Feasibility assessment of hydrogen distribution

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Abstract

The world faces increasing challenges in terms of energy and emissions due to growing consumption of fossil fuels. In the effort towards the decarbonization of the economy, different energy vectors of fuel are being considered, such as hydrogen.

The main objective of this work is to evaluate the hydrogen potential, energy and emissions impacts of hydrogen distribution. The hydrogen production is assumed to be through electrolysis process. Two ways of hydrogen distribution were considered, through: the existing pipeline and road transport. In the pipeline distribution the ratio of 15% hydrogen-Natural Gas was considered due to the infrastructure embrittlement risk. The variables evaluated from this type of transport are energy delivered, hydrogen percentage in the mixture, diameter and length. Then, two road transportation was evaluated: Gaseous hydrogen trailers and Liquid Organic hydrogen Carriers. For costs analysis, the processing and trucking were account.

The overall costs turn out to be cheaper for pipeline distribution, as they go from 500 € per day to around 63.300 € per day for the cheapest road transport option. Life Cycle analysis was performed to assess the energy balances and associated CO_2 emissions of hydrogen distribution pathways. The results show that the pipeline distribution has lower emissions with 0.15 t CO_2 per day than GH_2 with steel bottles, with 9.45 t CO_2 per day.

Keywords:

hydrogen distribution, feasibility, PEM electrolyzer, pipelines, road transport

Resumo

O mundo enfrenta desafios crescentes em termos de energia e emissões devido ao consumo crescente de combustíveis fósseis. De modo a se atingir uma descarbonização da economia, estão a ser consideradas diferentes fontes de combustível, como o hidrogénio.

O objetivo principal deste trabalho é avaliar o potencial de hidrogénio, os impactos da energia e das emissões da distribuição do hidrogénio. O processo de produção de hidrogénio considerado é a eletrólise. Foram consideradas duas formas de distribuição de hidrogénio, por meio: de pipelines já existentes e do transporte rodoviário. Na distribuição por pipelines foi considerada uma mistura de 15% hidrogénio/Gás Natural devido ao risco de fragilização da infraestrutura. As variáveis avaliadas neste tipo de transporte foram energia, percentagem de hidrogénio na mistura, diâmetro e comprimento. Em seguida, foram considerados dois tipos de transporte rodoviário: transporte de hidrogénio gasoso e hidrogénio líquido via camião. Para análise de custos, foram contabilizados o processamento e o transporte rodoviário.

Os custos gerais são mais baixos para a distribuição por pipelines, com 500 € por dia comparativamente a 63.600 € por dia para a opção de transporte rodoviário. A análise do ciclo de vida foi realizada para avaliar os balanços de energia e as emissões associadas para cada via de distribuição de hidrogénio Os resultados mostram que a distribuição através de pipeline tem menores emissões de 0.15 t CO_2 por dia, do que GH_2 com garrafas de aço, com 9,45 t CO_2 por dia.

Palavras-chave:

Distribuição de hidrogénio, viabilidade, eletrólise PEM, oleodutos, transporte rodoviário

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Nomenclature

1 Inlet

2 Outlet

α Volumetric ratio

ΔP Pressure variance [Pa]

η Efficiency [%]

γ Specific heat ratio

ν Specific volume [m^3/kg

ρ Density [kg/m^3]

A Area [m^2]

A, B, a_m, b_m Peng-Robinson parameters

AC Average installation cost [€/km]

C Material cost [€/metric ton]

CC Compression costs [€/h]

CF Capacity factor [%]

CRF Capital recovery factor

D Diameter [m]

DBT Dibenzyltoulene

E Energy delivered [MW]

FC Fixed costs [%]

g Gravity constant [m^2/s]

GH_2 Gaseous hydrogen Tanks

IC Investment costs [€]

L Length [km]

LHV Lowest heating value [MJ/m^3]

$LOHC$ Liquid Organic hydrogen Carriers

M Molar mass [kg/mol]

N Number of compression stages

OM Operations and maintenance

P Pressure for pipeline calculations [Pa]

p Pressure for truck calculations [bar]

PC Pipeline cost [€]

pc Pseudocritical properties

PIC Pipeline installation cost [€]

Q Flow [m^3/s]

R Ideal gases constant [J/K·mol]

SC Specific costs [€/kg]

st Steady

T Temperature [K]

t Thickness [mm]

v Velocity [m/s]

W Work [W]

Z Compressibility factor

1 Introduction

Back in 2015, the United Nations created The Sustainable Development Goals. Implemented by 193 countries all over the world, this plan is intended to end extreme poverty, reduce inequality and protect the planet, among other things, by 2030. There are a total of 17 goals that concern issues from gender equality to quality education. This work pretends to contribute to goal number 7, 'affordable and clean energy'.

With increasing global warming and environmental pollution, the development of renewable energy sources is becoming more essential because of its awareness increase. In this sense, hydrogen becomes a fascinating energy carrier. It is considered as the cleanest, most promising energy source in the 21st century. Why? Because it can be produced only by using water and electricity. Its emissions are mainly water vapor, emitting or generating no pollutants when combusted with oxygen. Its conversion to heat or power is simple and clean. The water is returned to nature, where it originally came from.

However, it is not as ideal as it sounds. The idea of a hydrogen based economy has not been pursued, as it was considered unfeasible compared to other ways of energy, [1]-[2]. Even though it is a clean source of energy, if its price is not competitive towards other ways of energy, why should companies or customers decide to use it? It would not be economically viable. Nevertheless, there is to remember that the processes involved on energy production have an impact on the environment [3]-[5], which could affect the economical factor, [6].

As time has gone by, there has been research regarding hydrogen as an energy vector. Considering it promising due to its great properties and abundance in the world, conclusions have changed [7]-[8], claiming its attainability as a new feasible way of energy. However, there are still several challenges to overcome.

Regarding hydrogen production, electrolysis processing has become the best option [9]-[10] due to its several improvements. Being the Proton Exchange Membrane, PEM, considered as the best of them all nowadays according to study [11].

When it comes to distribution, the main approach considered is reusing already existent ways of transport. More specifically, pipeline and road distribution. Nevertheless, there is to remember the effects carrying hydrogen can have on these infrastructures [13]-[15], as there are some specifications to keep in mind when reusing them as the properties of the carried products change.

For pipelines, it has already been proved to be a useable system [16], and there is work to study its optimum dimensions to make the transport as efficient as possible, mostly regarding the diameter [17]-[18]. In this case, there is not only to consider the properties of hydrogen by itself, but mixed with another gas, to create the mixture that will go through the pipes, [19]. In the present work, the gas considered to be mixed with hydrogen has been Natural Gas. Mixing both gases presents different thermodynamical issues, [24]-[25], to tackle when analyzing its behavior during the distribution process.

When it comes to road transportation, it is considered as one of the most used ways of distribution due to its versatility. There is more than one option to be considered with this type of transportation and it is advancing as research goes on, [26].

The present work, intends to contribute to the research done about the distribution process of hydrogen energy. Finding the most feasible way to transport the product and, that way, decrease the overall costs as much as possible. Making it attainable to enter the market by achieving a more competitive price point.

1.1 Motivation

Nowadays, the world revolves around energy. Its consumption grows day by day and it is because almost everything relies on it in order to function. Energy is present in almost every aspect in life, from factories to taking the car to go to the supermarket, or from turning on the TV to going on a trip by plane. Today, the energy industry is fossil carbon dependent. The main problems regarding this type of energy source, are the environmental impact and the fact that it is limited, making it more and more expensive as time goes by due to lower resource availability. That is why, there is the need to find new alternatives.

One of them is renewable energies, such as wind or sun power. These are not limited as they rely on natural sources, and their emissions are lower. According to Helman [29], wind energy emits around 11 g of CO_2 per kWh, compared to 44 g of CO_2 per kWh for solar power, 450 g of CO_2 per kWh for natural gas, and 1.000 g of CO_2 per kWh for coal. The difference in the emissions, from coal to these examples of renewable energies, goes up to 3 orders of magnitude.

Data from the IEA, International Energy Agency, shows that in Portugal renewable energies represent 24.4% of the share in primary energy consumption by year 2017. Even though it is a higher percentage compared to previous years, it is still not the predominant way of energy production. This is because, it is not ideal as its product depends on things that can not be controlled. For example, solar energy is dependent on sun hours. Meaning that energy is only produced when there is sunlight. The problem is, for example in this case, it would not be able to provide energy when it is mostly necessary, which would be at night when there is no natural light. A clear example is a house. Energy is used mostly during the evening, as it is when people come back from work. They need to cook for dinner, light up the house to see and heat it up for the winter. Simple things that require energy. If they relied on sun power to do all these things, they would not be able to do any of these in the evening. The main challenge renewable energies present is the ability to store it. An issue that is still being tackled day by day.

However, it still needs to be some way of energy supply. As seen, fossil energies are not lifetime solution and renewable energies are still not sufficiently developed. That is when hydrogen produced energy takes place.

hydrogen is a carbon-free way of energy with the highest calorific value, 120 MJ/kg, whose emissions are mainly water vapor. It is also a way of energy that can be stored, in contrary to renewable energies. Since hydrogen does not exist as a molecule in nature, it is produced by the conversion of materials, like water or carbohydrate. Sometimes this can be an accidental product in industrial processes, but it can happen intentionally by using processes such as electrolysis using PEM electrolyzers or alkaline water electrolyzers.

These processes need a source of energy and, even though the best choice would be to use clean ways, the most used nowadays comes from fossil energy, resulting in 830 Mt of CO_2 emissions annually, [26]. The reason why is simple, it is an easy way to cut down costs. The novelty regarding hydrogen energy means that there is not enough research done about, for example in the production processes.

Peneva et al. stated on study [16] that the price of hydrogen should be of $7 per kg in order to make it feasible to use instead of gasoline, while back in 2019 when the study was published, it was of $16.3 per kg.

Costs, this is the issue to tackle, and where most of the studies are focusing on. Authors Peneva et al., [16], talk about the need of hydrogen stations due to the increment of popularity of fuel cell electric vehicles. They also claim the need of 1.500-3.300 stations just in the US, when there were only 40 back in 2019. Examples like this show the growing importance of hydrogen energy development and, therefore, the necessity of research.

1.2 Hydrogen Distribution

As mentioned before, hydrogen is a relatively new way of converting energy. The main costs of this type of energy change depending on the work that is being researched. Peneva et al. claim in study [16] that the main costs are on hydrogen distribution, compression and dispensing costs; then U. Bossel et al. state in study [2] that production, packaging, storage, transfer and delivery of the gas are the key component of the economy; and lastly, study [7] from H. Nazir et al., concludes that costs are mainly based on storage and distribution. They all have one factor in common: the distribution process. Meaning it will be a determinant point when wanting to decrease overall costs.

Because of the novelty of using hydrogen in mobility, there is not enough experience to know which is the optimum way to distribute it. Bossel shows a solution on study [1] when using pipeline delivery for hydrogen. There is the possibility of reusing the infrastructure. Kuczynski et al. expressed a similar point on study [24]. hydrogen and methane, for example, are considered as similar gases. Therefore, most of the technological requirements for pipeline distribution would be identical. Nevertheless, there have to be modifications like sealing areas, because of diffusion losses, brittleness of materials and seals, compressor lubrication and other technical issues.

Reusing already existent infrastructure happened, for example, in Germany. Peneva et al. [16], investigated the hydrogen distribution display that started in November of 2006 on the edge of an industrial-park in Frankfurt, Germany. hydrogen started being supplied to the station by truck transport and high-pressure pipelines. It was compressed and stored in a large tank, making it possible to have 96% of availability. Up to 2019, when the study was published, there had only been one incident, which was related to insufficient purging, resulting to an excess of Nitrogen in vehicle tanks. However, fuel cells were not damaged and the final report concluded that transporting hydrogen with high pressure pipelines is technically feasible.

When studying road delivery of hydrogen, U. Bossel mentioned during work [1], that this way of transport is extremely inefficient due to the low density of the gaseous energy carrier. When liquid hydrogen is distributed by trucks there is a limitation in terms of volume and, low density products require more volume to bring the same weight of product, compared to another substance with higher density. For example, it would take 22 hydrogen tube trailers to deliver the same amount of energy as a single gasoline tanker, all because of the difference in density. This is mostly because the actual payload that is being transported when delivering compressed gases corresponds to 80% of the total tank, meaning the remaining 20% is returned to the gas plant. Nevertheless, the mentioned study is from 2006 and anticipates an efficiency growth due to technical developments. However, 14 years later, in work [26], the assumption of net hydrogen payload corresponds to a similar value. In the end, this is a huge drawback to this transportation as there will be need for more trucks which increases the overall costs.

hydrogen distribution is a recent topic and there are a few studies or research developed about it. Of course, when comparing it to other ways of energy production such as fossil, just like in work [1], the feasibility will not be as high economically-wise. Nevertheless, there is to remember that there is still work to be done and the final purpose, which is a cleaner, more sustainable world. Working on ways to make hydrogen distribution feasible will make a huge impact on the overall costs, as well as make it a lot easier to implement this way of energy into the actual market.

1.3 Objectives

The present work, intends to find which way of transporting hydrogen is the most feasible by studying the different types of distribution that are being used for other products nowadays, like gas distribution. By analyzing the behavior of the different variables on the possible transportation options, as well as understanding the thermodynamic involved in the process, there will be the keys to lower the costs on each of the delivery options and, eventually, find which of them is the most cost-efficient. That way, the total expenses of hydrogen energy can be lowered, making it competitive to already used ways of energy.

The main approach of this study is to distribute hydrogen as cheaply as possible, while keeping it as a clean way of energy. There is to remember that the final objective when using hydrogen as an energy vector, is finding new ways of clean energy to decrease the emissions as much as possible. However, this is the real world, considering costs is crucial for the market. Just like any other product, hydrogen costs need to be as low as possible. Like Bossel et al. stated on study [2], hydrogen can only establish itself in the market if it makes sense energetically. Otherwise, better options will overcome and conquer it, just like fossil energy is doing nowadays.

1.4 Literature review

The present work analyzes two different already existent distribution methods: pipelines and road transportation. The analysis done intends to find the best transport option for hydrogen. The criteria will be both economic and environmental. The topics researched are related to both of these ways of distribution, but towards delivering hydrogen.

As there has been no experimentation done during the present paper, results are solely theoretical. The purpose of literature review is to check if the results obtained doing the analysis have a similar behavior as the one's on the papers researched, and, if not, justify why. This could happen as there can be different assumptions, approximations or equations that interfere in the overall results. The purpose is to have a guideline to compare with the solutions calculated.

Starting by the approach from Oney et al. [17], the analysis is based on the momentum balance applied at two stations of the pipeline. It was assumed that the cross section was constant, a steady isothermal and compressible flow, adiabatic compression, negligible potential energy change and all the properties of the hydrogen-Natural Gas mixture were calculated by thermodynamic laws, using their volume fractions. Then, there was also an optimization process for the pipeline design. This process will determine different dimensions for the pipeline depending on each case of distance, hydrogen percentage in the mixture or energy delivered. More specifically, regarding the diameter. When studying the costs, inspiration comes mainly from study by Menon et al. on book [23]. Here expenses are mainly broken down into capital and operating costs. Capital costs comply expenses from materials and installation of the pipelines to compressor stations. Then, for operating costs, it concerns the expenses regarding transmission.

The present paper will also base the equations used from the momentum balance applied at two stations of the pipeline. Leading to the Renouard Equation, which will be the one used for the calculations. More specifically the version used on study [25]. Some of the assumptions applied are steady and compressible flow and isothermal. These will be detailed during the methodology section. The parameters of the mixture were calculated based on the ideal gas equation, written in the following sections as Equation 4. However, the LHV, lowest heating value, of the mixture was calculated according to the volume fractions just like on study [19]. During the present work, the optimization of the diameter, will not take place as it is not the main concern of the study. The objective is knowing how changing each one of the variables affects the system and which is more determinant for the overall costs. The parameters to analyze, such as energy delivered or hydrogen percentage in the mixture, will go from one value to another in a determined range of values to study its behavior on the overall distribution process. While another parameter is being studied, the rest will be kept constant. For example, when studying the length of the pipeline, this parameter will be changed in the described range of values while the diameter, energy delivered and hydrogen percentage in the mixture will be kept as constants. The analysis will take place in Portugal and will study the total costs in € per day. These will comply both piping, which involve installation and material costs, and operation costs, related to the energy needed to pump the product through the pipeline.

Even though the methodology is not the same, results from [17] will be used as an inspiration to criticize the solutions obtained by the calculations. The first behavior to analyze will be the dependency, on the total transmission costs, depending on the hydrogen percentage in the mixture.

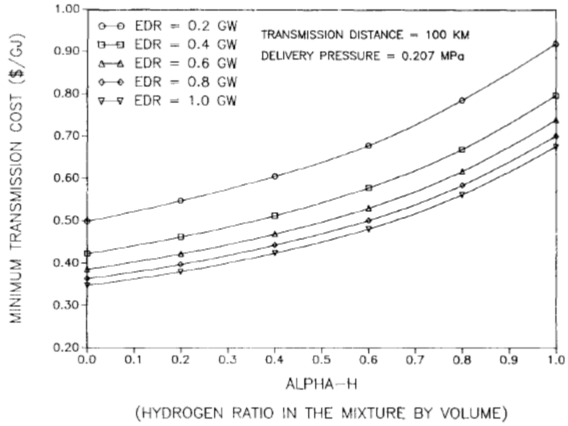


Figure 1: Results from [17] regarding minimum transmission cost's dependency on hydrogen percentage.

