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Hydrogen Acceptance in The Portuguese Transport Sector

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Thesis to obtain the Master of Science Degree in

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Declaration

Me, Pedro Maria de Lima Mayer Rosado student in Instituto Superior Técnico nº 82485, author of the dissertation to obtain the Master of Science Degree in MEGE, with the title Hydrogen Acceptance in The Portuguese Transport Sector, declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Thank you,

Pedro Rosado

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I would also like to thank my parents and my family, for all the support provided.

Abstract

English

This work is developed in the framework of the adoption of hydrogen as technology in the road transport sector, in the European markets and more specifically in the Portuguese one. Its main objectives are to analyse the status of development of H_2 technologies in Portugal, to understand if companies in the transport sector are prepared for the implementation of hydrogen and to identify economic impacts of hydrogen deployment in Portuguese transport companies.

The study is composed by three elements, a set of interviews targeting decision makers of the road transport companies sector, to understand their opinion towards H_2 and probability of investment in hydrogen vehicles, an inquiry completed by the workers of the same companies, to understand the level of acceptance of the first users of the technology and a cost analysis (TCO). including the various costs associated with hydrogen vehicles and compared to other alternatives.

Companies acknowledge the possibilities of hydrogen and are available to invest in this type of vehicles in the future, considering, however, that the costs associated with the technology are still too high, that there is a lack of infrastructure and that there is a lack of economical support to invest. There is still some discomfort associated with safety levels of the technology, with a significant part of workers and decision makers associating hydrogen with danger and risk of explosion. The enquiries showed that the workers have a basic level of knowledge about hydrogen, although they are willing to adopt the technology.

Keywords: Hydrogen, Acceptance, Transport, Portugal, TCO

Portuguese

Este trabalho enquadra-se no contexto da introdução da tecnologia de hidrogénio nos mercados europeus de transportes rodoviários, e mais especificamente no mercado português. Tem como principais objectivos analisar o estado de desenvolvimento das tecnologias associadas ao hidrogénio em Portugal, compreender se as empresas no sector dos transportes rodoviários estão preparadas para a implementação do hidrogénio e identificar os impactos económicos da entrada em funcionamento do hidrogénio nas empresas do sector.

O estudo é composto por 3 elementos, com a realização de entrevistas a decisores das empresas do sector rodoviário de transportes, de modo a compreender a opinião em relação ao hidrogénio e as probabilidade de investimento em veículos deste tipo, a realização de um inquérito aos trabalhadores destas mesmas empresas, para avaliar a aceitação dos primeiros utilizadores da tecnologia e uma análise de custos (TCO) que compara os custos associados aos veículos movidos a hidrogénio com outras alternativas.

As empresas estão cientes das potencialidades do hidrogénio, estando dispostas a investir em veículos deste tipo no futuro, considerando, contudo, que os custos associados á tecnologia são ainda demasiado elevados, que existe falta de infraestruturas e de apoios económicos para investir. Existe ainda algum receio relativamente aos níveis de segurança da tecnologia, com uma parte significativa dos inquiridos e dos entrevistados a associar o hidrogénio ao perigo e risco de explosão. Os inquéritos demonstraram um nível de conhecimento básico relativamente ao hidrogénio por parte dos trabalhadores, embora estes estejam dispostos a adotar a tecnologia.

Palavras-chave: Hidrogénio, Aceitação, Transportes, Portugal, TCO

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Nomenclature

ACEA	Association des Constructeurs D’Automobiles
DC	Direct Current
ECV	Electrically Chargeable Vehicles
EU	European Union
H_2	Hydrogen
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
LPG	Liquified Petrol Gas
ZEV	Zero Emissions Vehicles
CNG	Compressed Natural Gas
LNG	Liquified Natural Gas
APV	Alternatively Powered Vehicles
FCEV	Fuel Cell Electric Vehicle
FCEB	Fuel Cell Electric Bus
FCET	Fuel Cell Electric Truck
PHEV	Plug-in Hybrid Electric Vehicle
SMR	Steam Methane Reforming
PtG	Power to Gas
PEM	Polymer Electrolyte Membrane
AEL	Alkaline Electrolysis
SOEC	Solid Oxide Electrolysis
CAPEX	Capital Expenditure
HRS	Hydrogen Refuelling Station
LH_2	Liquified Hydrogen
TCO	Total Cost of Ownership
GHG	Greenhouse Gases

PV	Photovoltaic
LCOH	Levelized Cost of Hydrogen
DV	Diesel vehicle
DT	Diesel Truck
EV	Electric Truck
ET	Electric Truck
IUC	Circulation Tax
ISV	Tax over vehicles

1 INTRODUCTION

As the world is shifting towards the reduction of pollutant emissions, technology advances have been key in developing sustainable alternatives in the various sectors of our society: industrial, transport, energy, among others. As of 2019, global emissions reached a height of 33Gt of CO_2 worldwide, a number that is expected to grow in the coming years [1]. This has been a concern for most countries for several decades. Therefore, numerous efforts have been made throughout the years, in an attempt to reduce the human footprint in this planet, leading to multilateral agreements, the most recent and relevant being the Paris agreement, signed 2015, by 197 counties[2]. In what concerns the transport sector, a lot of focus has recently been given to finding viable alternatives to fossil fuels, such as coal, diesel , gas, among others that still power most of the transport systems in the world [3].

