively, at low, medium and high pressure. For safety reasons, two pressure switches are present in the compressor upstream and downstream. They are referred to the downstream pressure and to a pressure regulator (PR) that minimizes the flow of high-pressure hydrogen into the system. The external pressure switch (PS2) allows the compressor to terminate the process only if the pressure inside it corresponds to the set pressure. Tanks are protected by two valves: a solenoid valve and a mechanical valve. These are set at 10% of the maximum holding pressure and they discharge the gas in case of overpressure or other malfunctions in the control system. Basic security functions are controlled by pressure gauges (PG) in the pipes, pressure transducers (PT) and solenoid valves (SV), operated by a programmable logic controller (PLC), while continuity in case of electrical failure or interruption of the electricity supply line is given by buffer batteries.

Among these we recognize useful for the hydrogen distribution investigation focused on leakage mainly:

- NO
- GREATER THAN/MORE
- LESS

while as far as the parameters are concerned about leakage in external ambient, I underlined:

- STORAGE PRESSURE
- HYFROGEN FLOWRATE

As node I chose a point on the pipeline connecting compressor and tanks to underline line and storage problems.

Parameter	Word	Cause	Consequence	Protection	Comment	Top event
HYDROGEN FLOWRATE	NO	Compressor failure	No filling of pressure vessel	Solenoid valve locks the storage	Hydrogen is not compressed	NO
		Solenoid valve is closed	Increasing of pressure in compressor line	PS2 turns off the compressor and PRD is on	If PRD fails overpressure in line	NO
		Pieces of structure aren’t installed in right way	Leak in environment	-	Human error	TOP EVENT
	LESS	PRD open	Leak in environment	No	Possible ignition	TOP EVENT
		Solenoid valve half open	Delay in filling	-	Slow filling	-
		Lower PS2 switching off pressure	Compressor doesn’t work	No complete vessel filling	-	-
	MORE	Higher PS2 switching off pressure	Overpressure storage	Pressure gauge and PS2	Activation of storage vent	NO
		Pressure regulator fails, high	Overpressure	Pressure gauge and PS2	Activation of storage vent	NO

		flow from compressor				
Parameter	Word	Cause	Consequence	Protection	Comment	Top event
STORAGE PRESSURE	LESS	PRD open	Leak in environment	No	Possible ignition	TOP EVENT
		Solenoid valve half open	Delay in filling	-	Slow filling	-
		Lower PS2 switching off pressure	Compressor doesn't work	No complete vessel filling	-	-
		Pieces of structure aren't installed in right way	Leak in environment	-	Human error	TOP EVENT
	MORE	Higher PS2 switching off pressure	Overpressure storage	Pressure devices activate	Activation of storage vent	NO
		Pressure regulator fails, high flow from compressor	Overpressure	Pressure gauge and PS2	Activation of storage vent	NO

In some on-site stations, hydrogen is made by electrolysis. In Kjørbo, a Nel electrolyzer was used for the process, the type is still unknown because of the investigation, but it could be a Proton PEM Electrolyser. Its power is 2-6 Nm^3/h and it belongs to H Series electrolysers. These series are put on small-scale uses, indeed they need 6 Nm3/h of hydrogen gas at 99.9995% purity. It could be the adopted solution in the station also because it has small dimension, they are easy to maintain and they can be installed within hours.

(Casamirra et al., 2009)

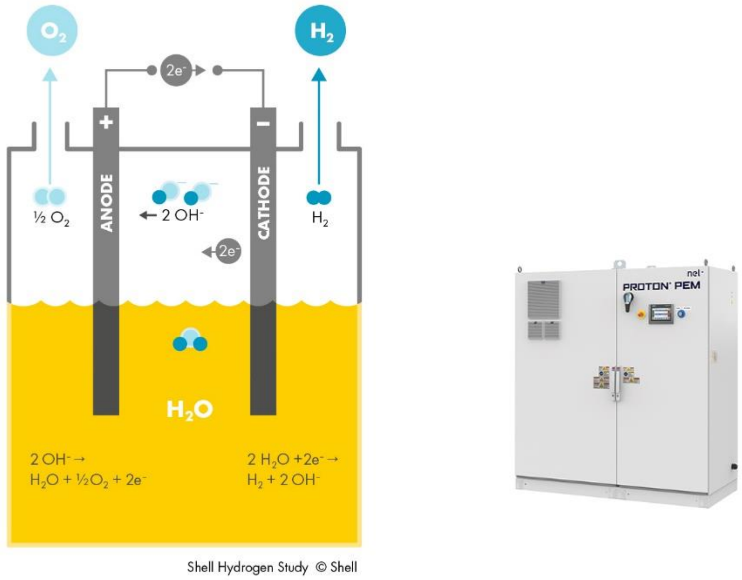


Figure 31:Electrolyzer structure(“electrolysis,” n.d.) *and Nel electrolyzer*(“Nel,” n.d.)

The critical parameter for the case could be the pressure inside the electrolyzer. For studying the anomalies which could happened during electrolysis guide words are indicated such as “more” and “less”. The picture n° 32 shows the possible structure of it.

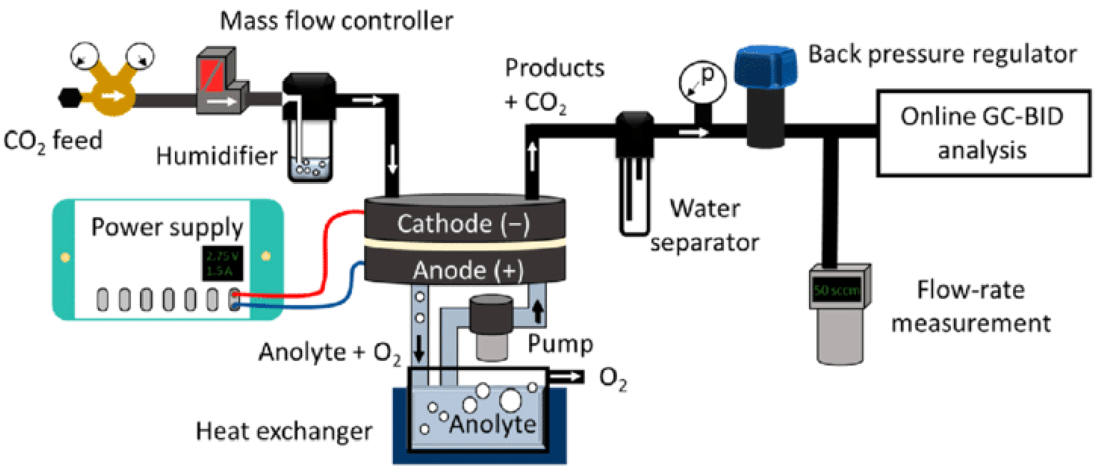


Figure 32: Electrolysis system(Kumaravel & , John Bartlett, n.d.)

Parameter	Word	Cause	Consequence	Protection	Comment	Top event
	LESS	Flow-rate not enough	Electrolyzer doesn’t work	measurement	-	-
		Valve of back pressure	Delay	-	Slow filling	-

PRESSURE		regulator opens				
		Mass flow controller is broken	Electrolyzer doesn't work	Not enough flow	-	-
	MORE	Flow-rate is too much	Electrolyzer works not properly	measurement	-	-
		Valve of back pressure regulator closed	Speed	-	Over filling	-
		Mass flow controller is broken	Electrolyzer doesn't work	overflow	-	-

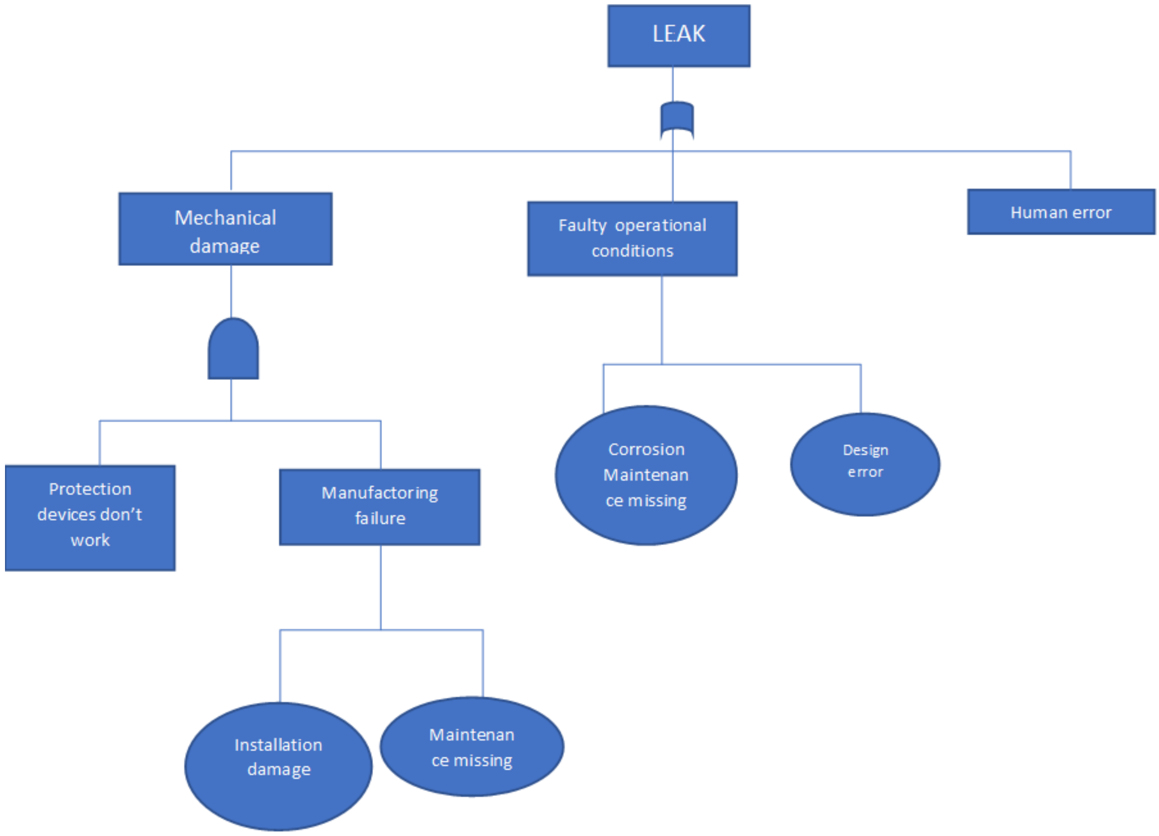
As revealed by the Hazop the loss in the environment can be caused by both of two parameters for overpressure in the compressor and storage phases. This loss, depending on the causing phenomenon size, will be detected as one from a small holes (less than 30 mm), or loss from bigger ones (more than 30 mm). I will not investigate properly the case, but dimension has been chosen for the study of damage scenarios assuming that the consequences of a hole greater than 30 mm are comparable and therefore cumulative with the consequences of a catastrophic breakage in the tank. In the case study of Kjørbo station, a small bolt leakage was found, which in any case led to an explosion due to the concentration of the element in an enclosed environment.

(Casamirra et al., 2009)

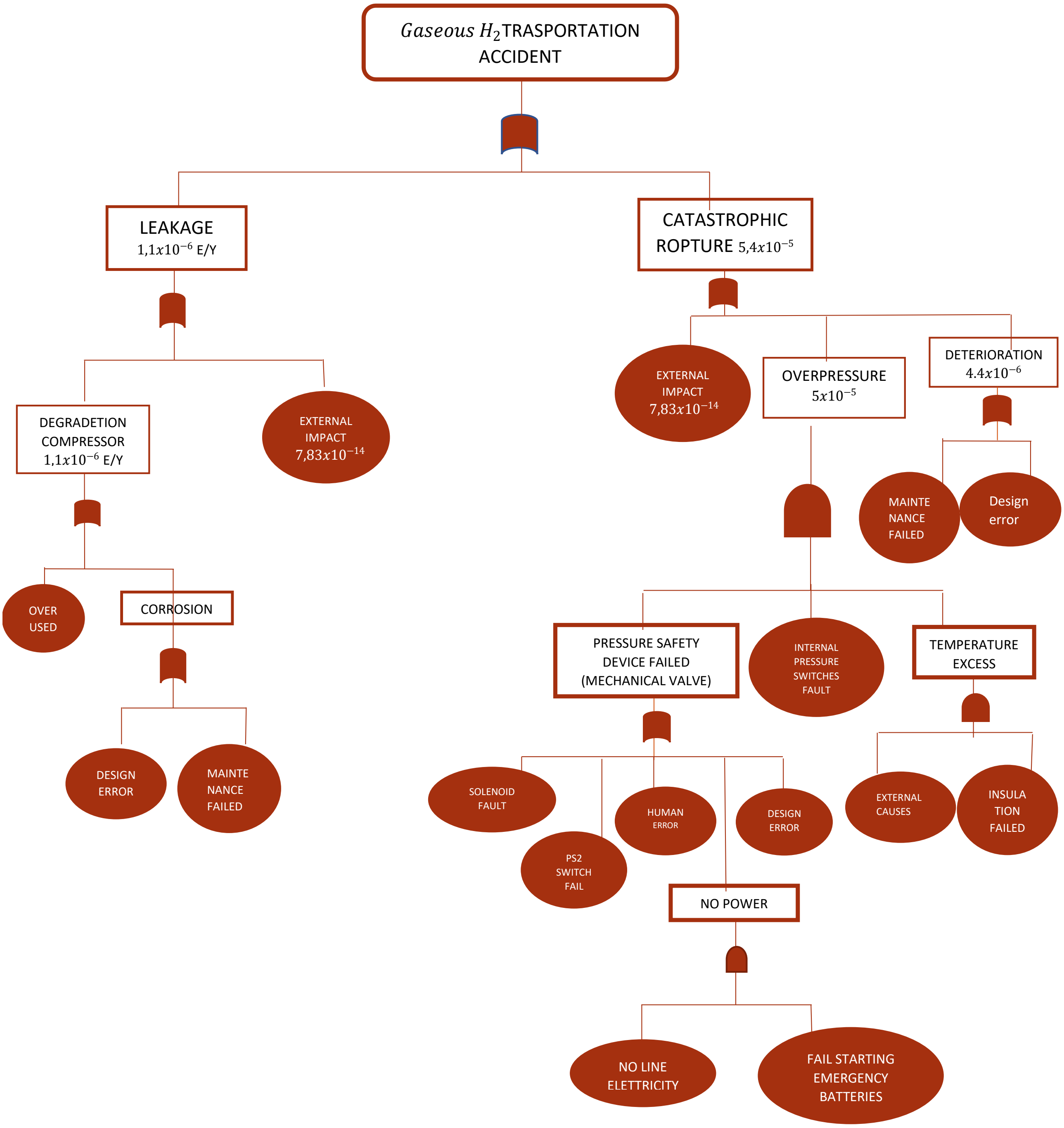
5.4 Fault tree analysis application

5.4.1 Kjørbo FTA

The basis cause is not yet discovered. In this work I analysed the possibilities that could bring it to the leak without going inside the case. Thesis leaves open this aspect for future investigation focusing on cost and safety optimisation in hydrogen transport and non-stationary situations.

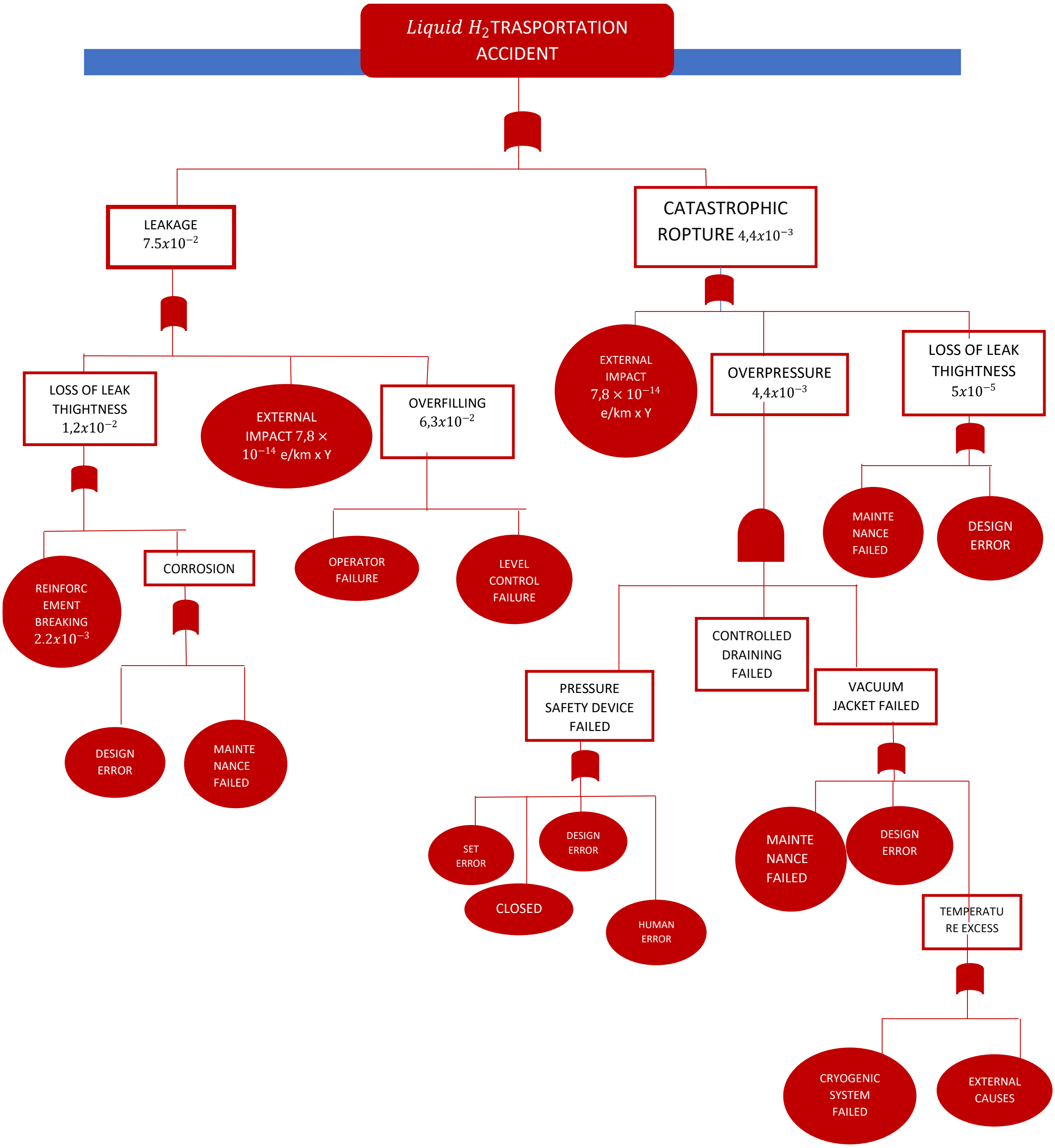

LEAK
Mechanical damage
Faulty operational conditions
Human error
Protection devices don't work
Manufactoring failure
Corrosion Maintenance missing
Design error
Installation damage
Maintenance missing

5.4.2 Road delivery FTA



Usually within the branches of the fault tree there is the generating cause probability of occurrence. In our case we found in the reference the estimated frequency for the event "compressor degradation" that together with the external impact due to a road accident will be the cause of the possible deviation during the transport of hydrogen gas.(Corchia, Giardina, Lombardo, & Messina, n.d.)

The probability at the apex of the tree will therefore be a frequency Event/year in case of leakage and, thanks to the probability defined in the right side of the tree that sees as main causes of the danger "external impact", "deterioration" and "overpressure", a probability of catastrophic failure.(Zhiyong, Xiangmin, & Jianxin, 2010) (Corchia et al., n.d.)(Brown A.E.P., Nunes E.N., Teruya C.M., Anacleto L.H., Fedrigo J.C. and Artoni, n.d.)



Also with regard to liquid transport, the probabilities of the causes were taken from scientific articles so that the tree would develop in the most exact way. While the external impact calculated in the next paragraph as a frequency is not significant for the probability of the final scenarios because it is too small in order of magnitude, the external impact calculated in the next paragraph as a frequency is not significant for the probability of the final scenarios because it is too small in order of magnitude.(Kikukawa, Mitsuhashi, & Miyake, 2009)

5.5 Estimated Norwegian road accidents frequency

To obtain a thesis that describes the situation of transport in Norway, I need to calculate the average of the accidents on the road for heavy trailers. They are subdivided in lorries, road trains and trucks and everyone could be part of an incident. Disposing of the Norwegian statistic bank, I could extrapolate the frequency of accidents for this kind of transports.

Table 8: vehicles involved in road accidents("Statistics Norway," n.d.)

	Vehicle involved in road traffic accident
	2018
Lorry without trailer	189
Road train	144
Other motor vehicle	98

$$\sum Road\ train + other\ vehicle = 144 + 98 = 242\ vehicles\ involved$$

Table 9: Registered vehicles("Statistics Norway," n.d.)

Registered vehicles [1]

	2018
Private cars [2]	2 768 864
Electric cars	195 351
Vans	476 873
Lorries	72 405
Busses	15 634
Tractors	284 679
Special purpose vehicles	6 716
Mopeds	163 436
Light motor cycles	26 754
Heavy motor cycles	165 782
Snow scooters	89 280
Trailers	1 444 937

[1] The statistics count all registered vehicles as of 31 December
[2] Includes ambulances, combined vehicles and motor homes

$$Registred\ vehicles = Trailers + Lorries = 72405 + 1444937 = 1517342$$

$$Accident\ frequency = \frac{242}{1517342} = 1{,}6 \times 10^{-4}\ \text{event/year}$$

Table 10: road traffic volume for type of vehicles("Statistics Norway," n.d.)

Road traffic volumes, by type of vehicle	
	2018
Total road traffic volumes (million km)	
All vehicles	46 000.0
All passenger cars	35 989.1
All buses	579.4
All vans and small lorries	7 388.4
All heavy lorries and road tractors	2 043.1
Average road traffic volumes per vehicle (km)	
All vehicles	12 924
All passenger cars	12 140
All buses	34 836
All vans and small lorries	14 186
All heavy lorries and road tractors	35 796

$$Accident\ frequency\ on\ 1\ km = \frac{Accident\ frequency}{Total\ road\ traffic\ volume} = \frac{1{,}6 \times 10^{-4}}{2043{,}1\ milion\ km}$$
$$= 7{,}83123685 \times 10^{-14} \frac{events}{km\ year}$$

From literature we know that only 5% of accident caused a leak/ropture.(Pasman & Rogers, 2012)

$$Leak\ frequency\ on\ 1\ km = 7{,}83123685 \times 10^{-14} \times 0{,}05 = 3{,}91561843 \times 10^{-15} \frac{leak\ events}{km\ year}$$

To have a great view of the real situation we need to add to this frequency, that is really low, the rate of failure of vehicle tubes in static condition. "Risk assessment by means of Bayesian networks: A comparative study of compressed and liquefied H2 transportation and tank station risks" reported that it is around 2×10^{-3} in both case of transport, gaseous and liquid one.

$$Route\ leak\ \ frequency = [3{,}91561843 \times 10^{-15} \times km] + 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 1\ North = [3{,}91561843 \times 10^{-15} \times 775] + 2 \times 10^{-3} \frac{events}{year} = 3{,}035 \times 10^{-12} + 2 \times 10^{-3}$$
$$\cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 2\ North = [3{,}91561843 \times 10^{-15} \times 785] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 1\ South = [3{,}91561843 \times 10^{-15} \times 160] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 2\ South = [3{,}91561843 \times 10^{-15} \times 138] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 1\ West = [3{,}91561843 \times 10^{-15} \times 351] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 2\ West = [3{,}91561843 \times 10^{-15} \times 378] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 1\ North\ Ammonia = [3{,}91561843 \times 10^{-15} \times 10{,}5] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 2\ North\ Ammonia = [3{,}91561843 \times 10^{-15} \times 15{,}8] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 1\ South\ Ammonia = [3{,}91561843 \times 10^{-15} \times 87{,}5] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 2\ South\ Ammonia = [3{,}91561843 \times 10^{-15} \times 95{,}6] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 1\ West\ Ammonia = [3{,}91561843 \times 10^{-15} \times 463] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

$$Route\ 2\ West\ Ammonia = [3{,}91561843 \times 10^{-15} \times 540] + 2 \times 10^{-3} \frac{events}{year} \cong 2 \times 10^{-3} \frac{events}{year}$$

5.6 Delivery investigation parameters

In order to unify the optimisation of the transport price with safety of the surrounding population and of workers who are in close contact with refuelling, transport and maintenance operations, it is necessary to well know the characteristics of the designated scenario. The parameters I am going to analyse are as follows:

1. Refuelling station locations
2. Station sizes
3. Station types
4. Weather conditions
5. Route
6. Transport quantities
7. Delivery starting points
8. Phase
9. Pressure
10. Temperature
11. Exposure

1. Location of refuelling station

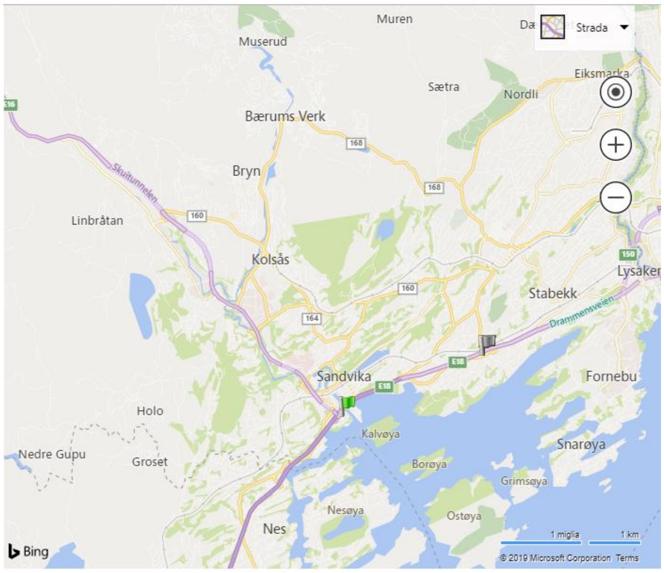


Figure 33: location(“Google maps,” n.d.)