According to Figure 1, a hydrogen-rich product will increase the overall transmission costs for the same transmission distance, delivery pressure and energy delivery. The diameter is not defined because of the optimization depending on the concentration of the mixture in each case. Therefore, a hydrogen-poor mixture would be better when wanting to reduce the overall expenses. Figure 2 shows the cost variance on the energy delivered.

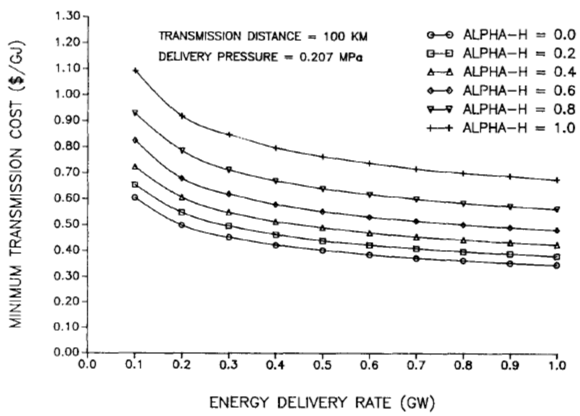


Figure 2: Results from [17] regarding minimum transmission cost's dependency on energy delivery.

Figure 2 shows that, as there is more energy delivered for a determined transmission distance, delivery pressure and hydrogen volume ratio, the transmission costs are going to decrease. Meaning high energy deliveries are going to be more beneficial to this type of distribution and, therefore, it will be better to do one big energy discharge than several small energy deposits. Then, there is to analyze the impact of distance, which is represented on Figure 3.

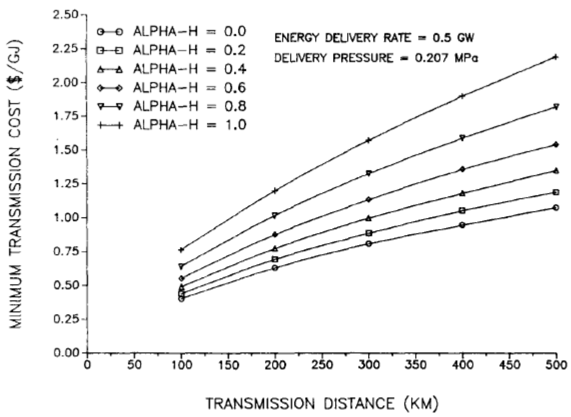


Figure 3: Results from [17] regarding minimum transmission cost's dependency on distance.

In this case, 1 GJ requires 8 kg of H_2 (LHV), 1 kg of H_2 costs 5€/kg, meaning transporting 8 kg of H_2 will cost 40€. The transportation represents 5.6% of the cost in the worst case. When delivering a mixture of hydrogen-Natural Gas with a constant energy delivery rate, composition and pressure, the increment of transmission distance makes the transmission costs increase. Therefore, this type of distribution is more expensive when the product has to be delivered for longer distances. This parameter is determined by the production and delivery point, so there is not much to do here. Lastly, there is to analyze the main issue studied by Oney et al. on study [17], the diameter.

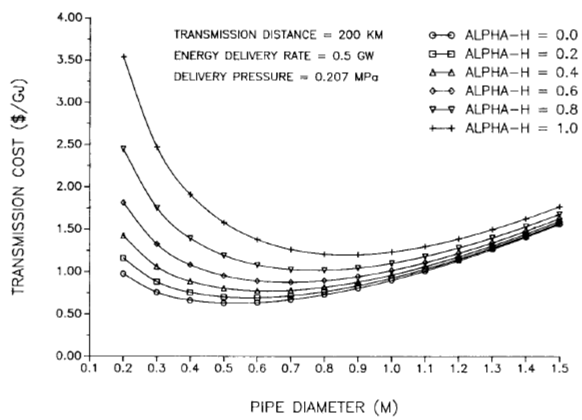


Figure 4: Results from [17] regarding transmission cost's dependency on diameter.

For a determined transmission distance, delivery pressure, composition of the mixture and energy delivery, the impact of the diameter on the cost does not change like the ones seen before. There is an optimum point where transmission costs are the lowest, but then they rise again. The reason why this happens is explained on Figure 5.

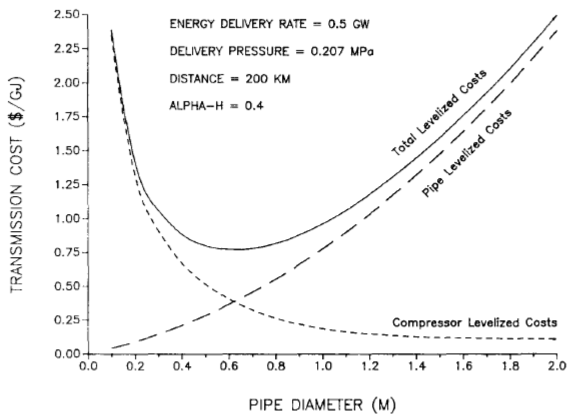


Figure 5: Results from [17] regarding costs' dependency on diameter.

Transmission cost's regarding the diameter are dependent on two variables. First, there is the investment, which are the piping costs, and then there are the operation costs, corresponding to the compressor costs. Smaller diameters result in lower pipe costs because there is not as much material used. However, it implies large pressure drops along the line, resulting in bigger pumping energy discharges. The opposite occurs when increasing the diameter. The point at which the two lines cross is the optimum diameter, for that specific case. Meaning, it is the diameter which provides the lowest overall costs.

When looking at the difference of costs between the cheapest and the most expensive case in Figures 1 to 5, the one with the widest range of values is from the diameter change, going up to $3.5 per GJ. This would actively demonstrate that it is probably the variable with the biggest influence and, therefore, the one that should be pay more attention.

It was verified on study [17] that the most feasible way of transport, via pipelines, would be a hydrogen-poor mixture, with bigger energy deliveries, shorter distances and finding an optimum diameter where piping costs don't overcome operation costs.

The second part of the work is going to be related to road transport. For this type of hydrogen distribution, inspiration comes from the study by Hurskainen et al. [26]. This work analyzes the total costs regarding three different types of road transport. These are studied for two energy deliveries, 2.5 and 10 MW, and three distances, 50, 150 and 300 km. Costs are divided on trucking, which is the delivery process itself, and processing costs, the processes needed to get the hydrogen into the desired state. Also, in the case of LOHC, there is a dependency on the CAPEX. Costs are also levelized annually and the final working unit is € per kg of hydrogen.

The methodology used in the present work will be the same. However, the analysis will take place for different transmission distances, in a determined range of values, to see the influence of the variable on the overall expenses. There will also be an analysis on the cost behavior depending on the energy delivered and the kind of transport used. Also, when it comes to LOHC, CAPEX will not be taken into account. Instead, the result will be based on the average value.

Results, from work [26], are displayed on Figures 6 and 7, depending on the distance, energy delivered and type of transportation studied.

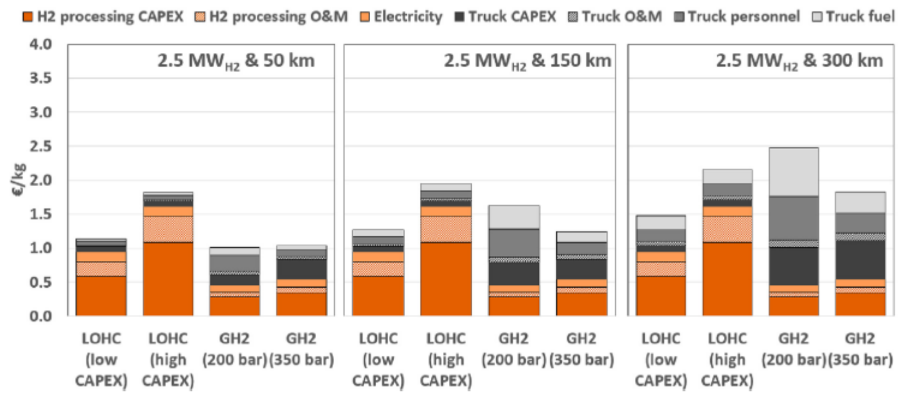


Figure 6: Results from [26] for 2.5 MW road transport regarding trucking and processing costs for each determined distance.

Figure 6 analyzes the cost for delivering 2.5 MW for each of the three ways of road transport, as well as each of the distance scenarios. When it comes to short distances, 50 km, the best option, according to [26], is GH_2 using steel bottles at around 1 € per kg. Then, as the distance increases, LOHC and GH_2 with composite bottles get more similar results at around 1.3-2 € per kg. Lastly, for longer distances, LOHC is the most beneficial at a price point of around 1.5-2.2 € per kg. Another thing to pay attention to, is the fact that trucking costs increase as the distance is longer, meaning that delivering the product will require higher expenses for longer transmission distances. However, processing costs seem to be stable regarding this parameter. Meaning its influence is almost null.

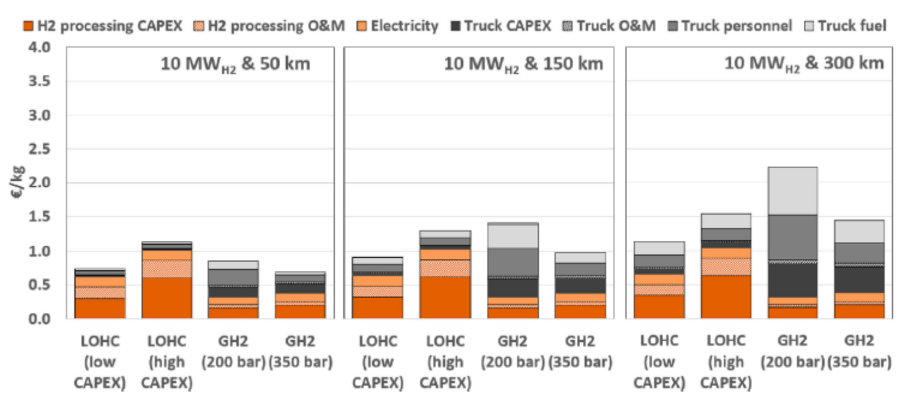


Figure 7: Results from [26] for 10 MW road transport regarding trucking and processing costs for each determined distance.

When delivering 10 MW, which is a higher energy deliver, costs tend to decrease as transporting more hydrogen makes the process more feasible. For shorter distances, GH_2 with composite bottles would be the best choice at 0.7 € per kg; medium distances would require LOHC or GH_2 with composite bottles at 1-1.3 € per kg; and, for long distances, there is to use LOHC at 1.3-1.5 € per kg. The transport choices are about the same when comparing to the previous case, but according to their results, road transport is benefited from high energy deliveries.

To sum up all the previous ideas gathered from the research papers, it is to conclude that neither of the ways of transport is benefited by long distances. Nevertheless, as it was stated before, this is a variable where there is not much to do as it is determined from the distance between production and delivery station. However, there are other variables where work can be done. Pipeline distribution also depends on composition in the mixture which, according to the results from study [17], should be as low as possible in order to lower transmission costs. This variable, composition of the mixture, is a determined value depending on the energy delivered when it comes to road transportation, meaning it will not be a value to work with. Moving on to the energy delivered, both road and pipeline distribution are benefited from high energy deliveries. Meaning that big energy deliveries will be more feasible than doing small constant doses. Then, there are the specific characteristics depending on the distribution path chosen, like diameter of the pipe in the case of pipeline distribution, or pressure, as well as capacity of the bottles used in the tanks, when it comes to road transportation. The specific methodology and assumptions for both ways of distribution, will be individually described and explained on the following section.

2 Methodology

When it comes to the methodology that will be followed during the present work, there is Figure 8. This figure represents the different methods to choose from when transporting hydrogen. From road transport with GH_2 trailers and two different bottles, steel or composite, or LOHC, to pipelines. This work analyzes the costs regarding taking the product from the hydrogen production station to the delivery point, as well as the emissions that come with this distribution. The analysis on the present study will consider both the distribution of the product as well as the processing to put the hydrogen mixture in and out of the delivery method chosen. The calculations will be developed using excel and EES (Engineering Equation Solver). The plots will be gathered from chartgo.

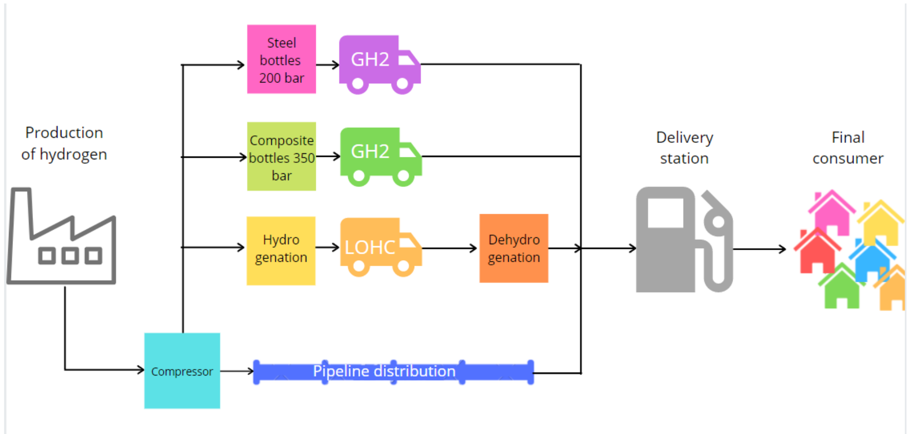


Figure 8: Paths studied for hydrogen distribution.

2.1 Pipeline transportation

Pipeline distribution is one of the ways to considered for hydrogen transportation. This distribution method is already used for products such as gas or water. However, the present work is going to study how to carry hydrogen mixed with something else. This analysis will consider a mixture with Natural Gas. By analyzing the behavior of this mixture in the pipe, while changing some of the variables like the hydrogen percentage in the mixture or the dimensions of the pipeline. The intention is to see how varying each of the parameters influences the overall costs. That way the main contributors can be tackled to lower the expenses to the minimum. The total costs will be separated between piping and operation costs.

2.1.1 Materials and construction

The first step when considering this way of transport is constructing the infrastructure. A great economy-effective option is reusing already existent pipelines. As Kuczynsky et al. stated on study [24], hydrogen is commonly considered a gas similar to methane, which is the main component in Natural Gas. Meaning most of the technological requirements are going to be identical. Nevertheless, when transporting hydrogen, there needs to be an increment on security as it could be dangerous, for example if hydrogen embrittlement occurs. The material, as well as the thickness of the walls, and the dimensions, are crucial to have a safe transportation. This is mostly because of the high pressure needed and the challenges that come when transporting hydrogen. Location is also a determinant factor, as a urban installation demands even higher safety measures.

A example, is the urban HyLine in Germany mentioned in study [16]. A highly populated area demands more precaution than if it was isolated. If something happens in a crowded area, that could be a catastrophe. Because of that, there is some research regarding this topic. To tackle hydrogen embrittlement a measure could be limiting the pressure, for example to 200 bar. This can generally be achieved by using thicker walls, which lead to higher pipe costs, and better materials, such as special steel. In the case of the HyLine in Germany, portrayed in work [16], the material used was DIN 1,4462. Overall, the experience was positive so far and after three years of experience, there were not any problems. It is possible to conclude that, if done right, it is safe enough to use it, even in urban areas.

Hydrogen embrittlement happens when the hydrogen permeation of the material used is low. There is also to consider its dependency on the time of exposition. Also, applying stress, just like the one from the mixture inside the pipe, can intensify the hydrogen charging process. There should always be a safety factor kept in mind, mentioned in [15], which will be higher for urban populated areas.

Because of all the extra security measures locations full of people imply, piping costs are higher when compared to the price of an isolated area. Nevertheless, location is a variable that relies on the placement of the hydrogen production station and delivery point. Meaning this factor is not something to control, but to deal with and try to make the biggest deal out of it. To simplify the analysis, a non urban area will be supposed, just like on study [14].

Pipe costs depend on the dimensions of the infrastructure, which are length and diameter. Bigger pipelines demand more expenses as there is need for more material. Oney et al. provide a method to find the optimum diameter on study [17]. This would balance both piping and operating costs. Even though it may have a huge impact on the overall results, this optimization analysis will not be done on the present work. The reason why is because the purpose is to study how each of the variables affect the price, not to find the optimum pipeline configuration. The diameter will range between 0.4 to 1.2 m, as they are the most common dimensions when it comes to pipelines according to study [13] from Froeling et al. When studying other variables, like hydrogen percentage in the mixture or energy delivered, there will be a set diameter of 0.8 m so changing its value does not interfere in other's results.

Distance, or the length of the pipeline, is the other dimensional parameter to determine. As stated before, its value relies on the distance from production to delivery point. It is also dependent on the area because, for example, the largest path taken in Portugal is a shorter than an average one that could be done in the US. To include as many cases as possible, the range of values when studying this variable is going to be wide and completely random. When not analyzing the dependency on distance, this factor will be 200 km. A value that would fit Portugal.