While there are several multilateral emission agreements in place, two stand out as the most important and global: the Kyoto Protocol and the Paris Agreement [4], [5]. The Kyoto Protocol signed in 1997 by 37 countries, including the EU countries, encompassed an emissions reduction target of 5% compared to 1990 levels, between 2008 and 2012 in its first commitment period. In 2012, a general amendment to the original Protocol, called the Doha amendment was adopted. Subscribing countries agreed to reduce emission values by 18% when compared to 1990s values [5]. Although the amendment was supposed to start being applied in 2013, it only came into force in December 2020. Besides implementation delays, major emitting countries did not sign the protocol, which meant that it targeted just 12% of the global emissions. The Paris agreement was the first legally binding global climate agreement to exist. It was signed in 2015, and for its implementation, it was necessary to ensure that at least 55 countries accounting for at least 55% of global emissions, would sign the agreement. The agreement sets a framework of measures, with specific goals such as limiting global warming to 2 ºC, peaking global emissions as soon as possible, creating a transparent global system where countries agree to report climate action measures to each other and to the public, and agree to come together every 5 years to assess the progress, and redefine goals. Key points in the Paris agreement are presented in Figure 1 [6].

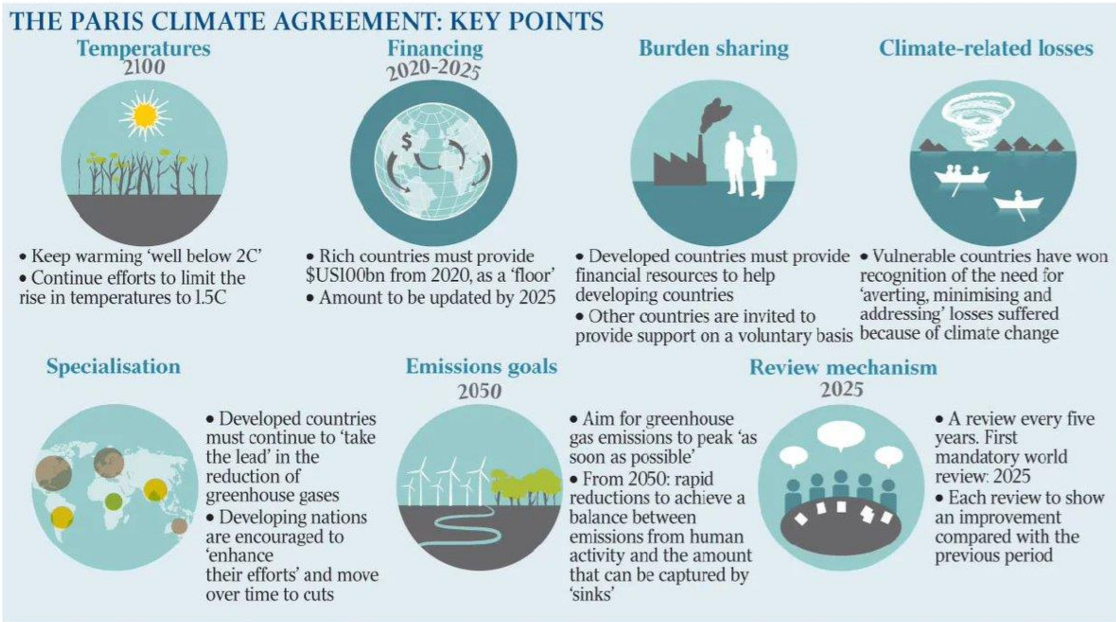


Figure 1: Paris climate agreement keys points [6]

The agreement also establishes a framework for the development of carbon neutral solutions and technologies, that could further help reducing emissions.

Although there is an urge for more climate action to be taken to achieve the goals of the Paris Agreement, its effects are already quite visible in the global economy, especially with the surge of new low carbon solutions and technologies that have formed a new market based on ecological efficiency. However, in many cases these solutions are still more expensive than conventional options. The UN estimates that Zero-Carbon solutions are only becoming competitive in economic sectors representing 25% of emissions, nonetheless it predicts that this figure will rise to 70% in 2030, due to technological advances [4]. The UN further adds that the power and transport sector have seen the biggest changes due this Agreement.

One of the main solutions in question is hydrogen, a colourless gas, discovered in 1766 by Henry Cavendish [7], considered the most abundant element in the universe. Being widely used for a long time now, it has several applications in industrial processes, agriculture, pharmaceutical sector, among others, and has been lately equated as a possible solution for transport, as a substitute for diesel and petrol vehicles, as well as batteries in electric vehicles. As it can be produced using only electricity and water, and its use creates almost no emissions, it is seen as a serious candidate to power the world in the future, and even more now, when countries are actively searching for ways of reducing their carbon footprint. As such, this dissertation will focus on the evaluation of the current state of hydrogen implementation and its production techniques, measuring the levels of its acceptance and the willingness of Portuguese companies to use hydrogen in the transport sector.

1.1 Hydrogen growth in recent years

In recent years the hydrogen market has been growing rapidly. As the world is now pivoting from heavy energy sources emissions to alternative solutions, hydrogen is becoming a great possibility in the pursuit for carbon neutral energy. According to a recent report developed by the hydrogen council in collaboration with McKinsey [3], there are, at this moment various governments and private companies investing in several hydrogen related projects, in a market that already has 6.5 million workers globally and around 6.6 million in capitalization. There was a massive growth in investments in hydrogen projects in the recent years, with around 200 hydrogen projects being presented in the beginning of this year amounting to 70 Billion dollars in investments in an execution phase from a total of 300B planned until 2030 [3].

