Hydrogen-Powered Long-Distance Transportation for Portugal

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The purpose of this work is to explore hydrogen as a future energy carrier for heavy modes of transportation. Hydrogen has a high energy density and can therefore meet the requirements of load carrying vehicles efficiently. The first step is to determine the techno-economic requirements and overall feasibility of switching to green hydrogen for modes such as Buses, Trucks and Trains. A three-scenario approach is used to predict the effects of different paths on the viability of this work. Next, three different distribution methods need to be examined to choose an ideal method from a feasibility standpoint. Conducting a cost analysis (CAPEX, OPEX, LCOH) will help provide a basis for the comparison. Among the studied pathways, it is discovered that the Dispersed Electrolyser distribution method showed the most promise when combined with the realistic scenario approach. An LCOH value of 4.92 €/kg H2 was achieved with potential to get it down further. The lack of reliance on trucks or pipelines to distribute the hydrogen fuel made it possible to achieve such a feasible LCOH value. Furthermore selling the by-product oxygen, from electrolysis, was consolidated as without it the pathways would not be economically viable. The sensitivity analysis conducted on the LCOH values determined that the value was directly dependent on electricity prices and the CAPEX. The study was able to confirm that H2 has a feasible future in the heavy-transport sector given the right conditions and pathways for its implementation.

INTRODUCTION

Energy systems around the world are undergoing substantial changes. Many of these changes are being driven by deliberate government policies, whether these are to put a country on a low-carbon transition path, reduce air pollution, secure energy independence and security, or reduce costs and improve efficiencies.

The EU is a leader in renewable energy technologies. It holds 40% of the world's renewable energy patents and in 2016 almost half of the world's renewable electricity capacity (excluding hydropower) was located within its borders [1].

The 2030 Climate and Energy Policy Framework that preceded the EU contribution to the Paris Agreement was adopted in October 2014. It set three key targets:

(i) a binding target of at least 40% reduction in greenhouse gas emissions by 2030 compared to 1990, for the EU

(ii) a binding EU-level target of at least a 32 % share of renewable energy in 2030

(iii) an indicative EU-level target to improve energy efficiency by at least 32.5 % in 2030 compared to projections of future energy consumption [2]

Most of the European nations have reached or are close to reaching their 2020 targets for renewable energy share in their final energy consumption mix. These percentages are likely to grow rapidly over the next few decades.

Renewable energy technologies/ sources (hydropower, wind power, solar power, marine energy, geothermal energy, heat pumps, biomass and biofuels) are alternatives to fossil fuels that contribute to reducing greenhouse gas emissions, diversifying energy supply and reducing dependence on fossil fuel markets, in particular oil and gas.

The EU 2020 targets are imperative to the 2030 climate and energy targets. In order to maintain its status as a global leader in the climate change revolution and ensure its leadership position in the renewables sector, all EU nations must double down on their efforts to increase the percentage of renewable energy capacity in their energy mix. This has help put them on a sustainable path towards meeting the 2030 targets [3].

With the clear and determined focus on renewable energy to power the future, the biggest question that always gets raised is its intermittent nature. The idea of using clean electricity as a fuel for industry and transport and the technologies that facilitate it have become a major topic of research and discussion in recent times.

Declining costs in available technologies have propelled interest in green fuels forward like never before. The price of lithium-ion batteries for Battery Electric Vehicles (BEV) has fallen by about 80% over the past five years. The global EV fleet is expected to reach 10,5 million by the end of 2020 [4].

Despite some major benefits of battery-based storage for clean electricity, the energy density of the technology poses a serious issue when considering its use in Industry and Heavy Transportation modes. Diesel has an energy density of 45.5 megajoules per kilogram (MJ/kg). Diesel has an energy density of 45.5 megajoules per kilogram. On the other hand, hydrogen has an energy density of around 120 megajoules per kilogram. In terms of power, the hydrogen energy density translates to 33.6 kWh/kg. Whereas, diesel contains about 12-14 kWh per kg[5]. Lithium-ion batteries have an energy density of around 1 MJ/kg. Hence, for heavy transport modes where weight plays a major factor, a huge amount of batteries would weigh down the vehicle in order to provide the same kind of range that diesel or hydrogen fuel cells would. Hence, the topic of Hydrogen as a fuel for heavy modes of transport has caused a stir in the energy sector.