There are some other variables to address, like energy delivered. This will depend on the country, the population and the needs of the people. The range of values studied will go from 0.1 to 1 GW. When set as a constant, the energy to deliver will be 0.5 GW. Both of the assumptions are as on study [17]. Lastly, there is the composition of the hydrogen-Natural Gas. It is a very important factor for efficiency and safety. According to research article from Jaworski et al. [14], its value should not go over 20%. This is so the gas' gross calorific value is enough for the mixture to meet the standard quality requirements. The quantity used when kept as a constant factor in the following calculations, is assumed to be 15%, because it was stated as the optimum proportion by Hurskainen et al. in study [14]. The reason why is because, with this percentage, the highest efficiency of combustion is achieved.

The values of the variables that will be used for the following calculations, when kept as constant, are displayed on Table 1.

Table 1: Values for the variables kept constant while analyzing one of the parameters.

Variable that is kept constant	
hydrogen percentage	15%
Energy Delivered	0.5 GW
Length	200 km
Diameter	0.8 m

2.1.2 Calculations

When it comes to pipeline distribution, the main challenge is dealing with the energy losses that occur due to the friction of the fluid with the walls of the pipe. These can be counteracted by adding power. The present work is going to state the variance of energy from inlet to outlet of the pipeline, as represented on Figure 9, as a variance of pressure factor. This will be then described as the energy needed to apply to pump the mixture through the pipe to counteract the pressure losses.

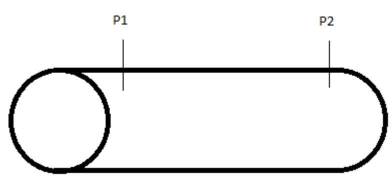


Figure 9: Representation of the pipeline.

To understand what happens to the product, in this case a hydrogen-Natural Gas mixture, from inlet to outlet of the pipeline, there is the momentum equation.

$$\frac{d}{dt}\int_{V_f}\rho\vec{v}dV = \int_{S_f}\vec{n}\vec{\vec{\tau}}dS + \int_{V_f}\rho\vec{f_m}dV \tag{1}$$

Equation 1 displays the balance of forces. It represents Newton's second law. The term on the left represents the variation of momentum in the fluid's volume. This variance of momentum is translated as energy losses, which happen because of the force the fluid exerts against the walls (second and third term as superficial or volume forces respectively). By assuming a compressible fluid, with average velocity and steady state conditions in a portion of the pipeline, the previous equation can be transformed into the general gas flow Equation.

$$\int_1^2 dp + \int_1^2 \lambda \frac{dL}{D_{in}} \frac{v^2}{2} \rho = \int_1^2 \rho dp + \int_1^2 \lambda \frac{dL}{D_{in}} \frac{v^2}{2} \rho^2 = \frac{M}{Z_{avr} R T_{avr}} \frac{P_1^2 - P_2^2}{2} + \lambda \frac{\Delta L}{D_{in}} \frac{v^2}{2} \rho^2 = 0 \tag{2}$$

To simplify the process, instead of using velocity the term to use will be flow. The relation between both is described on Equation 3.

$$v = \frac{Q}{A} \tag{3}$$

Where 'Q' is the flow and 'A' is the area the fluid is going through. The product transported in this case is a mixture of gases, specifically hydrogen and Natural Gas. That is why it is crucial to remind the main law regarding gas behavior, the ideal gases equation. This provides the pattern the gas follows under certain, for example, temperature and pressure conditions, among others.

$$PV = nRT \tag{4}$$

Where 'P' is the pressure of the gas; 'V' is the volume; 'n' represents the amount of substance; 'R' is the ideal gases constant; and 'T' is the temperature of the gas. The relation between volume and amount of substance is known as specific volume, described on Equation 5.

$$\nu = V/n \tag{5}$$

As it is dependent on the number of moles, it can also be written in function of molar mass and density.

$$\rho = \frac{PM}{ZRT} \tag{6}$$

Where 'ρ' is the density of the gas; 'M' is the molar mass; and 'Z' is the compressibility factor. In the case of ideal gases, the compressibility factor is 1, that is why it is not written on Equation 4. Combining Equations 1 and 6, as well as using flow instead of velocity, identity in Equation 3, there is Equation 7.

$$(\nu \rho)^2 = \frac{16 Q_{st}^2 P_{st}^2 M^2}{D_{in}^4 \pi^2 Z_{st}^2 R^2 T_{st}^2} \tag{7}$$

By applying some assumptions, this equation can be simplified. The density of the gas, Equation 6, can be considered the same both for average as well as at standard pressure conditions. Also, another approximation could be the relation of the molecular mass of the gas towards the air, displayed on Equation 8.

$$M = M_{air} \rho \tag{8}$$

After applying these assumptions, the general equation for gas flow 7, can be written as:

$$P_1^2 - P_2^2 = \lambda \frac{16 \Delta L Q_{st}^2 P_{st}^2 M_{air} \rho_{st}}{D_{in}^5 \pi^2 Z_{st}^2 R T_{st}} \tag{9}$$

Where 'λ' is the Darcy friction factor; and 'st' represents standard. This Equation was rearranged by Renouard back in 1952, and is known today as the Equation for gas flow.

$$P_1^2 - P_2^2 = 4810 L \rho_r \frac{Q_n^{1.82}}{D^{4.82}} \tag{10}$$

For unit purposes, the final version of this equation, which will be used in the present work, is the one used by Wlodek et al. on study [25].

$$P_1^2 - P_2^2 = 0.188 Z T L \rho \frac{Q_n^{1.82}}{D^{4.82}} \tag{11}$$

Where 'P_1' and 'P_2' represent the pressure respectively at inlet and outlet points of pipeline; 'T' is the temperature in the pipeline; 'L' is the length of the pipeline; 'ρ' is the relative density; 'Q_n' is the volumetric flow rate; and 'D' is the inner diameter of the pipeline.

To analyze the pressure drop through the pipe, there are some values that are still unknown. For example, the compressibility factor. This will be the first one to tackle. It can be calculated by using the Peng-Robinson equation of state.

$$Z^3 + (B-1)Z^2 + (A - 3B^2 - 2B)Z + (B^3 + B^2 - AB) = 0 \tag{12}$$

Where 'A' and 'B' are parameters that will be calculated with the following expressions, which are dependent on temperature and pressure conditions.

$$A = \frac{a_m P}{R^2 T^2} \tag{13}$$

$$B = \frac{b_m P}{R T} \tag{14}$$

Where 'a_m' and 'b_m' are also parameters of the Peng-Robinson equation of state, representing the mixing rules. These are described on Equations 21 and 24. These need the pseudocritical temperature and pressure, 'T_{pc}' and 'P_{pc}' respectively, of the mixture. According to Wlodek et al. on [25], from a thermodynamics point of view low values of hydrogen critical parameters and low molar mass have a large impact on its pipeline transportation. Therefore, they have been considered as the pseudocritical parameters of the mixture as well. The pseudocritical values used are displayed on Table 13.

$$a_m = 0.457 \frac{R^2 T_{pc}^2}{P_{pc}} \tag{15}$$

$$b_m = 0.078\frac{RT_{pc}}{P_{pc}} \tag{16}$$

Table 2: Pseudocritical parameters of hydrogen according to [25].

Variable	
Temperature	32.94 K
Pressure	1.2838 MPa

To know the average pressure in the pipeline, there is to recap the ideal gases Equation 4. However, as this is not an ideal case, there is to use a variation to this equation from Peng-Robinson. On study [24] it is stated that this technique is usually applied in the oil and gas industry. The Equation is the following.

$$P = \frac{RT}{\nu - b_m} - \frac{a_m}{\nu(\nu + b_m) + b_m(\nu - b_m)} \tag{17}$$

Where 'ν' is the specific volume, which can be calculated by using the ideal gases equation 4, but applying the compressibility factor as the product is considered as a real gas.

Continuing the parameter analysis of Equation 12, there is to know the temperature in the pipeline. According to study [25], a common approach is assuming a constant average value, which can be calculated with Equation 12.

$$T = T_0 + \frac{T_1 - T_2}{ln(\frac{T_1 - T_0}{T_2 - T_0})} \tag{18}$$

Where 'T_0' would represent the ambient temperature. As using this equation would make the analysis highly three-dimensional, and it is not the main purpose of the present work, it was simplified as a macro-analysis. The temperature used for the calculations is an average value for the inside of the entire pipeline. This parameter was set to 5℃ by Kuczynski et al. on study [24]. However, as the present study takes place in Portugal it will be assumed as 18℃.

Finally, the compressibility factor can be calculated by the iteration of equations 4, 12 and 17. The result is Z=1. Meaning the fluid transported in the pipeline behaves as an ideal gas. To continue with the other parameters to calculate the pressure drop in the pipeline, relative density is next. This value comes from Equation 6. The last term to analyze to use Equation 11 is the volumetric flow rate. This is going to be stated as the relation between the desired energy to deliver and LHV, lowest heating value, of the hydrogen-Natural Gas mixture.

$$Q = \frac{E}{LHV} \tag{19}$$

Where 'E', is the energy that is being delivered, which is a determined value; and 'LHV' is going to be calculated as the average value depending on the volumetric ratio.

$$LHV = \alpha_{NG} * LHV_{NaturalGas} + \alpha_{H} * LHV_{hydrogen} \tag{20}$$

Table 3: Lowest Heating Values of Natural Gas and hydrogen according to [19].

Substance	
Natural Gas	35.8 MJ/m^3
hydrogen	10.8 MJ/m^3

Where 'α_{NG}' and 'α_{H}' are the volume ratios; and '$LHV_{NaturalGas}$' and '$LHV_{hydrogen}$' are the lower heating value of Natural Gas and hydrogen respectively;. Values gathered from study [19] are on Table 14. hydrogen's LHV is three times lower than Natural Gas'. Meaning that a hydrogen rich mixture will require more flow to deliver the same quantity of energy. This concern was previously stated as expressed on study [14]. There needs to be a minimum of quality which relies on the properties of the mixture.

The approach of the present work is to study the variance of pressure between inlet and outlet point to see the energy required to make transportation possible, studying how the different variables affect the overall behavior of the fluid. The variables chosen to experiment with are hydrogen in the mixture, energy delivered, diameter and length of the pipe.

2.1.3 Costs

When analyzing costs regarding pipeline distribution there are two contributors, operation and piping costs. Expenses regarding operations concern the compression costs to impulse the product, in this case a mixture of hydrogen and Natural Gas, through the pipe. As pressure decreases, the fluid going through the pipe loses more energy, meaning there is to apply more so the fluid can keep moving. These costs can be calculated as a function of energy, which can be analyzed by using Equation 21.

$$W_{ideal} = \frac{\Delta P}{\rho * g} \rho * g * Q = \Delta P * Q \tag{21}$$

Where 'W_{ideal}' is the ideal work of the compressor to compensate the variance of pressure from inlet to outlet of the pipe; 'ΔP' represents the variance of pressure between inlet and outlet of the pipe; 'Q' is the flow of hydrogen-Natural Gas mixture going through the pipeline. As the present work considers a more realistic approach, an efficiency ratio will be applied. It was assumed to be 90% as it is a commonly used value.

$$W_{real} = \frac{W_{ideal}}{0.9} \tag{22}$$

Where $'W'_{real}$ is the real work needed; and $'W'_{ideal}$ is the work previously calculated representing the ideal state. Once the operation energy is known, there is to apply the electricity price to the compressor. The price was assumed to be 50 €/MWh, just like in study [26].

$$CC = \frac{50 * W_{real} * 3600}{10^6} \tag{23}$$

Where 'CC' states for compression costs; '50' is the electricity price in € per MWh; 'W_{real}' is the energy required; and '3600' and '10^6 are factors applied for unit purposes. Lastly there are investment costs related to the piping. The most used method when calculating this expense, is regression. Shiva et al. ised this method during [27] to calculate the cost of a pipeline distribution in the United States, which depended on the area. However, the present work will use for the method on book [23], where Menon et al. relate the pipe material cost to the dimensions of the pipe as well as the material cost. The coefficient applied is different because of the currency exchange. Changing from dollars to euros the equivalence is 1 € for $1.18. As a result, there is Equation 24.

$$PMC = 0.0219(D * 1.000 - t)tLC \tag{24}$$

Where 'PMC' is the pipe material cost; 'D' is the diameter of the pipe; 't' is the thickness of the pipe wall, assumed to be 13 mm.; 'L' is the length of the pipe; and 'C' is the pipe material cost, assumed to be 800 € per ton. The assumptions for thickness and material were gathered from [23]. Menon et al. mention in [23] that pipes are supplied with externally coat and wrap, which increases the cost by 5%. This factor is already applied in the constant. Then there is the pipe installation cost, which depends on the diameter. The relation is on Equation 7.

$$PIC = AC * L \tag{25}$$

Where 'PIC' is the pipe installation cost; and 'AC' is the average installation cost. This expense is dependent on the diameter of the pipe. Its values are displayed on Table 15.

Table 4: Typical pipeline installation costs according to [23]

Pipe diameter [m]	**Average cost [€/km]**
0.2	13.138
0.25	14.598
0.3	16.058
0.4	10.876
0.5	14.671
0.6	24.781
0.75	25.255
0.9	29.744

Therefore, the total piping costs is the sum of both of these costs.

$$PC = PMC + PIC \tag{26}$$

Where 'PC' are the piping costs in euros. Now there is to levelize the capital costs annually to calculate the total expenses per unit of energy. To do it there is the CRF, capital recovery factor, calculated with the following Equation.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{27}$$

Being 'i' the interest rate, considered as 8%; and 'n' the lifetime of the pipeline. To use the same interest rate for all the cases, the assumption by Hurskainen et al. on study [26] of 8% will be used when using this parameter. Then, regarding the lifetime of the pipeline Peneva et al. state an average value of 40 years on study [16]. Then, there is to divide the total expenses by the time it would be working.

$$TCOST = \frac{PC * CRF}{8760 * n * CF} + CC \tag{28}$$

Where 'TCOST' are the total costs in euros per hour; '8760' is the number of hours in a year; 'n' is the average lifetime of the pipeline, 40 years; and 'CF' is the capacity factor, assumed to be 90%.

2.2 Truck transportation

Another option to transport hydrogen is by trucking. This way of distribution does not only involve delivery, but processing hydrogen to the desired state. When considering this kind of transportation there is to choose between GH_2 (Gaseous hydrogen Tanks) and LOHC (Liquid Organic hydrogen Carriers), [26].

GH_2 is based on tanks that transport compressed hydrogen in gas form using bottles. These are mainly made out of steel or composite. To see which one is better there will be a comparison. This would be the traditional way of transporting via truck, for example for natural gas.

LOHC, on the other hand, is a novel way of transport that tackles storage and transporting challenges. The concept is the same as GH_2 trailers but, the main difference, is that the hydrogen transported is in a liquid state. Processing-wise, the only noticeable difference is the need for an extra step to put the mixture in and out of the carriers: hydrogenation and dehydrogenation respectively. This benefits the distribution by making it a reversible process. It also provides several advantages such as increased safety, high storage capacity, compatibility with the actual fuel infrastructure or even no hydrogen losses during transportation. However, it also has some drawbacks like high investments, heat transfer losses or the costs of the processing, which are mainly because of the lack of research. Again, just like hydrogen energy, due to its novelty.

The difference regarding their distribution process is almost none, [26]. However, calculations will compare their feasibility. The total costs can be divided into two parts: transporting costs and processing costs.

2.2.1 Costs

These calculations can be broken down to trucking costs, which involve taking the product from production point to delivery station; and processing costs, which are compression, storage and other site costs.

Starting by the trucking costs, these are dependent on fuel, investment, personnel and operations and maintenance. These dependencies can be perfectly seen on Equation 29, from study [26].

$$SC_{trucking}(\text{€/kg}) = \frac{IC_{trucking} * CRF_{trucking}}{\text{Delivered useable hydrogen per year}} + SC_{trucking,O\&M} + SC_{trucking,fuel} + SC_{trucking,personnel} \tag{29}$$

Table 5: Kilograms of hydrogen needed to be distributed depending on the energy delivered.

Energy delivered	kg of hydrogen needed per day
2.5 MW	1.800 kg
10 MW	7.200 kg

Being 'SC' the specific costs for trucking, operations and maintenance, fuel or personnel respectively; 'IC' the investment costs; 'CRF' the capital return factor; and 'Delivered useable hydrogen per year' the hydrogen delivered depending on the energy, displayed on Table 5, same assumption as study [26]. Investment costs represent the initial expense which is different depending on the type of road transportation chosen. Costs vary depending on LOHC and GH_2, but the Equation to calculate them is the same.

$$IC_{ann,trucking} = \text{\# of trucks} * CRF_{truck} * IC_{truck} + \text{\# of trailers} * CRF_{trailer} * IC_{trailer} \tag{30}$$

Table 6: Investment costs for trucks and trailers depending on the type of road transport.

Type of investment	
Truck	180.000 €
LOHC trailer	140.000 €
GH_2 steel bottles trailer	530.000 €
GH_2 composite bottles trailer	420.000 €

Where 'IC' represents investment costs and 'CRF' the capital recovery factor, both for trucks or trailers. Values displayed on Table 6. The number of trailers depends on the type of transportation we are using, 1 for GH_2 with composite bottles and LOHC and 2 for GH_2 with steel bottles, but the number of trucks is dependent on the energy delivered. This can be calculated with Equation 31.

$$\text{\# of trucks} = \frac{\text{trips per day}}{\text{max \ of trips per day per truck} * \text{truck availability}} \tag{31}$$

Where 'trips per day' is the number of times a truck has to go from production to delivery station; 'max of trips per day' is the maximum trips a truck can do in 24 hours, it was considered that trucks worked 24 hours per day meaning there is no break; and 'truck availability' is the percentage of time a truck is available, considered to be 90%. For this Equation there are some factors that are still unknown but can be calculated from these following Equations.

$$\text{trips per day} = \frac{\text{hydrogen demand}}{\text{Net hydrogen payload}} \tag{32}$$

Table 7: Net hydrogen tank payload depending on the type of road transport.