1.2 Hydrogen Legislation

As a recent innovation in terms of implementation in Portugal, legislation regarding hydrogen is still being developed to this day. The EU, however, has already developed a set of regulations and policies regarding the gas, to ensure its can be used safely, and can be correctly regulated in the economic markets, which some of the regulations directly promote. For example, the Renewable Energy Directive (EU) 2018/2001 legally defines renewable liquid and gaseous transportation ules from non-biological sources, also including hydrogen in clean energy goals for the EU, which are 32% of all energy consumed and 12% of the energy used in transport by 2030 [8]. The Fuel Quality Directive 98/70/EC while not explicitly promoting hydrogen, states that fuel suppliers must GHG life cycle emissions per unit of energy by 6% before 2020. As hydrogen is a very clean fuel in most cases, especially green hydrogen, this kind of legislation gives an impulse for its development. Another European legislation is the Alternative Fuels Infrastructure Directive 2014/94/EU which defines a list of minimum requirements for the implementation of alternative fuel' infrastructure, including HRSs [9].

In addition there is a number of projects and programmes supported by the EU that focus on the development of hydrogen and its legislation, such as the HyLaw project [10], which identifies, organizes and presents hydrogen related legislation, even in areas that relate indirectly with hydrogen development, such as labour, environment, safety and transport. Other initiatives like the EU hydrogen strategy (2020) [11], that as the goal of developing hydrogen and the establishment of the European Clean Hydrogen Alliance, to coordinate efforts between industry, authorities and society, facilitating possible synergies to be explored, and coordinating investment, have also significantly helped implementing H_2 [12].

As for Portugal, the national plan for Energy and climate 2030 (PNEC 2030) sets a series of specific goals to reach before 2030, such as reducing between 45 to 55% the emissions of GHGs compared to 2005, incorporating 47% of renewable energy in the total consumption and reducing by 40% the emissions in the transport sector [13]. The document also refers to the importance of "producing and incorporating renewable gases such as hydrogen and biomethane'', that could promote a substitution of fossil fuels in use and reduce the country's energetic dependence, while also recognizing the capabilities of hydrogen in energy storage. More recently, the National Strategy for Hydrogen (EN-H2) published in 2020, highlights the present and future role of hydrogen in the energy system and proposes a set of measures and goals in various sectors of the Portuguese economy to facilitate its implementation in the country. It also provides the establishment of a solid framework for short and long-term objectives for companies and promoters regarding green hydrogen projects and highlights its potential in the decarbonization of the country. The document also defines goals for 2030, such as 5% green hydrogen in all energy consumed, in the transport sector, 15% of hydrogen mixed in the natural gas grid, 50 to 100 HRSs, and 2 to 2,5 GW of installed electrolysers.

1.3 OBJECTIVES

As stated before, the goal of this thesis is to assess the willingness to adopt H_2 in the Portuguese road transport sector. Portugal is committing to a significant reduction of emissions in the road transport sector, and for this reason, the support and investment in low emission solutions, such as hydrogen powered vehicles, is expected to increase considerably in the coming years.

Therefore, to accomplish this objective, several tasks will be undertaken, namely:

- Analysis of the status of development of H_2 technologies in Portugal
- Assessment of companies in the road transport sector willingness and preparedness for the implementation of hydrogen
- Assessment of the economic impacts of hydrogen deployment in the Portuguese road transport sector?

The completion of these task will allow for a better understanding of the willingness to adopt hydrogen technologies in the road transport sector in Portugal, from both people and companies, therefore providing valuable information on the probability of a successful adoption of Hydrogen powered vehicles to occur in Portugal, in the coming years.

1.4 THESIS STRUCTURE

This thesis will start presenting a literature review on H_2 technology, including production techniques, economic analysis, ongoing projects, safety concerns and analysis to similar studies. The following section will present the methodology approach adopted, the tools selected, and data collected. The methodology section will be followed by a presentation of the main results and their discussion. Finally, a conclusions section will be presented, followed by the bibliography and appendices supporting the study.

2 LITERATURE REVIEW

2.1 Energy transport sector vehicle solutions

There are several options in the market when it comes to vehicles, fuel types and powertrains options. In recent years there has been a tendency for the diversification of powertrain options, with a considerable growth in use of electrically powered vehicles and increased use of other technologies such as natural gas vehicles among others. Therefore, this section will serve as an introduction of the powertrain and vehicle options available in the market.

2.1.1 Petrol vehicles

According to ACEA (Association des Constructeurs Européens d´Automobiles) in 2020 47,5% of all new vehicles sold in the EU had a petrol propulsion [14], making it the most popular choice among European buyers with almost 5 million petrol car sold in 2020. These vehicles are powered by an internal combustion engine (ICE) and have dominated the European market for the last century. Its major advantages are their reliability, range and, therefore a matured technology with an implemented network. Their biggest disadvantages are low efficiency, safety (highly flammable), their dependence on petrol and, consequently, large pollutant emitters, with several GHG emissions associated.

2.1.2 Diesel vehicles

Diesel vehicles are the second most utilized type of vehicles, with almost 3 million sales in 2020 in the EU [14]. Like petrol engines, diesel vehicles use an ICE as means of propulsion, sharing several similarities with them. Diesel is also the most used fuel in buses and trucks. Advantages are their reliability, implemented network, with more than 2600 refuelling stations in Portugal [15], and driving range, while its main disadvantages are high GHG emission levels, low efficiency and being a derivate of petrol.

2.1.3 Biofuels

Biofuels are alternative fuels, produced from crops wastes, animal fats, grease, among others, using renewable sources. The most commonly produced biofuels are Bioethanol and Biodiesel. Biofuels have very similar properties to fossil fuels and can be blended with fossil fuel without performance reductions [16]. They also have a better environmental performance than regular fuels and reduce country's dependency on imported oil.

Their main advantages, when comparing to fossil fuels, are a higher efficiency, a reduction in GHG emissions, reduction in the dependency of imported oil and the low levels of pollution when produced using renewable sources. One of the biggest disadvantages is the extensive use of monoculture and land. Other disadvantages are shortness of food, since biofuels use crops that have high levels of sugar in them, industrial pollution; the large quantities of water necessary to irrigate crops; the large amounts of fertilizers required and the susceptibility to weather changes [16], [17].