THEORY

The main focus of this study is to analyse the possible impact Hydrogen can have on this sector of Portugal's mobility. Transportation is a major contributor to climate change, emitting 32% of CO2 emissions in the EU. To achieve the 2-degree scenario, the region needs to eliminate about 72% of CO2 from the EU transportation fleet by 2050, equal to roughly 825 Mt [5].

A key technological question is how to store large amounts of energy at low weight and in a restricted space within the vehicle. While for some modes of transportation the battery will be the energy storage of choice, other applications require higher energy density for lightweight energy storage or longer driving ranges and faster recharging times.

The second key issue revolves around recharging/refuelling infrastructure. Energy needs to be efficiently distributed from renewable sources to vehicles. While a small share of EVs can be served with the current power grid, meaningful decarbonization requires either a different way of distributing energy, or massive upgrades to power grids.

Hydrogen is the most promising decarbonization option for trucks, buses, ships, trains, large cars, and commercial vehicles for four reasons.

- Hydrogen provides a way to achieve to full decarbonization, where other technologies only act as bridge technologies.
- Having a high energy density, Hydrogen is more suited to provide power for long ranges and high payloads.
- Despite the lack of infrastructure acting as a barrier, faster refuelling, flexible loading and smaller space requirements prove a compelling argument.
- Finally, hydrogen is the best alternative for trains and ships while, hydrogen-based synthetic fuels have the potential to decarbonize aviation [5].

Electrolysis

Electrolysis shows promise when considered for hydrogen production using renewable electricity. The process involves splitting water using electricity to produce hydrogen and oxygen. This process takes place in an electrolyser. These come in many different sizes and can be used for a variety of different purposes. From appliance sized to large-scale industrial purpose scale, electrolysers can be used in conjunction with renewable energy sources.

They consist of an anode and a cathode separated by an electrode. The type of electrolyte used in the process decides how a particular electrolyser functions.

Depending on the source of the electricity, electrolysis can produce hydrogen that has zero greenhouse gas emissions. When analysing the benefits and economic viability of hydrogen via electrolysis, the source of the electricity must be taken into account along with a few other factors such as cost, efficiency and emissions.

Potential for synergy with renewable energy power generation:

Hydrogen production via electrolysis offers a solution for renewable energy technologies that face problems of intermittency. For example, despite the cost of wind power declining, the variable behaviour of wind is a major issue that hurts the efficiency. If hydrogen is generated in combination with renewable energy, in times of excess production of electricity, the excess power can be used to generate and store hydrogen that can be used at a later time when the renewable source of electricity cannot meet the demand.

Types of Electrolysers: [6]

- AEC: It is the most mature technology from the list. It is commonly used for industrial-scale applications. These systems are readily available, are robust and have a lower capital cost compared to the technologies. However, lower current density and the required operating pressure create issues that affect system size and production costs. The time to start-up and fluctuations in power input are weaknesses that limit the system efficiency and gas purity. Hence, most development around this technology focuses on improving current density and operating pressure to enable dynamic operations such as working with renewable sources. Future cost reductions are expected to be linked to achieving economies of scale.
- PEM: It is based on the solid polymer electrolyte concept, in the 1960s. This was done in an attempt to overcome the drawbacks of AECs. This technology is less mature than AECs and is mostly used for small-scale operations. The higher power density, cell efficiency, flexible operation and highly compressed and pure hydrogen are its main benefits. This comes at a cost though, with disadvantages such as expensive catalyst and fluorinated membrane materials and a high complexity due to a high pressure environment requirement. It also has a shorter lifespan than AEC.
- SOEC: It is the least mature technology available. There is no commercially availability as yet. However, it has been developed for demonstrations on a laboratory scale. This technology uses solid-ion conducting ceramics as the electrolyte which allows for operations to take a much higher temperatures. The advantages are low material cost, a possibility to function in a reverse manner as a fuel cell and high electrical efficiency. One of the main disadvantages is the rapid material degradation as a direct consequence of high operational temperatures.