Type of road transport	**Net hydrogen payload**
LOHC trailer	1.400 kg
GH_2 steel bottles trailer	400 kg
GH_2 composite bottles trailer	900 kg

Where 'hydrogen demand' represents the quantity to deliver for a determined energy delivery and 'net hydrogen payload' is the maximum quantity of hydrogen a truck can transport, which depends on the type of transport. These values are on Table 7. Continuing with Equation 31, there is 'max # of trips'.

$$\text{max \# of trips} = \frac{24}{\text{total trip time}} \tag{33}$$

Where 'total trip time' is the number of hours it takes a truck to complete a route from production to delivery point. This factor can be calculated with the following Equation from [26].

$$\text{total trip time} = \frac{2 * \text{one-way distance}}{\text{average driving speed}} + \text{loading time} + \text{unloading time} \tag{34}$$

Table 8: Constants for calculating the total time per trip for each truck.

Variable	
Average driving speed	70 km/h
Loading + unloading time	2 h

Being 'one-way distance' the distance from production to delivery point; 'average driving speed' the average speed of the truck; 'loading time' the time it takes to put the mixture in the truck and 'unloading time' the time it takes to put it out of the truck. Values are gathered on Table 8. To finish calculating the investment costs, the next step will be to calculate the CRF. This is calculated using Equation 27, previously used for pipeline calculations. The interest is also considered to be 8 % and the lifetime is assumed to be 8 years. Then, moving on to operations and maintenance costs, there is Equation 35, from study [26].

$$SC_{trucking,OM} = \frac{\text{\# of trucks} * VC_{truck} * \text{annual drive distance} + \text{\# of trailers} * IC_{trailer} * FC_{trailer}}{\text{Delivered useful hydrogen per year}} \tag{35}$$

Where 'VC_truck' are the variable costs for trucks; 'annual drive distance' is the distance to drive per year, it will be considered a continuous delivery; ' of' is the number of trucks or trailer needed; 'IC' is the investment cost and 'FC' are the fixed costs, in this case for trailers, fixed costs represent 2% of the CAPEX for LOHC and 4% for GH_2. Next would be calculating the fuel needed.

$$SC_{trucking,fuel} = \frac{2\text{one-way distance} * \text{Fuel Consumption} * \text{Fuel Price}}{\text{Delivered useful hydrogen per truck}} \tag{36}$$

Table 9: Constants for calculating fuel cost for each truck.

Variable	
Fuel consumption	45 L
Fuel price	1.4 €/l

Where 'one-way distance' is the distance from production to delivery point; 'Fuel consumption' is the consumption of fuel per 100km; and 'Fuel price' is the price point of fuel, in this case diesel. Both of these values were gathered from study [26] and displayed on Table 9. Lastly, personnel has to be taken into account.

$$SC_{trucking,personnel} = \frac{\text{total trip time} * \text{ hourly salary}}{\text{Delivered useful hydrogen per truck}} \tag{37}$$

Considering an 'hourly salary' of 13 €/h, as it is the actual price in Portugal, and 'delivered useful hydrogen per truck' the maximum capacity per truck depending on the type of transport. All these calculations will be done regarding distance and for two different energy delivery situations: 2.5 and 10 MW, to see the influence of both on the overall expense.

To continue, the expenses regarding processing will be studied. Starting with those processes all types of transport have in common: compression and site costs, which regard , for example, piping. For compression, Equation 38 from [26] was used.

$$SC_{compression} = \frac{IC_{comp} * (CRF_{comp} + FC_{comp}) + E_{ann,comp}}{\text{Annual delivered useable hydrogen}} \tag{38}$$

Where 'IC' stands for the compressor investment costs; 'CRF' the capital recovery factor for 15 years;

'$E_{ann,comp}$' is the energy required for the compressor to work and the 'Annual delivered useable hydrogen' is the quantity of hydrogen needed per year depending on the energy delivered. Equation 39, gathered from work [26], provides the amount of energy needed in kJ.

$$E_{ann,comp} = W_{comp} * \text{Annual hydrogen production} * \text{Electricity price} \quad (39)$$

Where 'W_{comp}' is the work from the compressor per kilogram of hydrogen; and 'electricity price' is considered 50 €/MWh, just like in work [26]. According to the Equation, the work done by the compressor needs to be known. This can be calculated from the following Equation from [26].

$$W_{comp} = \frac{ZRT}{M}\frac{N_\gamma}{\gamma - 1}[\frac{p_2}{p_1}^{\frac{\gamma - 1}{N_\gamma}} - 1]\eta^{-1} \quad (40)$$

Table 10: Constants for calculating the work needed to do by the compressor.

Variable	
Z	2.5
R	8.314 J/mol·K
T	313 K
M	2.016 g/mol
η	75%

Where 'Z' is the hydrogen compressibility factor; 'R' is the universal gas constant; 'T' is the suction temperature; 'M' is the molar mass of hydrogenl; 'p_1' is the suction pressure, 1 bar; 'p_2'is the discharge pressure; 'γ' is the hydrogen specific heat ratio, 1.41; 'N' is the number of compression stages; and 'η' is the efficiency of the compressor. It was assumed as on work [26]. However, this value has increased up to 93%. Values are listed on Table 10. This Equation provides the work needed to do by the compressor to fill the tanks with hydrogen. The parameters will be the same besides the discharge pressure. Being 50 bar for LOHC, 200 bar for GH_2 steel bottles and 350 bar for GH_2 composite bottles. However, the discharge of pressure that occurs when using GH_2 has to be considered. That is why, in these cases, Equation 41 will be used. All data is gathered on Table 11.

$$p_{2,filling} = \frac{p_{mx} - p_{mn}}{log(\frac{p_{mx}}{p_{mn}})} \quad (41)$$

Table 11: Constants for calculating the work needed to do by the compressor.

Pressure	
Discharge LOHC	50 bar
Discharge GH_2 steel bottles	200 bar
Discharge GH_2 composite bottles	350 bar
Minimum	5 bar

Considering 'P_{mx}' the pressure of the bottle and 'P_{mn}' is the minimum pressure. After tackling the major processing cost, which is compression, the next step is to analyze other site costs that represent expenses like piping, building or engineering. These costs are gathered in the following Equation from [26].

$$SC_{site} = \frac{IC_{site} * CRF_{site}}{\text{Annual delivered useable hydrogen}} \tag{42}$$

Table 12: Investment cost for each compressor depending on the type of road transport.

Energy delivered	Type of road transport	Investment cost
2.5 MW	LOHC	750.000 €
	GH_2	500.000 €
10 MW	LOHC	1.500.000 €
	GH_2	1.000.000 €

Where 'IC_{site}' is the investment cost regarding each kind of transport and the energy delivered displayed on Table 12; 'CRF_{site}' is the capital recovery factor for all of these site costs which is considered to take 15 years; and 'Annual delivered useable hydrogen' which depends on the energy delivered. Lastly there are the extra costs regarding LOHC. First it is to put the mixture in and out of the carriers by hydrogenation and dehydrogenation respectively. This is calculated with the folowing Equations, [26].

$$SC_{hydrogenation} = \frac{IC_{hydrogenation} * (CRF_{hydrogenation} + FC_{hydrogenation})}{\text{Annual delivered useable hydrogen}} \tag{43}$$

$$SC_{dehydrogenation} = \frac{IC_{dehydrogenation} * (CRF_{dehydrogenation} + FC_{dehydrogenation})}{\text{Annual delivered useable hydrogen}} \tag{44}$$

Table 13: Investment cost hydrogenation and dehydrogenation.

Energy delivered	Process	Investment cost
2.5 MW	hydrogenation	1.400.000 €
	Dehydrogenation	1.250.000 €
10 MW	hydrogenation	3.200.000 €
	Dehydrogenation	2.700.000 €

Where ’IC’ represents the initial expenses for each of the processes. Data gathered from study [26] and displayed on Table 13; ’CRF’ is the capital recovery factor of the processes, which is assumed to be 15 years; and ’FC’ are the fixed costs that represent 4% of the investment. Finally, the last expense to calculate is storage. This is also exclusive from LOHC as it requires two stationary storage tanks, one for hydrogen rich and one for hydrogen lean LOHC. The way to calculate it is by using Equation 45, according to study [26].

$$SC_{storage} = SC_{tanks} + SC_{DBT} + DBT_{degradation} \quad (45)$$

Where ’SC’ represents the specific costs for tanks and DBT; and ’DBT’ is Dibenzyltoulene, which is the LOHC concept chosen due to its high enough melting point. Moving on to calculating the specific costs of tanks there is the next Equation.

$$SC_{tanks} = \frac{IC_{tanks} * CRF_{tanks}}{\text{Annual delivered useable hydrogen}} \quad (46)$$

Being ’IC_{tanks}’ the investment costs of the tanks, which was previously mentioned; and ’CRF_{tanks}’ the capital recovery factor for the tanks with a lifetime of 15 years. Next there is the specific cost of DBT, calculated with Equation 47 from [26].

$$SC_{DBT} = \frac{DBT_{storage} * DBT_{price} * CRF_{DBT}}{\text{Annual delivered useable hydrogen}} \quad (47)$$

Table 14: Variables to calculate the prize of Dibenzyltoulene used.

Variable	
$DBT_{storage}$	3 x Net tank payload
DBT_{price}	4 €/kg
CRF_{DBT}	15 years
$DBT_{degradation}$	0.1% of the cycles
Useable storage density	4.3% of the weight

Where ’$DBT_{storage}$’ is the amount that can be stored; ’DBT_{price}’ is the price of Dibenzyltoulene; and

'CRF_{DBT}' is the capital recovery factor. Values are on Table 12. Continuing with the last factor of Equation 45, there is the $DBT_{degradation}$ calculates with this Equation, [26].

$$DBT_{degradation} = \frac{DBT_{degradation} * DBT_{price} * \text{Useable storage density}}{\text{Useable storage density}} \quad (48)$$

Where '$DBT_{degradation}$' is the degradation of DBT; and 'Useable storage density' which is the storage available to use. Once all these costs have been analyzed, the next step is to compare the ways of transport.

2.3 Comparison of hydrogen distribution pathways

Once calculated the costs of both ways of transport, the next step is to see which of them results to be more feasible. The approach taken is setting a specific route to carry the mixture. To define this common route, the variables that take place in each of the distribution processes will be studied. Then, those in common will be set with the same value, as seen on table 1.

Table 15: Variables for the different type of transports

Pipelines	**LOHC Trucks**	GH_2 **Trucks**
hydrogen Concentration	Power Equipment	Type Of Bottle
Energy Delivered	Energy Delivered	Energy Delivered
Length	Distance	Distance
Lifetime	Lifetime	Lifetime
Diameter	-	-

According to Table 15, the energy delivered, the distance from production to delivery and the lifetime of the equipment are the equal for all three ways of transportation. Nevertheless, the last one does not have the same value and there is nothing to do about it, so it will not be considered as a common variable. The assumptions for these will be done regarding a hypothetical situation in Portugal.

The energy delivered data used as a reference is from 2019, as 2020's results are not representative due to the lack of regular function as of the pandemic. On study [28], it is stated that in 2020 the energy consumption increased as the quarantine months went by and then the activity peak decreased, meaning results differ from the previous years. The energy consumption gathered in this work is by the IEA, International Energy Agency, where the yearly consumption was stated as 51.4 TWh in the entire country.

The next value is the distance from production to delivery. As the analysis will be done in Portugal the distance is assumed to be one of the longest possible, 500 km. Lastly, there is a lifetime of 40 years for pipelines and 15 years for trucks. Even though it is a common parameter, it can not be common for both ways of transport.

To compare, the economical and environmental aspect will be evaluated. That way feasibility will be checked from different points of view. First step will be explaining the different expenses.

2.3.1 Economic Analysis

In this section there is to compare the overall distribution costs for each type of transport but, in this case, for the same route. To do so, the route will be analyzed individually for each type of transport. The analysis, in this section, will be based exclusively from an economic point of view.

For the pipelines, the variables composition of the mixture, energy delivery, diameter and length of the pipe were considered. Out of them, the only ones set are energy delivery, at 5 MW per year, and distance, at 500 km. The approach will be to calculate the total distribution costs for a hydrogen percentage of 15% hydrogen in the hydrogen-Natural Gas mixture, as it was mentioned to be the most optimum value; and a diameter of 0.8 m, because of its popularity among pipeline diameters.

Regarding trucks, it is already known there are three main ways to distribute hydrogen via road transportation: LOHC and GH_2 with steel or composite bottles. For these expenses the approach will be to start with those they have in common, like compression, to compare them and then continue by analyzing each the particular costs for LOHC. Ending with the total expenses of all three types of road transport.

Lastly, there is to compare the total costs between the four of them and see which results to be more feasible. This is an analysis solely based on the economic perspective.

2.3.2 Life Cycle Analysis

Events such as The Paris Agreement and the United Nation's Agenda for Sustainable Development 2015, Sustainable Goals, have raised awareness towards environmental topics like climate change. That is why the present work has to study the environmental aspects that come with hydrogen distribution and, the way to do it is a Life Cycle Analysis.

The Life Cycle Analysis (LCA) is a methodology that analyses a product during its lifetime, from its production to its utilization and end-of-life, including its recycling process. It is an important methodology to estimate the energy balance and environmental impact of a system and evaluate and compare different energy systems. It follows its growth, the critical mass and its eventual decline. Some of them are product development, market introduction, maturity, etc. Therefore, this way of analysis tackles a lot of different factors that involve several environmental issues.

Even though the present work does not study the social impact, it is also an interesting factor to considerate. Schlör et al. analyze the social impact of hydrogen production in study [3]. They study the footprint in three different European countries: Germany, Austria and Spain. Pointing out the importance of some of the social risk it involves like health, safety or democracy, and showing that it relies on the European institutions. Nevertheless, this work focuses on the events involved when providing hydrogen energy.

For this work, the first step of the hydrogen distribution process is producing the hydrogen. According to study [6], environmental issues related to the production of hydrogen, can be as significant as the economic aspects economically speaking. This happens because even though environmental impacts do not directly imply costs, they can develop expenses in the long run. Issues like pollution or excess waste are some of them. Problems that are being taken into consideration and costing more money now because of the impact they ended up having. Due to the importance of considering environmental impacts, the present paper has considered the hydrogen to be produced by a PEM (Proton Exchange Membrane) electrolyzer. Because, compared to other ways of electrolysis hydrogen production like alkaline water or solid oxide, the PEM electrolyzer is highly beneficial for the environment. This is because it uses low temperatures (20-80℃), produces very pure hydrogen and oxygen, has very good work features such as low gas permeability, high proton conductivity, high pressure operations, etc. Nevertheless, the costs are still high due to the materials needed for the electrocatalysis. However, this is still because of its novelty and, as technology advances, these expenses are expected to decrease.

Bossel, [1], stated that 200 MW of direct current electricity were needed to liberate 1 kg of hydrogen from 9 kg of water by electrolysis back in 2006. 12 years later in work [11], it was addressed that this kind of electrolyzer could produce 20 kg of hydrogen per MW installed. Meaning there have been improvements. Nowadays, the maximum per single PEM electrolyzer is 3 MW, but there can always be built a modular aggregation of individual units, which would increase it. Examples are projects developed in Germany, which obtained 10MW, or Austria, which managed to get 13 MW, [11].

The next step in the distribution process would be to mix it with natural gas, according to the established proportions. Then it would go the compressor where it could have three different paths.

One of the paths of distribution is pipelines. The compressor would have to pressurize the mixture to a determined point depending on the characteristics of the pipe. Then, it would make its way through the infrastructure from production to delivery station where it would be delivered to all of the final consumers.

Considering the LOHC carriers, hydrogen is in its liquid stage. The mixture would be pressurized to 50 bar and then taken to the carriers. The process to put it in them is called hydrogenation. Then, it would be transported to the delivery station where, to get the product out, it would go through dehydrogenation, which is the opposite process. Both of these make the distribution process reversible. Once it gets there, it can be consumed.

There are GH_2 tanks. This way of road transport can utilize two kinds of bottles: steel or composite. Nevertheless, the process is the same and the only difference is the pressure. Steel bottles carry the product at 200 bar while composite bottles have to be compressed to 350 bar. When the mixture is compressed in the bottles, they are taken to the tanks into the truck and carried to the delivery station, where they will finally be delivered to all of the end consumers.

Figure 10 illustrates all the considered described cases or routes.