2.1.4 Liquefied Petroleum Gas (LPG)

LPG is a cleaner alternative to other fossil fuels, with lower emissions of CO_2 (-33%), NOx (-84%) and lower sulphur content. It is a mixture of propane and butane, stored in compressed tanks (between 0 and 22 Bar) to maintain its liquid form [18]. LPG vehicles work via ICE and the process of combustion is practically the same as of petrol engines. This is quite important as most LPG cars are bi-fuel consumers, being able to run both Petrol, or LPG, and almost all petrol vehicles can be adapted for their engines to run with LPG.

As of 2021 there were 7.685.000 LPG registered vehicles in the EU [19], 3.2 % of all passenger vehicles in the EU, with these figures expected to grow in 2022 due to decarbonization targets.

Major advantages are easy installation in petrol vehicles, a greater autonomy, reduced emissions, being cheaper than petrol or diesel and, in many cases in the EU, less than half of the price per litre of petrol. Major disadvantages are the fact that it is a fossil fuel, loss of space due to the extra storage tank, and safety concerns since it is an odourless gas.

2.1.5 Electric Vehicles

Electric vehicles or EV's are the fastest growing alternative powertrain in the automotive industry with around 1.045.000 sales of electric vehicles in 2020 in the EU, with these figures doubling when considering HEV. Sales in Portugal have also grown in 2020, representing now over than 14% of all sales in the country when including HEV and 5,4% when only BEV are accounted for [20].

These vehicles use a DC system with a battery installed with an inverter to power an AC motor. For charging they use a charging station and can regenerate power when braking.

Electric vehicles are much cleaner than petrol and diesel, since they run on electricity, and thus have a much lower level of GHG emission. Due to this, they are considered as ZEV or Zero Emissions Vehicles since they do not produce any emissions while moving. However, emissions for EV are still not quite zero, since there are associated emissions with the electricity generation, especially in cases where sources aren´t renewable, and with the production of batteries.

2.1.6 Compressed Natural Gas (CNG) or Liquified Natural Gas (LNG)

Compressed Natural Gas (CNG) or Liquified Natural Gas (LNG) are a derivate fuel from natural gas. CNG is obtained by compressing natural gas to less than 1% of its volume at atmospheric temperature and is stored in vehicles at around 200 bar [21]. It can be used in a variety of vehicle types, such as light passenger vehicles, buses, light-duty cargo vehicles and in some cases heavy-duty vehicles. LNG is also obtained from natural gas, but instead of being stored at high pressure, like CNG, LNG is stored at -130ºC in order to maintain its liquid form [21]. LNG is used exclusively in Heavy-Duty vehicles, and while both types of fuel are originated from natural gas, and are used in ICEs, LNG is more commonly used for long distances. In Portugal, there are few vehicles and refueling stations available to the public, however, there is a number of bus companies that operate medium sized fleets, that usually have their own refueling station and in 2020 there were 30 vehicles registered requiring this fuel type [20].

2.1.7 Hydrogen powered Fuel Cell Electric vehicles (FCEV)

Hydrogen is a fuel that can either be produced from Natural gas, coal or using electricity and water to separate the H_20 molecules into Hydrogen and Oxygen. It can be stored either in liquid form, at -253 ºC in cryogenic vessels or at 350 Bar and700 Bar at highly pressurized vessels [22], [23], although pressurized storage is much more common in vehicles. FCEV have a very similar propulsion system to electric vehicles, but instead of using a battery, the energy that is stored in the hydrogen is converted to electricity and used to power the vehicle. The technology is used in various vehicle types, from light duty vehicles to trucks and buses as they produce no tailpipe emissions, have a high driving range and the refuelling process is very similar to the one of diesel and petrol. In Portugal there are very few hydrogen powered vehicles as of 2022, as there is only one refuelling station in operation at the moment [24]. (Figure 2)

Figure 2: Example of FCEVs operating in Portugal [25], [26]

2.2 Automotive Market

2.2.1 Present situation of the automotive market

Since cars appeared in beginning of the 20th century, revolutionizing the transport industry, significant changes have been made in its concept, with continuous changes and development being made to allow for quicker, more efficient as well as safer cars. An example of one of these changes is the introduction of the three point seat belt, a milestone in safety, that is applied in every vehicle nowadays [27]. However, one particular aspect that has remained largely untouched until recent years is the vehicles' fuel type, as well as its motorization. During the last century, petrol derivative fuels have maintained a dominant position in the automotive market due to the combustive properties, relatively low price, easiness to transport and to extract.

That said, petrol derivative fuels present several problems to our society, which have thus pushed for a transition to other alternatives. One of the main problems is that these vehicles produce large emissions of greenhouse gases, which implied several measures and technological implementations have been applied to reduce emissions per vehicle. Secondly, petrol reserves in the planet are dwindling, meaning that availability for these fuels is limited and is due to come to an end in the future. Lastly, the fact that oil derivate fuels are the main fuel used for transportation means many countries are entirely dependent on it, and since only a few countries in the world have oil reserves, this leaves non-producing countries exposed to political leveraging, as was the case during the 1970s energy crisis [28]. Thus, in recent decades, governments have pursued policies seeking to find environmentally friendly alternatives to diesel and petrol cars as a way of not only reducing emissions, but also increasing energetic independence of their countries. In Europe, for example, electric vehicles are regarded as a viable alternative to fossil fuel vehicles, and as such, several measures have been implemented to promote this transition: i) great investments have been made in the EU to implement the necessary infrastructure to accommodate EV's, ii) tax reductions or exemptions for electricity supply in charging stations, iii) and in some countries even additional taxes over diesel and petrol were applied, to persuade citizens into buying EV [29], [30].