Oxygen Benefit

During the water electrolysis process, half the moles of oxygen are produced along with the desired hydrogen as a by-product. Hence, in large scale operations of water electrolysis, large amounts of by-product oxygen will be produced alongside the hydrogen. This presents an opportunity to use this oxygen commercially. Oxygen is an important industrial gas that is used for many different processes such as wastewater treatment and combustion.

It will be key factor to bring down to the overall costs of implementing a hydrogen-based transportation network in Portugal. This study will be incorporating the oxygen benefit in the cost analysis for the hydrogen plant investment in order to understand how significant of an impact it could make.

METHODOLOGY

In order to achieve a comprehensive study of Hydrogen's Transport sector potential, the analysis of data conducted will be divided into two main sections. They are as follows:

Transport Conversion Scenarios: Using three different scenarios, with varying assumptions, in order to predict what the future of hydrogen based heavy transport could look like. Using these scenarios will help calculate the amount of hydrogen fuel required to support the transport sector. The next step would analyse the use of three different methods to distribute the produced hydrogen fuel to assess the best and most economical way to supply the transport sector's need.

Determining the TCO for each transport mode: In order to assess the viability of running long distance transportation on hydrogen fuel, the total cost of ownership (TCO) needs to be considered and evaluated against the those of traditional diesel vehicles and electric vehicles.

For the purpose of this study, the scenarios will start in the year 2022 and end in the year 2050. This is done to account for the COVID-19 pandemic and allow the Portuguese government the year 2021 to set their plans in place to execute hydrogen mobility projects.

Transport Conversion Parameters

Table 1: Base Parameters

Parameter	**Value Assumed**
Available Electricity Supply [7]	11-12 GWh (average)
Electricity Cost [8]	9,27€ Cents / kWhel (average)
Electricity Requirement for H2 Production [9]	54 kWh/kg H2
Number of Buses [10]	15.000
Number of Trucks [10]	120.000
Number of Diesel Trains [11]	59

Based on the number of vehicles of each transportation type, an assumption was made to split the hydrogen fuel production which would service the future fuel-cell versions of those vehicles. This production split is as follows:

- Trucks: 85% of hydrogen fuel production
- Buses: 10% of hydrogen fuel production
- Trains: 5% of hydrogen fuel production

The best approach to model future events is to anticipate multiple outcomes and analyse each one. For the purpose of this study, three scenarios were chosen to cover the broad range of possible events that could occur. They are as follows:

Pessimistic Scenario:

- Buses: 10% of all buses replaced by hydrogen fuel cell buses by 2050

- Trucks: 20% of all cargo trucks replaced by hydrogen fuel cell trucks by 2050
- Trains: 20% of all diesel replaced by hydrogen fuel cell trains by 2050

Realistic Scenario:

- Buses: 40% of all buses replaced by hydrogen fuel cell buses by 2050
- Trucks: 40% of all cargo trucks replaced by hydrogen fuel cell trucks by 2050
- Trains: 50% of all diesel replaced by hydrogen fuel cell trains by 2050

Very Optimistic Scenario:

- Buses: 100% of all buses replaced by hydrogen fuel cell buses by 2050
- Trucks: 100% of all cargo trucks replaced by hydrogen fuel cell trucks by 2050
- Trains: 100% of all diesel replaced by hydrogen fuel cell trains by 2050

The standard parameters for the AEC system are as given in Table 2:

