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 sources of fuel are being considered, such as hydrogen. The only drawback is the price due its novelty, as there is lack of research.

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 around 500 € per day to around 63.600 € for the cheapest road transport option, in this case LOHC. Life Cycle analysis was performed to assess the energy balances and associated emissions of hydrogen distribution pathways. The results show that the pipeline distribution has lower emissions with 0.15 t CO_2 per day, while the lowest emissions from road transport come from GH2 with steel bottles, at 9.45 t CO_2 per day.

Keywords: Hydrogen distribution, feasibility, PEM electrolyzer, pipelines, road transport

1 Introduction

Hydrogen's importance has been growing for the last years. It is no surprise that the most used way of energy is fossil. This is sustainable due to the limited resources as well as the pollution that comes with it. There is a need for alternatives.

Some are already in use like renewable energies, for example wind, solar or biomass. The emissions to the atmosphere are lower in comparison to fossil. According to C. Helman [1] wind power's emissions are, approximately, 11 grams of CO_2 per kWh and coal's are 1000 grams of CO_2 per kWh. The difference is of 2 orders of magnitude. However, not everything is positive. Renewable energies' main drawback is storage. There has not been found a feasible way to store the energy produced, which means that we would be dependent on the ambient circumstances like sunlight. This is not realistic as, for example, a house uses lights at night, which is when the sun is not out.

Hydrogen is a carbon-free energy that has been considered due to its high calorific value, 120 MJ/kg. Its emissions are mainly water and it can be produced intentionally with processes like electrolysis, or even as a consequence of industrial processes. Nevertheless, there are still some drawbacks regarding this type of energy. Research is very recent and feasibility is crucial to implement a new way of energy.

Producing hydrogen requires energy in processes like PEM electrolyzers or alkaline water electrolyzers. One of the sources is using fossil energy due to its low costs. However, this dismisses the purpose of using a cleaner way of energy. There is need of research to improve the production.

This study is going to work on the transport feasibility. Analyzing the possible different ways of hydrogen distribution. The main options are reusing already existent ways of transportation just like pipelines or trucks transport, which will be the ones studied.

The main objective is to provide a solution for the transport part of the process of developing hydrogen as a feasible way of transport. The study will not just be focused on the economical analysis but also on its Life Cycle.

2 Methodology

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 Natural Gas. 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 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 kept constant	
hydrogen percentage	15%
Energy Delivered	0.5 GW
Length	200 km
Diameter	0.8 m

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 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.

$$P_1^2 - P_2^2 = 0.188 ZTL\rho \frac{Q_n^{1.82}}{D^{4.82}} \quad (1)$$

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.

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

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

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

$$B = \frac{b_m P}{RT} \tag{3}$$

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 8 and 10. These need the pseudocritical temperature and pressure, 'T_{pc}' and 'P_{pc}'. The values used are displayed on Table 2.

$$a_m = 0.457 \frac{R^2 T_{pc}^2}{P_{pc}} \tag{4}$$

$$b_m = 0.078 \frac{R T_{pc}}{P_{pc}} \tag{5}$$

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

Variable	
Temperature	32.94 K
Pressure	1.2838 MPa

To know the average pressure in the pipeline, there is this equation from Peng-Robinson, usually applied in the oil and gas industry according to [3].

$$P = \frac{RT}{\nu - b_m} - \frac{a_m}{\nu(\nu + b_m) + b_m(\nu - b_m)} \tag{6}$$

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

Continuing the parameter analysis of Equation 2.1, there is to know the temperature in the pipeline. For simplification purposes it was assumed to be an average value, which is a usual practice. As the present study takes place in Portugal it will be assumed as 18°C. The last term to analyze to use Equation 1 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.

$$Q = \frac{E}{LHV} \tag{7}$$

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.

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. These costs can be calculated as a function of energy, which can be analyzed by using Equation 8.

$$W_{real} = \frac{\Delta P}{0.9 * \rho * g} \rho * g * Q = \frac{\Delta P * Q}{0.9} \tag{8}$$

Where 'W_{real}' 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 is applied, assumed to be 90%. 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 [4].

$$CC = \frac{50 * W_{real} * 3600}{10^6} \tag{9}$$

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 present work will use for the method on book [5], where Menon et al. relate the pipe material cost to the dimensions of the pipe as well as the material cost.

$$PMC = 0.0219(D * 1.000 - t)tLC \tag{10}$$

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 [5]. Then there is the pipe installation cost, which depends on the diameter. The relation is on Equation **??**.

$$PIC = AC * L \tag{11}$$

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 **??**.