An analysis of the current market of vehicles in Europe can provide a better understanding of how these measures are affecting it and how they have the potential to transform it completely. However, it must be taken into consideration that the analysis includes various markets in the European union grouped together, meaning that some of the data analysed might be more affected by a specific market. Due to this aspect, some of the conclusions might have a localized accuracy, or have a reduced value in some markets.

2.2.1.1 *Passenger vehicle market*

The number of vehicles reported by the ACEA (Association des Constructeurs Européens d´Automobiles) for the period of 2019 and 2020 of passenger vehicles sold by their fuel type in the European Union is presented in Table 1 [14].

Table 1 : Sales figures for passenger vehicles by fuel type in 2019 and 2020 according to ACEA [14]

	2019	2020	%Change
Diesel	4.106.951	2.778.817	-32.3
Petrol	7.514.812	4.713.778	-37.3
ECV	387.000	1.045.831	169.7
HEV	742.084	1.182.792	59.4
APV	254.270	208.372	-18.1

As can be seen, in the last two years the numbers of diesel and petrol passenger vehicles sold has reduced considerably (between 32% and 37%, respectively), while ECV (Electrically Chargeable Vehicles) sales had an accentuated increase of 169.7 % from 2019 to 2020. ACEA further reports that, in 2018, 60% of all vehicles sold in the EU were petrol driven and that, in 2020, this figure reached 47.5%. In the meantime, EV sales represented only 2% of all passenger vehicle sales in 2018 with an increase to 10.5% in 2020.

Even though sales might have been potentially affected by the ongoing COVID 19 pandemic that started in 2020, these figures show that the EU market is shifting towards the electrification of its transport system, proving the measures and incentives for EV's to be effective.

Portugal is one of the countries that has invested significantly in the transition for electric vehicles, having created a government managed company to develop and manage a growing charging grid [31] and creating several incentives for the acquisition of EV's, such as a 3000 € support for passenger vehicles. Therefore, the country has seen a rapid growth in EV sales, with 11% of all vehicles sold in 2020 being electric [32].

2.2.1.2 *Heavy Duty passenger vehicle market*

The Bus market in the EU has also started to see some significant changes during the last years. Table 2 presents data from the ACEA 2020 report for the full year sales of buses [14]. The first and most evident aspect when compared to the passenger vehicle market is the fact that diesel not only represents the large majority of sales, but also petrol doesn't have a considerable representation when considering these types of vehicles. Secondly, HEV, APV and ECV have also seen a significant increment of sales in number, accompanying the same trend of the passenger vehicles. In Table 2 sales of heavy-duty passenger vehicles are presented.

Table 2 : EU Sales figures for BUS vehicles by fuel type in 2019 and 2020 according to ACEA [33]

	2019	2020	%Change
Diesel	28.065	20.458	-27.1
Petrol	11	6	-45.5
ECV	1.448	1.714	18.4
HEV	1.957	2.662	36
APV	2.579	3.206	24.3

As can be seen in Table 2, the Bus market has seen a significant change in the last decades. If, in the early 2000's, almost all buses were diesel powered, in the last years this has changed considerably, first with the surge of LNG and GPL (Alternative fuels) and then with ECV's and Hybrid Buses. One of the reasons for that is that buses operate in fleets, and as such, it becomes easier to implement the necessary infrastructure for the new technology, in terms of charging without high cost.

2.2.1.3 Heavy Duty vehicle market

The heavy duty vehicle market in Europe is dominated by diesel trucks sales with over 95.6% of all sales in 2020, according to ACEA [34]. Compared to the passenger vehicle and bus markets, this makes a clear contrast, as diesel trucks seem to remain as the main option. Figures for the year of 2019 and 2020 can be consulted in Table *3*.

Table 3 *: EU sales figures for HDV sales in 2019 and 2020 according to ACEA* [34]

	2019	2020	%Change
Diesel	303.393	225854	-25.6
Petrol	235	210	-10.6
ECV	745	984	32.1
HEV	267	157	-41.1
APV	6.485	6.841	5.5

As can be observed in Table *3*, while diesel trucks dominate the market, the second most popular powertrains are alternatively powered vehicles, more specifically CNG vehicles followed by LNG, that have seen a consistent growth in the last years. As for ECVs and HEVs trucks, these haven't seen a significant rise in new registrations. There are several studies that examine this phenomenon, such as the one by Emir Çabukoglu (2018) that analysed the option of battery electric propulsion for HDV and concluded that electric trucks are not able to fully substitute diesel trucks, as they require heavy adaptations in the energy grid to support the fleet, battery swapping with batteries weighing up to 3 tons and very reduced driving ranges [35].

As to Hydrogen powered trucks, there are still very few in Europe, with only 11 registrations in 2020 [34].This is mainly due to the fact that there are very few models available at this moment, very few operational Hydrogen Refuelling Stations (HRS) for trucks and because fuel cell trucks are still significantly more expensive than its alternatives.

In Portugal the scenario is quite similar, there were 3525 new diesel registrations in 2020 , while natural gas accounted for 55 registrations and hybrid vehicles only 9 [34].

2.2.1.4 Fuel Cell Vehicles (FCV)

The first fuel cell vehicles in Europe were introduced in the early 2010's. Since then, the number of registered FCEVs in Europe has grown consistently and there are now 2255 registered vehicles (2021), according to the European alternative Fuel Observatory [19]. In Figure 3, the accumulated number of FCEV vehicles in the EU since 2014 is presented.