Table 2: AEC System Parameters

Hydrogen Output for 1 MW system	20 [12]	kg/h
Hours of Operation	8.000 [12]	h/yr
Hydrogen Output for 1 MW system	160.000	kg/yr
Capital Cost of AEC	800 [13]	€/kWel
Cost of Industrial Electricity	9,27 [8]	Euro cents/kWh
Electricity required	54 [9]	kWh/per kg H2
Cost of Hydrogen (without cost of electricity)	6,75 [14]	€/kg
Cost of electricity	5 [14]	€/kg
AEC Fixed O&M Cost	5% [14]	of CAPEX
AEC Variable O&M Cost (Raw Materials)	2,80 [15]	€/kg
Stack Replacement Cost	25% [15]	of Capex
Sale price of Hydrogen	2 [12]	€/kg

Hydrogen Distribution Methods

Transportation of produced hydrogen will be carried out one of three ways:

- Trucks: Transport hydrogen from parks and ports to refuelling stations along major highways and within cities. Assuming a 70:30 split for hydrogen utilization where, 70% can be reserved for use at fuelling stations on site at logistical parks and ports. The remaining 30% can be transported using trucks to refuelling stations.

- Pipeline: The pipeline will follow the same distribution split as the trucks. However, as the pipeline requires fixed infrastructure, it is important to connect the logistical parks and ports to the refuelling stations in major cities along the coast. This would follow the gas pipeline plan as seen in the figure 1 below. (E64, E65 and E43)

- Dispersed Electrolysers: The final method explores the idea of minimizing the need for hydrogen transport by dispersing the production across the country. Using the grid to power large scale electrolysers near the ports and industrial areas in combination with small scale electrolysers at fuel stations both along highways and in cities.

Figure 1: Pipeline Map [16]

Refuelling Stations

With transport conversion, generation and distribution covered the only that remains is to analyse the refuelling stations. The costs associated with them are in addition to the remaining investment and can significantly impact the overall economic outcome.

For the three main scenarios, another assumption is made with respect to refuelling stations. There are approximately 220 fuel stations in Portugal. The assumption is as follows:

-Realistic Scenario: 20% of fuel stations fitted with HRS

-Pessimistic Scenario: 10% of fuel stations fitted with HRS

-Optimistic Scenario: 40% of fuel stations fitted with HRS

RESULTS

Using the transport conversion scenarios the total cost of hydrogen fuel production is determined over the term of the scenario. Table 3 shows the results for the realistic scenario as an sample of the transport conversion results.

Table 3: Realistic Scenario Total Production Cost

Total Cost	€ 3,19 billion
Total Cost without oxygen benefit	€ 69,35 billion

Table 3 shows the clear impact of considering the oxygen benefit as part of the economic calculations.

These results are then used in combination with the distribution method costs to determine which pathway is the most suitable. Figures 2,3 and 4 represent the total cost of the Hydrogen systems including production, distribution and the cost of refuelling stations. Upon observing the data, it was found that the Dispersed Electrolyser scenario was the most favourable and economically viable pathway. Table 4 shows the final costs of this particular pathway.