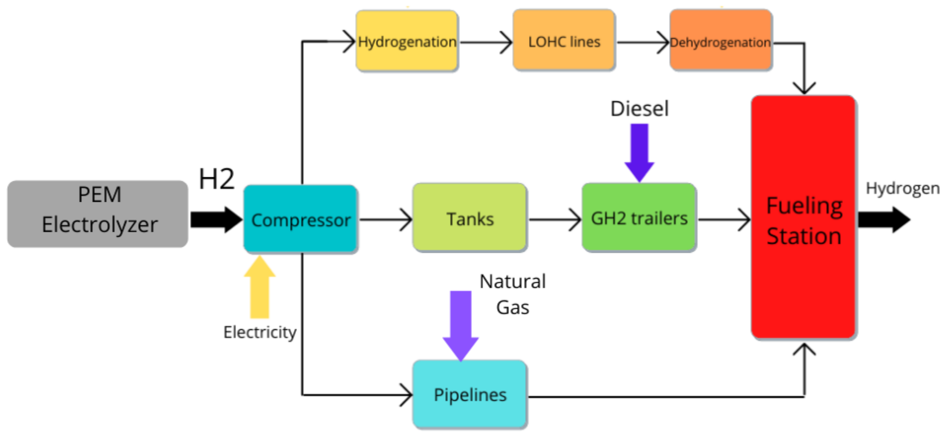


Figure 10: Delivery Scheme for hydrogen distribution possibilities.

Table 16 summarizes all the data that was considered. Data, which was briefly introduced in the previous paragraphs, was gathered from articles [4], [9], [10] and [26].

Table 16: Values for Life Cycle calculations

PEM Electrolyzer	
Electricity demand	33.6 kWh/kgH_2
Water	2 l/kgH_2
hydrogen pipeline	
Pressure $level_{max}$	200 bar
Diameter	0.81 m
Length	500 km
Tank transport	
Pressure level GH_2 Steel Bottles	200 bar
Pressure level GH_2 Composite Bottles	350 bar
Pressure level LOHC	50 bar
Storage capacity Steel Bottles	400 kg
Storage capacity Composite Bottles	900 kg
Storage capacity LOHC	1400 kg
hydrogen fueling station	
Capacity	850 kg/d
Utilization factor	80 %
Pressure $level_{max}$	880 bar
Pressure $level_{out}$	700 bar

The present work was applied to the Portuguese case. The data based used for energy consumption during the analysis comes from the IEA, International Energy Agency. All the data is from year 2019 as there are some differences in the consumption patterns comparing to 2020 due to the pandemic, seen in work [28]. The total CO_2 emissions from the electricity produced were a total of 43,8 Mt, as well as an electricity consumption for that year was of 51.4 TWh. A simple way to study the CO_2 emissions is relating both of these values. This can be done by assigning the value of total CO_2 emissions to the total energy consumption. Therefore, the relation between these is 0.852 t CO_2/MWh.

Emissions provided from pipeline distribution will be based on the electricity needed to pump the product through the pipe. This approach will also be done regarding truck transportation, during the processing of the mixture. Nevertheless, in this case, there is to remember that it does not only require energy for treating the hydrogen, but from the diesel as well. To calculate it, there is the electricity energy and the CO_2 emission factor. The approach will be by using the following Equations, from research article [5]:

$$E_e = [(1-f)(\frac{1}{eff_{grid}}\sum\frac{W_{e,i}}{eff_{e,i}})^{Nat} + f + (\frac{1}{eff_{grid}}\sum\frac{W_{e,i}}{eff_{e,i}})^{Imported}] - (1MJ)^{Output} \quad (49)$$

$$CO_{2e} = [(1-f)(\frac{1}{eff_{grid}}{}_{e,i}c_i)^{Nat} + f + (\frac{1}{eff_{grid}}{}_{e,i}c_i)^{Imported}] \quad (50)$$

Equation 49 will be used to calculate the energy needed for pumping the hydrogen-Natural Gas product through the pipeline as well as the processing the hydrogen in the case of truck transport. Then Equation 50 will tackle the emissions regarding diesel for road distribution. As the same route is calculated for both truck transports, the energy result from Equation 49 will be the same for LOHC and GH_2.

Methodology, results and conclusions regarding calculations for each type of distribution will be addressed and discussed in the following sections.

3 Results and discussion

3.1 Pipelines' delivery costs

3.1.1 Properties of the Mixture

When transporting a gas, there are some parameters to study such as the temperature or pressure of transportation. As in the present work the product to transport is a mixture of two gases, hydrogen and Natural Gas, the mixture will have its own unique parameters.

Starting by the compressibility factor, Z, this factor is dependent, as seen on Equation 12, on 'A' and 'B' which are parameters dependent on the temperature and pressure, Equations 13 and 14. The temperature considered in the present work was of 298 K as an average value. However, pressure was kept as unknown and was calculated using Equation 17. This Equation is also dependent on the Peng-Robinson parameters

'a_m' and 'b_m', Equations 21 and 24 respectively, which are dependent on the pseudocritical properties of the mixture. These are the only values that could be calculated by now. Pressure can not still be calculated because it is also dependent on the specific volume, 'ν', of the mixture. The approach here was to assume the ideal gases Equation, Equation 4, but adding the parameter 'Z' as it is not considered an ideal gas.

As the compressibility factor, pressure, specific value and parameters depend on each other, the way to solve it was by iterating these Equations between them until there was a common result. Iterations were done by program EES. The final results are displayed on Table 17.

Table 17: Parameters of the hydrogen-Natural Gas mixture.

Property of the mixture	
Temperature	298 K
Pressure	51.87 MPa
Z	1
A	$2.2 \cdot 10^{-7}$
B	$3.394 \cdot 10^{-7}$
a_m	0.026
b_m	$1.62 \cdot 10^{-5}$
ν	47.77 m^3/kg
ρ	0.02 kg/m^3

As it could be expected, these parameters do not depend on the dimensions of the pipeline or the energy delivered. However, something interesting is that these parameters are independent of the composition of the mixture. Meaning, they will be the same for all the cases that will be studied in the following section.

3.1.2 Composition of the Mixture

Composition of the mixture is the variable that determines the percentage of hydrogen carried by the product through the pipes, which is mixed with Natural Gas. Ending up with the final product to distribute, which is a hydrogen-Natural Gas mixture. Jawroski et al. stated on [14] that this value should not be over 20% for security purposes. To focus only on the composition parameter the other variables, diameter, length of the pipeline and energy delivered, will be kept as constants according to the values on Table 1.

As stated on the previous section, the parameters on Table 17 will not change depending on the percentage of hydrogen that is being transported. Nevertheless, there are other factors dependent on this factor, for example its lowest heating value. Back to Equation 20, it can be seen that this variable relies on the percentage of hydrogen in the total hydrogen-Natural Gas mixture. Its values are represented on Figure 11.

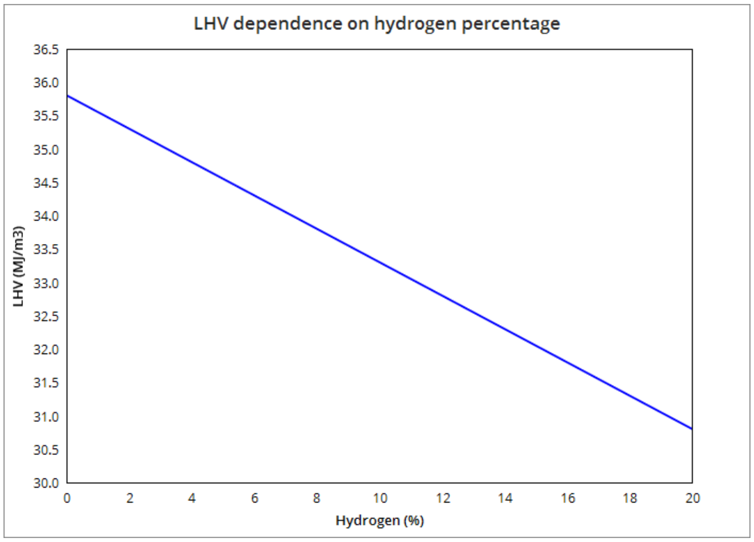


Figure 11: LHV dependence on hydrogen in the mixture.

This Figure shows that increasing the hydrogen percentage in the mixture leads to lower LHV. This implies higher flows when delivering the same amount of energy when using a hydrogen rich mixture. This behavior can be seen on Figure 12.

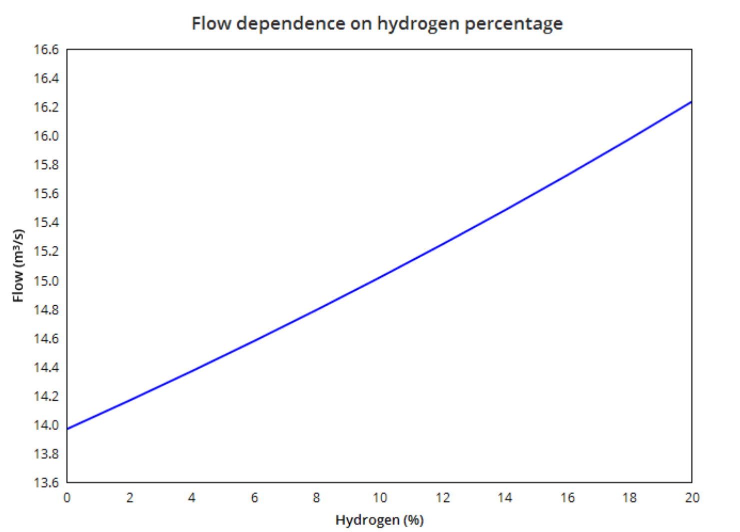


Figure 12: Flow dependence on hydrogen in the mixture.

With this Figure the previous conclusion can be verified. hydrogen rich mixtures require a higher flow demand to deliver the same amount of energy. Regarding composition of the mixture, these are the two parameters to calculate. Now there is to know the variance of pressure between inlet and outlet of the pipeline by applying to Equation 11. Figure 13 represents this pressure variance assuming the inlet pressure, P_1, is 5 MPa.

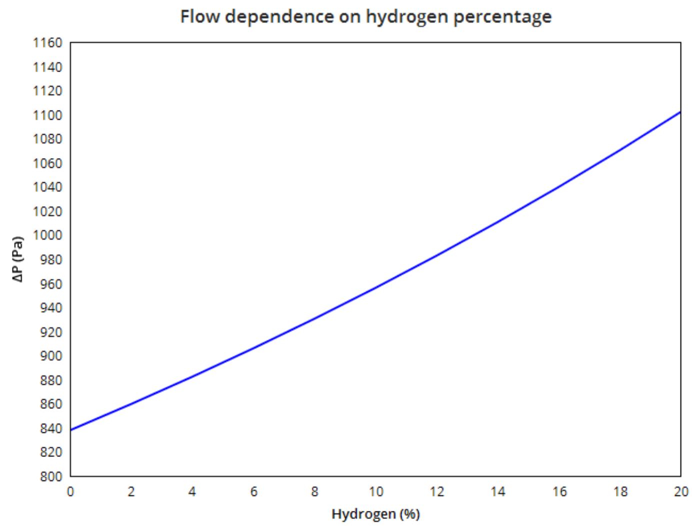


Figure 13: Variance of pressure dependence on hydrogen in the mixture.

As there is more hydrogen in the mixture there are more energy losses, which are represented as a pressure drop from inlet to outlet of the pipeline. The energy required to pump the hydrogen-Natural Gas product to compensate this loss is represented on Figure 14, which was calculated from Equation 21 and applying a 90% efficiency factor.

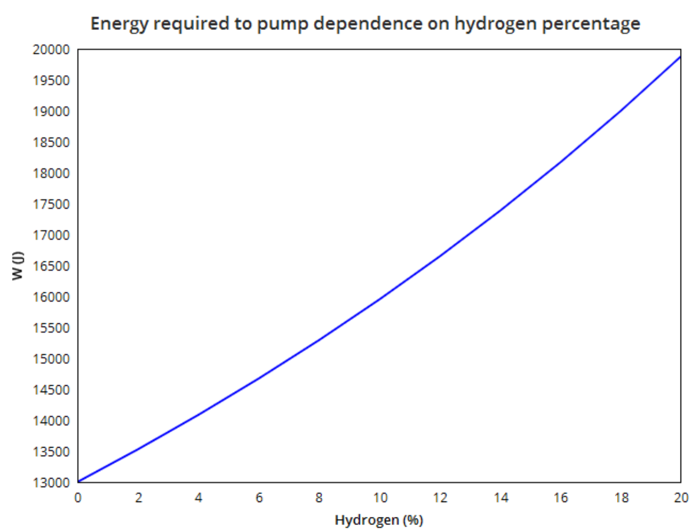


Figure 14: Energy required to pump the hydrogen-Natural Gas mixture through the pipe dependence on hydrogen in the mixture.

Results show that, when there is more hydrogen in the mixture, more energy to pump is required. When reviewing results from study [17] on section 'Literature review', the behavior seems to be similar. Transmission costs increase as the mixture delivered is richer in hydrogen. Even though Figure 14 represents the energy required to pump, compression costs are directly related to the energy consumption meaning that higher energy requirements imply more expenses to transport the product through the pipeline. This would lead to the conclusion that a hydrogen-poor mixture will be better to decrease the overall costs.

3.1.3 Energy delivered

The next parameter to analyze will be the energy to be delivered. This factor will range from values 0.1 to 1 GW just like on paper [17]. As the composition of the mixture is set to 15% hydrogen, as stated on Table 1, the LHV of the hydrogen-Natural Gas will be the constant value of 32.05 MJ/m^3. Figure 15 represents the amount of flow needed to deliver each quantity of energy.

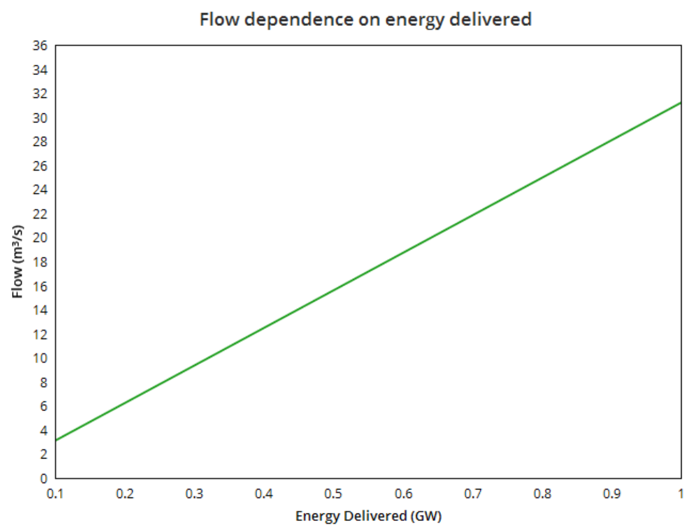


Figure 15: Flow dependence on energy delivered.

As it could be expected, when the energy to deliver increases so does the flow needed to distribute. To continue the analysis, there is the variance of pressure between inlet and outlet of the pipe, which is represented on Figure 16.

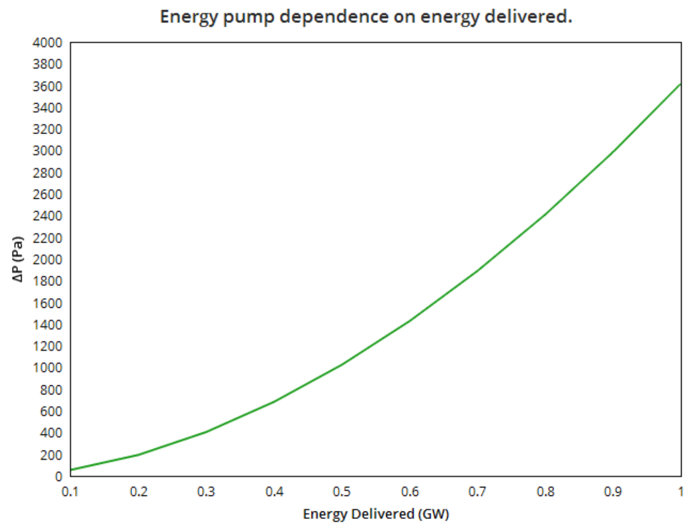


Figure 16: Variance of pressure dependence on energy delivered.

Higher energy deliveries imply larger pressure drops. This will require more energy to pump the product through the pipeline. The conclusion was plotted on Figure 17.

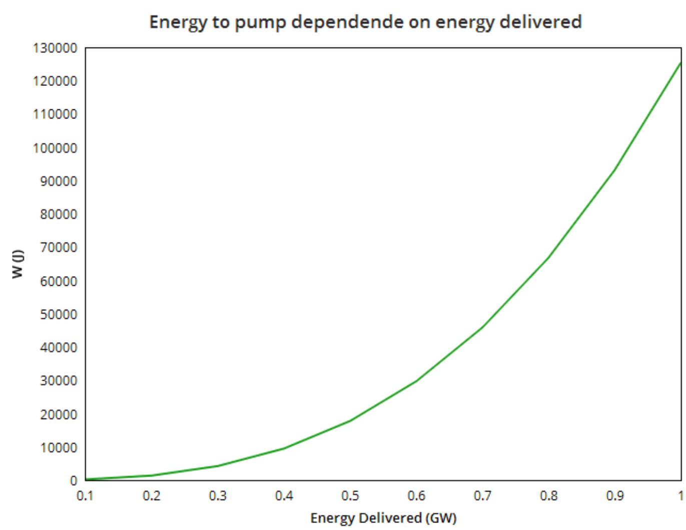


Figure 17: Energy required to pump the hydrogen-Natural Gas mixture through the pipe dependence on energy delivered.