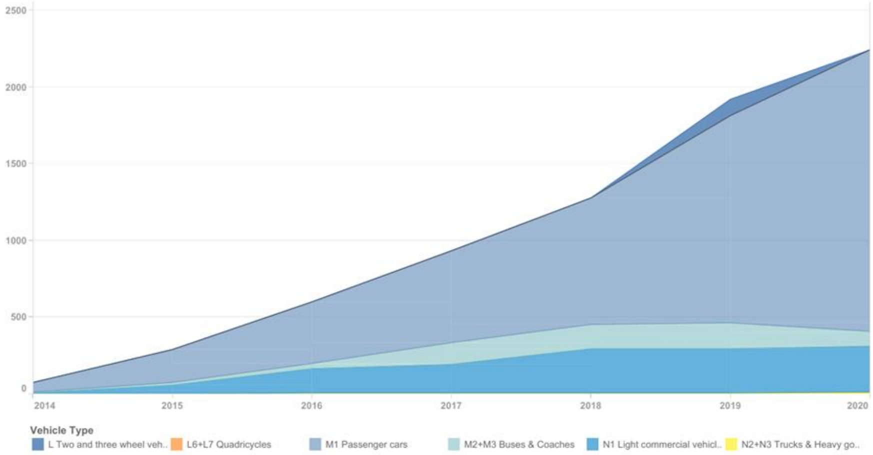


Figure 3 : Cumulative number of registered FCEV by year in EU [Source: Fchobservatory] [36]

Two main conclusions can be drawn from Figure 3: first, the number of FCEV's has risen significantly in the last years, proving that its adoption is possible and that an increasing number of people are willing to invest in an H_2 vehicle. Secondly, the fleet size is still relatively small, especially when compared to the approximately 9 Million cars that were sold in the EU last year [14]. This factor can be explained by a variety of reasons: i) high costs associated with the implementation of the HRS grid and, since only 125 HRSs existed in the EU as of 2020 [10], and ii) the absence of a sufficient number of refuelling stations to stimulate a faster adoption and growth of the H_2 fleet now. However, further investments on a large-scale deployment of HRSs are underway, and as such, it can be expected that this number will rise significantly in the coming years [37].

While the situation could be compared to the adoption of EV's, that also started to appear in the market around the same period, the fact that electricity was available almost everywhere strongly contrasts with the absence of hydrogen sources, especially green H_2 and distribution means (HRS's, pipelines, storages, etc).

As can be seen in Figure 4, Germany, France and the Netherlands have the highest number of registered FCEVs in Europe. While Germany is the European country with the largest fleet of H_2 vehicles currently, France has the largest commercial FCEV's vehicle [36].This also shows that while some countries have already invested in Hydrogen infrastructure and vehicles, many haven´t done it yet, which is considerably hindering Hydrogen vehicle's adoption. However, with the release of new carbon targets in the upcoming Euro 7 regulation, and with European commission allocating more funding towards H_2 related projects, more countries have pledged to invest in FCEV's [38].

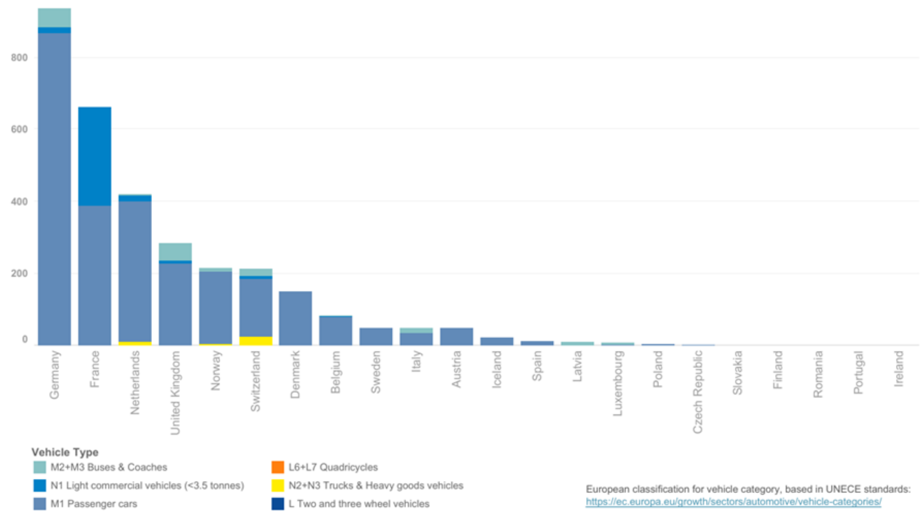


Figure 4 : Cumulative number of registered FCEV by country in EU [Source: Fchobservatory] [36]

2.2.2 Future of the automotive market

The automotive market is at a point where several technologies competing with ICE engines have been introduced and are beginning to gain market share. This is already visible in the car market (light passenger vehicles), Table 1, where all the alternatives to ICE engine already represent around 25% of all sales in the passenger vehicle market [14], and in the bus market (heavy duty passenger vehicles), were alternatives to diesel have achieved a 27% market share, as can be verified in Table 2. As such, predicting how this market will evolve is a difficult task, since there are several technologies growing in sales at this moment, but also many variables are to be considered, such as tax policies, economic health of a country, people's attitudes towards each technology or even the effects of unpredicted events, such as wars, shortness of materials, or even pandemics [39].

Due to the ongoing covid-19 pandemic, for example, vehicle sales fell from 83.7 million in 2019 to 72 million in 2020 globally, with the fall being attributed to a weaker economy. However, during the same period, HEV increased from 2.8% to 3.2% of global sales, PHEV from 0.6% to 1.2% and BEV sales increased from 1.8 to 2.8% [39] . This was attributed mainly to several key models released in 2020 that incentivised sales, but also due to the current growth trend that EVs have enjoyed in the latest years. The Covid-19 pandemic also deeply affected car sales predictions, for example, a report made by Deloitte published in January 2019 (right before the pandemic hit the world) has proven to be inaccurate just a year later, as the virus increased the adoption of EV in many countries considerably [40].