Table 3: Typical pipeline installation costs according to [5]

Diameter [m]	**AC [€/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.

$$PC = PMC + PIC \tag{12}$$

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

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{13}$$

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 [4] 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 [6].

$$TCOST = \frac{PC * CRF}{8760 * n * CF} + CC \tag{14}$$

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 transport

Another very used way of delivery is road transportation. In this work truck transport will be studied more specifically. This type of transportation gathers two different options, LOHC, Liquid Organic Hydrogen Carriers, and GH2, Gaseous Hydrogen Tanks.

LOHC is a very novel way of transport that tackles storage and transporting challenges. Its transportation is based on the processes of hydrogenation and dehydrogenation, which get the product in and out of the hydrogen carriers.

GH2 is the other option studied. These are basically high pressure tanks that contain hydrogen, which are transported by trailers. In this type of transportation we can choose between steel bottles, 200 bar, or composite bottles, at 350 bar.

The analysis for this type of transport is going to be focused on the economical feasibility.

Starting by trucking costs, which involve initial investment, fuel, personnel, operations and maintenance. The difference between transportations will only take place on the investments, the rest of the factor will be assumed to be the same. It will be calculated with equation 15.

$$SC_{trucking}(€/\text{kg}) = \frac{IC_{trucking}CRF_{trucking}}{\text{Delivered useable H2 per year}} + SC_{trucking,O\&M} + SC_{trucking,fuel} + SC_{trucking,personnel} \quad (15)$$

Process costs, common to both ways of road transport, involve compression, storage and site costs, such as buildings or engineering. Equations 16, 17 and 21, are used for compression, storage and site costs respectively.

$$SC_{comp} = \frac{IC_{comp} * (CRF_{comp} + FC)}{\text{Annual delivered useable hydrogen}} + \frac{E_{ann,comp}}{\text{Annual delivered useable hydrogen}} \quad (16)$$

$$SC_{storage} = SC_{tanks} + SC_{DBT} + DBT_{degradation} \quad (17)$$

$$SC_{tanks} = \frac{IC_{tanks}CRF_{tanks}}{\text{Annual delivered useable hydrogen}} \quad (18)$$

$$SC_{DBT} = \frac{DBT_{storage}DBT_{price}CRF_{DBT}}{\text{Annual delivered useable hydrogen}} \quad (19)$$

$$DBT_{deg} = \frac{DBT_{deg}DBT_{price}\text{Useable storage density}}{\text{Useable storage density}} \quad (20)$$

$$SC_{site} = \frac{IC_{site}CRF_{site}}{\text{Annual delivered useable H2}} \quad (21)$$

2.3 Comparison

To know which of the ways of transport introduced is better, there will be a comparison economically and another one according to their emissions. The process will consist on analyzing the different variables for each of the ways of transportation and make the common ones have the same value. These are distance of delivery, lifetime and energy delivered.

The approach is to select a determined route in Portugal and calculate both expenses and impact on the environment. According to the common variables mentioned before, the route will be for 500 km and delivering 5MWh per year, according to the consumption per capita on year 2019 from the IEA, International Energy Agency. Results are considered from year 2019 as they are more representative than 2020 because of the pandemic.

The next step is doing the Life Cycle analysis. This involves the course of events which bring into existence a new product. Like its growth, critical mass or eventual decline. We will suppose that the hydrogen delivered comes from a PEM electrolyzer and follows the different routes represented on Figure 1.

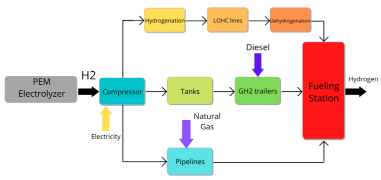

Figure 1: Delivery Scheme

The energy used and the CO_2 emission were determined according to research article from A. F. Ferreira [7].

3 Results

3.1 Pipeline transport

Results were calculated using 'excel' and 'EES', Engineering Equaiton Solver. Then plotted using 'chartgo'. The variances of pressure calculated are displayed in figure 2.