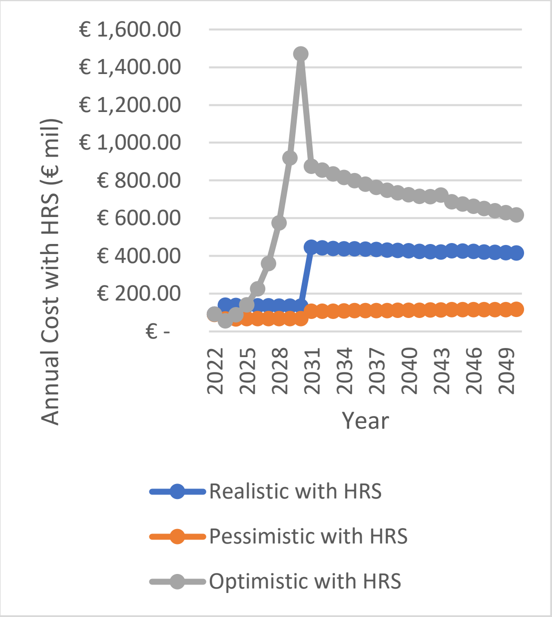

Figure 2: Truck Distribution Method with HRS

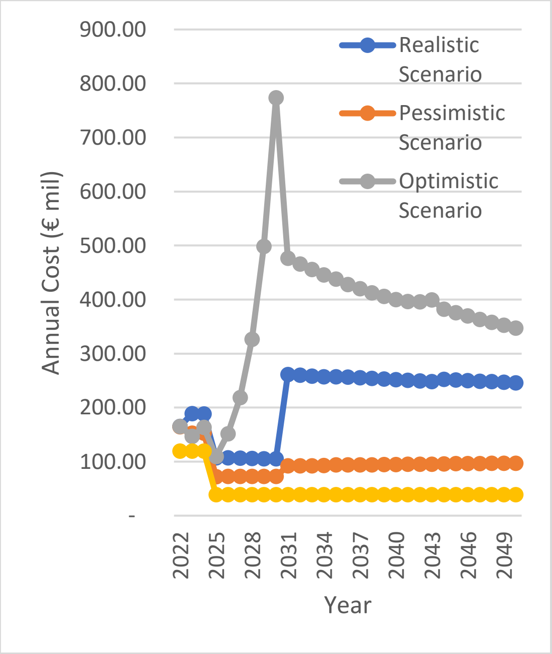

Figure 3: Pipeline Distribution Method with HRS

Table 4: Dispersed Electrolyser Total Cost

Realistic Scenario	Final Cost	€ 1,09 billion
	Final Cost with HRS	€ 12,02 billion

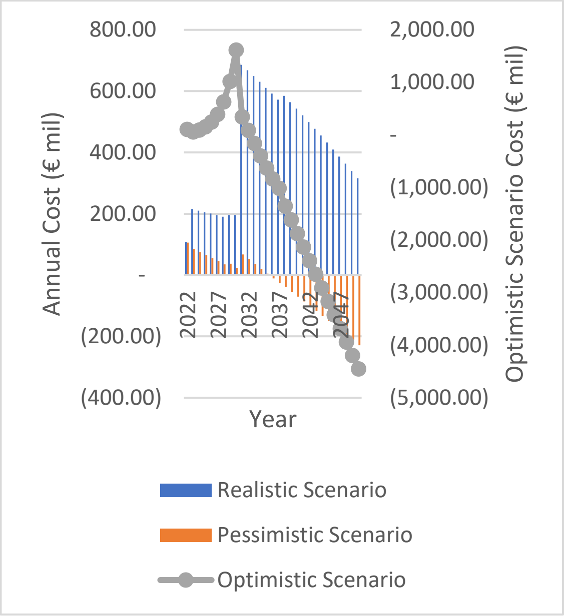

Figure 4: Dispersed Electrolyser Method with HRS

For this particular pathway, the LCOH value was calculated using the realistic scenario conditions. The value obtained was € 4,92/kg of H2.

This value is very promising and is quite close to the ideal LCOH value required for making hydrogen-based mobility competitive.

Finally, the TCO values were assessed for each vehicle type. Table 5 shows the value of each vehicle type in comparison to electric and diesel counterparts.

Table 5: TCO Values

Truck TCO (€/km)		
Electric	Diesel	Fuel Cell
0,9	0,82	0,88
Bus TCO (€/km)		
Electric	Diesel	Fuel Cell
0,86	0,81	0,91
Train TCO (€/km)		
Electric	Diesel	Fuel Cell
8	6,6	7,2

The TCO values are promising as they are more cost-competitive than their electric counterparts. However, there is still room for improvement as the diesel alternatives are still cheaper.

Conclusions

This study was conducted in order to understand the possible outcomes of implementing a hydrogen-based transportation system for heavy vehicles. Three different scenarios were created to assess the possible conditions that may exist when attempting to implement such a network in real life. These scenarios helped guide the study to decide how much of the transport sector could be powered using hydrogen. The next step of the study explored different distribution techniques to make the produced hydrogen fuel available across the country. This step experimented with three different methods in order to determine the most feasible way forward. Another part of this study was to look at the current TCO values of owning and operating a hydrogen-powered vehicle. Using a direct comparison with electric and diesel-powered vehicles, the TCO value was examined for all three vehicle types. Furthermore, a sensitivity analysis was conducted to examine the effect of varying CAPEX and Daily Distance driven. This allowed for a better understanding of the TCO value can be improved going forward.