In Table *4* some of the car sales predictions for 2030 are presented, divided by powertrain. The blue rows are predictions exclusively for the EU and the white rows are global predictions.

Table 4*: Predictions of car sales in 2030, by each powertrain, in percentage [2], [3], [29],[32]]*

Predictions	Year	BEV	HEV+PHEV	ICE	APV	FCEV
Schaeffler	2018	30	40	30	-	-
Deloitte	2020	20	10	70	-	-
European climate foundation	2018	15	33	50	-	2
Graham Conway	2021	39	50	10	-	1
Mckinsey	2019	23	16	61	-	-
International Energy Agency	2021	53	8	38	-	1
NREL	2019	12	35	52	-	-

As it can be seen, predictions on the evolution of the automotive market vary considerably when it comes to powertrains. BEV vehicles are expected to grow significantly in sales with all studies pointing them, along with hybrid engines, to be an essential part of the decarbonization targets. As such, ECV's are expected to represent at least 39% of all car sales in Europe by 2030. On the other hand, ICE engines sales are forecasted to decrease exponentially in the coming years. With several countries planning to be banning ICE in the future, such as Norway in 2025, UK, Ireland, Netherland and Sweden 2030, there is a tendency for ICE vehicle sales to reduce even further. Moreover, future regulations on emissions such as Euro 7 in EU and LEV IV in the USA will tighten even further the allowed emissions per vehicle, meaning ICE engines will need to be more sophisticated, and as such more expensive as well [38][41].This will also provide better conditions for the adoption of hydrogen vehicles in EU, as support and financing from the European Commission and local governments for hydrogen infrastructure and fleet renewals are expected to be assigned.

2.3 Hydrogen production and acquisition investment costs

2.3.1 Total Cost of Ownership (TCO) of hydrogen vehicles

Accompanying the expansion of EV's, several studies have been published that compare TCO'S of BEV with ICE vehicles among others, along with predictions for the next years.

Anatole Desrevaux, in his techno-economic comparison between diesel and electric vehicles [42] concluded that on average the TCO of Electric vehicles was 1000 € lower than the TCO of diesel vehicles in France, considering a 5 year period of ownership. The author compared three different scenarios: urban case, extra-urban case, and Highway use, for three different periods of ownership (3, 5 and 8 years) and considering an annual distance of 9500 km. Results showed, that EV were mostly dominant in urban scenarios, especially considering long term ownerships (savings between 72 € and 1952 €). In the extra-urban case, results were less favourable to EV's, with the difference in TCO between -317 € and 1563 € (Figure 5). As for the highway use scenario EV's TCO was lower , except for short ownerships (3 years) [42].

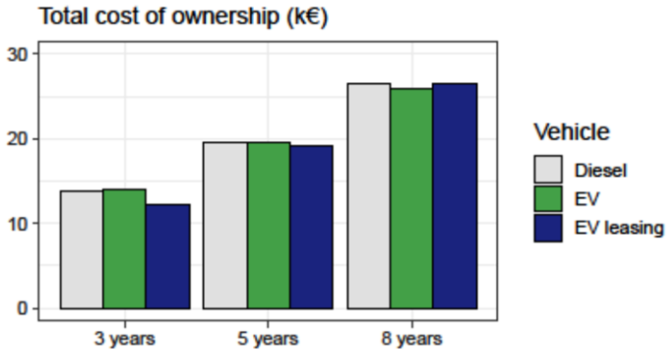


Figure 5 : TCO for the extra-urban case, for diesel vehicle and electric vehicles [42]

Main conclusions from this study were that there was a TCO advantage for EV's in France, mainly due to favourable tax conditions, although the authors point out that even without tax supports EV's have a solid TCO. Also, depreciation rates and governmental incentives are the main factors influencing TCO.

Another study released by BEUC (Bureau Européen des Unions des consommateurs - 2021), provides a complete analysis and forecast of the TCO of petrol and diesel combustion engines ICE, BEV's, Hybrid vehicles, PHEV, and also Fuel Cell vehicles (H_2) [43]. It provides an analysis and preview of the TCO's for first, second and third owners of vehicles bought between 2020 and 2030 in nine different countries of the European union: Cyprus, Belgium, France, Germany, Italy, Spain, Portugal, Slovenia and Lithuania. The study provides not only a comparison for current costs, but forecasts for the next ten years regarding the evolution of the TCO's of the various vehicle types, analysing cost differences for multiple ownerships, CO2 emissions of each vehicle, battery range and life of electrically chargeable vehicles, among others. Main results were that medium BEV were the cheapest drivetrain´s available as of 2020, with predictions pointing for medium and large Battery electric cars to reach the same status in 2024 and 2026 respectively.(See Annex 1) It is worth noting that all forecasts in the study were made considering a 16 year lifetime for vehicles, which might provide a slightly more favourable scenario for BEV's, since most studies have shown their TCO's tend to lower with the time increases and in reality most people switch vehicles before that.

In Figure 6 and Figure 7 it is possible to observe the comparison between petrol ICE vehicles, the most abundant in EU, and all the other alternatives in terms of TCO for the years 2020 and 2025 considering medium car sizes.