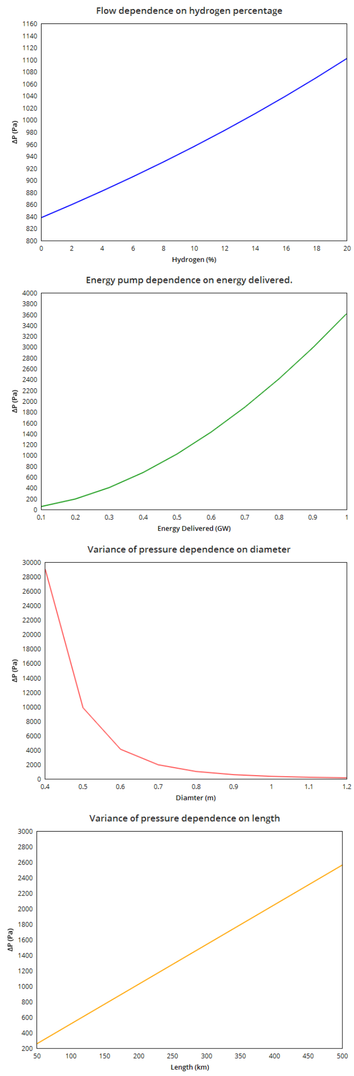

Figure 2: Variance of pressure dependence on hydrogen percentage in the mixture, energy delivered, diameter and length of the pipe.

Once dependencies are known, the next step is to calculate the energy required to pump. These results are displayed in Figure 3.

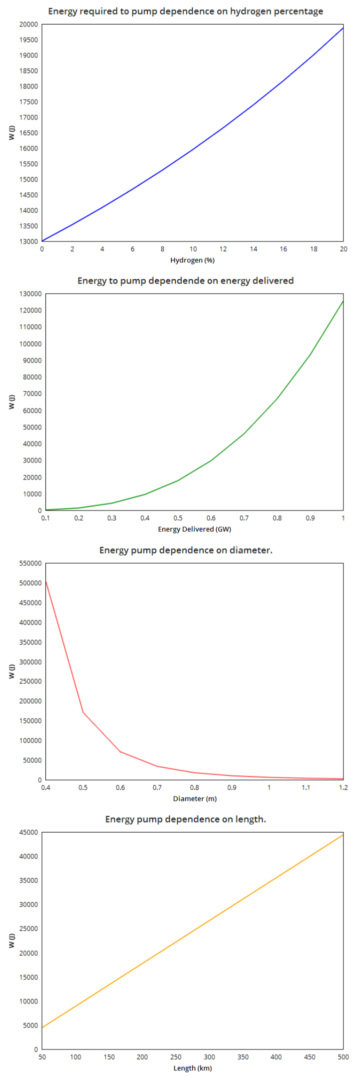

Figure 3: Energy required to pump dependence on hydrogen percentage in the mixture, energy delivered, diameter and length of the pipe.

These results show that the best choice, according to pumping expenses, would be low hydrogen percentage in the mixture; low energy deliveries, as long as the customer demand is complied; big diameters, before they hit the plateau and keeping in mind the piping costs; and short distances, but this is not something out of control.

Piping costs dependency on variables is null when it comes to composition of the mixture as well as energy delivered at 35.48 M€, including both material and installation costs. However, there is a variance when it comes to changing the diameter and length. This is pictured on Figure 6.

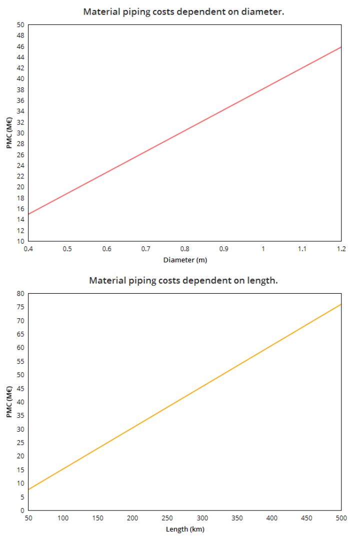

Figure 4: Piping cost dependence on diameter and length of the pipe.

3.2 Truck transport

Starting by processing costs on Figure 5.

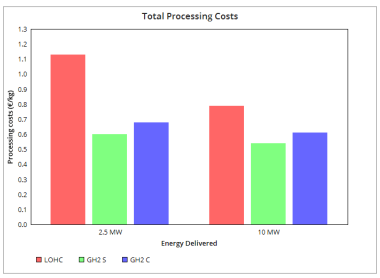

Figure 5: Total Processing Costs, including storage, compression and other site costs, of road transport for LOHC, GH_2 with steel bottles and GH_2 with composite bottles, dependent on energy delivered.