As the map shows, the selected case studies are very close to each other. The green flag defines the Kjørbo station, while the grey flag defines the Høvik station. The first is located in VGQF+7H Sandvika, Bærum, while the second in Sandviksveien 17, 1363 Høvik.(“Google maps,” n.d.)

They have been chosen for their proximity so as to be able to assume without a large percentage of error that they are in the same conditions of study.

2. Size of refuelling station

The ordinary dimensions of storage in hydrogen stations vary from 1 to 3 tons. It depends on the hydrogen demand for the case study and on the phase of the element. In production and storage station case, we need to divide again the sector. The amount of hydrogen request from the population could be made by electrolysis or extracted from other materials, as seen in the previous introductory chapter. Electrolyzer fuel stations have usually as storage range from 300 kg to 700 kg, for a pressure of 700 bar (Degli & Di, 2009)in the high compression phase. Stations with a 500 kg capacity would be considered if they will have same model as Kjørbo. Conversely, in this paper, optimization on electrolyzed stations is not studied, choice due to their source usually is not carried because it is water. In these pages, delivery of ammonia will be analysed to do a transport optimization on this P&S type. Storage stations could be liquid or gaseous ones. In liquid storage case at 5 bar and 20 K will be considered a capacity of 17000 litres(Kikukawa et al., 2009), since a hydrogen market has not been developed yet, noticing considered close position and the explained demand in this chapter. Indeed gas hydrogen storage stations have three tanks with three different pressures and the amount they could store it is around 30000 kg.(Centre & Technologies, 2021) I must define a threshold beyond which refuelling is necessary. Usually engineers tend to design stations so that they can cover the demand for 7 to 10 more days. On this point of view refuelling threshold could be taken as 7/10 days. These will be equal to a fixed percentage of the stocked which has been estimated on the demand. In the near future, hydrogen car number will correspond to the request of fuel kilograms in the region of Akershus where hydrogen will become main substitute for fossil fuels.(Cardella et al., 2017)(Stiller et al., 2010)(Kikukawa et al., 2009)

Calculation:

Table 11: registered vehicles("Statistics Norway," n.d.)

Registered vehicles [1]

	2018	Change in per cent 2017 - 2018	Change in per cent 2013 - 2018
Private cars [2]	2 768 864	1.1	9.2
Electric cars	195 351	40.6	999.3
Vans	476 873	1.3	9.7
Lorries	72 405	-1.9	-8.9
Busses	15 634	-2.5	-11.1
Tractors	284 679	1.3	9.9
Special purpose vehicles	6 716	-7.4	-14.7
Mopeds	163 436	-5.0	-7.2
Light motor cycles	26 754	3.1	25.3
Heavy motor cycles	165 782	1.0	25.7
Snow scooters	89 280	1.5	16.9
Trailers	1 444 937	2.7	17.2

[1] The statistics count all registered vehicles as of 31 December
[2] Includes ambulances, combined vehicles and motor homes

- So far, therefore, there are 2 768 864 cars registered in Norway.

For the estimation of the demand, reference is made to the 2014-2018 statistics, which show the division of vehicles by type of fuel. Oil substitution methods are spreading and it can be seen from the dizzy growth of "other fuels" vehicles in five years.

Table 12: Number of cars per type("Statistics Norway," n.d.)

	Private cars				
	2014	2015	2016	2017	2018
Petrol	1 328 380	1 295 739	1 196 148	1 139 998	1 075 179
Diesel	1 186 194	1 243 235	1 276 947	1 294 493	1 290 442
Paraffin	16	13	9	8	11
Gas	120	129	116	169	223
Electricity	38 652	69 134	97 532	138 983	195 351
Other fuel	999	1 013	91 054	144 630	189 650

- In the county of Akershus, containing the municipality of Oslo, lives about 10% of the Norwegian population. In a temporal space of 5 years, cars with "other fuel" have had an increase in this region of more than 162 times passing from 489 to 79 302.

Table 13: private cars("Statistics Norway," n.d.)

	Private cars					
	2013	2014	2015	2016	2017	2018
LF1 Oslo and Akershus						
Petrol	304 627	302 511	302 181	281 727	270 135	256 166
Diesel	258 880	272 890	275 024	268 990	254 429	239 594
Paraffin	2	2	2	1	1	2
Gas	57	76	76	60	79	66
Electricity	7 733	15 021	25 354	36 223	53 787	76 537
Other fuel	489	207	209	33 208	58 746	79 302

- Following researches indicate an increase in the general exploitation of hydrogen. It will lead to a 50% increase in the number of hydrogen powered cars by 2050.

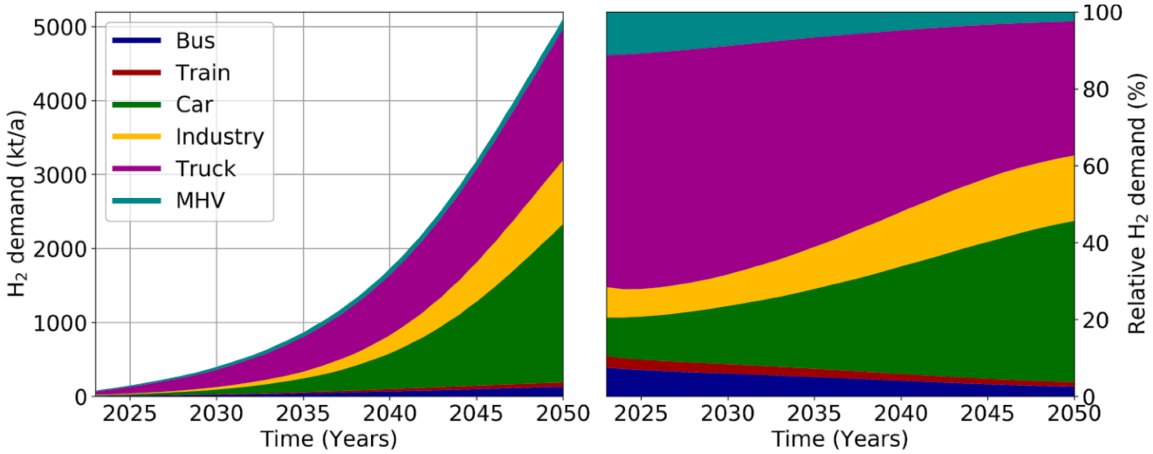


Figure 34: Graph of estimation (Simonas Cerniauskas Thomas Grube, Aaron Praktiknjo, n.d.)

The 50% theory is corroborated by the figure n° 35 where the study represents the car pool in Norway In the future.

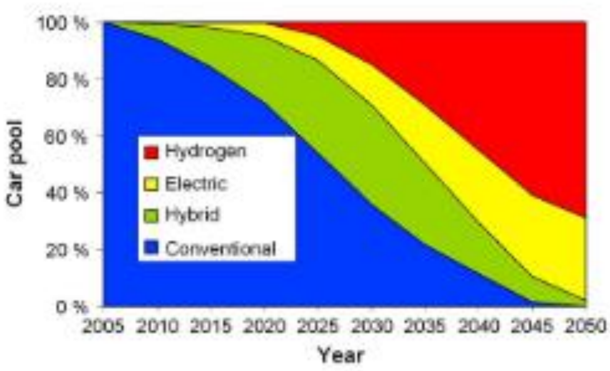


Figure 35:(Stiller et al., 2010)

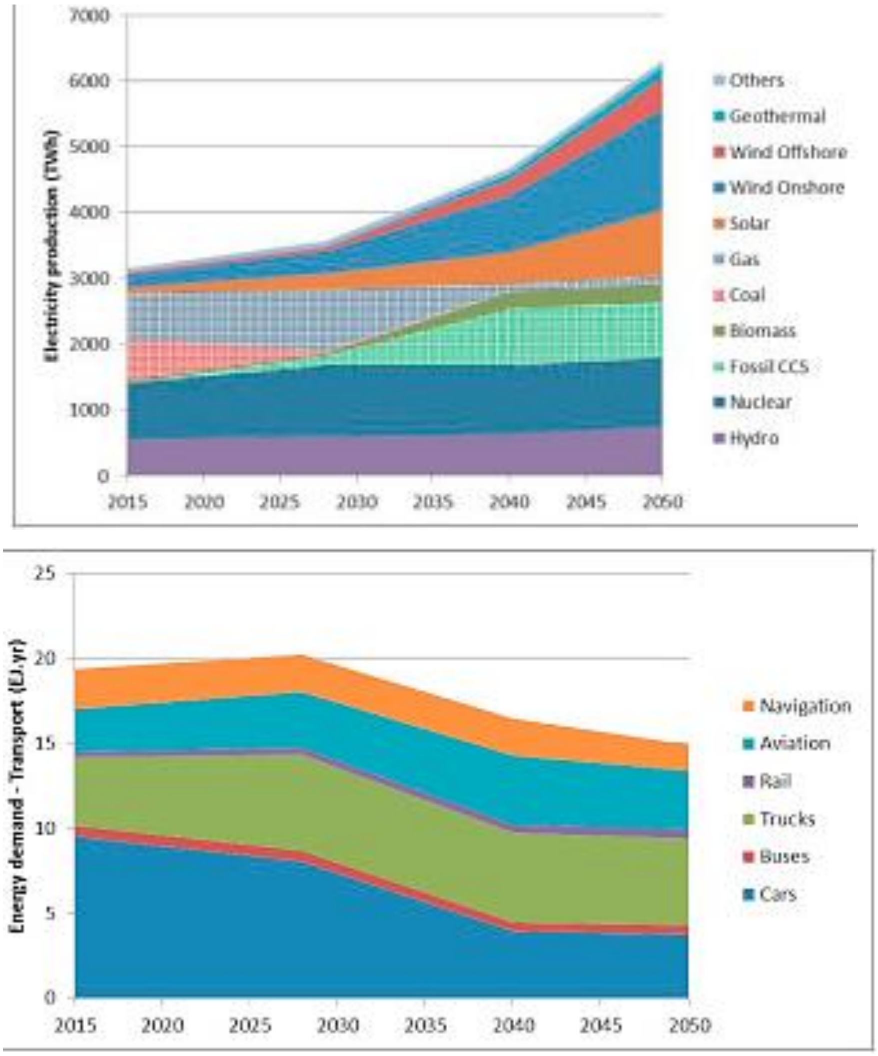


Figure 36: Demand in the future(Herib Blanco, Jonatan J.Gómez, Vilchez, Wouter Nijs, n.d.)

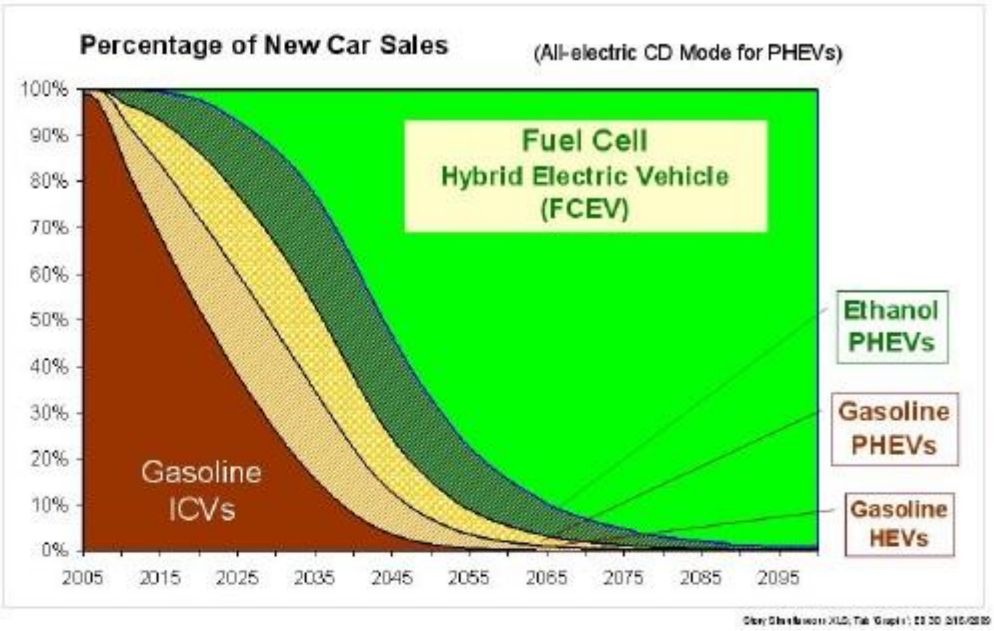


Figure 37: Fraction of new car light duty vehicle sales in the US for the Fuel Cell Electric Vehicle Scenario. Reprint from International Journal of Hydrogen Energy (IJHE)

Dr. C.E. Sandy Thomas in the article "Hydrogen-Powered Fuel Cell Electric Vehicles Compared to the Alternatives" claims that by the end of the century, 98% of new cars sold are FCEVs in the FCEV scenario.

Taking into account the year 2050 he estimates a 50% of hydrogen cars. Assuming constant to 2018 the vehicles number in Akershus County (651667), our estimation of the size will be done:

$$Stimate\ number\ of\ H2\ cars\ = 50\%\ H2\ cars\ in\ 2050 = 325834\ H2\ cars$$

Knowing that, on average, with one kilo of hydrogen, cars designed today can cover more than 100 km. Average consumption per car is calculated by dividing kilometres covered by a vehicle (12924) with the used fuel for 100 km.

Table 14: Road traffic volumes("Statistics Norway," n.d.)

Road traffic volumes, by type of vehicle	
	2018
Total road traffic volumes (million km)	
All vehicles	46 000.0
All passenger cars	35 989.1
All buses	579.4
All vans and small lorries	7 388.4
All heavy lorries and road tractors	2 043.1
Average road traffic volumes per vehicle (km)	
All vehicles	12 924
All passenger cars	12 140
All buses	34 836
All vans and small lorries	14 186
All heavy lorries and road tractors	35 796

$$Estimated\ annual\ consumption\ for\ 1\ car = \frac{12924\frac{km}{year}\times 1kg}{100\ km} = 129\frac{kg}{year} = \frac{130}{360} = 0{,}3583\ kg/day$$

$$Dayly\ total\ demand = 325834 \times 0{,}3583 = 116757{,}183\ kg/day$$

If we were to make the hypothesis of having only the stations which are already built, marked in the map by a flag, in the studied region we would have that the daily demand in each station is:

$$Daily\ one\ station\ demand = \frac{116757{,}183}{11} = 10614{,}289\ kg/day$$

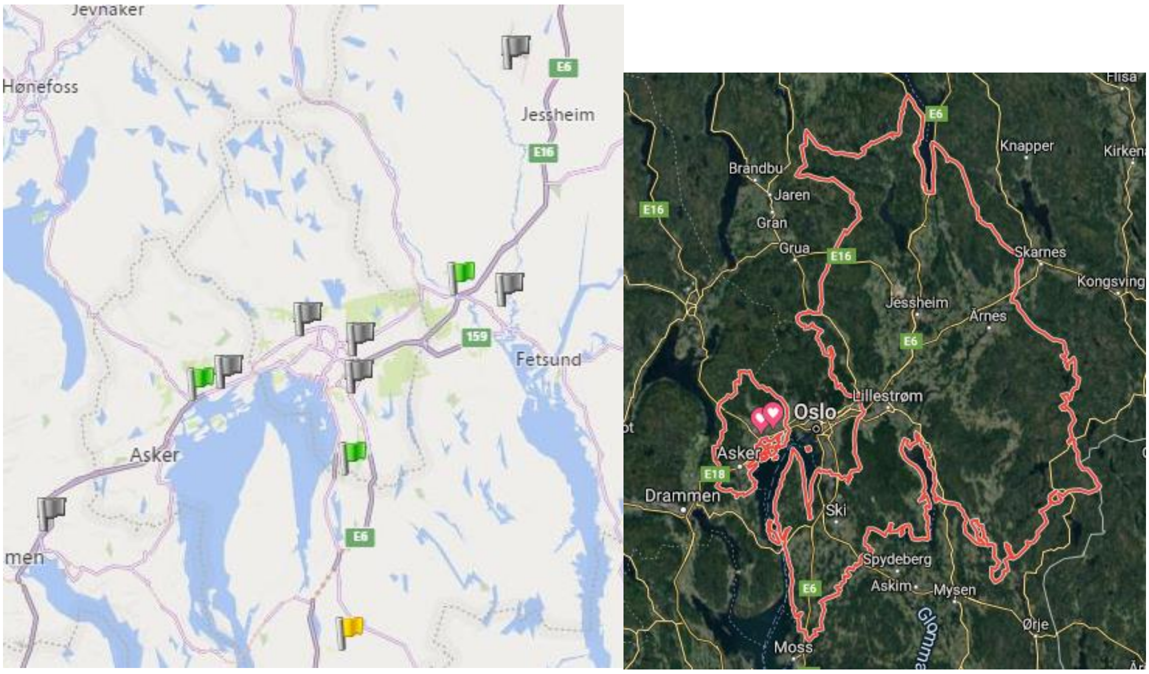


Figure 38: Stations in Akershus and Map(“H2 station. org,” n.d.)(“Google earth,” n.d.)

To understand if it might be a true number in 2050, it is compared with the number usually refills every day according to statistics by calculating the number of hydrogen cars that can be refilled in this way by one station. In average one tank of h2 car is about 3-8kg in high pressure, so we can use 5 kg as a mean of storage making the hypothesis we are speaking about Hyundai Nexo. (“Hyundai,” n.d.)

$$Daily\ cars\ number = \frac{10693{,}23}{5} = 2138{,}646 = 2139\ cars\ for\ station$$

As it is possible to see on the web site https://www.h2stations.org/stations-map/?lat=49.139384&lng=11.190114&zoom=2 for interactive fuel station maps, right now in the considered area only 11 stations are built and most of them are closed; in this condition fuel stations will be overused and so certainly this number could not describe the reality. This is due to the low number of stations and to the limit caused by the re-pressurization problem. The market will grow up and with it the HRS number.

Papers, you can find on scientific portals, concern other countries and it is too difficult to find literature data exactly matching with your case study. In the same time real dimensions of tanks are not available for public because Norwegian authorities are still working on Uno-X kjørbo station investigations. That is the reason why to define the demand I thought an empiric method comparing some studies about the demands and capacities of hydrogen stations.

Table 1 – Technical specifications of HRSs in the Netherlands.

HRS#	1	2	3	4	5	6
Location	Helmond	Rhoon	Amsterdam	Arnhem	Delft	Apeldoorn
Name	Helmond-1	Rhoon	Amsterdam-1	Arnhem	Delft	Apeldoorn
Operator	WaterstofNet	Air Liquide	GVB Amsterdam	VéBé Van Steijn	Connexxion	KIWA
Supplier	Ballast Nedam	Air Liquide	Linde	HyGear	Air Liquide	KIWA
Opened in	2013	2014	2003	2010	2008	2011
Active (status end 2016)	Yes	Yes	No (closed 2015)	No (closed 2012)	No (closed 2008)	No (closed 2015)
Configuration style	Complex	Complex	Complex	Complex	Complex	Complex
Accessibility	Semi-public	Public	Restricted	Public	Restricted	Restricted
Multi fuel station	No, only H2	No, only H2	No, only H2	Yes, H2 retrofitted	No, only H2	No, only H2
Dispensed H2	Gaseous	Gaseous	Gaseous	Gaseous	Gaseous	Gaseous
Service pressure (bar)	350/700	350/700	350	350	350	350
Refuelling strategy	Automated cascade	Booster assisted automated cascade	Booster assisted automated single bank overflow	Automated cascade	Booster assisted semi-automated cascade (slow fill)	Booster assisted manual single bank overflow
H2 supply	Electrolysis	Pipeline	Electrolysis	SMR + Delivered	Delivered	Delivered
Production capacity (kg/h)	2,7	–	5,4	0,5	–	–
Storage volume (L)	2655	2800	10250	2640	25410	9600
Storage pressure (bar)	450, 950	450, 950	300,438	200,420	200,350	200
Compressor (#)	Yes (2)	Yes (2)	Yes (1)	Yes (1)	Yes (1)	Yes (1)
Pre-cooling	Yes (up to −40 °C)	Yes (up to −40 °C)	No	No	No	No
Nozzles (#)	2	3	1	1	1	1
Refuelled vehicles	Cars, buses, garbage truck	Cars, buses	Buses	Bus, delivery truck, cars	Bus	Bus

Figure 39: stations in Netherlands(Honselaar, Pasaoglu, & Martens, 2018)

To quantify the amount, we should consider lot of factors affect each other: Mechanical factors like the brand and the type of compressor or cryogenic pump utilized and the pressure we want to reach, and environmental ones. Also in the same country as shown by imagine belonging the study on Netherlands' stations, we can see how different could be the capacity moving from Amsterdam (10250 L) to Delft with 25410 litres or Helmond with only 2655 litres. In some articles like "Liquid hydrogen pump performance and durability testing through repeated cryogenic vessel filling to 700 bar"(Petitpas & Aceves, 2018), one of most relevant factor for this effect is the population density, so the method will be developed in three steps considering only the population influence:

1. Searching data corresponding to hydrogen daily demand somewhere.
2. Calculating ratio between their populations and finding of amount in considered zone (Akershus and Oslo municipality) related it.
3. Comparing ratios results by papers and the report by Hyundai, defining in this way an estimate demand for 2050.

Limitation of the method is using only the population and not all the factors, but they are not known yet.

<u>Step 1:</u>

The studies which I pointed out to get it are:

- "A short-term analysis of hydrogen demand and refuelling station cost in Shenzhen China" made by Xiaotong Liua, Shuyang Zhangb, Jun Donga, Xinhai Xua of the School of Mechanical

Engineering and Automation, Harbin Institute of Technology (located in Shenzhen, China, Department of Aerospace and Mechanical Engineering, The University of Arizona, Tucson, USA).

- “Risk assessment for liquid hydrogen fueling stations”, conceived by Shigeki Kikukawaa, Hirotada Mitsuhashia and Atsumi Miyakeb belonging to Japan Petroleum Energy Center, New Fuels Department, 3-9 Toranomon 4-Chome, Minato-ku, Tokyo 105-0001, Japan Yokohama National University, 79-7 Tokiwadai, Hodogaya-ku, Yokohama 240-8501 in Japan.

Table 1 – Specifications of liquid hydrogen fueling station model.