Figure 17 shows that the energy required to pump the hydrogen-Natural Gas mixture through the pipeline increases as more energy is delivered. The variance of pressure is significantly higher when compared to Figure 14, up to 1 order of magnitude. Nevertheless, the behavior when compared to study [17], Figure 2, does not follow the same pattern. The reason why this occurs is because the diameter used by Oney et al. on study [17] changes to obtain the most optimum situation. However, in the present work, diameter was kept as a constant to focus on the variable that is being analyzed, in this case how much energy is being delivered.

The fact that the energy required to pump the hydrogen-Natural Gas mixture through the pipeline increases as there is more energy delivered, implies a question. Will there be a point where there is more energy required than delivered? Because, if it happened, it would not make sense to distribute the product. It would all be losses, not only economically but energetically as well. For the case proposed in the present work this would not happen until the energy decided to deliver is over 35 GW. Then, the pressure in the outlet of the pipeline, P_2, would reach a negative value, meaning it would be producing vacuum, which would be needed to overcome.

For the range of values this case would not happen, the work needed to pump the product through the pipe, compared to the energy delivered, is 10.000 times less. However, it is a factor to consider and keep in mind as, in other cases, it could occur.

3.1.4 Diameter of the pipeline

Starting analyzing the first parameter regarding the infrastructure of the pipeline, there is the diameter. This factor will be studied in a range of values from 0.4 to 1.2 m as, according to Froeling et al. on [13], these are the most commonly used pipeline diameters. The parameters of the hydrogen-Natural Gas mixture will be the same as on Table 17. Regarding the LHV, the value will be the same as in the case of energy delivered, 32.05 MJ/m^3. Nevertheless, the flow will also be a constant value as the energy delivered is also going to be considered as a constant. Its value will be of 0.5 GW, as stated on Table 1. Both of these parameters determine a need of 15.6 m^3/s of 15% hydrogen-Natural Gas mixture. Continuing with the analysis of the diameter, the only parameter to study is the variance of pressure from inlet to outlet, which is displayed on Figure 19.

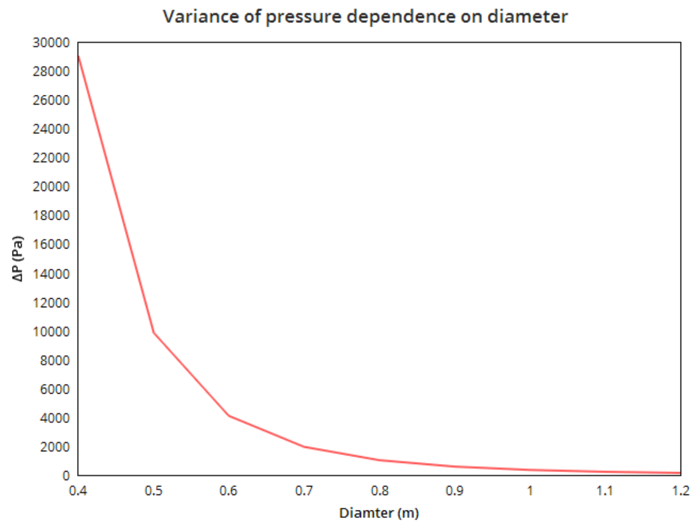


Figure 18: Variance of pressure dependence on diameter.

The relation between variance of pressure, from inlet to outlet of the pipeline, and energy required to pump the hydrogen-Natural Gas mixture through the pipeline is portrayed on Figure 19. The difference on the pattern of the plots will not be different, as it happened with the composition and energy analysis. The purpose of plotting both of them is seeing the range of values they move in.

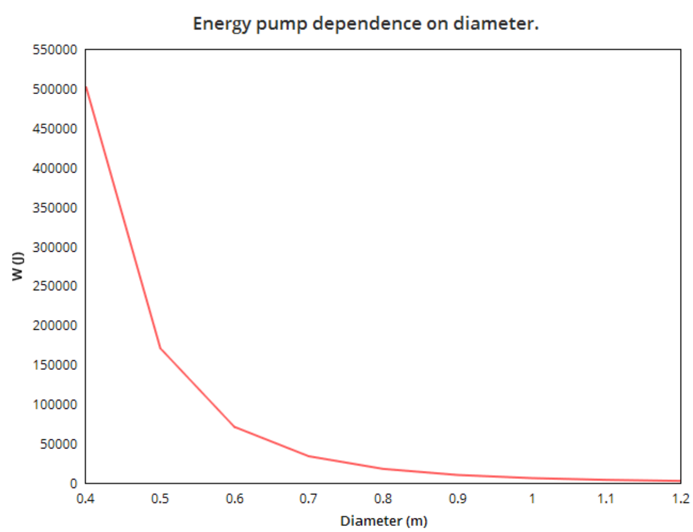


Figure 19: Energy needed to pump the hydrogen-Natural Gas mixture through the pipe dependence on diameter.

Lower diameters imply large pressure drops which lead to higher compression costs. This means that higher diameters are better when considering this expense. Oney et al. came up with the same behavior, as seen on Figure 4, on study [17]. However, there is to remember this is not the only cost to consider. When debating about the diameter of the pipeline there is also to consider piping costs, which will increase as the diameter is bigger. This point will be discussed on the costs section of the results.

Something interesting to notice as well, is the plateau in the graph when the diameter is approximately over 0.8 m. As stated before, the higher the diameter the better. However, this plateau could be a determinant factor to relate both compression and piping costs, just like on Figure 5 from study [17].

3.1.5 Length of the pipeline

Regarding the length of the pipeline, the only parameter affected is the variance of pressure between inlet and outlet of the pipeline, just like in the case of the diameter. The behavior depending on the value of the distance is displayed on Figure 21.

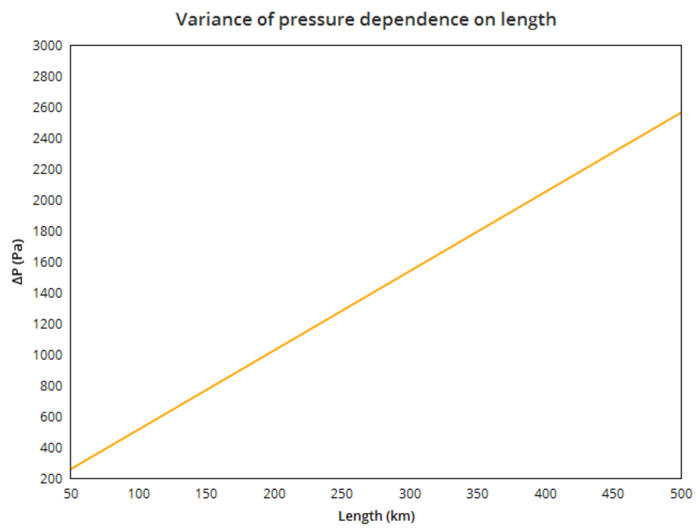


Figure 20: Variance of pressure dependence on length.

Once the variance of pressure in the pipelines is known, there is to analyze the energy required to pump the product through the pipe.

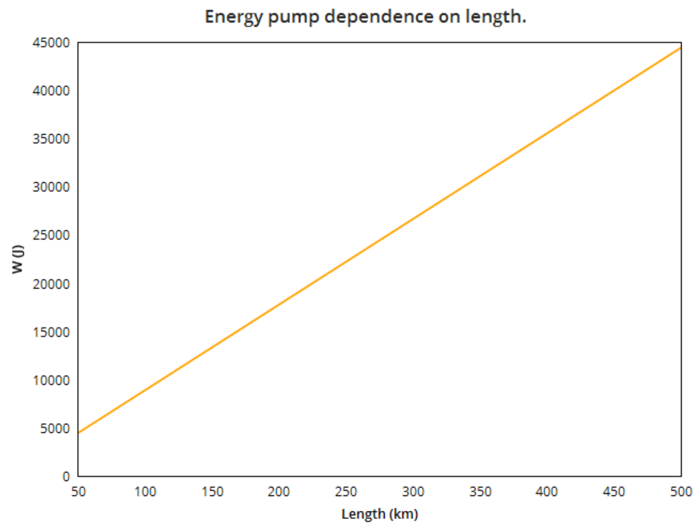


Figure 21: Energy needed to pump the hydrogen-Natural Gas mixture through the pipe dependence on length.

As the distance increases so does the energy needed to pump the hydrogen-Natural Gas mixture through the pipeline. Compared to Figure 3 from study [17] by Oney et al., the pattern is the same. Costs increase as the distance is larger. However, unlike the other variables studied like composition of the mixture or energy delivered, length is a given value. It is set by the distance from production to delivery point, meaning there is not much to do about it. Also, it is important to notice that the difference of energy needed in the range of values studied, and therefore the total transmission costs, is not as big when compared to other variable's results like the diameter. This could also be because of the range used. Therefore, it will be studied in detail in the following costs section. There is to remember that this is also a variable that is linked to the dimensions of the infrastructure, meaning it will have an impact on the piping costs. This will be discussed on the costs section.

3.1.6 Overall costs

When considering the costs when distributing via pipelines, there is to differentiate between compression and piping costs.

Compression costs are directly related to the energy required to pump, as stated before. This energy is pictured on Figures 14, 17, 21 and 23, depending on the variable that is being studied. These expenses can be calculated by using Equation 23. The costs per hour related to this variance of energy required go from 2.341 to 3.578 € when analyzing composition of the mixture; 34 to 22.589 € for energy delivery; 90.577 to 453 € when studying the diameter; and 799 to 7.995 € for the length. Based on these results the biggest price range is from changing the diameter. It could be by chance, but the difference goes up to 2 orders of magnitude. Meaning this may be the variable that impacts the transmission costs the most.

Piping costs comply investments, both for material and installation costs. When considering the values on Table 1, when the variables are kept constant, the pricing is of 30.38 M€ in the case of material cost and 5.1 M€ for installation. Both were calculated with Equations 24 and 25 respectively. Coming up to a total of 35.48 M€. When leveling these costs, using Equations 27 and 28. Ending up with yearly piping costs of 74.386 €. This case would only be valid when studying both composition of the mixture and energy delivery in the present work. When changing the diameter and the length of the pipeline these values do not apply as Equation 24 is dependent on both of these dimension variables.

In the case of the diameter, for the range of values analyzed, the total material piping costs are displayed on Figure 22.

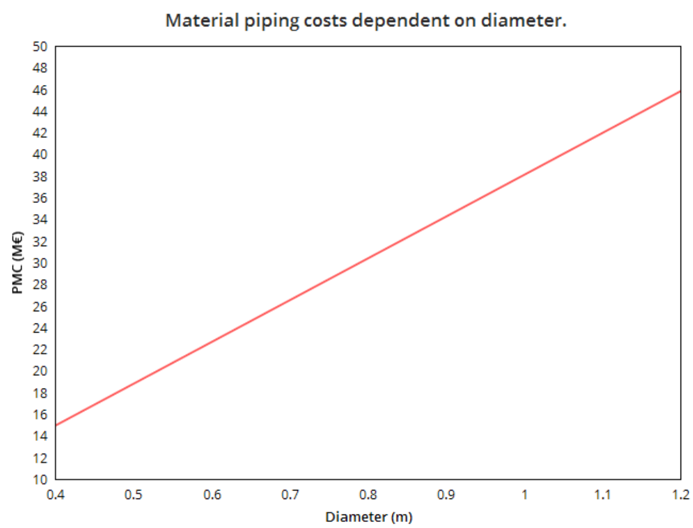


Figure 22: Material piping costs dependent on the diameter.

As represented on Figure 22, increasing the diameter in this range of values could increase the material expenses up to 30 M€. Here is where the plateau from Figure 19 takes a huge influence. Out of the plateau, for example from a diameter of 0.4 to 0.5 m, the material cost difference is of 4.2 M€, while the energy required to pump goes from 503 kJ, in the case of 0.4 m, to 170 kJ with a 0.5 m diameter. This is a decrease of 66%. In the beginning of the plateau, the difference in material costs from a 0.8 to 0.9 m diameter is of around 4 M€, from 30.38 to 34.24 M€, while the energy required to pump is 7.7 kW lower, 43% less energy required. More into the plateau, for example from 1.1 to 1.2 m diameter, the energy needed to pump goes from 3.8 to 2.4 kJ, a 36.8% decrease, in energy while the material cost would go up to 45.8 M€. As it can be seen, material costs are linear while compression costs have a more constant pattern.

Regarding installation costs, in this case they are a constant value of 5.1 M€, as length considered is a constant value of 200 km. When not considering length as a constant parameter both installation and material costs are affected. Starting with the material costs there is Figure 23.

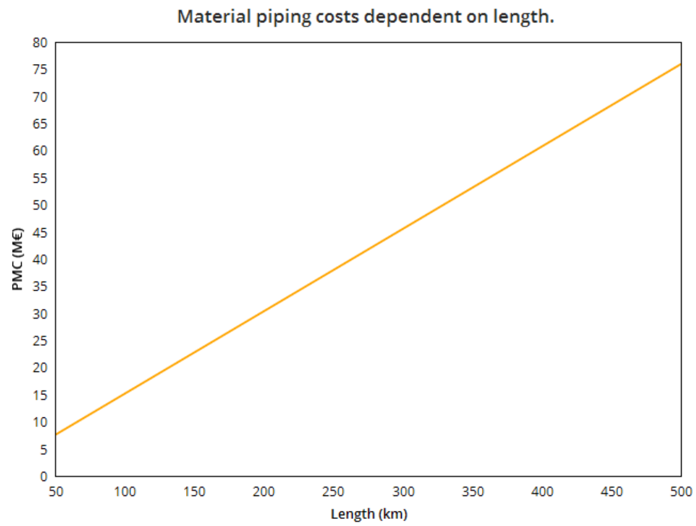


Figure 23: Material piping costs dependent on the length.

Unlike when changing the diameter, larger values for length imply both bigger compression, as seen on Figure 21, and material costs. Therefore, the conclusion here is that the shorter the distance the better. However, as previously stated, this is a variable where there is not much control on, as it is determined by the production and delivery point. When calculating piping costs for variable length there is not only a variable material cost, but also installation. This is plotted on Figure 24.

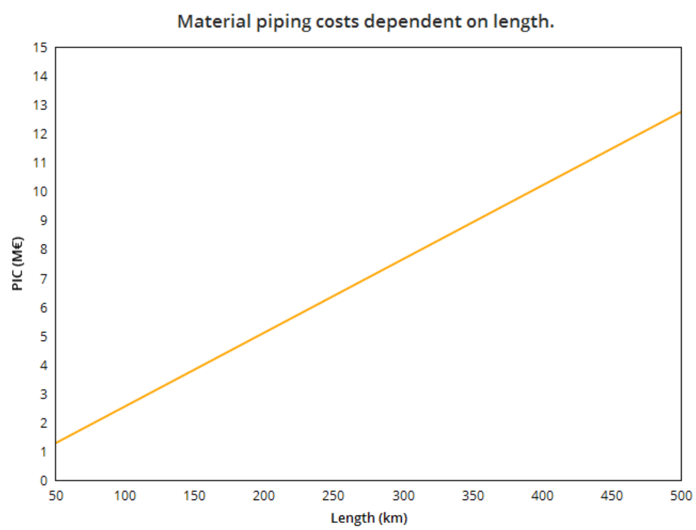


Figure 24: Piping costs for installation dependent on the length.

The same conclusion as before can be applied here. Expenses increase as the distance is larger, but there is not much to be done about it. The only solution available would be focusing on the other variables, composition of the mixture, energy delivered and diameter to compensate these expenses.

3.2 Truck Transportation's Costs

3.2.1 Trucking Costs

Starting by analyzing trucking costs, it was considered four components: investment, personnel, fuel and operations and maintenance. The last three have a dependence on distance, which means there is going to be a big influence regarding this variable. Figures 25, 26 and 27 show the costs regarding each type of transport for both energy deliver cases depending on the distance, red represents 2.5 MW and green 10 MW.

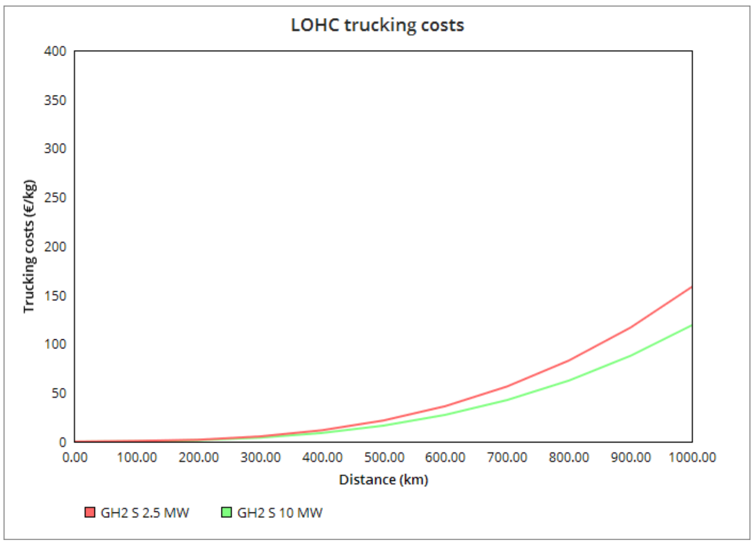


Figure 25: LOHC trucking costs depending on distance.

For LOHC Figure 25 shows a difference on costs depending on the energy delivered. As distance increases, trucking expenses have a noticeable difference where, as more energy is delivered, this expense decreases. Meaning, it is a better option for bigger energy deliveries. Also, there is an increment on costs as distance is larger due to its dependency on fuel, personnel but most of all, operations and maintenance.