The maximum variance is of 5 €/kg. Meaning that transporting a lot of product could be crucial to the total costs. The best choice will be GH_2 trailers using steel bottles, which will be benefited from higher energy deliveries.

Trucking costs, on the other hand, are the ones that comply the expenses for delivering from production to delivery point. These are represented on Figure 6.

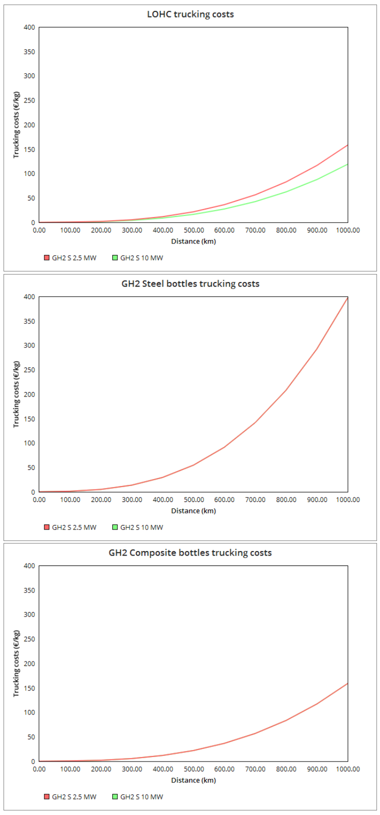

Figure 6: Trucking costs for LOHC, GH_2 using steel bottles and GH_2 using composite bottles, dependent on energy delivered.

When comparing trucking costs it is obvious that all three increase with distance. However, this is more noticeable on GH_2 using steel bottles. This is due to its lower bottle capacity in comparison to the other two options, requiring more trips to deliver the same amount of energy.

Another important issue is the influence of trucking and processing on the overall costs. That is plotted, for 2.5 MW delivered, in Figure 7.

Figure 7: Costs' influence for LOHC, GH_2 with steel bottles and GH_2 using composite bottles.

The dependency changes with distance. Short distances, shorter than 200 km, are mostly processing costs, meaning the best choice will be using GH_2 with steel bottles. Then, as distance increases, trucking costs take most of the expenses. Then the variable to study is energy delivered as, for lower energy deliveries, GH_2 with composite will be the best choice while, bigger energy deliveries, will require using LOHC for maximum feasibility.

3.3 Comparison of hydrogen distribution pathways

The comparison was made by setting a common route for both ways of transport. This would take place in Portugal, delivering 5 MW for a 500 km distance.

The economic analysis for pipeline distribution is considered ideal with a 90% margin of error to make it more realistic. The total expense for delivering is of about 530 € per day. In contrast, road transport requires 63.300 € per day for the cheapest option, being LOHC; then 179.794 € per day for GH_2 using steel bottles, and lastly 81.196 € per day for GH_2 with composite bottles. Economically the best choice is pipeline distribution. Nevertheless, there is still to consider the Life Cycle analysis.

The CO_2 emissions were evaluated from the power needed to transport the Hydrogen/Natural Gas mixture. When it comes to pipeline distribution emissions are of 0.15 t CO_2 per day. When it comes to trucking emissions, the total emissions for LOHC and GH2 steel or composite are 9.46 t CO2/kg, 9.45 t CO2/kg, 9.45 t CO2/kg respectively. Between these results GH2 has lower emissions than LOHC. Nevertheless, pipelines' emissions are lower, making it the best choice according to Life Cycle analysis, as well as the economical point of view.

4 Conclusion

Pipeline transportation has a lot of variants depending mostly on the infrastructure. If it is possible, the best choice would be to reuse already existing pipelines and adapt them to transport hydrogen. However, if it is not the case and there is a need to build new ones, the diameter of the pipeline should be the main priority, balancing both operating and piping costs. It is also important to keep an eye on the energy delivered, to make sure the energy required to pump is not higher than the energy delivered, as it would mean energy losses.

When it comes to trucking, the type of transport is going to depend on the distance as well as energy delivered. For distances shorter than 200 km, GH_2 using steel bottles will be the most feasible as its processing costs are the cheapest and, in that case, the represent the majority of the expenses. When distance gets larger then the determinant parameter is how much energy is delivered. For bigger energy deliveries LOHC will be the option to go for, while smaller energies will require GH_2 with composite bottles.

Overall, economically and from an environmental point of view, the most feasible way to transport hydrogen, nowadays and according to the route set as common both for pipelines and truck transport, is the pipeline distribution.

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