No. of cars refueled/h	10
Refuel capacity/car	38 L (30 Nm^3)
Amount of liquid hydrogen refueled/h	380 L/h (300 Nm^3/h) (= 10 cars/h × 38 L/car)
Liquid hydrogen storage tank	Pressure: 0.35 MPa, Capacity: 17,000 L
No. of dispensers	2

Figure 40:(Kikukawa et al., 2009)

- “Safety aspects of future infrastructure scenarios with hydrogen refuelling stations” thought up by F. Markert, S.K. Nielsen, J.L. Paulsen and V. Andersen Systems members of Analysis Department, Ris National Laboratory, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde in Denmark.

On-site storage capacity refuelling station	> 30 ton

Figure 41:(Markert, Nielsen, Paulsen, & Andersen, 2007)

Step 2:

- The first work I selected makes the ratio like:

Population in Shenzhen = 12 530 000

Population Akershus + Oslo= 596704+660987= 1 257 691

Year	Number of FCVs on the road			Daily H_2 demand (kg/day)		
	Cautious	Moderate	Optimistic	Cautious	Moderate	Optimistic
2016	80	480	640	43.7	262	349.3
2017	201	1090	1539	109.7	594.7	839.8
2018	384	1863	2799	209.6	1017	1527.8
2019	661	2845	4564	360.5	1552.7	2490.9
2020	1078	4090	7028	588.5	2232	3835.8
2021	1709	5666	10457	932.7	3092.4	5707.1
2022	2659	7661	15205	1451.3	4181.1	8298.3
2023	4089	10181	21736	2231.5	5556.5	11862.6
2024	6232	13360	30640	3401.4	7291.2	16722.4
2025	9432	17360	42640	5147.9	9474.3	23271.6

Figure 42:(Liu, Zhang, Dong, & Xu, 2016)

Observing the growth during 2016-2025 e supposing its stable year by year after 2025 for each cases (cautious $< 2000\frac{kg}{day}$ $per\ year, moderate > 2000\frac{kg}{day} per\ year\ \ and\ optimistic\ > 2200\ per\ year$), an estimation could be possible.

Fixing a growth not stable for nature could rend the study too out of the reality. So, I decided to compare the data of 2025.

$$\text{Cautious Demand}_{\text{Askershus+Oslo}} = \frac{1257691}{12\,530\,000} \times 5147{,}9 = 0{,}10037 \times 5147{,}9 = 516{,}71\ kg/day$$

This is the cautious case. If we consider the moderate (5% of total selling market) and the optimistic (15%) cases we will have:

$$\text{Moderate Demand}_{\text{Askershus+Oslo}} = \frac{1257691}{12\,530\,000} \times 9474{,}3 = 950{,}98\ kg/day$$

$$\text{Optimistic Demand}_{\text{Askershus+Oslo}} = \frac{1257691}{12\,530\,000} \times 23271{,}6 = 2335{,}87\ kg/day$$

- Following the second paper, which considers a Shell hydrogen fuel station in Japan in Showa, the ratio will be:

  Population in Showa = 20338

  Population Askershus + Oslo= 596704+660987= 1257691

$$\text{Demand}_{\text{Askershus+Oslo}} = \frac{1257691}{20338} \times \left(38\ l\ \times 10\frac{cars}{h}\right) = 61{,}84\ \times\ 9120\frac{l}{day}$$

$$= 563975{,}9\frac{l}{day} \times\ 70{,}8\frac{g}{l} = 39929\frac{kg}{day}$$

  This result has to be read taking in your mind that Showa it’s a really small city with an area of $\sim 9km^2$, so despite the ratio is so high we should calculate also land ratio with the number of refuelling stations that we can have. Another limitation is the phase, liquid and not gaseous, for that reasons for liquid stations I will consider 17000 litres as the example.

- Last report speaks about the capacity of the station considered in Copenhagen urban area.

$$\text{Capacity}_{\text{Askershus+Oslo}} = \frac{1257691}{1308893} \times\ 30000\ kg = 0{,}96088 \times\ 30000\ kg = 28826{,}44\ kg$$

<u>Step 3:</u>

Using the same average of car/h=10 of the last paper coinciding with the study of Hyundai experts, in this work it is considered a mean of 240 cars/day(“Hyundai,” n.d.). In 2050 stations will be equipped with more robust equipment that could be active in a continuous recharging 24 hours a day and for quantities of at least 1200 kg. Hyundai Motor Group already built stations without storage in high pressure (900bar),but these require a downtime for re-pressurizing its recharging system by compressors.

If the average is 1200 kg requested per day, the capacity of the station at least it is:

$$Weekly\ demand_{\ 2050} = 1200 \times 7 = 8400\ kg$$

Taking into account the threshold usually made by designers of 10 days, data is consistent with a view between moderate and optimistic in the second paper comparation. While it corresponds to the third paper quantity because the population is almost co-vident.

$$Threshold\ 10\ days + Weekly\ demand_{\ 2050} = (1200 \times 10) + 8400kg = 20400\ kg$$

Ending I am going to analyse the transport options with as liquid station size 17000 litres and for gaseous storage of 28826,44 kg to be precautionary.

It is necessary also consider a threshold around 5-10 % of capacity because tanks usually are never completely empty. It means I will add 840 kg to the weekly demand and I will obtain 9240 kg.

$$Supply\ threshold = 10\%\ of\ capacity$$
$$Supply\ threshold\ for\ gas = 10\%\ of\ 28826{,}44 = 2882{,}644\ kg$$
$$Supply\ threshold\ for\ liquid = 10\%\ of\ 17000 = 1700\ l$$
$$\boldsymbol{Capacity\ liquid\ stations = 17000 + 1700 = 18700\ l}$$
$$\boldsymbol{Capacity\ gas\ stations = 28826,44 + 2882,644 = 31709,084\ kg}$$

3. Type of station

- Storage
- Production and storage

4. Weather conditions

Using the "yr" statistics, shown in figures n°26,27,28, I will find the average weather condition of June 2019. This is possible because the measuring station in Asker is only 9km far from case study stations.

Months	Temperature				Precipitation		
	Average	Normal	Warmest	Coldest	Total	Normal	Highest daily value
Sep 2019	10.7°C	10.5°C	22.9°C Sep 21	3.1°C Sep 19	153.2 mm	102.0 mm	42.6 mm Sep 28
Aug 2019	15.9°C	14.7°C	26.5°C Aug 2	7.6°C Aug 22	149.5 mm	106.0 mm	37.2 mm Aug 11
Jul 2019	17.0°C	15.9°C	31.4°C Jul 26	6.7°C Jul 5	67.8 mm	90.0 mm	13.8 mm Jul 21
Jun 2019	14.6°C	14.6°C	27.3°C Jun 6	6.8°C Jun 2	115.8 mm	72.0 mm	30.6 mm Jun 7
May 2019	9.5°C	9.9°C	23.9°C May 21	-2.4°C May 3	121.7 mm	66.0 mm	18.8 mm May 10
Apr 2019	7.5°C	3.5°C	22.5°C Apr 29	-5.0°C Apr 1	29.3 mm	50.0 mm	24.3 mm Apr 28
Mar 2019	1.6°C	-0.9°C	15.6°C Mar 21	-9.6°C Mar 12	121.9 mm	62.0 mm	26.4 mm Mar 13
Feb 2019	0.0°C	-4.6°C	10.6°C Feb 13	-12.8°C Feb 4	110.6 mm	52.0 mm	16.9 mm Feb 2
Jan 2019	-3.0°C	-4.7°C	9.6°C Jan 4	-13.1°C Jan 29	43.6 mm	64.0 mm	11.3 mm Jan 28
Dec 2018	-1.8°C	-3.2°C	6.3°C Dec 1	-12.1°C Dec 14	85.4 mm	66.0 mm	20.9 mm Dec 3
Nov 2018	2.5°C	0.4°C	10.5°C Nov 12	-9.2°C Nov 24	149.3 mm	99.0 mm	41.5 mm Nov 12
Oct 2018	7.0°C	5.9°C	17.0°C Oct 10	-3.3°C Oct 29	49.9 mm	111.0 mm	32.7 mm Oct 31
Sep 2018	13.0°C	10.5°C	22.3°C Sep 4	-0.5°C Sep 25	117.2 mm	102.0 mm	33.8 mm Sep 10

Figure 43: yr statistics("Weather parameters," n.d.)

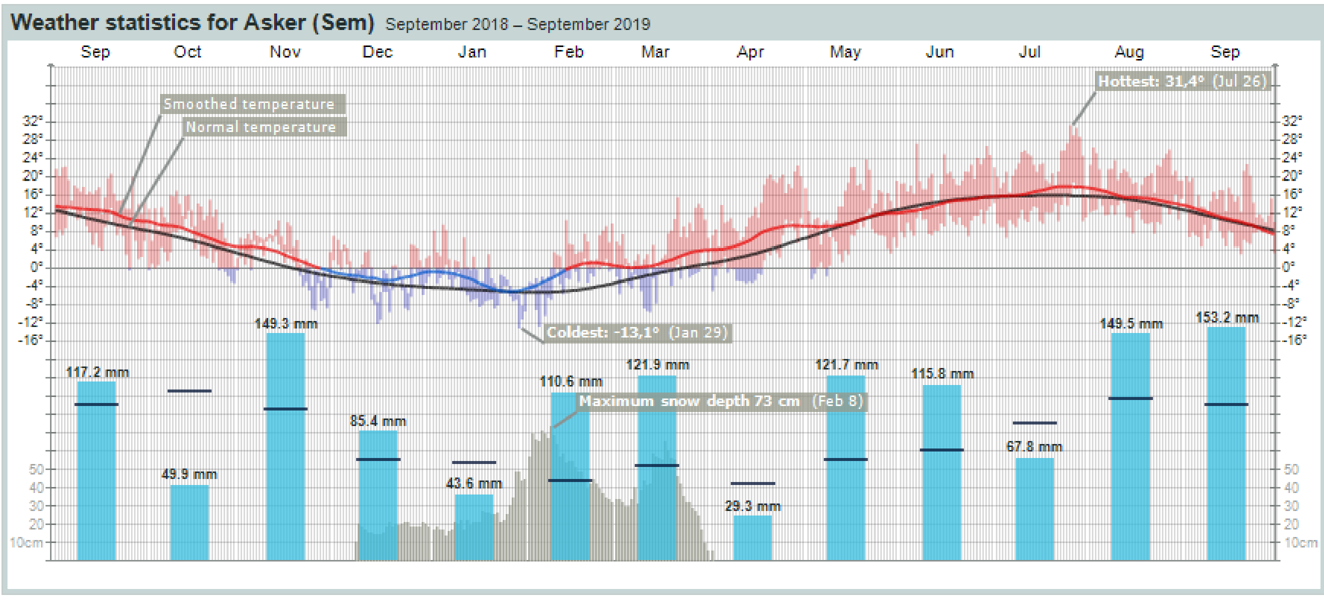


Figure 44: Temperature("Weather parameters," n.d.)

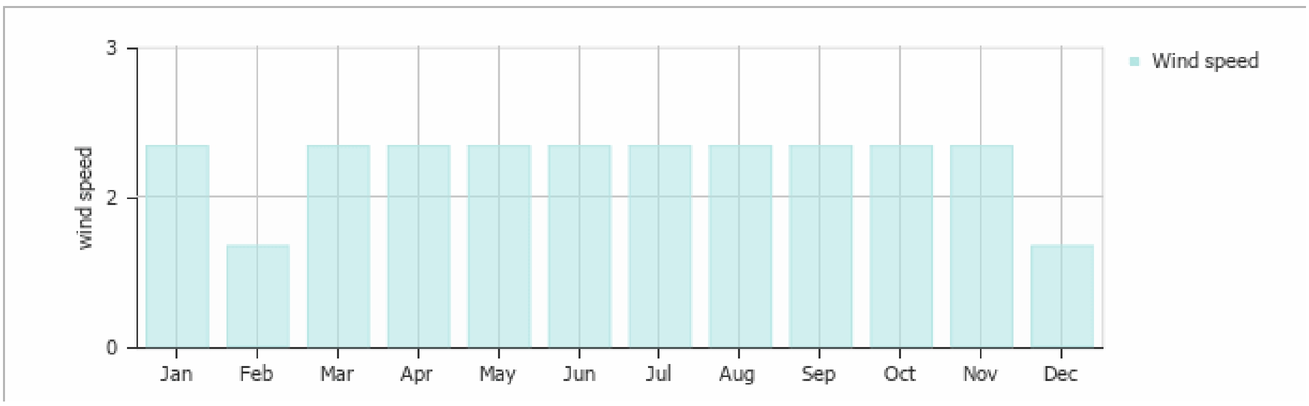
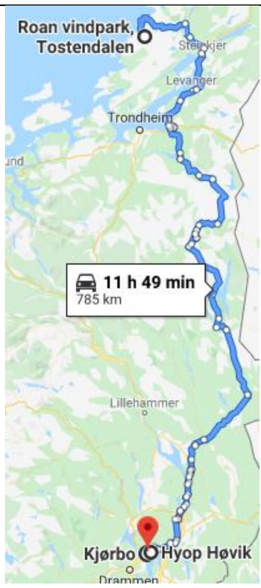
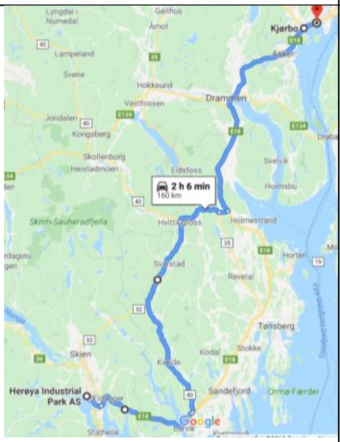
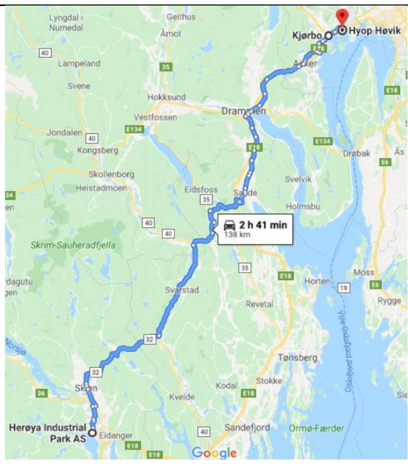
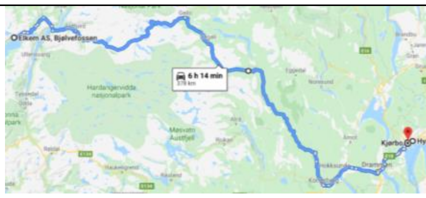


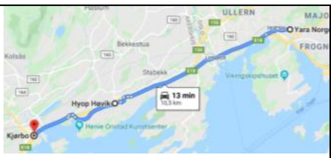
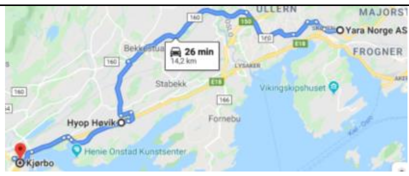
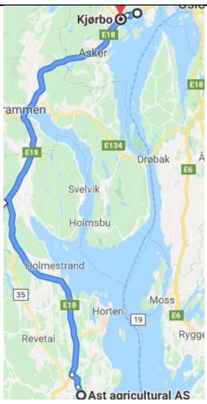
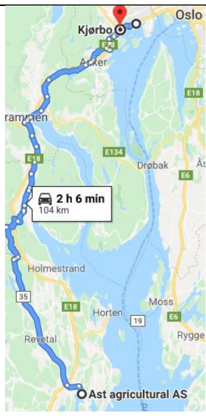
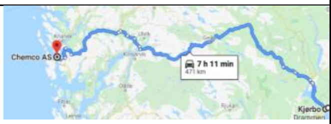
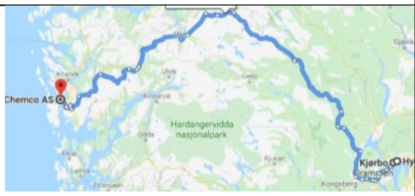
Figure 45: Wind("Weather parameters," n.d.)

5. Route

Table 15: routes("Google maps," n.d.)

	Hydrogen			
	Path 1		Path 2	
North		Crossing the E6 for 775 km for a time of 10h and 38 minutes from Roan vindpark, Tostendalen, Primær Fylkesvei 715, Brandsfjord, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)		Crossing the E18 for 785 km for a time of 11h and 49 minutes from Roan vindpark, Tostendalen, Primær Fylkesvei 715, Brandsfjord, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)
South		Crossing the E18 for 160 km for a time of 2h and 6 minutes from Herøya Industripark AS, Hydrovegen, Porsgrunn, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)		Crossing the Fv32 for 138 km for a time of 2h and 41 minutes from Herøya Industripark AS, Hydrovegen, Porsgrunn, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)
West		Crossing the Rv7 for 351 km for a time of 5h and 23 minutes from Elkem AS, Bjølvefossen, Ålvikvegen, Ålvik, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)		Crossing the Rv 7 and Fv 40 for 378 km for a time of 6h and 14 minutes from Elkem AS, Bjølvefossen, Ålvikvegen, Ålvik, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)

	Ammonia	
	Path 1	Path 2

North		Crossing the E18 for 10.5 km for a time of 13 minutes from Yara Norge AS, Drammensveien, Oslo, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)		Crossing the Fv 26 for 14,2 km for a time of 26 minutes from Yara Norge AS, Drammensveien, Oslo, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)
South		Crossing the E18 for 94,2 km for a time of 1h and 7 minutes from Ast agricultural AS, Kjelleveien, Tønsberg,Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)		Crossing the Fv 35 for 104 km for a time of 2h and 6 minutes from Ast agricultural AS, Kjelleveien,Tønsberg, Norvegia to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)
West		Crossing the E18 for 471 km for a time of 7h and 11 minutes from Chemco AS, Skiftesvikvegen,Strusshamn, Norway to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)		Crossing the Fv 164 and sandviksveien for 543 km for a time of 8h and 53 minutes Chemco AS, Skiftesvikvegen, Strusshamn, Norway to Sandviksveien 17, 1363 Høvik, Norvegia (Hyop Høvik) and afterwards Kjørboveien 1, 1337 Sandvika, Norvegia (Uno X hydrogen station Kjørbo)

6. Transport quantity

Transported quantity is often linked to the shape and the type of transport. As already seen in the large quantities >1000 kg/day stations, for market demand>150 tonnes per day, the most convenient type of delivery is the tube one, already used in 1950 for the transport of gas containing 50% hydrogen and then replaced to optimise methane transport.

Conventional delivery is around 180 bar-250 bar in gas tank trailer(Bassi, 2004). This is intended for small uses ~200 kg/day and short distances because of their small payload (~300 kg). If larger quantities of 1000 kg/day are required, high pressure tube trailers are used at 500 bar with a capacity of 1000 kg.(Liu et al., 2016)

Liquid supply is suitable for high final demand >500 kg/day and long delivery distances. There are usually two types of truck with a capacity of 3000 or 5000 kg.

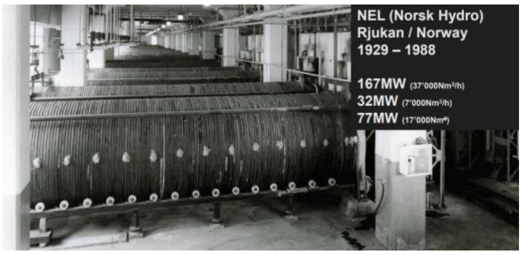
Quantities studied in this work:

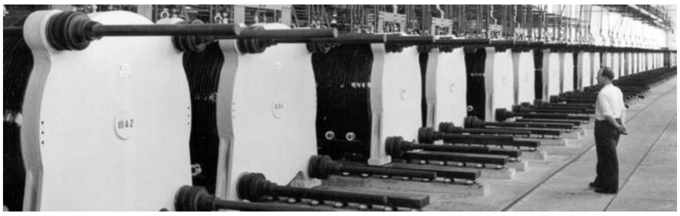
- high pressure tube trailer: 1000 kg
- Small gas tank trailer: 300 kg
- 5000 kg max per liquid
- 3000 kg per other kind of trucks
- Ammonia: 45000 litres (31,3 kg with density 0,73 kg/m3)

(NCE MARITIME CLEANTECH, 2019)(Cardella et al., 2017)(Nilsen, Solgaard Andersen, Hydro ASA, Haugom, & Rikheim, n.d.)(Mori & Nomura, 2013)

7. Starting points of delivering

During last century, in Norway two of largest electrolyser plants supplied by hydro power in the world had been closed. We could think of taking a step back for the south starting point and reusing the electrolysis of water on a large scale as was the case with the plants in Rjukan and Glomfjord. Their production was around 30000 Nm3/h with an energy consumption of 135 MW each. (Langås, 2015)





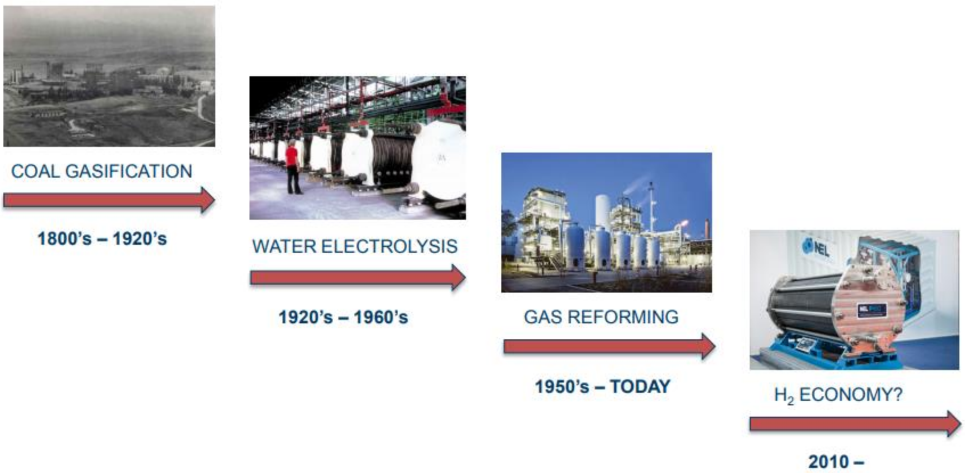


Figure 46:(Langås, 2015)

In the north we can use the assumption of Yara Norge AS, big chemical company leader in nitrogen fertilizer production, but also nitrates, ammonia, urea and other nitrogen-based chemicals one, as a starting point for delivering of ammonia. While about pure hydrogen distribution, we can begin our study from Fosen wind farm, divided in 6 pants whose major is the Roan one, used as starting point. On the East side the presence of the sea favours the ship pathway, but it is not analysed in this work. For West it is employed as beginning Elkem AS foundry site, one of Norwegian plants for supplying silicon-based advanced materials, whose main goal is until 2020 use hydrogen as a clean energy closing their furnace.