Finally, the study was concluded by deciding that the Dispersed Electrolysis method of distribution combined with a realistic scenario had the best feasibility for a hydrogen-powered transport network. The LCOH value obtained from this particular pathway was € 4,92/kg of H2. This particular value is very promising and should encourage the adoption of hydrogen-based mobility.

The next steps for a study such as this one would be to explore the commercial and personal vehicle sector for hydrogen conversion. Cars and ships would be the ideal modes of transportation to analyse. Furthermore, ways to reduce hydrogen storage and dispensing costs should be looked at as the refuelling stations make up a significant portion of the investment expenditure.

References

[1] European Commission, "THE EUROPEAN UNION LEADING IN RENEWABLES," [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/cop21-brochure-web.pdf. [Accessed 04 June 2020].

[2] European Commission, "2030 climate & energy framework," [Online]. [Accessed 04 June 2020].

[3] European Commission, "Share of energy from renewable sources 2018 infograph," 2019. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Share_of_energy_from_renewable_sources_2018_infograph.jpg. [Accessed 04 June 2020].

[4] R. Irle, "Global BEV and PHEV Volumes for 2020 H1," 2020. [Online]. Available: https://www.ev-volumes.com/. [Accessed 08 July 2020].

[5] Fuel Cell and Hydrogen Joint Undertaking, "Hydrogen Roadmap Europe," Fuel Cell and Hydrogen Joint Undertaking, Belgium, 2019.

[6] A. I. S. A. J. S. O.Schmidt, "Future cost and performance of water electrolysis: An expert elicitation study," Imperial College London, London, 2017.

[7] REN, "Market Information," 2020. [Online]. Available: https://www.mercado.ren.pt/EN/Electr/MarketInfo/Load/Pages/Actual.aspx. [Accessed 21 August 2020].

[8] Statista, "Prices of electricity for the industry in Portugal from 2008 to 2019, by consumption," 2020. [Online]. Available: https://www.statista.com/statistics/595841/electricity-industry-price-portugal/. [Accessed 19 June 2020].

[9] C. LICHNER, "Electrolyzer overview: Lowering the cost of hydrogen and distributing its production," 2020. [Online]. Available: https://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/. [Accessed 14 May 2020].

[10] ACEA, "Report: Vehicles in use - Europe 2018," 2018. [Online]. Available: https://www.acea.be/statistics/article/report-vehicles-in-use-europe-2018. [Accessed 14 May 2020].

[11] Comboios de Portugal, "Technical Report," 2019. [Online]. Available: https://www.cp.pt/StaticFiles/Institucional/1_a_empresa/3_Relatorio_Contas/2019/contas-consolidadas-2019.pdf. [Accessed 14 May 2020].

[12] P. D. R. P. d. C. Neto, "The Importance of Green Hydrogen for Sustainable energy of Portugal," 2020. [Online]. Available: https://www.linkedin.com/posts/rui-costa-neto-60106920_rui-costa-neto-greenfest-hidrog%C3%A9nio-verde-activity-6715288002903515136-9Iac. [Accessed 5 September 2020].

[13] IEA, "The Future of Hydrogen," 2019. [Online]. Available: https://www.iea.org/reports/the-future-of-hydrogen.

[14] K. T. K. J. C. Kuckshinrichs Wilhelm, "Economic Analysis of Improved Alkaline Water Electrolysis," *Frontiers in Energy Research,* vol. 5, p. 1, 2017.

[15] J. L. H. Z. B. L. G. L. Z. Yang, "A New Direct Coupling Method for Photovoltaic Module-PEM Electrolyzer Stack for Hydrogen Production," Fuel Cells, vol. 18, no. 4, pp. 543-550, 2018.

[16] Theodora, "Spain and Portugal Pipelines map," [Online]. Available: https://theodora.com/pipelines/spain_and_portugal_pipelines.html. [Accessed 6 September 2020].