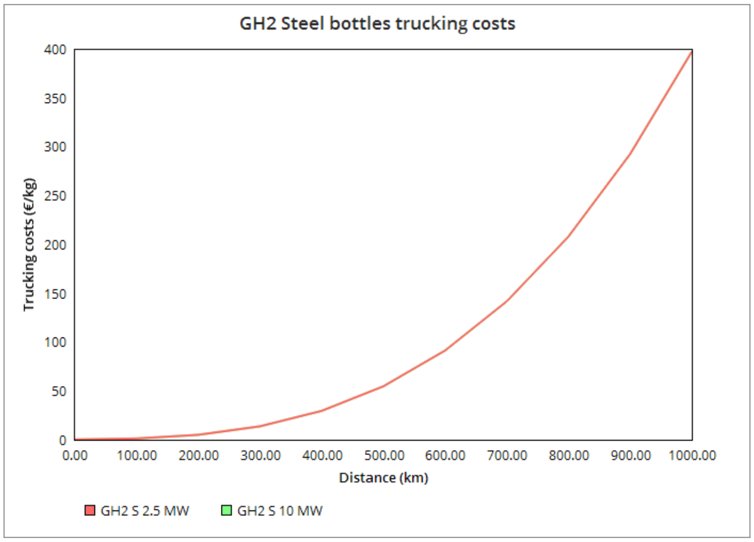


Figure 26: GH_2 with steel bottles trucking costs dependence on distance.

The same increment with distance occurs when distributing hydrogen with GH_2 trailers using steel bottles. However, there is not a clear distinction between delivering 2.5 or 10 MW. This would mean that the energy delivered, int his case, does not make an impact. It is also important to notice the increment in price compared to 25. For there same distance there is a difference up to 200 € per kg compared to LOHC. The reason why this happens is because of the capacity difference. LOHC can carry up to 1.400 kg per trip while GH_2 with steel bottles can transport only 400 kg per trip. This would lead to a need for more trucks when delivering the same amount of hydrogen.

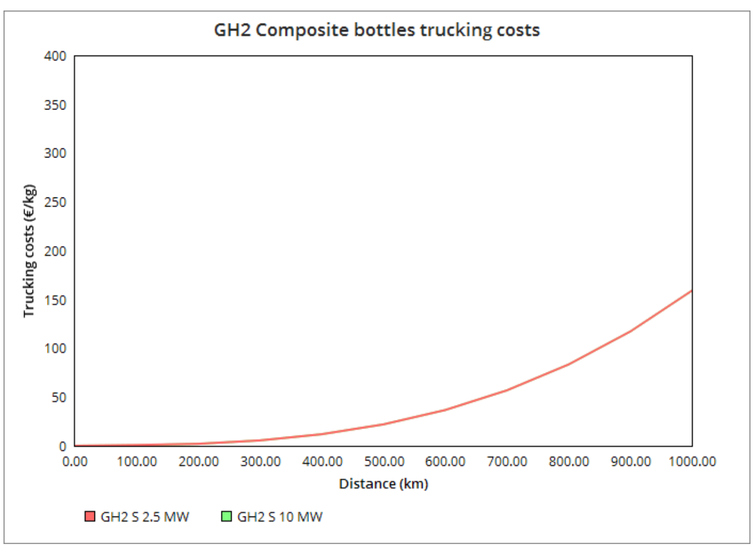


Figure 27: GH_2 with composite bottles trucking costs dependence on distance.

For GH_2 trailers with composite bottles there is the same conclusion, as for GH_2 using steel bottles, regarding energy deliveries. It is not crucial when it comes to this cost. However, it is more balanced to costs to LOHC. This is due to its truck capacity, 900 kg, which makes the number of trucks needed more even between both ways of transport.

Therefore, the type of transport to choose, when only considering trucking costs, is going to depend on the energy delivered and the distance. For both energy deliveries the most feasible option is going to be LOHC, for any distance. However, when possible, it would be better to go for big energy deliveries, as it makes the distribution increase its feasibility. Trucking is not the only expense when it comes to road transport, so the next step is to analyze the processing of the product.

3.2.2 Compression Costs

Compression is the main process part when it comes to getting hydrogen into its desired state. Its costs are represented on Figure 28, regarding which way of truck transport is used and how much energy is delivered.

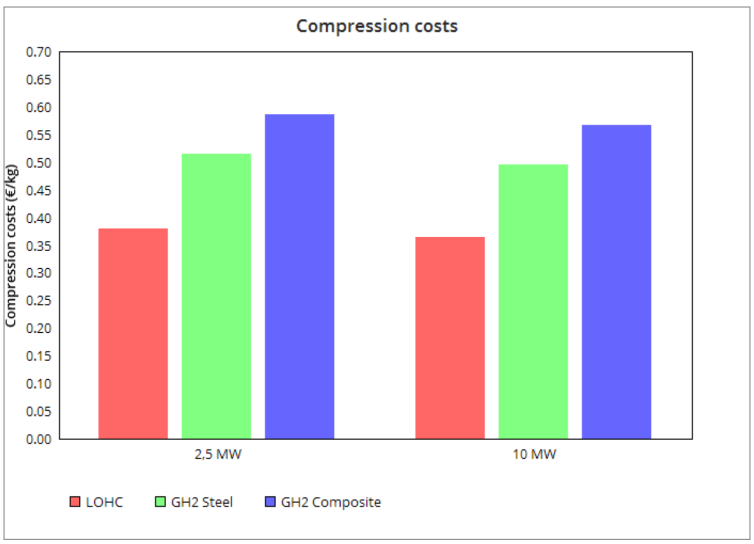


Figure 28: Compression Costs.

According to this expense, seen on Figure 28, the best option would be LOHC as its compression costs are the lowest at 0.38 €/kg for 2.5 MW and 0.36 €/kg for 10 MW. This makes sense as GH_2 needs to be compressed to higher pressures than LOHC. LOHC requires 50 bar pressure while GH_2 using steel bottles are at 200 bar and composite bottles are at 350 bar. Again, costs are lower as energy deliveries increase because of the increment in distribution feasibility. This is because carrying more makes the feasibility of the transport increase. According to this, there is to conclude that this kind of transport benefits from bigger energy deliveries rather than small continuous discharges.

3.2.3 Site Costs

These represent other costs, which are not involved in the processes of production or delivery, such as piping, engineering or buildings. Their values are shown on Figure 29, depending on the energy to deliver, as well as the type of transport to use.

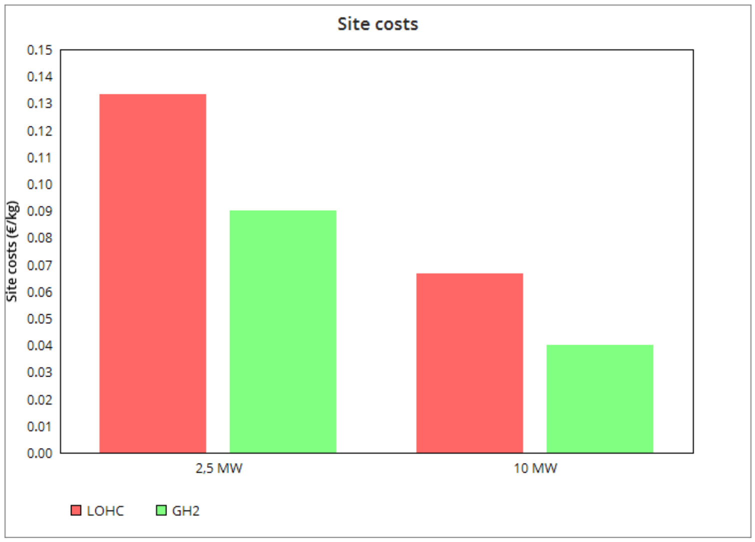


Figure 29: Site Costs.

Results show that expenses are lower in the case of GH_2, at 0.09 €/kg for 2.5 MW and 0.04 €/kg for 10 MW. This makes sense as LOHC is a novel way of transport, which means there is a lack of research and, therefore, there is not enough information about the optimum infrastructure. On this expense it can also be seen the impact on energy delivery as, when transporting more hydrogen, feasibility increases. Conclusions, regarding how much energy should be delivered, is still the same.

3.2.4 Processing Of LOHC Costs

Moving on to the processing costs involved only when distributing by LOHC, there is hydrogenation and dehydrogenation. They are, respectively, the processes to get hydrogen in and out of the carriers. As they are exclusive processes for LOHC, this means they are going to be extra costs GH_2 trailers are not going to have to deal with. Results from calculations are shown on Figure 30 depending on the energy delivered (2,5MW or 10MW):

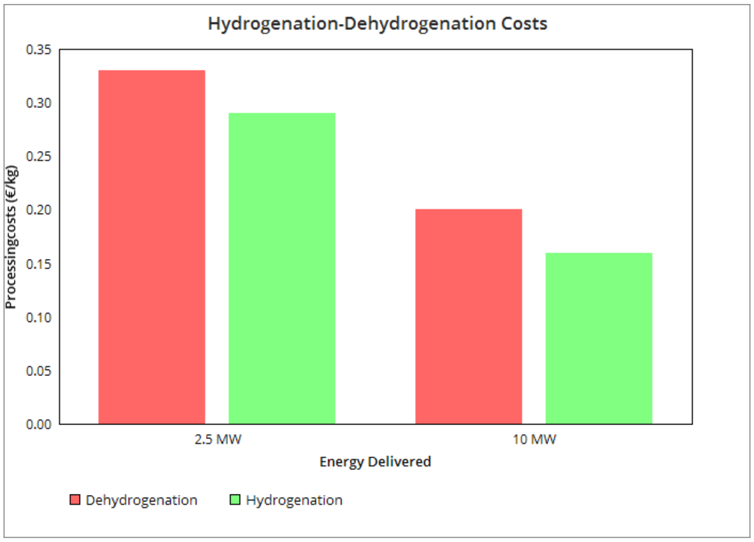


Figure 30: Processing Costs for LOHC.

This extra processing adds up to 0.62 €/kg to LOHC's processing costs. Also, the analysis shows again that delivering more energy is more feasible for the process, which has been a common factor for all the previous cases.

3.2.5 Storage Costs

Considering storage costs which are also exclusive for LOHC. These would be two stationery tanks, both for the hydrogen source and utilization sites. Results are displayed on Figure 31.

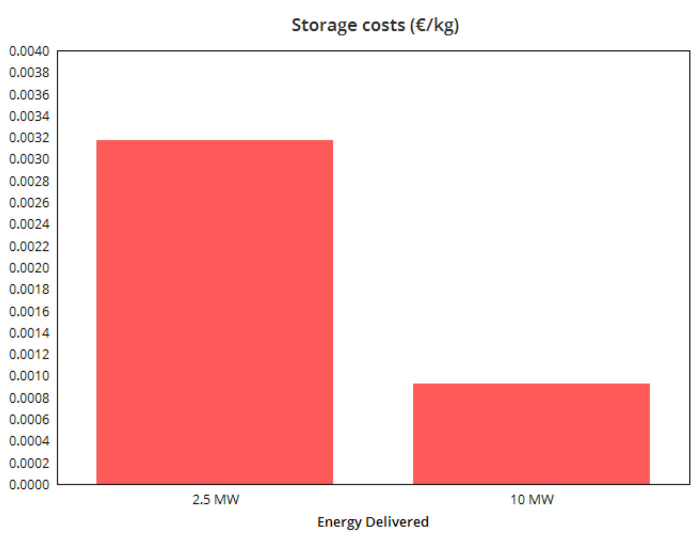


Figure 31: Storage Costs regarding LOHC.

This would also be an added expense for LOHC, in this case up to 0.003 €/kg, and there is also a decrease on the price when delivering more energy, which reaffirms the increased feasibility in distribution costs when making bigger energy deliveries.

3.2.6 Overall costs

Looking back at all the analysis made about every part of the processing, there is not a common choice for all of the different expenses. That is why the next step is going to be to sum up all these costs to see which of them provides the lowest expenses. These are displayed on Figure 32, depending on energy delivered and type of road transportation.

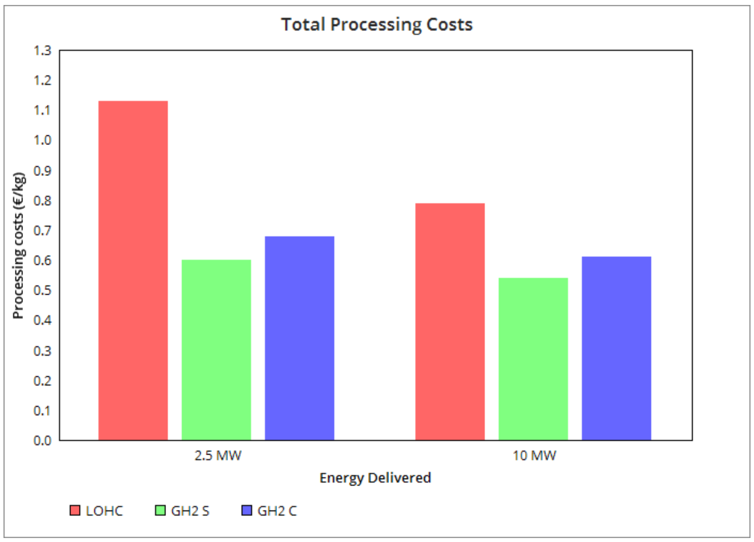


Figure 32: Total processing costs for road transport.

This analysis finally confirms that, according to processing costs, delivering more energy is more feasible than small energy discharges for all three types of road transport. Obviously, it is more noticeable in the case of LOHC than GH_2 using steel bottles, but there is still a difference. Also, according to these costs, the best approach would be GH_2 with steel bottles for both energy deliveries, with a price point of 0.6 €/kg for 2.5 MW and 0.54 €/kg for 10 MW. These price points coincide with the values from Figure 7, which shows results from Peneva et al. on [26]. However, this is the final conclusion regarding processing costs, but there is to remember trucking costs which were previously analyzed. Summing up both of the expenses, results are plotted on Figure 33 regarding distance and type of road transport.

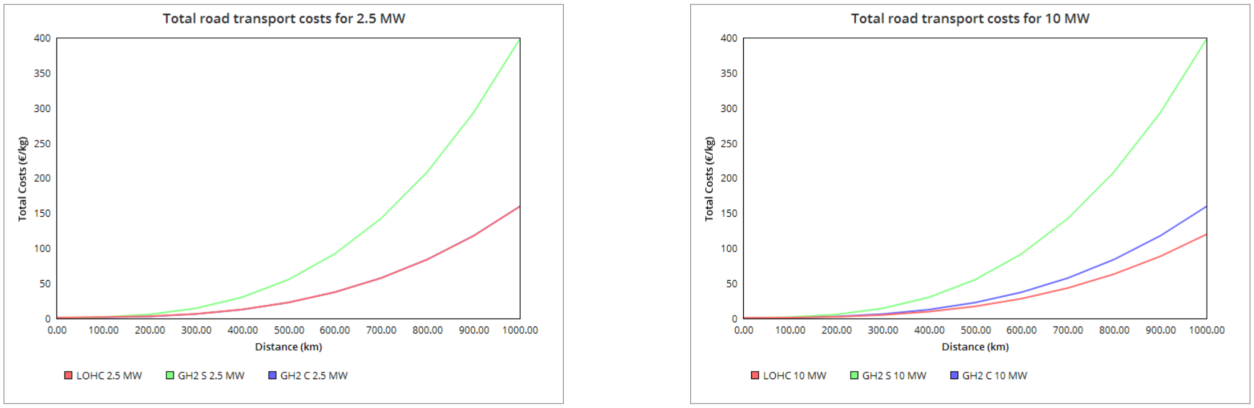


Figure 33: Total road transport costs for 2.5 and 10 MW energy deliveries

The main difference to point out is that, on the plot on the left there are two lines while on the 10 MW delivery there are three. This is because the total costs for LOHC and GH_2 using composite bottles when delivering 2.5 MW are almost identical, and they blend into the same line. For example halfway, at 500 km, costs add up to 22.74 €/kg for LOHC while for GH_2 with composite bottles they are 22.64 €/kg. Meanwhile, for the same distance GH_2 with steel bottles' expenses are 55.29 €/kg, which is the double the price.

Therefore, regarding energy deliveries, the best choice for 2.5 MW is going to be GH_2 with composite bottles and for 10 MW it is LOHC. If it was necessary to choose only one of them for any energy delivery, the choice should be LOHC due to its similar results regarding GH_2 with composite bottles for lower energy deliveries.

This behavior seems to replicate the solutions addressed from study [26] on the 'literature review' section. As seen on Figures 6 and 7. When the energy delivered is 2.5 MW and distance is 50 km both GH_2 options are equally a good choice, while LOHC is more expensive. As distance increases, steel bottles become a worse option than composite due to its expenses' increment, while composite bottles as well as LOHC are more stable. Lastly for 300 km LOHC will be the option to go for, keeping in mind results from this work show the average between CAPEX. For 10 MW deliveries costs also decrease and the same choices are displayed. For the shortest distance composite bottles are the winners while, when length gets longer, the choice should change to LOHC. Results are not exactly the same due to different approximations and assumptions.

Now, when it comes to distance, the approach should be using GH_2 with composite bottles for distances shorter than 600 km for 2.5 MW deliveries and shorter than 200 km for 10 MW energy deliveries. The reason why this happens is because of the different influence trucking and processing have on the overall expenses depending on distance. This can be seen on figures 34, 35 and 36, displayed by type of road transport, energy delivery and regarding distance.