- North:
  Ammonia, Yara Norge AS, Drammensveien 131, 0277 Oslo
  Hydrogen, Roan vindpark, Tostendalen, Fv715, 7194 Brandsfjord
- South:
  Hydrogen, Herøya Industrial Park AS, Hydrovegen 55, 3936 Porsgrunn
  Ammonia, Ast agricultural AS, Kjelleveien, Tønsberg
- West:
  Hydrogen, Elkem AS, Bjølvefossen, Ålvikvegen 1055, 5614 Ålvik
  Ammonia, Chemco As, Skiftesvikvegen 50, 5302 Strusshamn

8. Phase of delivering

- Liquid hydrogen
- Gaseous hydrogen
- Liquid Ammonia

9. Pressure

- 5 bar for 5000kg trucks
- 3 bar for 3000 kg trucks
- high pressure tube trailer: 500 bar
- small gas tank trailer: 180 bar-250 bar
  (in the work it is used a pressure of 250 bar for precautionary condition)
  (Mori & Nomura, 2013)(Cardella et al., 2017)(US DRIVE, 2017)(Moradi & Groth, 2019)

10. Temperature

- -244 °C for 5000 kg trucks(Honselaar et al., 2018)(Moradi & Groth, 2019)

- -247,15°C for 3000 kg trucks
- Atmospheric

11. (AA.VV., 2003)(Degli & Di, 2009) (NCE MARITIME CLEANTECH, 2019)**Exposure**

Going to analyse the different routes according to the regions crossed, the average number of people exposed per route can be obtained considering the density. Regions involved are important as well as the number of kilometres for which they are crossed in different scenarios.

$$Population\ density = \frac{Habitants}{Surface} = \left[\frac{n°}{km^2}\right]$$

$$D_{Arkeshus} = \frac{596\ 704}{4\ 918} = 121{,}33 \sim 122\ \frac{n°}{km^2}$$

$$D_{Oslo} = \frac{660\ 987}{4\ 54} = 1365{,}68 \sim 1366\ \frac{n°}{km^2}$$

$$D_{Hedmark} = \frac{195\ 443}{27398} = 7{,}133 \sim 8\ \frac{n°}{km^2}$$

$$D_{Oppland} = \frac{188\ 945}{25192} = 7{,}5 \sim 8\ \frac{n°}{km^2}$$

$$D_{Trondelag} = \frac{418\ 453}{41260} = 10{,}14 \sim 11\ \frac{n°}{km^2}$$

$$D_{Telemark} = \frac{172\ 527}{15296} = 11{,}28 \sim 12\ \frac{n°}{km^2}$$

$$D_{Vestfold} = \frac{245\ 160}{2225} = 121{,}33 \sim 122\ \frac{n°}{km^2}$$

$$D_{Buskerud} = \frac{278\ 028}{14911} = 18{,}65 \sim 19\ \frac{n°}{km^2}$$

$$D_{Hordaland} = \frac{517\ 601}{15438} = 33{,}53 \sim 34\ \frac{n°}{km^2}$$

Route 1 North to Roan vindpark by main street E6:

Oslo for 20km → 27320 exposed people

Akershus for 9 km + 69 km → 9516 exposed people

Hedmark for 73 km →584 exposed people

Oppland for 216 km → 1728 exposed people

Trondelag for 388 km →4268 exposed people

Tot. exposed people= 43416

Tot. length= 775 km

$$Route\ density = \frac{Exposed\ people}{Route\ lenght} = \frac{43416}{775} = 56{,}02\,\frac{n°}{km^2}$$

Route 2 North to Roan vindpark:

Oslo for 27 km →36882 exposed people

Akershus for 12 km + 73 km →10370 exposed people

Hedmark for 290 km →2320 exposed people

Trondelag for 383 km →4213 exposed people

Tot. exposed people= 53785 exposed people

Tot. length= 785 km

$$Route\ density = \frac{Exposed\ people}{Route\ lenght} = \frac{53785}{785} = 68{,}52\frac{n°}{km^2}$$

Route 1 South by main street E18:

Telemark for 18 km → 216 exposed people

Vestfold for 60 km + 34 km → 11468 exposed people

Buskerud for 6 km + 23 km → 551 exposed people

Askershus for 19 km → 2318 exposed people

Tot. exposed people= 14553 exposed people

Tot. length= 160 km

$$Route\ density = \frac{Exposed\ people}{Route\ lenght} = \frac{14553}{160} = 90{,}96\frac{n°}{km^2}$$

Route 2 South:

Telemark for 35 km → 420 exposed people

Vestfold for 25 km + 31 km →6832 exposed people

Buskerud for 4 km + 23 km → 513 exposed people

Askershus for 20 km → 2440 exposed people

Tot. exposed people= 10205 exposed people

Tot. length= 138 km

$$Route\ density = \frac{Exposed\ people}{Route\ lenght} = \frac{10205}{138} = 73{,}95\frac{n°}{km^2}$$

Route 1 West:

Hordaland for 93 km → 3162 exposed people

Buskerud for 235 km → 4465 exposed people

Askershus for 23 km → 2806 exposed people

Tot. exposed people= 10433 exposed people

Tot. length= 351 km

$$Route\ density = \frac{Exposed\ people}{Route\ lenght} = \frac{10433}{351} = 29{,}72\frac{n°}{km^2}$$

Route 2 West:

Hordaland for 90 km → 3060 exposed people

Buskerud for 258 km → 4902 exposed people

Askershus for 30 km → 3660 exposed people

Tot. exposed people= 11622 exposed people

Tot. length= 378 km

$$Route\ density = \frac{Exposed\ people}{Route\ lenght} = \frac{11622}{378} = 30{,}75\ \frac{n°}{km^2}$$

In every simulation, I will add the driver as a single person exposed.

("Statistics Norway," n.d.)("Regioni_della_Norvegia," n.d.)

5.6.1 Combination of parameters

The parameters previously considered are assembled to outline possible scenarios. In this way, 30 scenarios are obtained for cost and safety analysis.

Table 16: Case studies

Scenario	Location	Station size	Station Type	Delivering Pressure	Delivering Temperature	Weather	Route	Quantity	Element	Starting point	Phase
1	Kjørbo	30000kg	P&S	7	Atm	14.6°C	1	45000 l	Ammonia	North	Liquid
2	Kjørbo	30000kg	P&S	7	Atm	14.6°C	2	45000 l	Ammonia	North	Liquid
3	Kjørbo	30000kg	P&S	7	Atm	14.6°C	1	45000 l	Ammonia	South	Liquid
4	Kjørbo	30000kg	P&S	7	Atm	14.6°C	2	45000 l	Ammonia	South	Liquid
5	Kjørbo	30000kg	P&S	7	Atm	14.6°C	1	45000 l	Ammonia	West	Liquid
6	Kjørbo	30000kg	P&S	7	Atm	14.6°C	2	45000 l	Ammonia	West	Liquid
7	Høvik	18700 l	S	5	-244°C	14.6°C	1	5000 l	Hydrogen	North	Liquid

		5 bar									
8	Høvik	30000kg 700bar	S	500 bar	Atm	14.6°C	1	1000 kg	Hydrogen	North	Gas
9	Høvik	18700 l 5 bar	S	5	-244°C	14.6°C	2	5000 l	Hydrogen	North	Liquid
10	Høvik	30000kg 700bar	S	500 bar	Atm	14.6°C	2	1000kg	Hydrogen	North	Gas
11	Høvik	18700 l 5 bar	S	3 bar	-247,15°C	14.6°C	1	3000 l	Hydrogen	North	Liquid
12	Høvik	30000kg 700bar	S	250 bar	Atm	14.6°C	1	300 kg	Hydrogen	North	Gas
13	Høvik	18700 l 5 bar	S	3 bar	-247,15°C	14.6°C	2	3000 l	Hydrogen	North	Liquid
14	Høvik	30000kg 700bar	S	250 bar	Atm	14.6°C	2	300 kg	Hydrogen	North	Gas
15	Høvik	18700 l 5 bar	S	Atm	-250,207°C	14.6°C	1	5000 l	Hydrogen	South	Liquid
16	Høvik	30000kg 700bar	S	500 bar	Atm	14.6°C	1	1000 kg	Hydrogen	South	Gas
17	Høvik	18700 l 5 bar	S	Atm	-250,207°C	14.6°C	2	5000 l	Hydrogen	South	Liquid
18	Høvik	30000kg 700bar	S	500 bar	Atm	14.6°C	2	1000kg	Hydrogen	South	Gas
19	Høvik	18700 l 5 bar	S	3 bar	-247,15°C	14.6°C	1	3000 l	Hydrogen	South	Liquid
20	Høvik	30000kg 700bar	S	250 bar	Atm	14.6°C	1	300 kg	Hydrogen	South	Gas
21	Høvik	18700 l 5 bar	S	3 bar	-247,15°C	14.6°C	2	3000 l	Hydrogen	South	Liquid
22	Høvik	30000kg 700bar	S	250 bar	Atm	14.6°C	2	300 kg	Hydrogen	South	Gas

23	Høvik	18700 l 5 bar	S	Atm	-250,207°C	14.6°C	1	5000 l	Hydrogen	West	Liquid
24	Høvik	30000kg 700bar	S	500 bar	Atm	14.6°C	1	1000 kg	Hydrogen	West	Gas
25	Høvik	18700 l 5 bar	S	Atm	-250,207°C	14.6°C	2	5000 l	Hydrogen	West	Liquid
26	Høvik	1206,83 kg 700bar	S	3 bar	-247,15°C	14.6°C	1	3000 l	Hydrogen	West	Liquid
27	Høvik	18700 l 5 bar	S	500 bar	Atm	14.6°C	2	1000 kg	Hydrogen	West	Gas
28	Høvik	30000kg 700bar	S	250 bar	Atm	14.6°C	1	300 kg	Hydrogen	West	Gas
29	Høvik	18700 l 5 bar	S	3 bar	-247,15°C	14.6°C	2	3000 l	Hydrogen	West	Liquid
30	Høvik	30000kg 700bar	S	250 bar	Atm	14.6°C	2	300 kg	Hydrogen	West	Gas

5.7 Risk analysis

Safety factor is fundamental in an organization which wants to be state-of-the-art with the international contest and to follow new rules about worker, environment and good principles. To optimize a phenomenon you need to study all types of costs. These include safety costs based on the level that you want to achieve. It must be said that it is not easy to set an acceptable level of safety for types of accidents that could be caused by the loss or catastrophic breakdown of a hydrogen tank, whether it is moving on trucks or whether it is stationary at the refuelling station. This is due to the fact that the acceptability threshold does not preclude the possibility of an unwanted event occurring, which in cases such as these can cause considerable damage to people and property in the surrounding areas. Then to establish the threshold of tolerability of the event we prefer to follow in the footsteps of the article "Idealhy" published in 2013. The title is significant and it abbreviates “integrated design for demonstration of efficient liquefaction of hydrogen”, a subject dealt with in detail. The extract taken into consideration is the "Qualitative Risk Assessment of Hydrogen Liquefaction, Storage and Transportation" which in chapter 3.1 cites the UK legislation setting the limit for individual risk at 10^{-6} for general population. If it is exceeded, it will be necessary to mitigate the risk by making changes to the system in order to reduce the consequences of damage or the probability of occurrence.

(Zhiyong, Xiangmin, & Jianxin, 2010)(Kasai, Fujimoto, Yamashita, & Nagaoka, 2016)

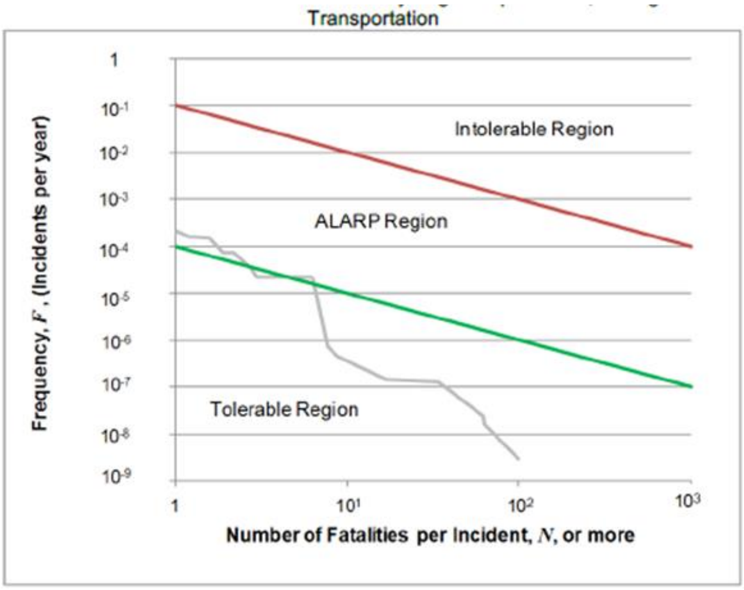


Figure 47: Indicative societal risk curve for road transportation and storage(

5.7.1 Safeti software

In this project it is used the software "Safeti" by DNV-GL to find the great solution or some solutions that respect the threshold for keeping population safe during transportation. It works on some sections where user can build his/her three inserting all details about the situation you would to analyse. These sections are about present materials that could act together or alone, route conditions, components, weather conditions, population, ignition probability etc. Everyone can be added to the maps whose scale can be set in the beginning of the study. Once every data is fixed, it is possible to simulate the case finding the scheme that linked frequencies of events and fatalities. It is supposed to be acceptable the line between the yellow and the green one, so my goal is to find a pathway that will be under that one. Safeti bases its graph F-N on a system database about different ways to fault for different events.

5.8 Cost analysis

The final step for sizing and optimizing a supply structure is to calculate the cost of delivery about component and route levels. The investment risk and under-utilisation of a refuelling station, and the capital investment during the first period of electric fuel cell vehicles selling are of the major obstacle for full commercialisation of hydrogen vehicles. Based on the previously defined delivery scenarios and on the hydrogen per hour demand, the analysis regarding hydrogen supply and its pathways is crucial to understand trade-offs and impacts the new economy could show up if it will apply to the market. For hydrogen transmission, distribution and refuelling, the various technological options, that follow different market conditions, are the key to understand the picture. Capital costs of the stations is about half of the investment. In addition to the cost of the structure, predominant conditions for estimating the market cost for consumers, are:

- type of vehicle (e.g. light or heavy duty vehicles)
- the daily demand
- the capacity and use of filling stations
- hydrogen supply options between liquid delivery or gas or on-site production
- the size of the city and population
- the ownership rate of the vehicles and the annual miles travelled
- hydrogen vehicles market penetration
- fuel supply protocol implemented

Listed below you can define the cost of delivery as the sum of formalized costs in EUR/kg H2:

- total capital costs
- operating and maintenance costs
- energy costs
- Annual and cumulative cash flows

(US DRIVE, 2017)

To analyse prices and competitivity with other fuels we should study every stage of the supply chain. It is otherwise important to think about how hydrogen is made and about its storage and basis for market availability. It is part of the price also the mode with factories produce hydrogen:

- by gas reformation without CCS
- by electrolysis for compressed hydrogen

Considering only the costs of hydrogen, thus eliminating capital costs and operating costs that are highly variable, hydrogen fuel is not competitive in the current market.

The current merchant price of LH2 delivered in Norway is more than eight times higher in Euro/kWt than marine gas oil, while as regards road transport Hyop estimates the price of hydrogen on delivery to 90 NOK/kg per 100 km of driving at normal speed. Norwegian Centres of Expertise (NCE) Maritime CleanTech wrote in "Norwegian future value chains for liquid hydrogen" that fuel transported from Europe to South Norway has a price around 15 EUR/kg out of every consideration for selling. In the other hand, they estimated the price for LH2 made and liquified in Norway between 3,5 and 7,5 EUR/kg and getting it close to the bio-diesel amount spent in KWh.

This position is taken also by Air Products for LH2, global producer of liquid hydrogen. In commercial scale, economical liquefaction is dominated by Linde 10%, Air Products 40% and Praxair 31%, which study for their interests the shared market place. The largest market owner cites a reduced price of almost 4 times in Europe at 7.1 Euro / kg LH2 in current time and studying over ocean the case of Californian plants they found a price of 5.4 Euro / kg. The price difference is probably generated by the lessness tons per day facility of Air Product comparing with the Californian one. Their chemical factories are built for a large demand of 5 tons per day while in Norway Air products counts only 1 or 2 tons of production.

As for energy carriers, the costs of ammonia are already set by an established value chain from ISPT (2017). Ammonia is the vector produced with hydrogen itself from the reformation without ccs, therefore without emissions, its price varies between 300-350 dollars per ton, while in the studies for the Svalbard islands it is estimated a price of NOK 5000 per ton starting from small production plants based on renewable energy electrolysis.

(Marine Insight 2016, DNV GL 2018, IEA Bioenergy 2017)(NCE MARITIME CLEANTECH, 2019)

Fuel	***Retail price EUR/kg (ex. vat)[168]***	***Calorific value (kWh/kg)***	***Spec. fuel Consumption (g/kWh)***	***Efficiency powertrain***	***Cost in EUR per kWh***	***Corresponding LH_2-price EUR/kg LH_2***
LH_2 Norway	15,4	33,3	60,1	50 %	0,92	**N.A.**
LH_2 Europe	7,1	33,3	60,1	50 %	0,43	**N.A.**
LH_2 US	5,4	33,3	60,1	50 %		**N.A.**
CH_2 (250 bar) Norway	10,2	33,3	60,1	50 %	0,61	**10,2**
MGO	0,61	11,97	185,6	45 %	0,11	**1,9**
Bio-diesel	1,68	10,20	188,3	45 %	0,32	**5,3**
LNG	0,76	12,50	177,8	45 %	0,14	**2,3**
LPG	1,10	12,90	172,3	45 %	0,19	**3,2**
Ammonia (fuel cell)	0,51	5,17	193,4	55 %	0,18	**3,0**
Ammonia (combustion)	0,51	5,17	193,4	50 %	0,20	**3,3**
Methanol	0,8	6,39	313	50 %	0,25	**4,2**

Figure 48: Details for H2 economy(Nilsen et al., n.d.)

In the same study, methanol is mentioned as vector and its price is based on hydrogen electrolysis. Present prices above in the figure are based on the industrial knowledge of the project partners and information from suppliers. The corresponding LH2 price in EUR/kg is:

- Around 3 EUR/kg for Ammonia, a bit expensive if it is made for combustion (3,3 EUR/kg)
- 4,2 EUR/kg for methanol

  Currently the market price of one kilogram is around 0.8 euro, which means that in relation to the price of hydrogen contained in it is 40 nok/kg. Being a liquid, methanol has a higher density than hydrogen, which, however, compensates with an energy content much higher at 33.3 kWh/kg compared to 5.56 kWh/kg of methanol. The cost of transport is estimated to be between $15 and $40 per ton per leg depending on the size of the chemical tanker and the distance to be covered. (NCE MARITIME CLEANTECH, 2019)

This generic view is qualitative. Available data are about technologies still not built for commercial scale, but only the experimental one, then, analysis is calculated on sector estimates by experts. Those are

uncertain in this phase of proof of concept, so we should consider some level of errors. In this work my goal will be to find the most advantage pathway considering the final cost of hydrogen as 90 NOK/kg for liquid H2 distribution and 110 NOK/kg for gaseous one considering the superior amount in production and transport stage. To confirm the price, we can take into account the station in Bozen (South Tyrol), where 1 kg of gaseous H2 is sold for 11,29 EUR, VAT (fee of the country) excluded.
(h2-suedtirol.com)

5.8.1 Production cost

Important part of the cost is depending from which type of production was utilized to obtain the fuel. Objective of hydrogen will be completely "green", but at the moment it is still produced for 95%- 96% from fossil fuel origins. The cake-graph here reported from the report of liquid hydrogen used also in the previous paragraph describes the percentages.

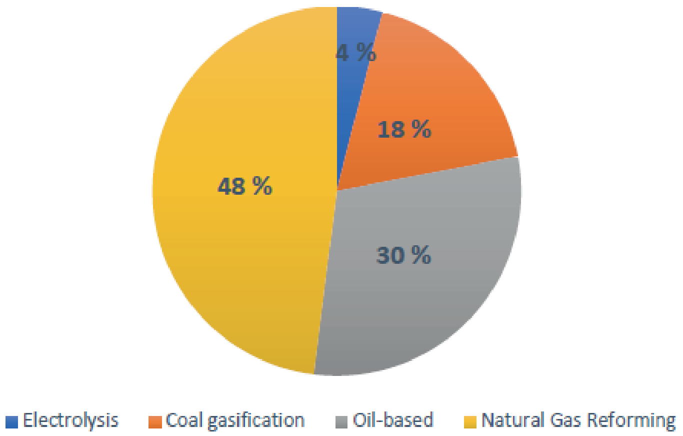


Figure 49:Hydrogen by production method(NCE MARITIME CLEANTECH, 2019)

1. Electrolysis: 4% which is growing up rapidly in those years.
   Researchers are working on this type to find a 100% renewable method for powering the process with green electricity. Today, most of the times, source comes from a mix of renewables and fossil sources. Norway is an example to follow in this field for NVE (2018) because of CO2-emission factor. In 2017 was 16,4 g/kWh, while the EU-mix in 2016 was estimated by European Environment Agency (2018) to 295,8g/kWh.
   In a literature with the growing up of the green request is expected also the decreasing of the costs for this process. The International Renewable Energy Agency counts in some studies a development in total system for alkaline electrolysers which might make possible a decreasing of the price from 750 EUR/kW in 2017 to 480 EUR/kW in 2025. On a long time view they published a gap from 1200 EUR/kW to 700 EUR/kW for PEM electrolysers.
   (Irena 2018 – Total system cost include power supply and installation costs)

Hinicio, part of EU-project Fuel Cells and Hydrogen – Joint Undertaking (FCH-JU), speaks about 5-7 Euro/kg in 2030 because it found three studies converging same conclusions, but, during years, this price was reduced for decreasing of the electrolysers cost about 50 (alkaline) and 60 (PEM) percent and increasing of efficiency that mitigating the ratio kWh/kg of hydrogen.

Some studies have spoken about ranges of cost estimates production cost of 4-5 Euro/kg in order to achieve profitable solutions for end users in mobility (land) and industry.

2. Steam Methane Reforming (SMR): 48% of natural gas reforming

   Taking into an account in 2014 five different European markets were detected for selling hydrogen for 2,2 and 5,0 Euro/kg, best of them are competitive with at 2,5 Euro/kg H2. If we think about SMR production, without adding in the plan compression, storage and dispensing, United States Department of Energy reports values like 1,7 and 2,1 USD/kg in a natural gas study, while Kawasaki has estimated using brown coal fuel and without considering export to Japan, costs should be around 24 yen/Nm3 or just below 2 Euro/kg hydrogen for their Australia-based production plants. This means that hydrogen has a cost, 2-4 Euro/kg H2 from SMR and 4-8 Euro/kg H2, related to the form of production and the infrastructure used chain for this purpose.

The industry initiative Zero Emission Platform claims this will stabilise and become independent of these factors in 2050. Markets obviously are still distinguished by geo-localization, in 2018 IRENA has estimated for Japan a price equal to 3 USD/kg while for Norway another one equal to 5 USD/kg and 6 USD/kg for Europe. On average, therefore, to date it fluctuates between 5-6 USD/kg H2 and a retail price of 13-16,5 USD/kg.

(NCE MARITIME CLEANTECH, 2019)(Baldwin & Investigator, 2012)(US DRIVE, 2017)

Source	Production cost/kg	Retail Price/kg	Year	Compressed/ Liquid	Electrolysis/SMR
FCH-JU (2017)	4-5 Euro		2025	Compressed	Unknown
Hinicio (2015)	5-7 Euro		2030	Compressed	Unknown
E4 Tech (2014)	2,2-5,0 Euro		2014	Compressed	Electrolysis
E4 Tech (2014)	2,5 Euro		2014	Compressed	Gas reformation
US DOE* (2012)	1,5-1,9 Euro		Price for period of 2020-2039	Compressed	Gas reformation
Idealhy (2013)	1,72 Euro		N.A, price for specific plant 50t/day	Liquid	Electrolysis
Kawasaki (2018)	2 Euro		Estimation current project plans	Liquid	Coal gasification
ZEP (2017)	2-4 Euro		Current market price	Compressed	Gas reformation
ZEP (2017)	4-8 Euro		Estimated current market price	Compressed	Electrolysis
ZEP (2017)	3 Euro		2045-2050	Compressed	Electrolysis/gas reformation
Shell (2017)	Ca 1,5-4 / 1,8-3 Euro		Weighted current / projected market price	Compressed	Gas reformation
Shell (2017)	Ca 6-8 / 4 Euro		Weighted current / projected market price	Compressed	Electrolysis
IRENA* (2018)	4,4-5,3 Euro		Estimated current market price	Compressed	Electrolysis
IRENA* (2018)		11,5-14,5 Euro	Estimated current market price	Compressed	Electrolysis
IRENA* (2018)	0,9-2,6 Euro		2025-2030	Compressed	Electrolysis
IRENA* (2018)		4,4-6,1 Euro	2025-2030	Compressed	Electrolysis
GCSP (2019)*	2,7-2,8 Euro		2019	Compressed	Electrolysis (Alkaline and PEM)
GCSP (2019)*	3 Euro		2019	Liquid	Unknown
DNV-GL* (2019)	2-5 Euro		2030	Compressed	Electrolysis (Alkaline and PEM)
DNV-GL* (2019)	1-1,6 Euro		2030	Compressed	Gas reformation
Greensight[46]		7,1 Euro ex. Distribution	Current market price	Liquid	Gas reformation
Greensight		11 Euro incl. distribution	2020 in Norway in the Oslo-area, commercial long-term contract	Compressed	Electrolysis
Greensight		7,5 Euro incl. distribution	2023/4 in Norway in the Oslo-area, commercial long-term contract	Compressed	Electrolysis
Klebanoff & Pratt (2016)*		5,2-6,5 Euro	Current market price	Liquid	Unknown – prob. Gas reformation

Figure 50: Different cot for different conditions(NCE MARITIME CLEANTECH, 2019)

The current thesis focuses on Norway, which is a pioneer in the sector. DNV-GL in its recent papers shows that by 2030 the price of hydrogen in this country will reach levels of economic convenience dependent on energy input CCS and choice of technology never reached before. It is estimated an amount of 9 to 16 kr/kg H2 from gas reformation, 3 USD/kg for hydrogen from electrolysis and a hypothesis of 3.5 USD/kg for liquefied hydrogen. The reported data have been made public in the Green Coastal Shipping Programme where this picture comes from.

Large scale technology is constantly changing and as reported in the IDEALHY-project, to liquefy one kilo of hydrogen requires about 1-1.5 EUR spent on electricity. In Norway it is estimated at 0.1 Euro/kWh so the amount needed is 11-15 kWh to liquify 1 kg of compressed hydrogen. (NCE MARITIME CLEANTECH, 2019)

Mentioned literature and table above show all confusion still present in indefinite hydrogen market which seems to stabilize year after year at a price equal to the production cost of 2-3 Euro/kg for compressed hydrogen and for large scale liquid hydrogen around 2 Euro/kg.

5.8.2 Storage costs

Prices wrote in the last paragraph and in the table above concern only the production, but as I already said, using hydrogen as a fuel means we should count also the amount of the storage and the transport. Since we are speaking about liquid hydrogen, tanks are expensive for the cost of materials for insolation and stock cost is calculated usually with a standard constant multiplied the quantity of the gas embodied energy (GJ). For some studies this method is applicated to all kind of storage tanks, also for gaseous at low, medium or high pressure and nanostructures, or other type of carrier with solid or liquid arrays.

Liquid storage cost is still unclear. Different references give us different results. The level is 45-50 percent higher tank than LNG-tanks. LNG-tanks have typically an investment cost of 30-40 USD/kg for tanks above 100 tons and 80-100 USD/kg for smaller cryogenic tanks. (*Green Coastal Shipping Programme)*

1. A price of 625 000 USD is indicated for a 4,2 tons LH2-tank by Klebanoff & Pratt (2016).
2. The US Department of Energy reports a current price for a LH2-storage tank containing 3500 m3 at 6,6 million USD, with an “ultimate goal” of a price reduction to 3,3 million USD. *(Energy.gov 2015)*

Considering Containers of large volume and high thermal insulation using the mentioned method by Shiga H. and others in “Large-scale hydrogen production from biogas-International Journal of Hydrogen energy, vol.23- N° 8, 1998”, we will get:

- For liquified hydrogen

$$C_{S-P\ H2} = 4160.65 \times qH2\ (a\ 75\ atm)$$

$$C1_{s-p\ H2} = 0.0073 \times qH2^{\ -0.32}$$

$$qH2 = energy\ of\ stored\ gas\ GJ$$

$$C_{s-p\ H2} = plant\ cost\ (\ \$\ )$$

$$C1_{s-p\ H2} = stock\ cost\ (\$/GJ)$$

- For gaseous hydrogen stored in liquid form

$$C_{L-H2} = 792.54 \times QH2$$
$$C1_{L-H2} = 198.135 \times QH2^{-0.2}$$

$$QH2 = energetic\ quantity\ in\ liquid\ hydrogen\ (\ GJ/Year\ )$$
$$C_{L-H2} = liquidation\ plant\ cost\ (\ \$\ )$$
$$C1_{L-H2} = liquefaction\ cost\ (\$/GJ)$$
$$C_{S-LH2} = 2.05 \times 104 \times qLH2^{\ 0.67}$$
$$C1_{S-LH2} = 14.04 \times N \times qLH2^{-0.33}$$
$$qLH2 = energy\ in\ liquid\ hydrogen\ (GJ)$$
$$CS - LH2 = storage\ structure\ cost\ (\ \$\ )$$
$$C1S - LH2 = storage\ cost\ (\$/GJ)$$
$$N = number\ of\ storage\ days$$

(National Research Council, Institute of Applied Physics "Nello Carrara", Department of Energy "Sergio Stecco", University of Florence " Production of hydrogen from fossil and renewable sources")

About gaseous storage the situation is more delineated thank to the popularity of the element in chemical plant. It is mostly governed by the pressure, considering the conditions mentioned in the paragraph 1.5.3.2 "Gas storage" current estimates about an initial investment speak of $600/kg for low pressure tank, $1,100/kg medium pressure one and $1,450/kg for the high pressure stock.

5.8.3 Transport cost

Delivering of hydrogen is a central argument in the discussion about the new fuel. On transport level liquid hydrogen is convenient if the necessity is great. Fixing the dimensions of a container, liquid truck could stock five times the amount storable if it would be gas. This is positive when the delivery takes place on several stations or rarely, but in the initial phase where we are living it is often in gaseous form to avoid the need for vaporizers.

As reported on the 2015 web version pdf from K. Weil, S. Dillich, F. Joseck, and M. Ruth, "H2 Production and Delivery Cost Apportionment," Program Record 12001, the aim is to reach the cost of $2.00/kg. The mentioned objective is the FCTO goal of Hydrogen Delivery Multi-year Research, Development, and Demonstration (MYRD&D) Plan. The writers put the deadline for tube trailer pathway at the current year (2020), but they might expand the target to all other pathways in the future.

(Department of Energy, n.d.)

About liquid delivery, referring again to Klebanoff & Pratt (2016), the final cost of hydrogen is divided in:

- Production 38,5%
- Liquefaction 45,2%
- Transport 16,4%

As wrote above in the introduction of this chapter, the final liquid hydrogen cost is around 90 NOK/kg. With an easy proportion we can find the delivering cost per 1 kg.

$$Transport\ cost\ LH2 = \frac{90\frac{NOK}{kg} \times 16{,}4}{100} = 14{,}76\frac{NOK}{kg}$$

On this view for this work I will consider the established price of 1,79 EUR/kg for gaseous delivery and 1,49 EUR/kg for the liquid one.

5.8.4 Operating cost

Final cost of hydrogen is due to adding operating costs mentioned in the introduction of this paragraph.

To finalize this work on delivery optimization, I will focus on the operating cost of transport divisible in:

1. Operator cost
2. Fuel cost

To insert the first factor in the study, I calculated the earning in transportation and storage sector in Norway gauged on 1 kilometre.

Table 17:("Statistics Norway," n.d.)

Average monthly earnings by section

	Monthly earnings	
	2017	2018
All industries	**44 310**	**45 610**
Agriculture, forestry and fishing	36 210	37 440
Mining and quarrying	69 950	72 700
Manufacturing	45 460	46 800
Electricity, gas and steam	57 880	59 630
Water supply, sewerage, waste	41 930	42 690
Construction	42 060	43 240
Wholesale and retail trade: repair of motor vehicles and motorcycles	39 920	41 020
Transportation and storage	44 110	45 150
Accommodation and food service activities	30 300	31 300
Information and communication	57 690	59 730
Financial and insurance activities	63 890	66 080
Real estate activities	53 060	54 750
Professional, scientific and technical activities	55 010	56 490
Administrative and support service activities	37 760	38 860
Public administration and defence	47 370	48 600
Education	43 650	44 730
Human health and social work activities	40 940	42 230
Arts, entertainment and recreation	38 880	40 010
Other service activities	41 040	41 960

The Table n°17 represents the monthly average salary in 2018 for this section for employees. Converting the salary reported in the table in NO("Statistics Norway," n.d.)K, a worker in transportation is payed 4565,84 EUR/month.

Table 18: road traffic volume*("Statistics Norway," n.d.)*

	2018
Total road traffic volumes (million km)	
All vehicles	46 000.0
All passenger cars	35 989.1
All buses	579.4
All vans and small lorries	7 388.4
All heavy lorries and road tractors	2 043.1
Average road traffic volumes per vehicle (km)	
All vehicles	12 924
All passenger cars	12 140
All buses	34 836
All vans and small lorries	14 186
All heavy lorries and road tractors	35 796

Knowing by a second statistic that one vehicle runs 35796 km/yr, the vehicle amount per month is 2983 km/month. Clearly, behind the wheel there is one operator a time and that makes the calculation of the cost of one driver per km basic:

$$Operator\ cost\ per\ km = \frac{4565{,}84\ EUR/month}{2983\ km/month} = 1{,}53\ EUR/km$$

The second aspect is really variable depending on weight, fuel cost and vehicle brand and type. I will assume vehicles powered by diesel and its cost 1,71 EUR/l in Norway dating back January 2020.

(www. Regjeringen.no)

Referring to "Average mileage cost of diesel consumption cost by enterprises haulage" document written by the Italian ministry of infrastructure and transport, I could discern five categories of trucks depending on the weight.

I. More than 26 tons
II. 11,5-26 tons
III. 7,5-11,5 tons
IV. 3,5-7,5 tons
V. Less than 3,5 tons

With respective consumption:

I. 2,8 km/l
II. 4 km/l

III. 4,7 km/l
IV. 4,9 km/l
V. 8,5 km/l

Using the current cost of the fuel, it means:

I. 0,61 EUR/km
II. 0,42 EUR/km
III. 0,36 EUR/km
IV. 0,35 EUR/km
V. 0,20 EUR/km

Specifically for the cases study and considering an average weight of 7,5 tons for an empty truck, the table shows the matches:

Table 19: Category and cases

Case	Quantity	Category
1-2-3-4-5-6	45000 l (30717 kg Ammonia)	I
7- 9-15-17-23-25	5000 l (355 kg H2)	III
8-10-16-18-24-27	1000 kg H2	III
11-13-19-21-26-29	3000 l (213 kg H2)	III
12-14-20-22-28-30	300 kg H2	III

Chapter 6

Results

6.1 Safeti results

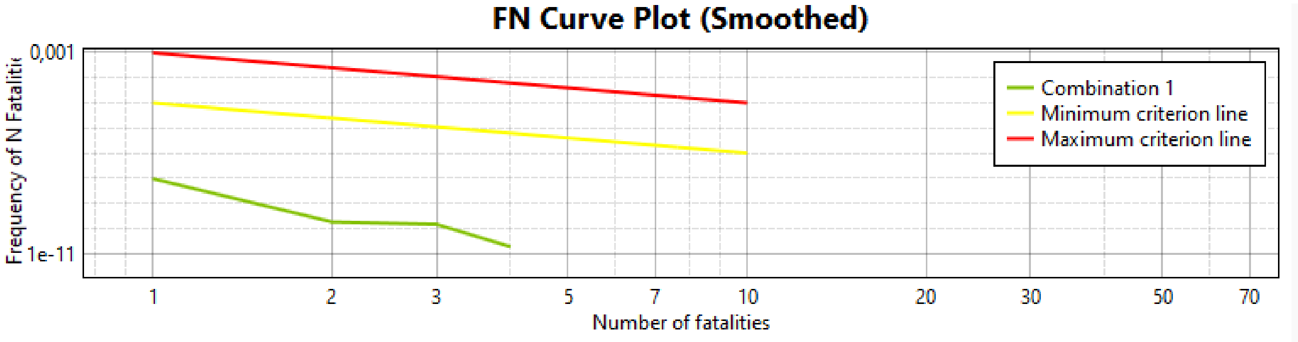


Figure 51: Kjørbo FN

Table 20: Frequencies and fatalities

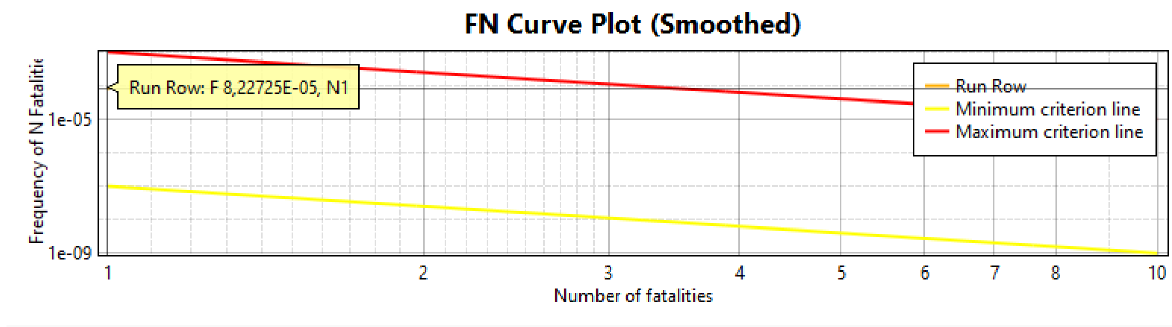
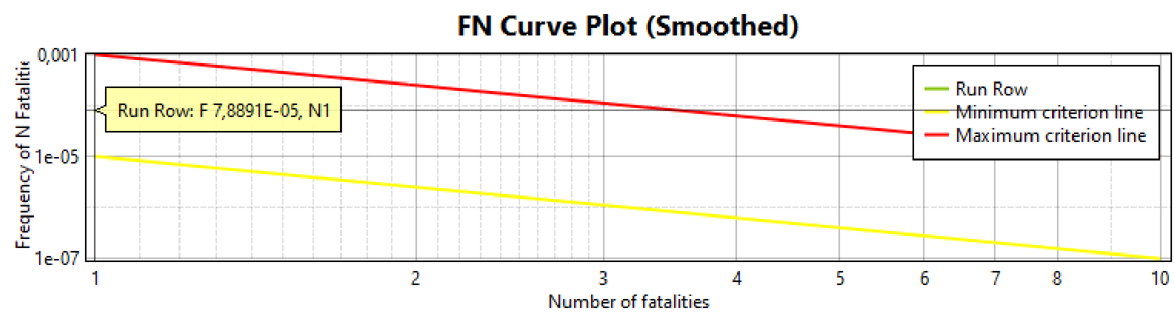
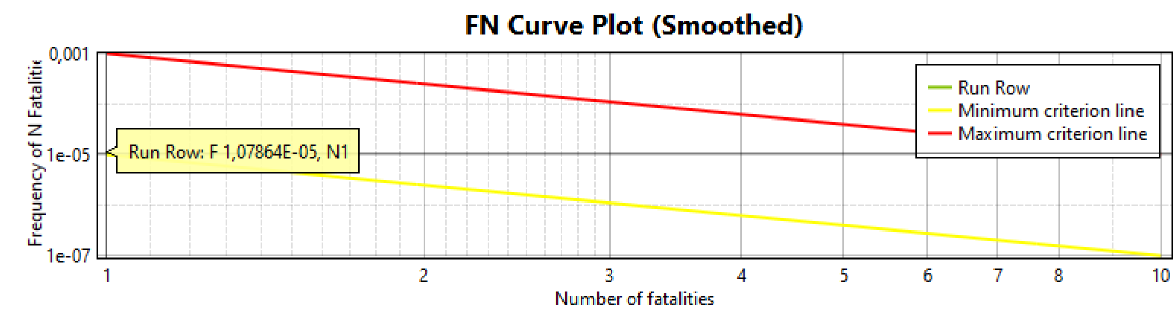
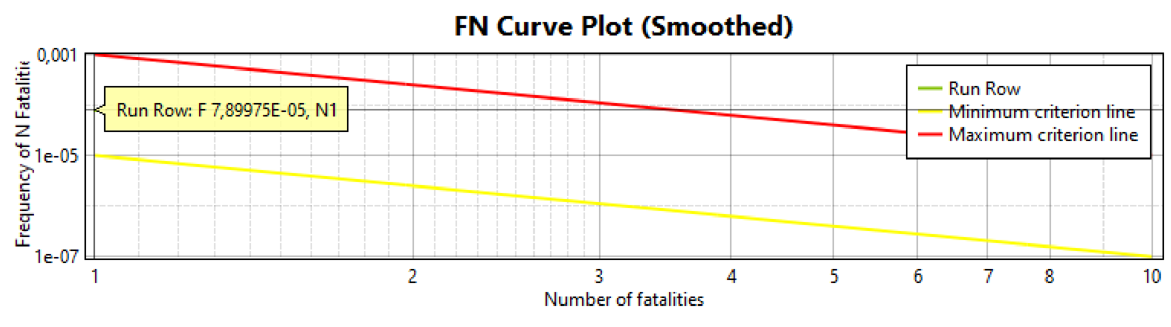
NumberofFatalitiesN	FrequencyOfNFatalities (/AvgeYear)
1	9,44268E-09
2	1,78616E-10
3	1,43803E-10
4	1,83379E-11

Only the presence of the station is obviously less than a transport so it would seem more convenient from the point of view of safety to produce on site by electrolyzer as can be seen from the graph. This, however, should be verified by studying the production process step by step, a topic not covered in this thesis of transport optimization, but that leaves the topic open for further study.

6.1.1 Ammonia safety results

The transport of Ammonia is preferable from the point of view of costs related to the amount of hydrogen that can be obtained, but as you can see from the graphs all the Run Row are not acceptable for the dispersion in case of release for toxicity. Authorities have not yet liberalised the sale and transport of ammonia outside the production facilities, but they are also developing engines powered directly by ammonia.

Table 21: Ammonia FN curves

Case 1	
Case 2	
Case 3	
Case 4	

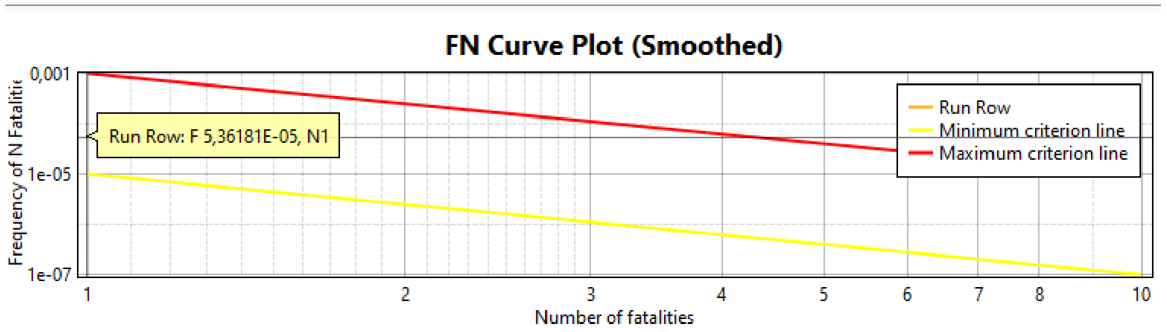
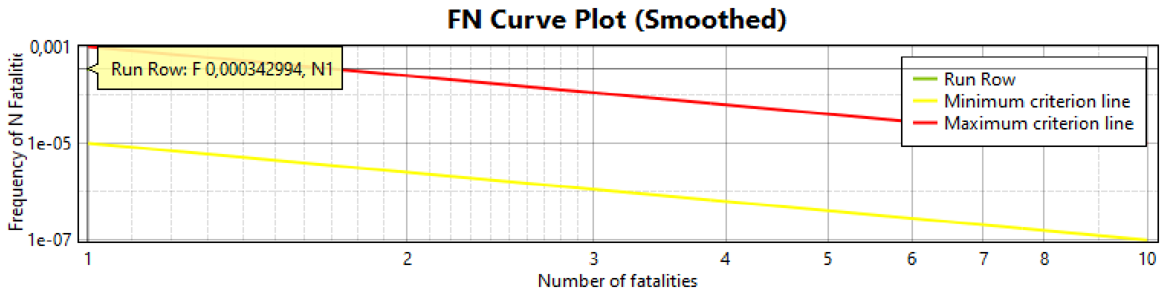
Case 5	
Case 6	

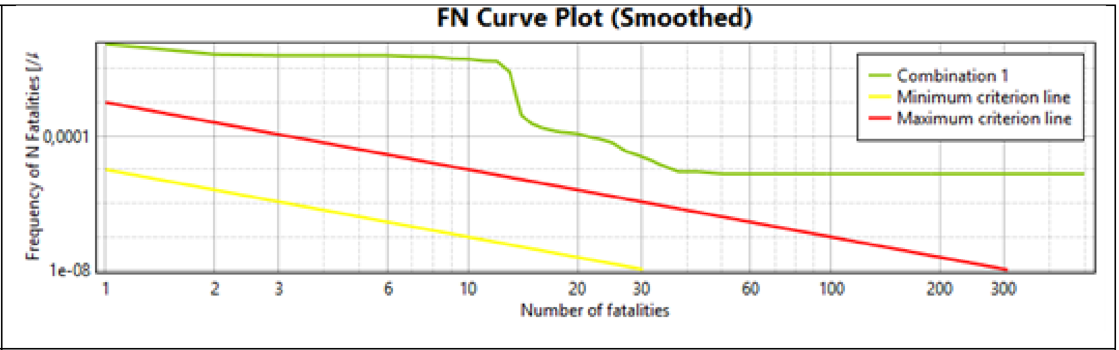
Table 22: Ammonia Frequencies and fatalities

Case AMMONIA	N	F (/AvgeYear)
1	1	8,22725E-05
2	1	7,8891E-05
3	1	1,07864E-05
4	1	7,89975E-05
5	1	5,36181E-05
6	1	0,000342994

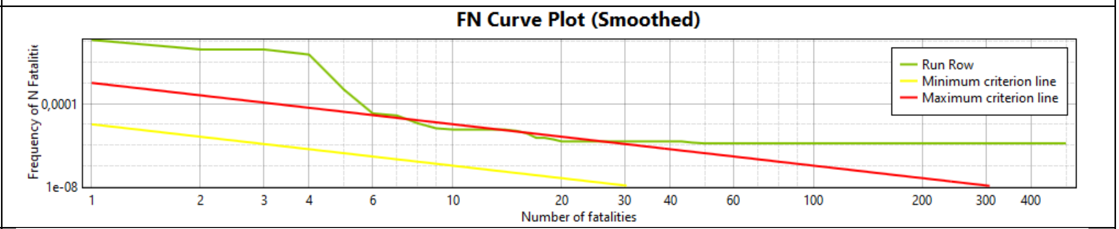
6.1.2 Hydrogen safety results

Table 23: Hydrogen FN curves

Case 7



Case 8



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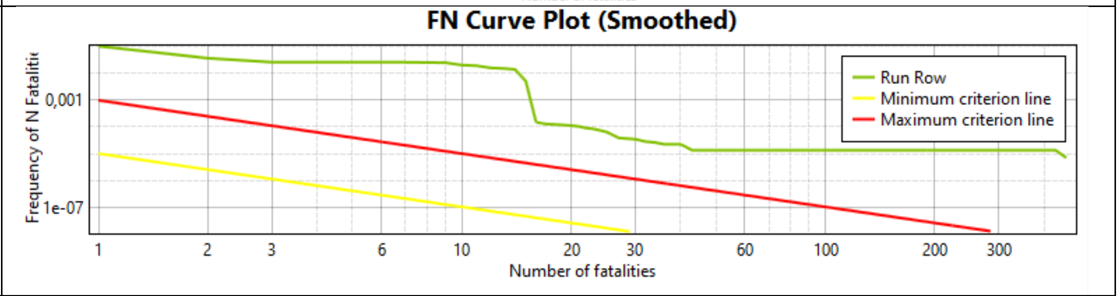

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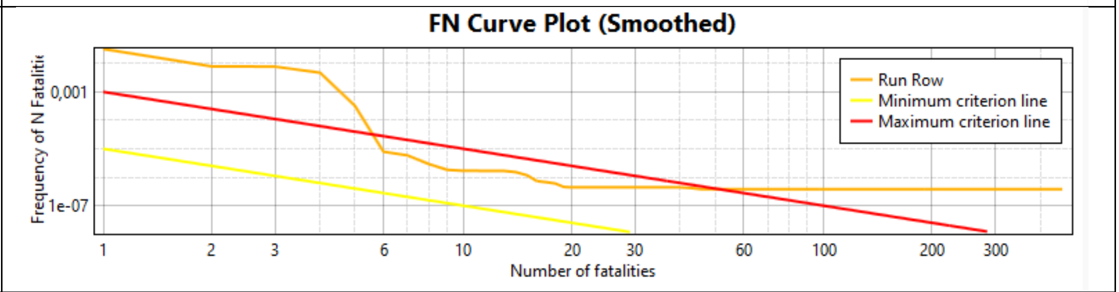