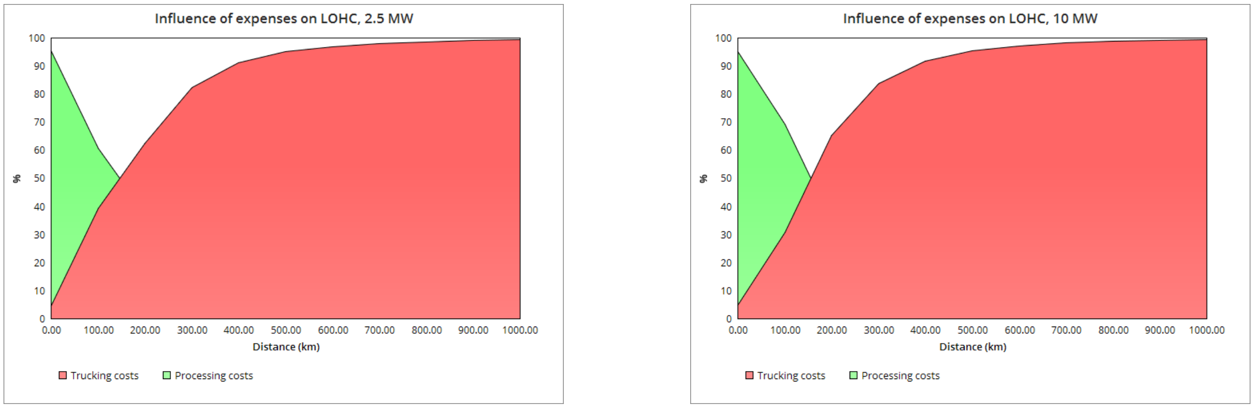


Figure 34: Costs' influence on LOHC for 2.5 and 10 MW regarding distance.

In the case of LOHC trucking costs turn out to be more than 50% of the expense when distance is greater than 150 km for both energy deliveries. This type of road transport is the one with the least trucking costs, therefore, the fact that more than half of the overall costs are regarding this expense benefits its feasibility. This verifies the statement from work [26] about this type of transport, it is better for long distances.

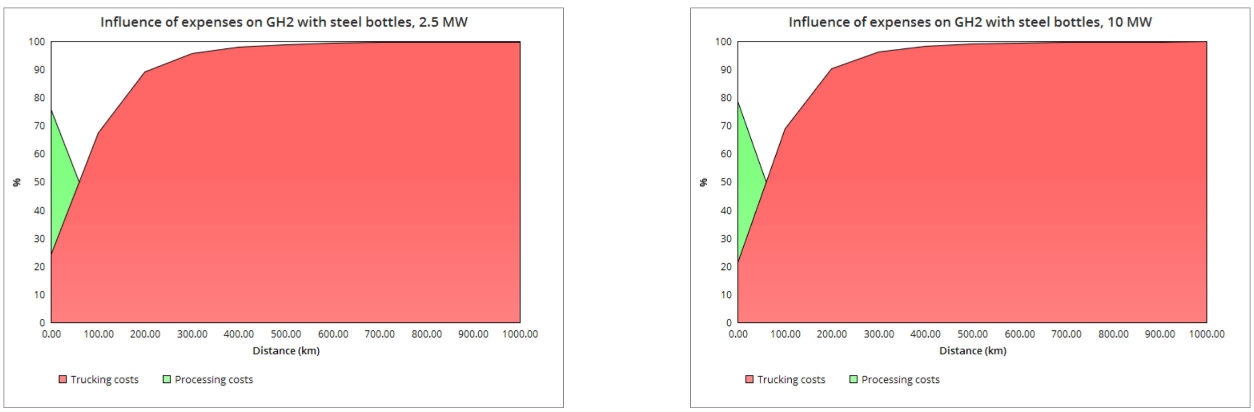
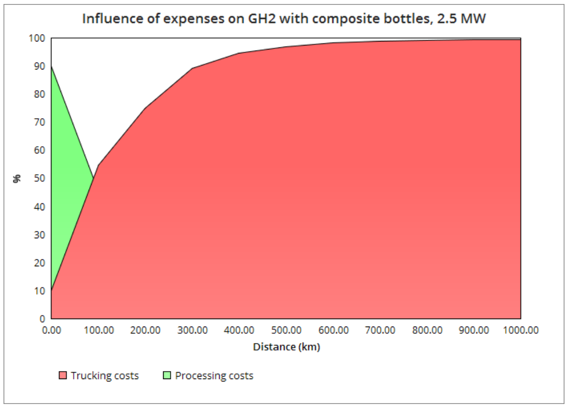


Figure 35: Costs' influence on GH_2 with steel bottles for 2.5 and 10 MW regarding distance.

When it comes to GH_2 with steel bottles, the distance where trucking costs have more influence is before 60 km. This is a drawback as its trucking costs are the highest due to its low useable capacity per truck, 400 kg per tank. On the other hand, its processing is the cheapest of all, but this is not enough to outcome the expenses regarding trucking, leading to the highest costs of all three for all distances and energy deliveries studied.



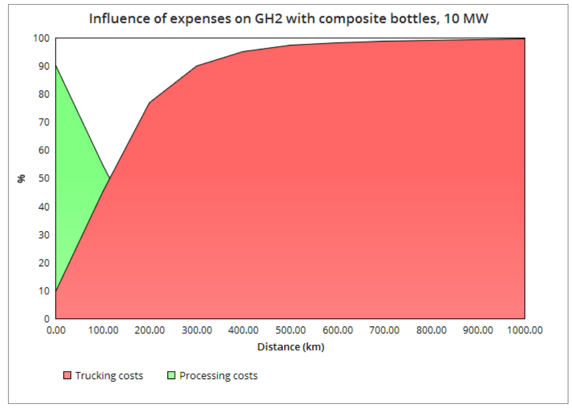


Figure 36: Costs' influence on GH_2 with composite bottles for 2.5 and 10 MW regarding distance.

In the case of GH_2 using composite bottles, the distance where trucking costs overcome processing is 200 km. This way of transport has low trucking costs, similar to LOHC mostly for lower energy deliveries, as well as low processing costs, a difference up to 0.08 €/kg compared to GH_2 with steel bottles.

As seen on Figures 34, 35 and 36, distance is key to the overall expenses in this kind of transport because of the influence trucking costs take. These increment with distance so that is why, road transport, would be more ideal for shorter distances. Nevertheless, there is to remember this is factor that is determined from the distance between production and delivery point, so there is not much to do about it than choosing the right way of road transport. Regarding energy delivery, it has been proved that bigger energy deliveries make the process more feasible and it even prolongs the influence of processing which lowers the overall costs. These conclusions had already been stated on the literature review section of the paper, which confirms the veracity of these results, Figures 6 and 7.

3.3 Comparison of hydrogen distribution pathways

3.3.1 Economy Analysis

Starting by the pipelines' economic analysis, there is to divide between compression and piping costs. Compression costs, also known as transmission costs, depend on variables such as length of the pipeline, flow or diameter as seen on Equation 11. The parameters already set on the route considered are a 500 km length and 5 MW energy delivery. Then, for the composition of hydrogen-Natural Gas mixture, it was assumed to be 15% hydrogen as, according to Jaworski et al. on study [14], it is the minimum value so the gross calorific value does not drop enough not to meet the quality requirements. Then, regarding the diameter, it was assumed as 0.8 m, just like in the analysis, because it is the average value in the most commonly used range. Once these parameters are set there is to calculate the flow of hydrogen-Natural Gas required by applying Equation 19, which is 0.16 m^3/s.

Now, by using Equation 11, the outlet pressure of the pipeline is known as 4.99 MPa. Which leads to a variance of pressure along the pipe of 28.03 Pa. The reason why there is a unit change is so the result is expressed more precisely. To compensate this energy losses, the power needed to pump is of 4.86 J, after the efficiency was applied. This leads to hourly compression costs, Equation 23, of 0.87 €.

Moving on to piping costs, the installation costs are only dependent on length, which was stated as 500 km. Making piping installation costs result in 12.75 M€. Then, regarding piping material costs, there is Equation 24. Resulting into 75.95 M€. However, even though the sum of these correspond to the initial investment, the costs still have to be levelized for the 40 years of lifetime of the pipeline. After applying Equation 28, the overall expenses per hour are 22.10 €. This means that daily the expenses to distribute a 15% hydrogen-Natural Gas mixture for 500 km is, approximately, of 530.48 €.

When it comes to truck transport, in order to deliver 5 MW of energy, the hydrogen payload should be of 3.600 kg per day according to [26]. Starting by considering processing costs, these add up to 1.29 € per kg for LOHC, 0.52 for GH_2 using steel bottles and 0.59 €/kg for GH_2 with composite bottles. In total, the daily expense is of 4.392 € for LOHC, 1.872 € for GH_2 using steel bottles and 2.124 € for GH_2 with composite bottles. Then, for trucking costs only, expenses are of 16.36 €/kg, which result in 58.908 € per day in the case of LOHC; 49.42 €/kg which are 177.922 € per day for GH_2 with steel bottles; and 21.96 €/kg turn to 79.072 € per day if choosing GH_2 using composite bottles.

All and all, the best approach regarding this specific route when it comes to road transport, is LOHC with a daily cost of 63.300 €, followed by GH_2 using composite bottles with a daily expense of 81.196 € and, lastly GH_2 with steel bottles whose daily costs are 179.794 €. It was expected as LOHC has been proved the be the best method for long distances, even though its processing costs are the highest.

Nevertheless, when comparing the total economic costs regarding the four possible distributions, pipeline is, without a doubt the best approach from an economic perspective. Even though LOHC turns out to be the most feasible way of road transport, expenses are way too high in comparison, almost 120 times higher. Pipelines would provide the same service for a much cheaper price, meaning they should be the approach for this specific route when considering the economic perspective.

3.3.2 Life Cycle Analysis

In this section, results are based on the total CO_2 emissions coming from the energy needed to provide the product. Regarding pipelines, the energy needed is about 17.49 kWh. Applying the factor stated on the Life Cycle section, 0.852 t CO_2/MWh, the total carbon dioxide emissions are 0.015 t CO_2 per day.

When it comes to trucks, both LOHC and GH_2 need electricity to turn the hydrogen from the PEM electrolyzer into gaseous form. It was assumed that the electricity came from fossil energy, as it corresponds to 96% of the actual hydrogen production according to study [6]. The calculations were based on Equations 50 and 49 from study by Ferreira et al. [5]. Starting by calculating the energy needed for processing, Equation 49, it is 11.088 MJ/kg of hydrogen. Afterwards, there is the emission's conversion factor, 9.447 t CO_2/kg of hydrogen, to be introduced and calculate the overall impact. Then, regarding emissions from the diesel used by the trucks from Equation 50, is of 8.96 kg CO_2/kg for LOHC, 2.56 kg CO_2/kg for GH_2 steel bottles and 5.76 kg CO_2/kg for composite bottles. In the end, the overall total emissions result to be 9.456 t CO_2/kg for LOHC, 9.449 t CO_2/kg for GH_2 using steel bottles, and 9.453 t CO_2/kg for GH_2 when using composite bottles. Results show two main points, that the impact on emissions are mainly from processing the product, and that, the best choice for truck transport, from an environmental point of view, is GH_2 using steel bottles.

Overall, if there was only to consider the environmental point of view to choose which distribution way to use, pipeline transportation is the one. However, there is to remember the present work only uses the CO_2 emissions for the analysis. A full Life Cycle analysis involves more environmental impacts, like human toxicity or climate change. As it is not the main objective of the present paper, the analysis was simplified to the CO_2 emissions.

4 Conclusion

Hydrogen energy is a novel topic several researchers are tackling day to day. Nevertheless, there is still not much known about it yet. The main problem is not only its production but the delivery costs. The approach that has been used is adapting already existent delivery methods, in this case pipelines and truck transport. There is to adapt them to cope with the technical characteristics hydrogen triggers.

Starting by the pipelines, these were studied based on the following variables: composition of the mixture, energy delivered and dimensions of the pipeline, which involve diameter and length. According to the results obtained during the analysis, the most influential in the overall cost is the diameter. It should be the first variable to tackle in order to lower the costs as much as possible. This is due to its contribution to both compression and piping costs. There is to find the optimum point where the transmission is balanced with the material costs. Then, there is the composition of the mixture. This can range from 0 to 20% volume range of hydrogen in the composition transported. The ideal would be using a value from 15-20% to reach the minimum gross calorific values required for quality purposes. Lastly there are energy delivered and length. These are the factors where there is not much to do as the energy to deliver is determined by the final consumer, and the length of the pipeline depends on the distance from the station where hydrogen is produced to where it is delivered. Nevertheless, if there is a chance to choose, lower energy deliveries as well as shorter distances would benefit this kind of transportation.

On the other hand, truck transportation is a kind of delivery that, even though it requires processing, it is mostly dependent on the delivery process. More precisely, on the distance between production and delivery point. A variable there is not much to do about, as it is determined. The choice to go for, regarding this type of transportation, changes depending on range of values from this variable. For short distances, less than 50 km, the best choice is GH_2 with steel bottles. Then, for medium distances, from 50 to 300 km, the most feasible option is GH_2 with composite bottles and, lastly, for long distances, assumed as longer than

300 km, LOHC is the type of transportation to go for. Nevertheless, the energy delivered also influences the overall costs, being benefited from big discharges as the distribution becomes more feasible both for delivery and processing costs, more specifically for LOHC. As more energy is transported, there is need for more quantity of hydrogen and, therefore, more capacity, which LOHC provides in contrary to GH_2 tanks. Environmentally, there is to remember that truck deliveries count with the emissions from trucks themselves which have a great influence on the overall impact.

To sum up everything so far, the most feasible way to transport hydrogen based on the research available nowadays, both from an economic and environmental point of view, is pipeline distribution. Economically, the overall costs are much lower when compared to trucking costs. These could also be lowered even more if reusing the already existent infrastructure for other product's distribution. Nevertheless, there would also be the need to condition the pipelines to deal with the possible technological challenges hydrogen may bring, like the already mentioned hydrogen embrittlement. Then, when considering an environmental point of view, it is also the best choice as the impact is barely noticeable in comparison to truck transportation. Overall, currently, pipelines are the best option. Nevertheless, there is to remember the huge impact research has had in the past few years, and that this could change in the near future.

5 Future Work

hydrogen, nowadays, is considered as the cleanest way of energy as well as the most promising. There are multiple techniques to obtain it, from industrial processes, as an accidental product, or from a specific techniques such as reforming fossil fuels, decomposition of hydrogen-containing resources or water electrolysis. However, the main drawback is still the economic factor which makes it not feasible for companies to implement it. As work [2] stated 'the hydrogen economy can establish itself only if it makes sense energetically. Otherwise, better solutions will conquer the market'. That is why future work should be related mostly on this.

There is already some research related to it. For example, to optimize the way of production. According to [6], there are some recent studies which demonstrate that hydrogen production combined with anaerobic digestion, improves the end use energy ratio and reduces operational costs.

Another aspect would be development of raw materials, which would reduce costs as new renewable resources would be in use. It would not just benefit economically but socially and environmentally.

In addition, process coupling could also benefit to this kind of energy, as explained in work [12]. Combining essential processes like PC electrolysis and wind power would improve efficiency, application prospects, market competition and operational flexibility and convenience.

Then there is study [18], which is more focused on the distribution of the product by implementing an exergoeconomic analysis, which gives a balanced solution between economic and energy factors. According to it the employment of heat exchangers and rotary work exchangers could hugely contribute to reducing the energy consumption. Therefore, operating costs would be reduced and the capital costs of heat exchangers and turbines could be paid back more easily. They state that considering heat and pressure recovery is very necessary for the optimization of hydrogen distribution network in refineries.

Nevertheless, there is to remember that reality is not perfect. Even though research increases on this subject, there is to remember that not everything can be solved. Study [2] states that, as hydrogen is the lightest of all gases, its physical properties do not fully match the requirements of the energy market. All the processes from production to storage or delivery are so energy consuming that other alternatives should be considered. Economy will look for practical solutions and select the most energy and cost-saving procedures. And therefore the "Pure-hydrogen-Only-Solution" may never become reality.

This negative point of view towards hydrogen economy was given back in 2006. Nevertheless, this work is not pessimistic as the other economy proposed is a "Liquid-Hydrocarbon Economy". This would be based on two natural cycles of hydrogen and carbon dioxide. According to this energy system carbon would become the key element in sustainable energy. This would be as it would come from biomass made out of a hydrogen-to-carbon ratio of two. In the methanol synthesis two additional hydrogen atoms would be attached to every bio-carbon. Instead of converting biomass into hydrogen, hydrogen from renewable sources or even water could be added to biomass to form methanol by a chemical process. In this economy, carbon atoms would stay bound in the energy carrier until its final use. They would then be returned to the atmosphere (or recycled). This process could be true not only for methanol, but also for ethanol or other synthetic hydrocarbons.

There should never be energy wasted, even less for idealistic goals. But, as seen, there have already been several improvements and research is finding new ways to improve the feasibility of this way of energy. Even though the world may not become 100% hydrogen powered, it could end up being part of the energy economy contributing to a cleaner energy and therefore, a cleaner world. In the end every drop counts.

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