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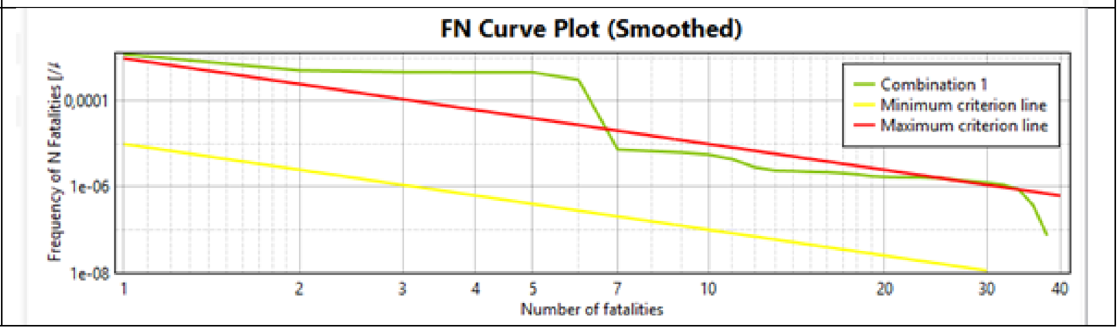

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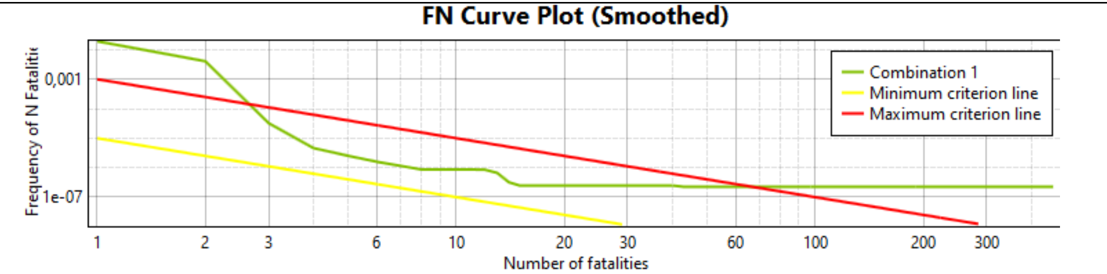
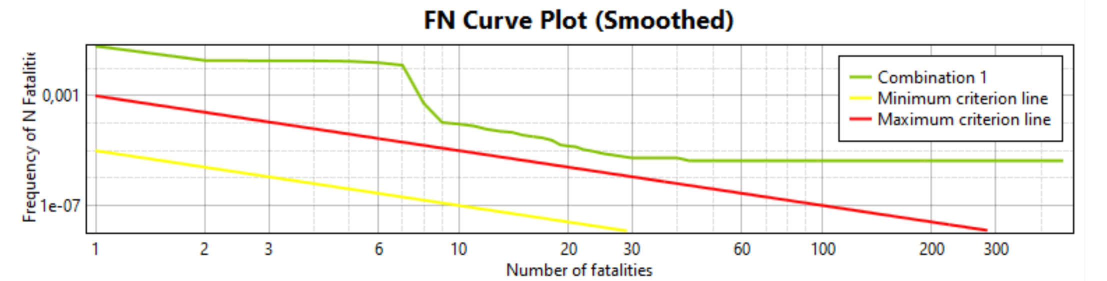


Case 13



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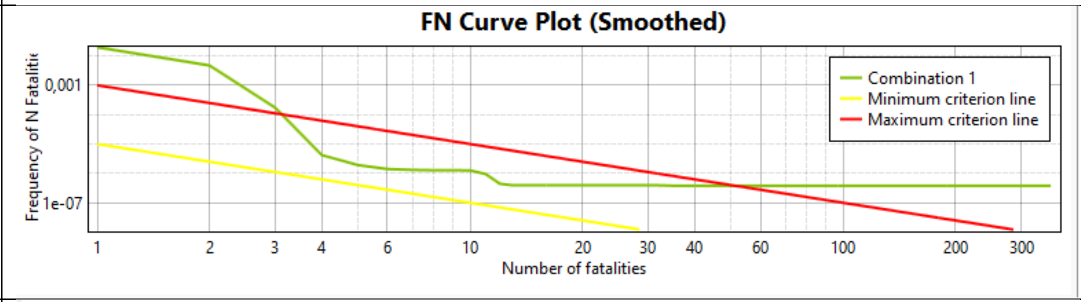

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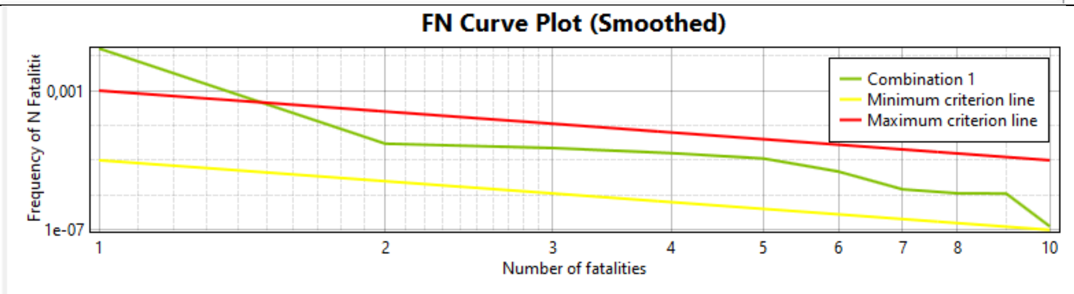
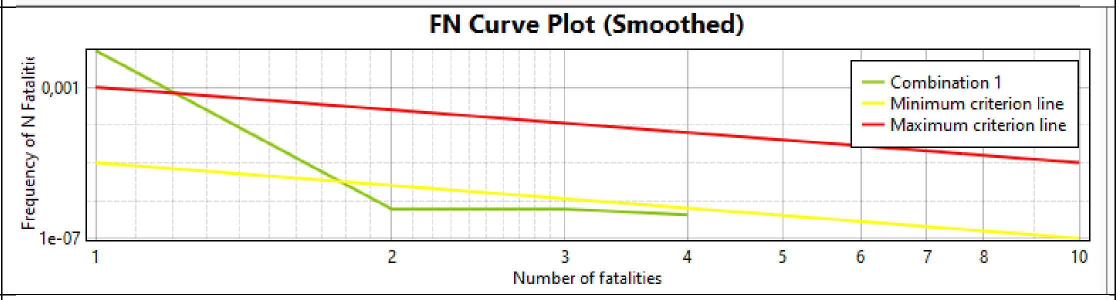
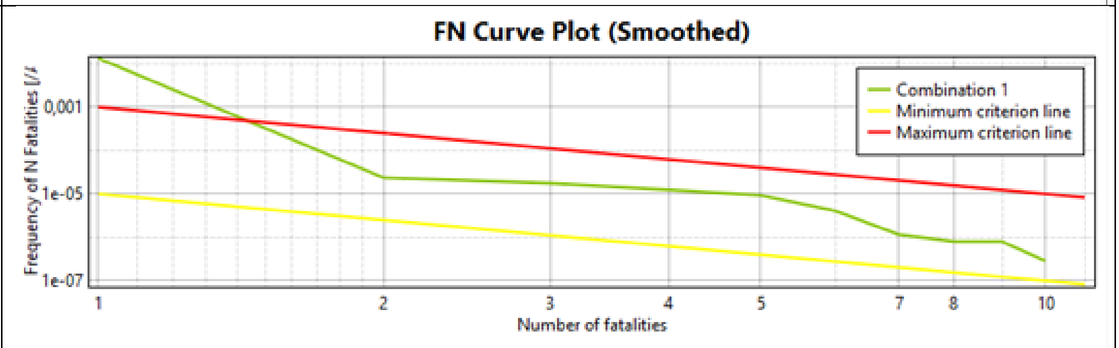


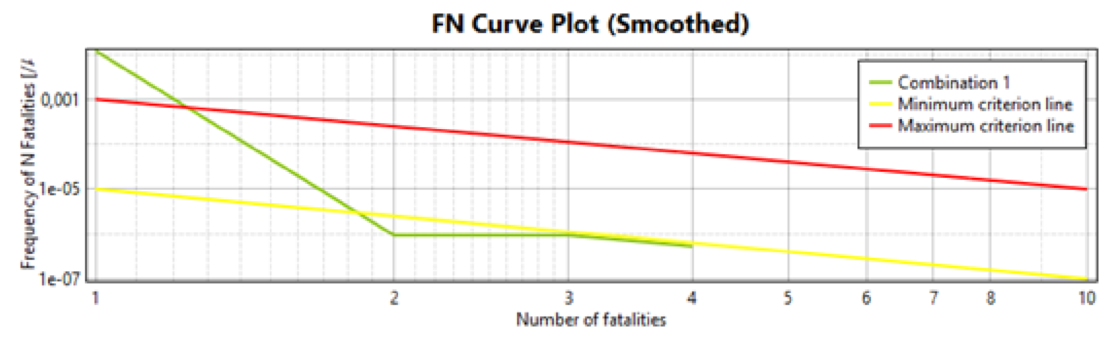
Case 16



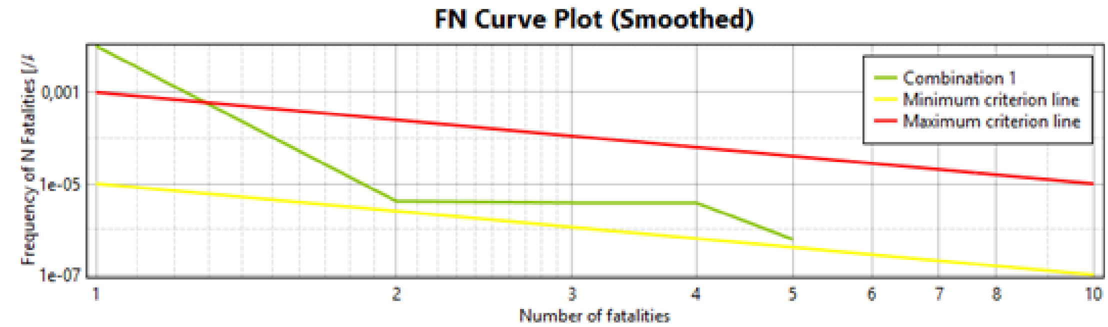
Case 17



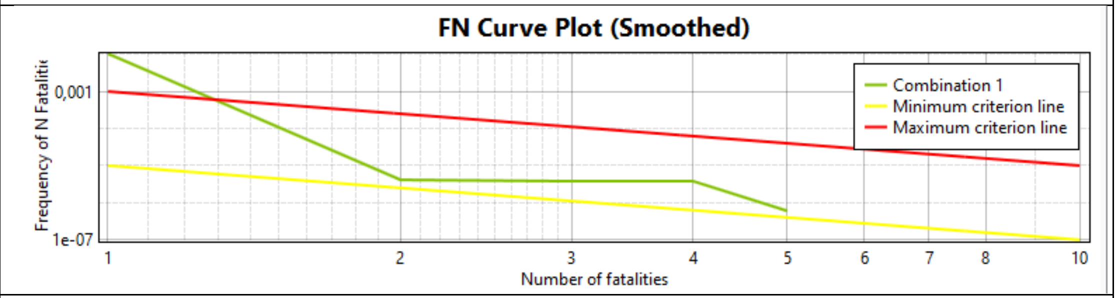
Case 18



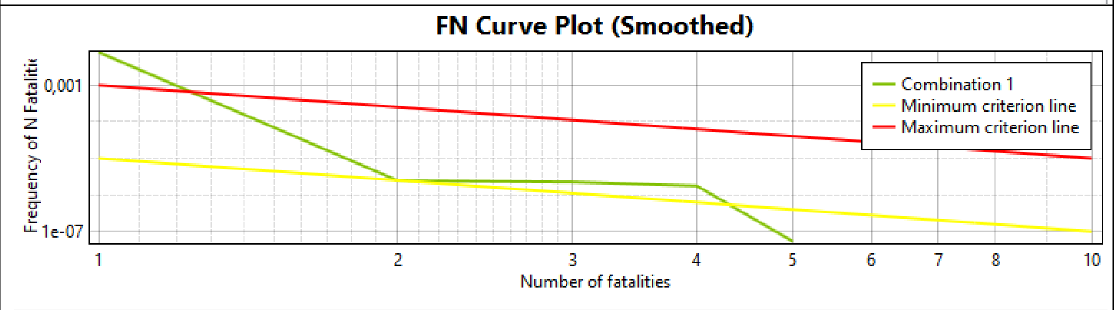
Case 19



Case 20



Case 21



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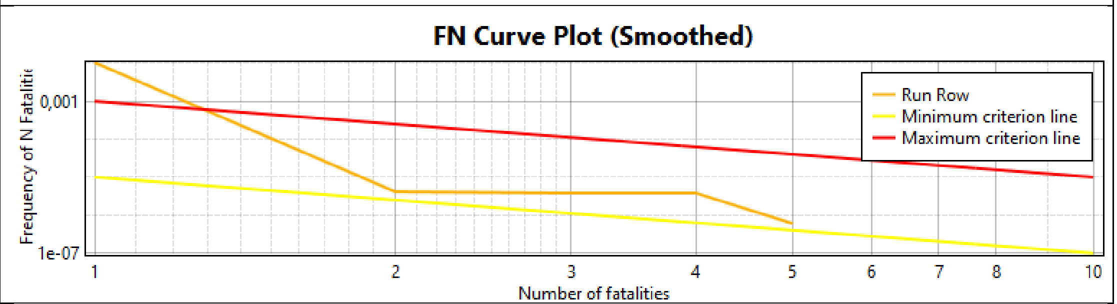

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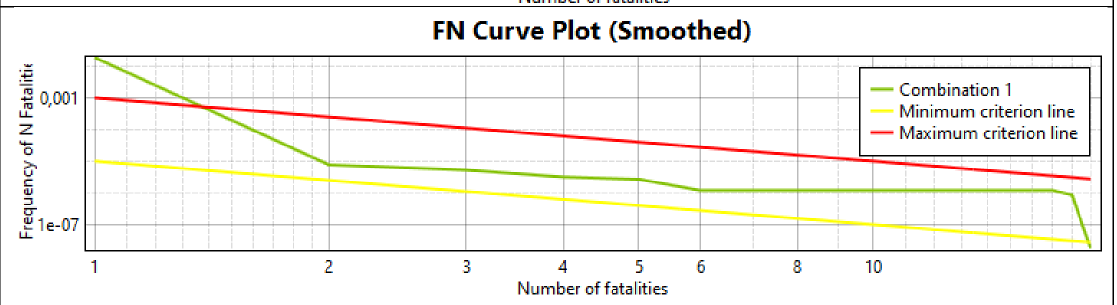

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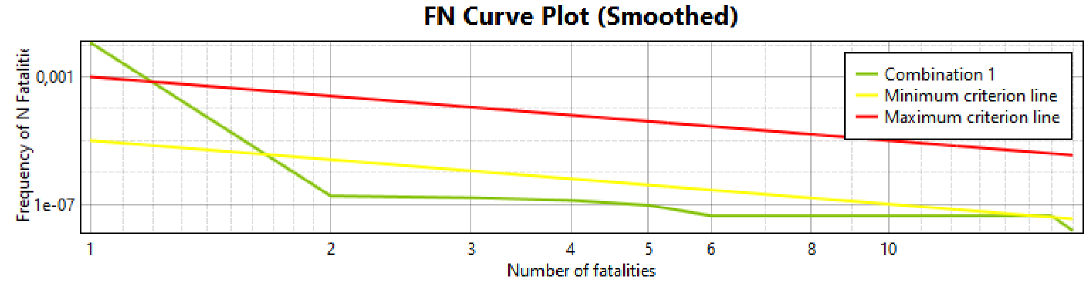
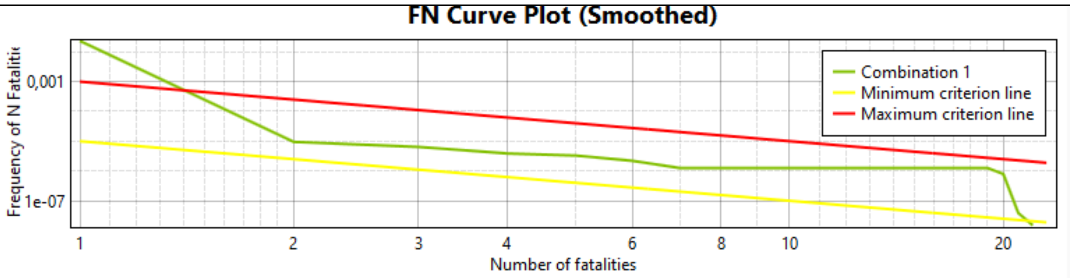
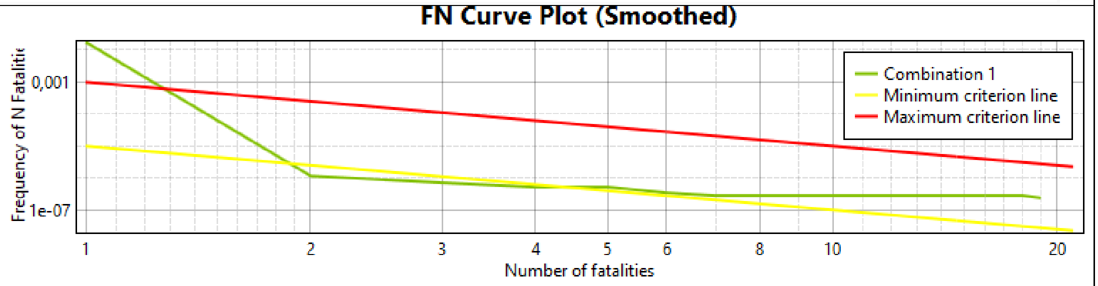


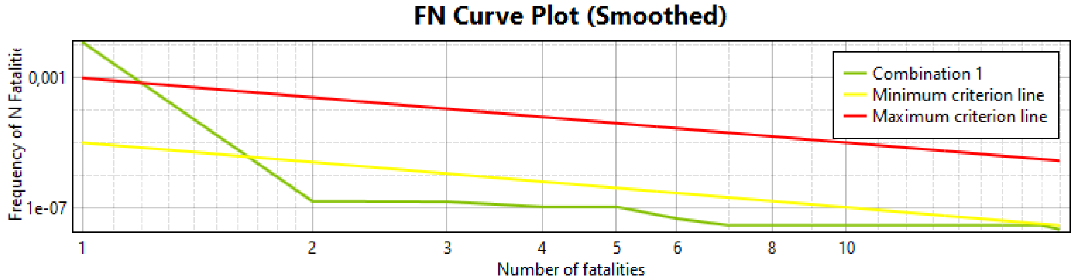
Case 25



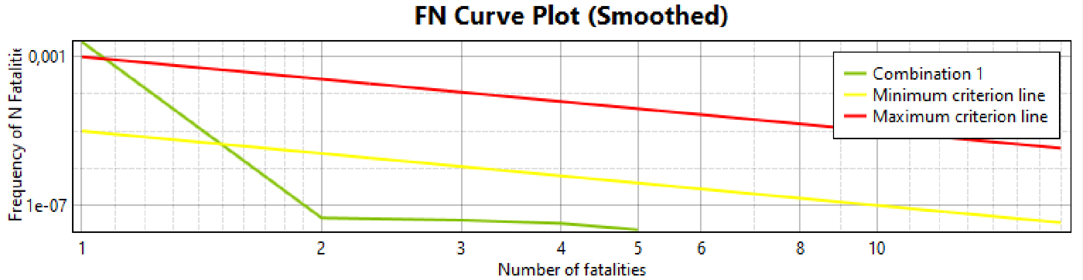
Case 26



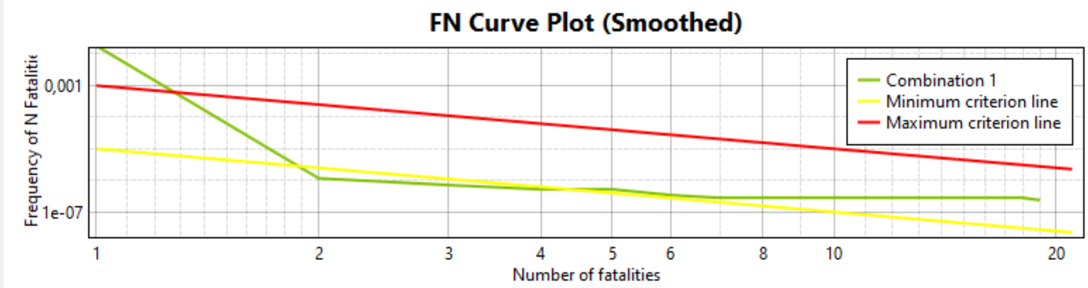
Case 27



Case 28



Case 29



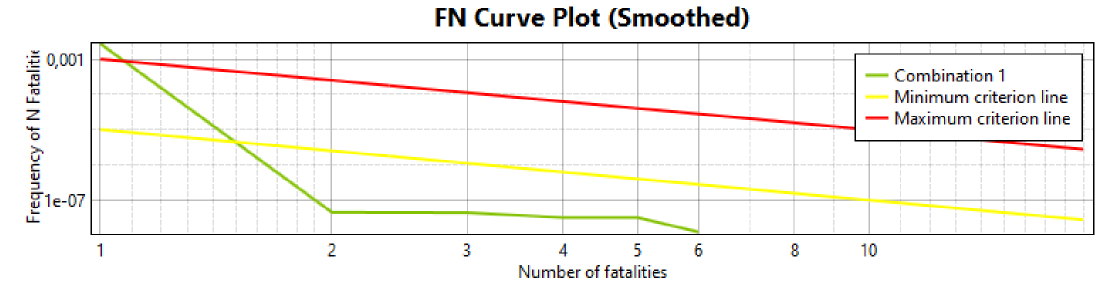
Case 30	FN Curve Plot (Smoothed) Frequency of N Fatalitie 0,001 1e-07 1 2 3 4 5 6 8 10 Number of fatalities Combination 1 Minimum criterion line Maximum criterion line

Table 24:frequencies and fatalities

Case 7		Case 8		Case 9		Case 10		Case 11		Case 12		Case 13		Case 14	
N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F	N	F(/AvgeYear)	N	F (/AvgeYear)
1	0,053275835	1	0,118227974	1	0,107398085	1	0,032157771	1	0,001239256	1	0,0193625	1	0,065260112	1	0,019624459
2	0,026759101	2	0,041042104	2	0,038181204	2	0,007867999	2	0,00052333	2	0,004084303	2	0,019460497	2	0,004739127
3	0,024918951	3	0,041018106	3	0,027163967	3	0,007708875	3	0,000478517	3	3,26632E-05	3	0,019103354	3	0,000173363
4	0,024766203	4	0,02330859	4	0,027049053	4	0,004717045	4	0,000469991	**4**	**4,63419E-06**	4	0,018962877	**4**	**4,21247E-06**
5	0,024759032	5	0,000467941	5	0,027021777	5	0,000321745	5	0,000469445	5	2,52896E-06	5	0,018314	5	1,92261E-06
6	0,024636636	6	3,36033E-05	6	0,026999189	**6**	**7,90545E-06**	6	0,000315277	6	1,59268E-06	6	0,016241023	6	1,41446E-06
7	0,023089349	7	2,66561E-05	7	0,026979005	7	5,86054E-06	**7**	**7,42924E-06**	7	1,15266E-06	7	0,013134877	7	1,31755E-06
8	0,022498971	8	1,11847E-05	8	0,026432384	8	2,94308E-06	8	6,85945E-06	8	8,69776E-07	8	0,000538864	8	1,28491E-06
9	0,019907178	**9**	**6,40107E-06**	9	0,025885072	9	1,83233E-06	9	6,35861E-06	9	8,69776E-07	9	0,00010679	9	1,28444E-06
10	0,01931286	10	5,60085E-06	10	0,021090509	10	1,68668E-06	10	5,67725E-06	10	8,69776E-07	10	9,37095E-05	10	1,26299E-06
11	0,017030908	11	5,60085E-06	11	0,019847399	11	1,68642E-06	11	4,43611E-06	11	8,69516E-07	11	7,94565E-05	11	9,54903E-07
12	0,016521402	12	5,60045E-06	12	0,016459772	12	1,68454E-06	12	2,87659E-06	12	8,56762E-07	12	5,96064E-05	12	4,45774E-07
13	0,007997998	13	5,59241E-06	13	0,015802631	13	1,66913E-06	13	2,40936E-06	13	6,68852E-07	13	5,08401E-05	13	3,93825E-07
14	0,00041099	14	5,51805E-06	14	0,014456199	14	1,50871E-06	14	2,34616E-06	14	3,21809E-07	14	4,6876E-05	14	3,93825E-07
15	0,000228525	15	4,83031E-06	15	0,00513363	15	1,18421E-06	15	2,26056E-06	15	2,49073E-07	15	3,67733E-05	15	3,93825E-07
16	0,000173701	16	3,73588E-06	16	0,000150818	16	7,31707E-07	16	2,20885E-06	16	2,49073E-07	16	3,25098E-05	16	3,93825E-07
17	0,000148178	17	2,24148E-06	17	0,000129929	17	6,70866E-07	17	2,09557E-06	17	2,49073E-07	17	2,92874E-05	17	3,93825E-07
18	0,000131211	18	2,2032E-06	18	0,000124506	18	6,03809E-07	18	1,95128E-06	18	2,49073E-07	18	2,41998E-05	18	3,93825E-07
19	0,00012472	19	1,86519E-06	19	0,000119403	19	4,56043E-07	19	1,77935E-06	19	2,49073E-07	19	1,62675E-05	19	3,93825E-07
20	0,000116369	20	1,49473E-06	20	0,000112928	20	4,41791E-07	20	1,71872E-06	20	2,49073E-07	20	1,46933E-05	20	3,93825E-07
21	0,000102072	21	1,49473E-06	21	0,0001046	21	4,41791E-07	21	1,69215E-06	21	2,49073E-07	21	1,38057E-05	21	3,93825E-07
22	8,8497E-05	22	1,49473E-06	22	9,097E-05	22	4,41791E-07	22	1,67625E-06	22	2,49073E-07	22	1,10246E-05	22	3,93825E-07
23	8,13942E-05	23	1,49473E-06	23	8,50885E-05	23	4,41791E-07	23	1,67019E-06	23	2,49073E-07	**23**	**9,94952E-06**	23	3,93825E-07

25	6,24445E-05	25	1,49473E-06	25	6,52586E-05	25	4,41791E-07	25	1,59818E-06	25	2,49073E-07	25	7,80441E-06	25	3,93825E-07
27	3,62975E-05	27	1,49473E-06	27	3,88753E-05	27	4,41791E-07	27	1,43001E-06	27	2,49073E-07	27	6,68666E-06	27	3,93825E-07
30	2,4686E-05	30	1,49473E-06	30	3,48041E-05	30	4,41791E-07	30	1,27578E-06	30	2,49073E-07	30	5,41397E-06	30	3,93825E-07
32	1,87088E-05	32	1,49473E-06	32	2,84559E-05	32	4,41791E-07	32	1,13018E-06	32	2,49073E-07	32	5,39966E-06	32	3,93825E-07
34	1,38003E-05	34	1,49473E-06	34	2,62037E-05	34	4,41791E-07	34	8,61292E-07	34	2,49073E-07	34	5,39966E-06	34	3,85849E-07
36	1,09392E-05	36	1,49473E-06	36	2,25431E-05	36	4,41791E-07	36	3,69245E-07	36	2,49073E-07	36	5,39966E-06	36	3,77929E-07
38	8,69226E-06	38	1,49473E-06	38	2,25282E-05	38	4,41791E-07	38	7,33992E-08	38	2,49073E-07	38	5,39966E-06	38	3,77929E-07
40	8,69226E-06	40	1,49473E-06	40	2,25282E-05	40	4,41791E-07	40	3,98105E-11	40	2,49073E-07	40	5,39966E-06	40	3,77929E-07
43	8,69226E-06	43	1,49473E-06	43	1,34015E-05	43	4,17772E-07			43	2,26405E-07	43	4,31432E-06	43	3,77929E-07
46	8,17032E-06	46	1,30964E-06	46	1,34015E-05	46	3,79843E-07			46	2,26405E-07	46	4,31432E-06	46	3,77929E-07
50	7,54473E-06	50	1,19329E-06	50	1,34015E-05	50	3,79843E-07			50	2,26405E-07	50	4,31432E-06	50	3,77929E-07
53	7,54473E-06	53	1,19329E-06	53	1,34015E-05	53	3,79843E-07			53	2,26405E-07	53	4,31432E-06	53	3,77929E-07
56	7,54473E-06	56	1,19329E-06	56	1,34015E-05	56	3,79843E-07			56	2,26405E-07	56	4,31432E-06	56	3,77929E-07
60	7,54473E-06	60	1,19329E-06	60	1,34015E-05	60	3,79843E-07			60	2,26405E-07	60	4,31432E-06	60	3,77929E-07
63	7,54473E-06	63	1,19329E-06	63	1,34015E-05	63	3,79843E-07			63	2,26405E-07	63	4,31432E-06	63	3,77929E-07
66	7,54473E-06	66	1,19329E-06	66	1,34015E-05	66	3,79843E-07			66	2,26405E-07	66	4,31432E-06	66	3,77929E-07
69	7,54473E-06	69	1,19329E-06	69	1,34015E-05	69	3,79843E-07			69	2,26405E-07	69	4,31432E-06	69	3,77929E-07
73	7,54473E-06	73	1,19329E-06	73	1,34015E-05	73	3,79843E-07			73	2,26405E-07	73	4,31432E-06	73	3,77929E-07
77	7,54473E-06	77	1,19329E-06	77	1,34015E-05	77	3,79843E-07			77	2,26405E-07	77	4,31432E-06	77	3,77929E-07
80	7,54473E-06	80	1,19329E-06	80	1,34015E-05	80	3,79843E-07			80	2,26405E-07	80	4,31432E-06	80	3,77929E-07
87	7,54473E-06	87	1,19329E-06	87	1,34015E-05	87	3,79843E-07			87	2,26405E-07	87	4,31432E-06	87	3,77929E-07
90	7,54473E-06	90	1,19329E-06	90	1,34015E-05	90	3,79843E-07			90	2,26405E-07	90	4,31432E-06	90	3,77929E-07
97	7,54473E-06	97	1,19329E-06	97	1,34015E-05	97	3,79843E-07			97	2,26405E-07	97	4,31432E-06	97	3,77929E-07
100	7,54473E-06	100	1,19329E-06	100	1,34015E-05	100	3,79843E-07			100	2,26405E-07	100	4,31432E-06	100	3,77929E-07
105	7,54473E-06	105	1,19329E-06	105	1,34015E-05	105	3,79843E-07			105	2,26405E-07	105	4,31432E-06	105	3,77929E-07
110	7,54473E-06	110	1,19329E-06	110	1,34015E-05	110	3,79843E-07			110	2,26405E-07	110	4,31432E-06	110	3,77929E-07

115	7,54473E-06	115	1,19329E-06	115	1,34015E-05	115	3,79843E-07			115	2,26405E-07	115	4,31432E-06	115	3,77929E-07
120	7,54473E-06	120	1,19329E-06	120	1,34015E-05	120	3,79843E-07			120	2,26405E-07	120	4,31432E-06	120	3,77929E-07
125	7,54473E-06	125	1,19329E-06	125	1,34015E-05	125	3,79843E-07			125	2,26405E-07	125	4,31432E-06	125	3,77929E-07
130	7,54473E-06	130	1,19329E-06	130	1,34015E-05	130	3,79843E-07			130	2,26405E-07	130	4,31432E-06	130	3,77929E-07
135	7,54473E-06	135	1,19329E-06	135	1,34015E-05	135	3,79843E-07			135	2,26405E-07	135	4,31432E-06	135	3,77929E-07
140	7,54473E-06	140	1,19329E-06	140	1,34015E-05	140	3,79843E-07			140	2,26405E-07	140	4,31432E-06	140	3,77929E-07
145	7,54473E-06	145	1,19329E-06	145	1,34015E-05	145	3,79843E-07			145	2,26405E-07	145	4,31432E-06	145	3,77929E-07
150	7,54473E-06	150	1,19329E-06	150	1,34015E-05	150	3,79843E-07			150	2,26405E-07	150	4,31432E-06	150	3,77929E-07
160	7,54473E-06	160	1,19329E-06	160	1,34015E-05	160	3,79843E-07			160	2,26405E-07	160	4,31432E-06	160	3,77929E-07
170	7,54473E-06	170	1,19329E-06	170	1,34015E-05	170	3,79843E-07			170	2,26405E-07	170	4,31432E-06	170	3,77929E-07
180	7,54473E-06	180	1,19329E-06	180	1,34015E-05	180	3,79843E-07			180	2,26405E-07	180	4,31432E-06	180	3,77929E-07
190	7,54473E-06	190	1,19329E-06	190	1,34015E-05	190	3,79843E-07			190	2,26405E-07	190	4,31432E-06	190	3,77929E-07
200	7,54473E-06	200	1,19329E-06	200	1,34015E-05	200	3,79843E-07			200	2,26405E-07	200	4,31432E-06	200	3,77929E-07
210	7,54473E-06	210	1,19329E-06	210	1,34015E-05	210	3,79843E-07			210	2,26405E-07	210	4,31432E-06	210	3,77929E-07
220	7,54473E-06	220	1,19329E-06	220	1,34015E-05	220	3,79843E-07			220	2,26405E-07	220	4,31432E-06	220	3,77929E-07
230	7,54473E-06	230	1,19329E-06	230	1,34015E-05	230	3,79843E-07			230	2,26405E-07	230	4,31432E-06	230	3,77929E-07
250	7,54473E-06	250	1,19329E-06	250	1,34015E-05	250	3,79843E-07			250	2,26405E-07	250	4,31432E-06	250	3,77929E-07
270	7,54473E-06	270	1,19329E-06	270	1,34015E-05	270	3,79843E-07			270	2,26405E-07	270	4,31432E-06	270	3,77929E-07
300	7,54473E-06	300	1,19329E-06	300	1,34015E-05	300	3,79843E-07			300	2,26405E-07	300	4,31432E-06	300	3,77929E-07
320	7,54473E-06	320	1,19329E-06	320	1,34015E-05	320	3,79843E-07			320	2,26405E-07	320	4,31432E-06	320	3,77929E-07
340	7,54473E-06	340	1,19329E-06	340	1,34015E-05	340	3,79843E-07			340	2,26405E-07	340	4,31432E-06	340	3,77929E-07
360	7,54473E-06	360	1,19329E-06	360	1,34015E-05	360	3,79843E-07			360	2,26405E-07	360	4,31432E-06	360	3,77929E-07
380	7,54473E-06	380	1,19329E-06	380	1,34015E-05	380	3,79843E-07			380	2,26405E-07	380	4,31432E-06		
400	7,54473E-06	400	1,19329E-06	400	1,34015E-05	400	3,79843E-07			400	2,26405E-07	400	4,31432E-06		
430	7,54473E-06	430	1,19329E-06	430	1,34015E-05	430	3,79843E-07			430	2,26405E-07	430	4,31432E-06		
460	7,54473E-06	460	1,19329E-06	460	**7,00093E-06**	460	3,79843E-07			460	2,26405E-07	460	4,31432E-06		

500	7,54473E-06	500	1,19329E-06

Table 25:frequencies and fatalities

Case 15		Case 16		Case 17		Case 18		Case 19		Case 20		Case 21		Case 22	
N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)
1	0,01620842	1	0,009247637	1	0,013157848	1	0,011968218	1	0,01036374	1	0,01036374	1	0,00789226	1	0,01036374
2	2,97843E-05	**2**	**5,93429E-07**	2	2,35347E-05	**2**	**9,29198E-07**	**2**	**4,11749E-06**	**2**	**4,11749E-06**	**2**	**2,45632E-06**	**2**	**4,11749E-06**
3	2,23425E-05	3	5,92809E-07	3	1,75199E-05	3	9,28724E-07	3	3,79785E-06	3	3,79785E-06	3	2,24098E-06	3	3,79785E-06
4	1,60127E-05	4	4,15246E-07	4	1,24234E-05	4	5,31144E-07	4	3,78974E-06	4	3,78974E-06	4	1,76889E-06	4	3,78974E-06
5	1,11977E-05			**5**	**9,26002E-06**			5	5,98403E-07	5	5,98403E-07	5	5,33136E-08	5	5,98403E-07
6	**4,69548E-06**			6	4,07295E-06							6	3,32057E-09		
7	1,45875E-06			7	1,15961E-06							7	3,32057E-09		
8	1,12388E-06			8	8,02569E-07							8	1,7656E-09		
9	1,10381E-06			9	7,97534E-07										
10	1,26291E-07			10	2,86815E-07										
				11	4,98699E-11										

Table 26: Frequencies and fatalities

Case 23		Case 24		Case 25		Case 26		Case 27		Case 28		Case 29		Case 30	
N	F (/AvgeYear	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)	N	F (/AvgeYear)
1	0,018887211	1	0,012011016	1	0,023374518	1	0,017826157	1	0,012997817	1	0,002491407	1	0,017826157	1	0,002698108
2	**7,65828E-06**	**2**	**1,82522E-07**	**2**	**9,49491E-06**	**2**	**1,16127E-06**	**2**	**1,55676E-07**	**2**	**4,632E-08**	**2**	**1,16127E-06**	**2**	**4,51791E-08**
3	5,26291E-06	3	1,59103E-07	3	6,40066E-06	3	7,11866E-07	3	1,5057E-07	3	4,01559E-08	3	7,11866E-07	3	4,41201E-08
4	3,15834E-06	4	1,31346E-07	4	3,87914E-06	4	5,22924E-07	4	1,03811E-07	4	3,27677E-08	4	5,22924E-07	4	3,19827E-08

5	2,69E-06	5	9,20678E-08	5	3,29794E-06	5	5,22911E-07	5	1,03294E-07	5	2,22734E-08	5	5,22911E-07	5	3,18695E-08
6	1,20023E-06	6	4,31782E-08	6	2,19706E-06	6	3,42162E-07	6	4,48417E-08	6	9,2112E-09	6	3,42162E-07	6	1,25035E-08
7	1,20023E-06	7	4,31782E-08	7	1,25968E-06	7	2,81505E-07	7	2,79129E-08	7	9,2112E-09	7	2,81505E-07	7	6,89474E-09
8	1,20023E-06	8	4,31782E-08	8	1,25966E-06	8	2,81505E-07	8	2,79129E-08	8	9,2112E-09	8	2,81505E-07	8	6,89474E-09
9	1,20017E-06	9	4,31782E-08	9	1,25966E-06	9	2,81505E-07	9	2,79129E-08	9	9,2112E-09	9	2,81505E-07	9	6,89474E-09
10	1,2E-06	10	4,31782E-08	10	1,2595E-06	10	2,81505E-07	10	2,79129E-08	10	9,2112E-09	10	2,81505E-07	10	6,89474E-09
11	1,2E-06	11	4,31782E-08	11	1,25941E-06	11	2,81505E-07	11	2,79129E-08	11	9,2112E-09	11	2,81505E-07	11	6,89474E-09
12	1,19976E-06	12	4,31782E-08	12	1,25941E-06	12	2,81505E-07	12	2,79129E-08	12	9,2112E-09	12	2,81505E-07	12	6,89474E-09
13	1,19911E-06	13	4,31782E-08	13	1,25941E-06	13	2,81505E-07	13	2,79129E-08	13	9,2112E-09	13	2,81505E-07	13	6,89474E-09
14	1,19911E-06	14	4,31782E-08	14	1,25941E-06	14	2,81505E-07	14	2,79129E-08	14	9,2112E-09	14	2,81505E-07	14	6,89474E-09
15	1,1991E-06	15	4,31782E-08	15	1,25906E-06	15	2,81505E-07	15	2,79129E-08	15	9,2112E-09	15	2,81505E-07	15	6,89474E-09
16	1,1991E-06	16	4,31782E-08	16	1,25836E-06	16	2,81505E-07	16	2,79129E-08	16	9,2112E-09	16	2,81505E-07	16	6,89474E-09
17	1,1991E-06	17	1,47942E-08	17	1,25836E-06	17	2,81505E-07	17	2,79129E-08	17	3,15605E-09	17	2,81505E-07	17	6,89474E-09
18	8,59327E-07			18	1,25835E-06	18	2,81505E-07	18	2,79129E-08			18	2,81505E-07	18	6,89474E-09
19	1,81943E-08			19	1,25683E-06	19	2,37592E-07	19	2,08511E-08			19	2,37592E-07	19	5,15043E-09
				20	7,90844E-07	20	1,32873E-09					20	1,32873E-09		
				21	3,85267E-08	21	4,61592E-10					21	4,61592E-10		
				22	1,50242E-08										
				23	6,17278E-10										

Most of the solutions are out of the tolerable line for the societal risk used to evaluate the acceptance in this work. As reported in the "Indicative Societal Risk Curve for Road Transportation and Storage" figure n° 29 by Integrated design for demonstration of efficient liquefaction of hydrogen (IDEALHY), tolerable zone for liquid hydrogen transportation and storage starts at 10^{-4} , incentivised by me in relation to the English legislation to 10^{-6} to generalize the transportation. All the remaining curve points that exceed this deadline have to be mitigated. Mitigation measures could be preventative and ameliorative.

Preventative measures could include:

" • Good design in general

- Well designed vent system
- Process monitoring (pressure, temperature, gas concentration)
- Safety detection systems for leaks
- Robust procedures and staff training
- Inter-locks to prevent non-compliance with procedures
- Minimum sizing of vulnerable components, such as transfer hoses.

Ameliorative measures include the use of fire-fighting systems or fire/blast walls although care needs to be taken to ensure that mitigation of one hazard does not increase the severity of another – for example, the use of confining walls may reduce a fire hazard beyond the wall but its presence may increase the likelihood of gas accumulation and the severity of an explosion. The use of bunds around storage tanks will extend the duration of certain hazardous events (such as fires) but will reduce the hazard range and it is expected that bunding of large storage tanks would be undertaken."

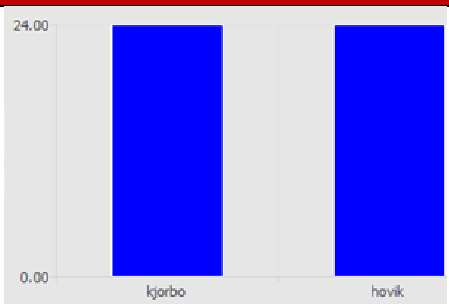
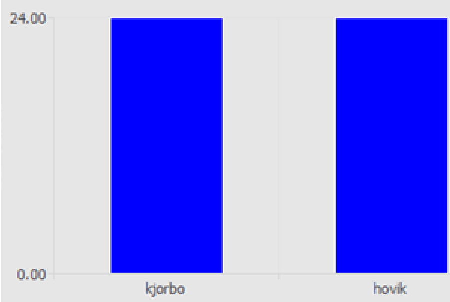
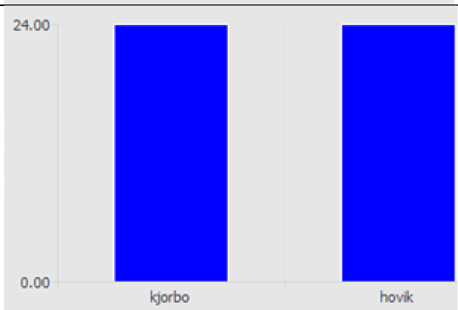
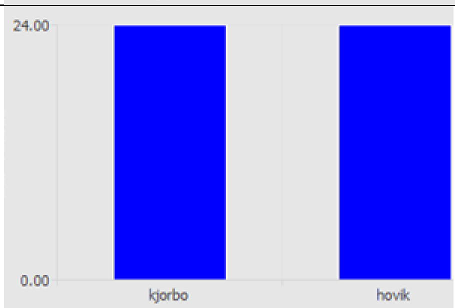
(IDEALHY)

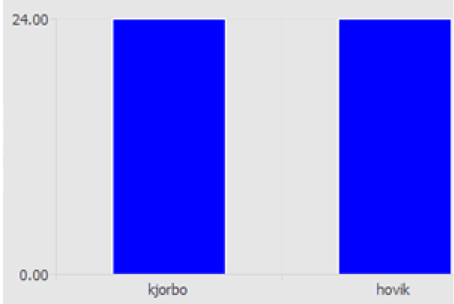
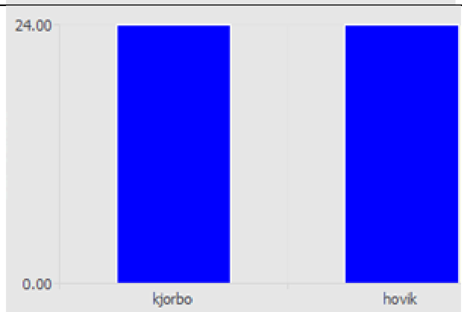
6.2 Exstendsim results

6.2.1 Ammonia trucks

The trucks studied for ammonia delivery have same quantity of the carrier so the number of vehicles does not change, but the cost will be different between routes. It depends on the amount of kilometres whose the route is made. Knowing the process for ammonia, with a good extrapolation efficiency, 18% pure hydrogen can be obtained. Calculating this percentage from the 30,000 kg of ammonia stored, result is 5400 kg of H2 in a stationary tank. With the same procedure 45000 litres transported, equal to 30717 kg, will become an amount of 5529.06 kg of H2 in delivery per truck.

Table 27: Trucks and costs for Ammonia

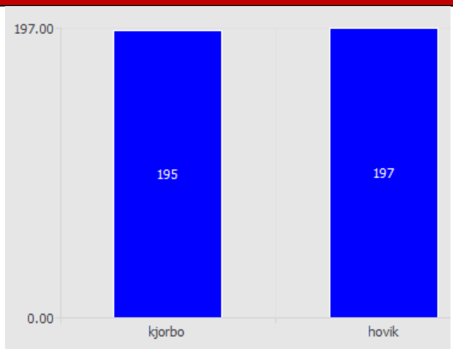
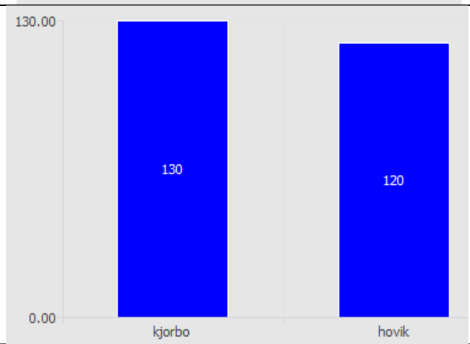
<table>
<tr><th>CASE</th><th>NUMBER OF TRUCKS</th><th>COST of TRANSPORT</th></tr>
<tr><td>1</td><td>
</td><td>$$To\ Kjørbo = 0{,}61\frac{EUR}{km} \times 12{,}5km = \mathbf{7,63\ EUR}$$
$$To\ Høvik = 0{,}61\frac{EUR}{km} \times 10{,}5km = \mathbf{6,41\ EUR}$$</td></tr>
<tr><td>2</td><td>
</td><td>$$To\ Kjørbo = 0{,}61\frac{EUR}{km} \times 16{,}2\ km = \mathbf{9,88\ EUR}$$
$$To\ Høvik = 0{,}36\frac{EUR}{km} \times 14{,}2km = \mathbf{8,66\ EUR}$$</td></tr>
<tr><td>3</td><td>
</td><td>$$To\ Kjørbo = 0{,}61\frac{EUR}{km} \times 94km = \mathbf{57,34\ EUR}$$
$$To\ Høvik = 0{,}61\frac{EUR}{km} \times 109km = \mathbf{66,49\ EUR}$$</td></tr>
<tr><td>4</td><td>
</td><td>$$To\ Kjørbo = 0{,}61\frac{EUR}{km} \times 104km = \mathbf{63,44\ EUR}$$
$$To\ Høvik = 0{,}61\frac{EUR}{km} \times 119km = \mathbf{72,59\ EUR}$$</td></tr>
</table>

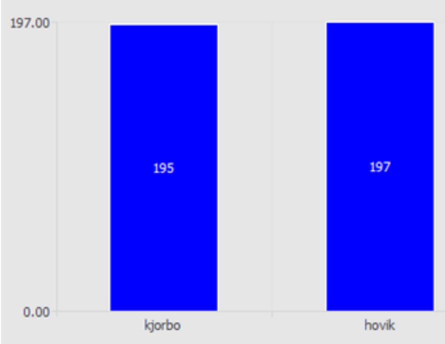
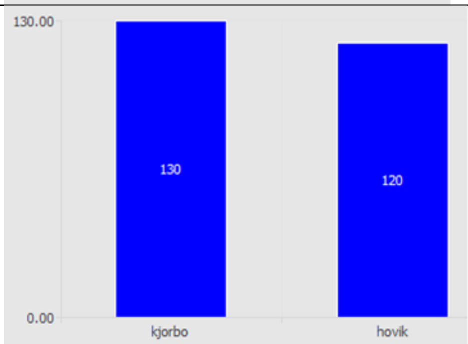
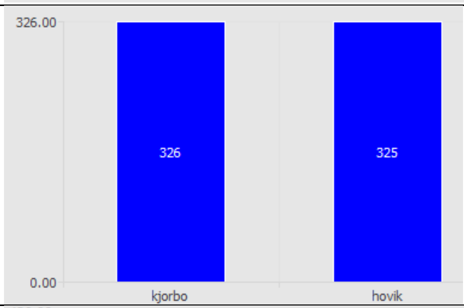
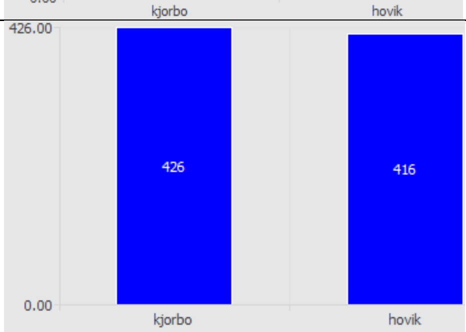
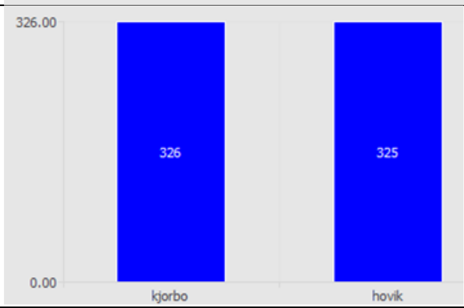
5		$To\ Kjørbo = 0{,}61 \frac{EUR}{km} \times 471km = \mathbf{287,31\ EUR}$ $To\ Høvik = 0{,}61 \frac{EUR}{km} \times 473km = \mathbf{288,53 EUR}$
6		$To\ Kjørbo = 0{,}61 \frac{EUR}{km} \times 543km = \mathbf{331,23\ EUR}$ $To\ Høvik = 0{,}61 \frac{EUR}{km} \times 545km = \mathbf{332,45\ EUR}$

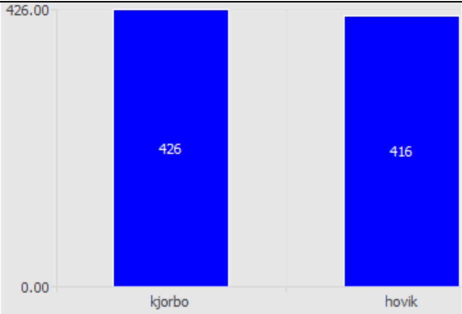
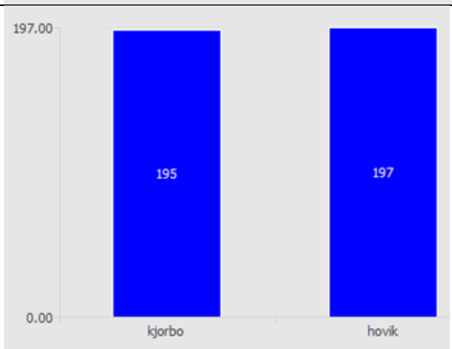
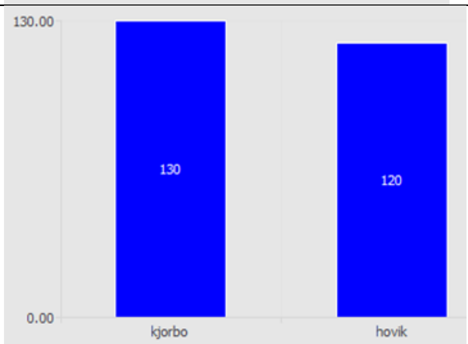
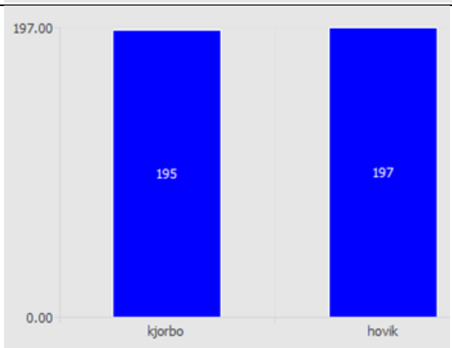
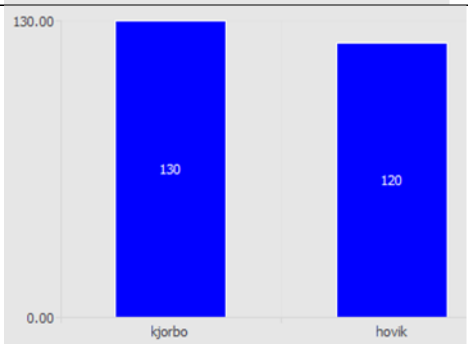
6.2.2 Hydrogen trucks

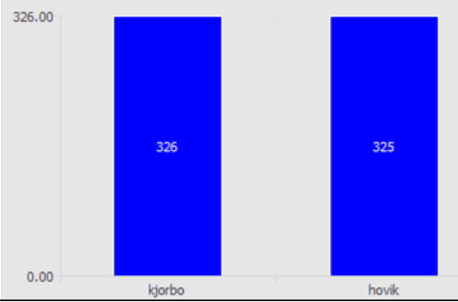
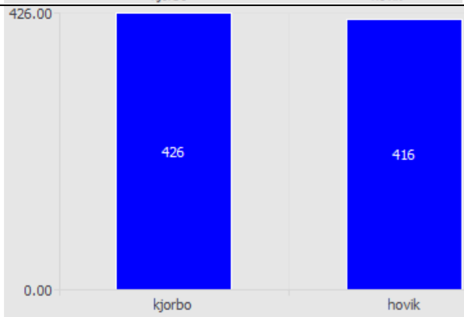
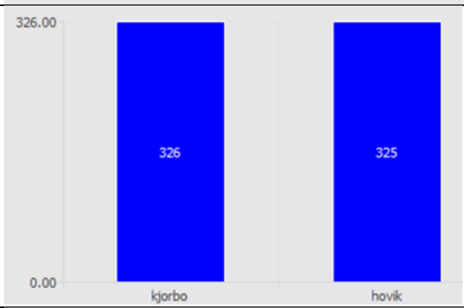
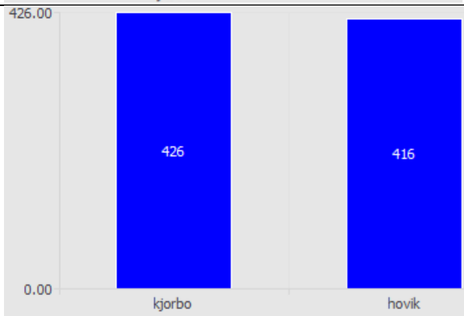
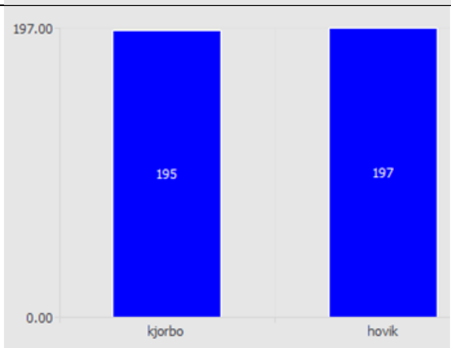
In the beginning of hydrogen market place the study from Hyundai could not describe the reality: 24h/day is a goal not yet got for the normal stations in Norway. Uno-X stations, closed few months ago, worked for 8 h/day. The reason is the necessary depressurization of the compressor after a fixed number of cycles. To simulate this condition, I will insert in the program the mentioned frequency of arrivals (10 cars/h) for 8 h/day which means on 24 hours a frequency of 3,33 car/h.

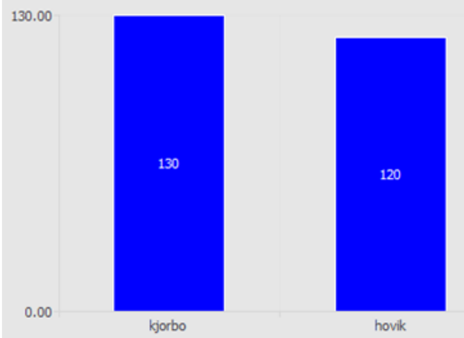
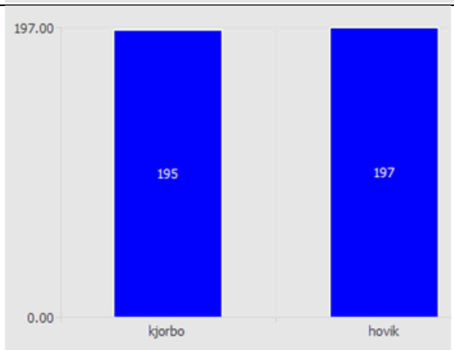
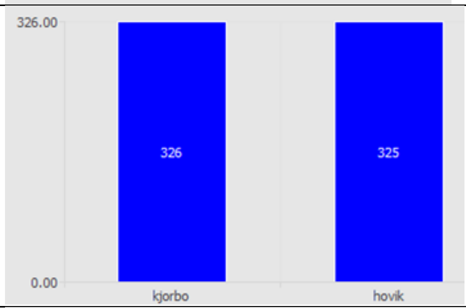
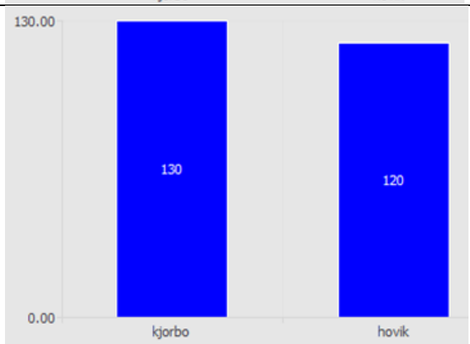
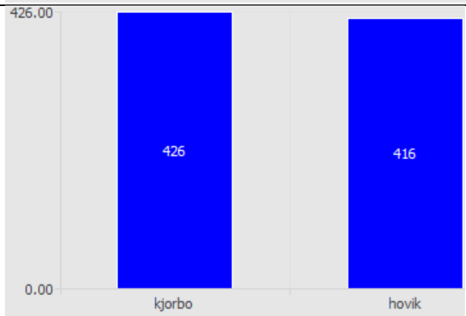
Table 28: trucks and costs for hydrogen

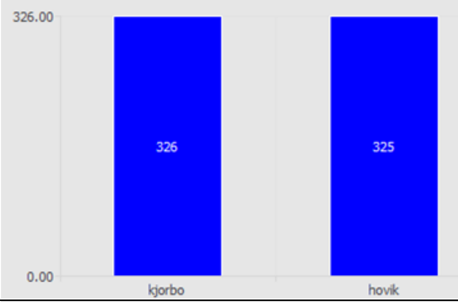
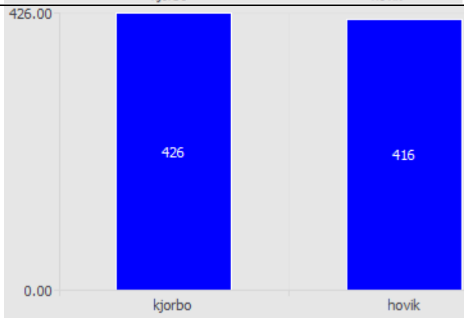
CASE	NUMBER OF TRUCKS	COST of TRANSPORT
7		$To\ Kjørbo = 0{,}36 \frac{EUR}{km} \times 760km = \mathbf{273,60\ EUR}$ $To\ Høvik = 0{,}36 \frac{EUR}{km} \times 775km = \mathbf{279\ EUR}$
8		$To\ Kjørbo = 0{,}36 \frac{EUR}{km} \times 760km = \mathbf{273,60\ EUR}$ $To\ Høvik = 0{,}36 \frac{EUR}{km} \times 775km = \mathbf{279\ EUR}$

9		$To\ Kjørbo = 0{,}36 \frac{EUR}{km} \times 770km = \mathbf{277,20\ EUR}$ $To\ Høvik = 0{,}36 \frac{EUR}{km} \times 785km = \mathbf{282,60\ EUR}$
10		$To\ Kjørbo = 0{,}36 \frac{EUR}{km} \times 770km = \mathbf{277,20\ EUR}$ $To\ Høvik = 0{,}36 \frac{EUR}{km} \times 785km = \mathbf{282,60\ EUR}$
11		$To\ Kjørbo = 0{,}36 \frac{EUR}{km} \times 760km = \mathbf{273,60\ EUR}$ $To\ Høvik = 0{,}36 \frac{EUR}{km} \times 775km = \mathbf{279\ EUR}$
12		$To\ Kjørbo = 0{,}36 \frac{EUR}{km} \times 760km = \mathbf{273,60\ EUR}$ $To\ Høvik = 0{,}36 \frac{EUR}{km} \times 775km = \mathbf{279\ EUR}$
13		$To\ Kjørbo = 0{,}36 \frac{EUR}{km} \times 770km = \mathbf{277,20\ EUR}$ $To\ Høvik = 0{,}36 \frac{EUR}{km} \times 785km = \mathbf{282,60\ EUR}$

14		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 770km = \mathbf{277,20\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 785km = \mathbf{282,60\ EUR}$
15		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 145km = \mathbf{52,20\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 160km = \mathbf{57,60\ EUR}$
16		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 145km = \mathbf{52,20\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 160km = \mathbf{57,60\ EUR}$
17		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 123km = \mathbf{44,28\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 138km = \mathbf{49,68\ EUR}$
18		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 123km = \mathbf{44,28\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 138km = \mathbf{49,68\ EUR}$

19		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 145km = \mathbf{52,20\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 160km = \mathbf{57,60\ EUR}$
20		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 145km = \mathbf{52,20\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 160km = \mathbf{57,60\ EUR}$
21		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 123km = \mathbf{44,28\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 138km = \mathbf{49,68\ EUR}$
22		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 123km = \mathbf{44,28\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 138km = \mathbf{49,68\ EUR}$
23		$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 336km = \mathbf{120,96\ EUR}$ $To\ Høvik = 0{,}36\frac{EUR}{km} \times 351km = \mathbf{126,36\ EUR}$

<table>
<tr><td>24</td><td>
</td><td>$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 336km = \mathbf{120,96\ EUR}$
$To\ Høvik = 0{,}36\frac{EUR}{km} \times 351km = \mathbf{126,36\ EUR}$</td></tr>
<tr><td>25</td><td>
</td><td>$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 363km = \mathbf{130,68\ EUR}$
$To\ Høvik = 0{,}36\frac{EUR}{km} \times 378km = \mathbf{136,08\ EUR}$</td></tr>
<tr><td>26</td><td>
</td><td>$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 336km = \mathbf{120,96\ EUR}$
$To\ Høvik = 0{,}36\frac{EUR}{km} \times 351km = \mathbf{126,36\ EUR}$</td></tr>
<tr><td>27</td><td>
</td><td>$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 363km = \mathbf{130,68\ EUR}$
$To\ Høvik = 0{,}36\frac{EUR}{km} \times 378km = \mathbf{136,08\ EUR}$</td></tr>
<tr><td>28</td><td>
</td><td>$To\ Kjørbo = 0{,}36\frac{EUR}{km} \times 336km = \mathbf{120,96\ EUR}$
$To\ Høvik = 0{,}36\frac{EUR}{km} \times 351km = \mathbf{126,36\ EUR}$</td></tr>
</table>

29		$To\ Kjørbo = 0{,}36\dfrac{EUR}{km} \times 363km = \mathbf{130,68\ EUR}$ $To\ Høvik = 0{,}36\dfrac{EUR}{km} \times 378km = \mathbf{136,08\ EUR}$
30		$To\ Kjørbo = 0{,}36\dfrac{EUR}{km} \times 363km = \mathbf{130,68\ EUR}$ $To\ Høvik = 0{,}36\dfrac{EUR}{km} \times 378km = \mathbf{136,08\ EUR}$

Chapter 7

Optimization

Optimization is the achievement of the most advantageous possible result with data terms and in relation to a specific purpose. In my case, the chosen data were related to the state of the art for quantity of road transport, possible supply sources at various cardinal points designated as starting ones and data related to the study location. As far as intention is concerned, in this thesis safety in transportation of hydrogen or its carriers is sought combined with its cost-effectiveness. Recalling the considered threshold for individual risk of 10^{-6}, the acceptable cases with only one death above the limit are:

- 16, 18,19, 20,21,22,23,24,25,26,27,28,29 and 30.

While the first six cases concerning ammonia vector are not studied in the optimization as its toxicity exceeds acceptable risk levels.

As we know risk cannot be eliminated, risk 0 does not exist. That is why I have considered cases with more than one facility under the threshold. It corresponds to the driver, who was included separately in the study. Indeed he is count as a single operator unlike the rest of the exposed persons defined according to an average population density.

Among these highlighted cases, in order to obtain the best condition of safe transport, the economic factor has been compared:

Table 29: economical aspect

Case	Kjørbo	Høvik
16 19 20	52,20 EUR	57,60 EUR
18 21 22	44,28 EUR	49,68 EUR
23 24 26 28	120,96 EUR	126,36 EUR
25 27 29 30	130,68 EUR	136,08 EUR

Table 30: Number/yr and N/Week

Case	Kjørbo Trucks/yr	Høvik Trucks/yr	Kjørbo Trucks/week	Høvik Trucks/week
18	130	120	2,5	2,31
21	326	325	6,27	6,25
22	426	416	8,19	8

From the cost, red highlighted in the table, and the number of trucks needed for delivery according to the demand defined in the previous chapters, the optimized case number is 18.

Its peculiarities are:

1. 0,011968218 Probability of 1 death (driver) and $9{,}29198 \times 10^{-7}$ for two fatalities.
2. 3 trucks of 1000 kg are enough for one week.
3. Cost of delivery:

$$\text{Kjørbo}\,\frac{\text{Trucks}}{\text{week}}\ \text{cost} = (44{,}28 \times 3\,) \times 2 = 265{,}68\ EUR/week$$

$$\text{Høvik}\,\frac{\text{Trucks}}{\text{week}}\ \text{cost} = (49{,}68\ \times 3) \times 2 = 298{,}08\ EUR/week$$

$$Operator\ cost\ to\ \text{Kjørbo}\ = \left(1{,}53\,\frac{EUR}{km} \times 123km\right) \times 2 = 376{,}38\ EUR$$

$$Operator\ cost\ to\ \text{Høvik}\ = \left(1{,}53\,\frac{EUR}{km} \times 138\ km\right) \times 2 = 422{,}28\ EUR$$

It is doubled because of the way back.

In a week the operator will drive to the stations 2 or 3 times depending on the request, as the results showed with 2,5 and 2,31 trucks/week.

$$Total\ delivery\ cost\ to\ \text{Kjørbo (twice)} = 265{,}68\,\frac{EUR}{week} + (376{,}38\ EUR\ \times 2) = 1018{,}44\ EUR/week$$

$$Total\ delivery\ cost\ to\ \text{Kjørbo (three times)} = 265{,}68\,\frac{EUR}{week} + (376{,}38\ EUR\ \times 3) = 1394{,}82\ EUR/week$$

$$Total\ delivery\ cost\ to\ \text{Høvik (twice)} = 298{,}08\,\frac{EUR}{week} + (\ 422{,}28\ EUR\ \times 2) = 1142{,}64\ EUR/week$$

$$Total\ delivery\ cost\ to\ \text{Høvik (three times)} = 298{,}08\,\frac{EUR}{week} + (422{,}28\ \ EUR\ \times 3) = 1564{,}92\ EUR/week$$

4. Gaseous delivery at 500 bar and atmospheric temperature (14.6°C) for a station of 30000kg compressed at 700bar. This means that the compressor will not have much trouble compressing the delivered gas by 200 bar and the transport will be done anyway for an effective fuel volume.
5. No need to vaporize fuel at the station for car refill. Saving on vaporization costs, not only in terms of plant structure, but also in terms of electricity consumption.
6. In a day of 8 working hours with an amount of 10 cars per hour, you will have 80 cars per day that will refuel 5 kg of fuel. Considering the cost of hydrogen gas previously reported of 11.29 euro /kg the daily income of the station would be equal to:

$$Daily\ income\ for\ 1\ station = 80\ \frac{cars}{day} \times 5\ kg \times 11{,}29 \frac{EUR}{kg} = 4516\ \frac{EUR}{day}$$

7. With only 30 minutes difference between the roads company could avoid tolls of private ones.

Chapter 8

Conclusion

In the previous pages, an attempt has been made to accentuate the importance of the studies carried out to date on hydrogen fuel. Researchers look at it as an ideal alternative energy thanks to its multifunctionality as a fuel for transportation sector, distributed heat and power generation, and for energy storage. It, seen as fuel of the future, that could lead to more sustainable energy systems and improve the living conditions whose we are satisfied with today. Being the only one with zero emissions, if it is produced from renewable sources, it would involve first of all the reduction of pollution, but also everything that follows. Reduction in the expenditure in health care to treat skin cancer caused by fine dust emitted by exhaust gases from cars, possible wealth division because, unlike oil, hydrogen is producible everywhere, reduction in pollution from oil extraction of the water and the earth are only some examples of refinements. Providing a detailed analysis of the hydrogen infrastructure focused on a network of production, storage, and transportation facilities, the starting review presents different approaches that are used for the planning and design of the future hydrogen supply chain. The work done focuses on road transport in order to find a solution that is both cost and safety optimized at the same time. To do this, study field was initially reduced to the southern part of Norway in Askershus County and Oslo Municipality. These regions were chosen in particular following the accident at Kjørbo station in June 2019. This event led to an interruption in development and sale of hydrogen throughout Norway and remaining stations carrying this brand in the world. The public immediately wondered whether hydrogen was at least as safe fuel as better known fuels such as petrol, diesel and LPG. In order to answer this question, transport optimisation was therefore carried out not only from cost point of view, but also and above all from point of view of safety. The delivery was chosen as a study phase mainly because it involves the population over long distances and crosses several regions. Analysing the existence of two types of hydrogen stations, production and storage or only storage, I decided to optimize the transport from north, south and west passing through two types of roads (highways or state roads), of two stations close to each other (15 km away). Assuming in the first six cases they are production and storage while in the rest cases they are only storage. In the first case, since production usually takes place by electrolysis starting from water, I decided to investigate the transport of a new carrier, ammonia, which is drawing a lot of attention to itself in current years. In the second case, the differences between cases are the considered parameters, such as transport phase, pressure, temperature and quantities transported. Of all the possible solutions reported, it has been confirmed that in today's developing market, overpressure transport is the best because it is less expensive and safer. The results obtained from the risk analysis carried out using DNV-GL's Safeti software and the logistics analysis carried out using Exstendsim 10 software define case 18 as the best from the point of view of cost and safety. The solution obtained of 1000 kg transported in overpressure is optimal for the specific case, but to date in Norway is one of the most common methods of transporting hydrogen. This is confirmed by the "Hylaw" project where the regulation of hydrogen transport is mentioned and in paragraph 6 the last purchases of 1000 trucks for road transport are recalled.(Regolamentazione, Cigolotti, Mcphail, & Tommasino, n.d.)Despite the higher volumes transported in liquid phase, it is still too expensive in terms of production and in the specific case of the south of Norway had higher probability of death than the designated optimised case. Optimisation method and the approach could be use as powerful tool for the efficient planning in future clean routes. The study can be expanded to cover other areas in Norway, but also in Europe, or outside Europe. Widening the horizons to maritime, rail and pipeline trade, the study of an optimal solution would lead to a complete view of the situation and a clear scenario concerning every economic and safe possibility of hydrogen transport. Further investigation could involve the other fundamental stages of the supply chain such as production and storage, thus also involving electrolyzer stations such as kjorbo. Moreover, recalling the reasons for the closure of the second station chosen for the Hovik study, the economic study of the impact that the accident is having on the stock markets, investments and European subsidies, for example, for the opening and construction of a branched hydrogen infrastructure, could be expanded.

Then, hydrogen economy has been recognized to be the long-term way to reach the main goals for an economic and environmental sustainability.

Chapter 9
Appendix

Appendix A:
Figure and table indexes

Appendix B

Bibliography

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