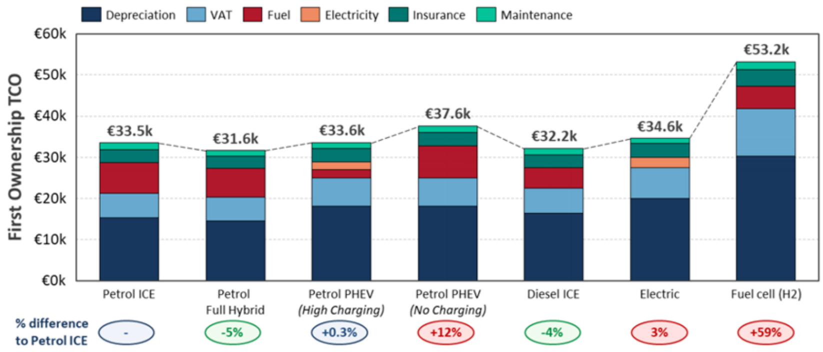


Figure 6: TCO of new medium cars for each powertrain in 2020 [Source: BEUC] [43]

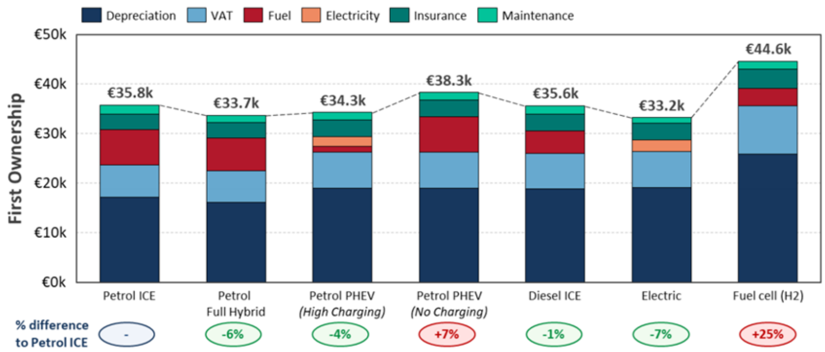


Figure 7: TCO of new medium cars for each powertrain in 2025 [Source: BEUC] [43]

As can be seen Figure 6, in 2020 diesel ICE vehicles presented the lowest possible TCO of all medium vehicles, with depreciation being the main driving factor of all costs. As for the 2025 predictions, BEV's become the alternative with the lowest TCO closely followed by Petrol hybrid and PHEV. As for Fuel cell vehicles, it can be said that its TCO is still considerably superior to the other options on the market, although that difference is significantly lower in the 2025 prediction (around 25% more expensive). This difference can be explained because H_2 vehicles have a larger depreciation rate than other vehicles since they are still in an implementation phase, which can be reduced either if early adoption of this new technology is significant, thus reducing depreciation, or if additional funding from EU governments is allocated. The main conclusions of the study pointed that BEVs are becoming the cheapest option in the European market, and as such, the authors forecast that they will become the dominant powertrain in terms of sales in the next decade. Moreover, they consider that an uptake in BEV sales and other alternative fuels is essential to reach Euro 7 emissions target, which is currently forecasted to come into force between 2022 and 2024.

2.3.2 Assessing hydrogen's investment costs

One of the most important factors to the success of a new technology is how viable it is as an investment option. As such it is important for possible investors to understand the costs that are related to hydrogen namely infrastructure, maintenance, vehicle costs among others

M. Minutillo et al. (2020) conducted a study focused on the levelized cost of hydrogen production via water electrolysis on-site for Italy [44]. The authors identified that the main factors in terms of costs are the production capacity, the plant size and the energy source. As such they contemplated three different production capacities (50 kg/day (micro), 100 kg/day(small) and 200 kg/day(medium)) and three different percentages of grid energy supply levels (25%, 50% and 100%) to understand how much these two aspects influence the total HRS costs. For comparison they also computed the cost for off-site production, to give us a direct comparison between off and on site.

$$LCOH = \frac{Total\ Costs\ (€)\ -\ Electrical\ Revenue\ (€)}{H_2\ Annual\ Production\ (kg)} = \frac{C_{inv,a} + C_{rep,a} + C_{O\&M} - Rev_{el}}{M_{H_2}}$$

To compare the different scenarios described above Minutillo et al. used the LCOH or Levelized cost of Hydrogen, which considers not only investment costs but also other others such as operational and management costs over its expected lifetime. The results of the study confirmed that the plant size significantly affects the costs, as the LCOH reduces with the increase of the plant size and the costs also increment proportionally with the percentage of grid supply, due to the increase of PV installed capacity.

Table 5: HRS component costs according to configuration [44].

Table 6 – Total costs for the HRS configurations.

Electricity mix	HRS configuration	CAPEX (k€)	OPEX (k€/ year)	REPLEX (k€)
Full Grid (100%)	Micro_FG	521.03	169.66	443.74
	Small_FG	967.38	310.62	812.80
	Medium_FG	1508.27	559.91	1198.45
High Grid (75%)	Micro_HG	747.13	139.91	443.74
	Small HG	1417.68	255.97	812.80
	Medium_HG	2411.72	460.71	1198.45
Mid Grid (50%)	Micro_MG	973.23	131.60	443.74
	Small_MG	1867.98	241.05	812.80
	Medium_MG	3316.12	434.64	1198.45
Low Grid (25%)	Micro_LG	1199.33	130.13	443.74
	Small_LG	2318.28	238.79	812.80
	Medium_LG	4219.57	431.72	1198.45

The conclusion was that a Medium sized Plant and Mid Grid feed (50% grid supply) was the combination with the lowest LCOH estimated in 9,29 €/kg. It is important to note that these values were estimated for the Italian market and might be different for different regions with different electricity prices and conditions.

In terms of infrastructure costs, there are multiple studies that have evaluated the cost of installing a refuelling station. For example Bonhoff et al. (2016) in its study suggested a HRS´s cost of around 1 million euros for an HRS with off-site capacity, and quite similar values were estimated by the IEA and the hydrogen council [3], [45], [46].

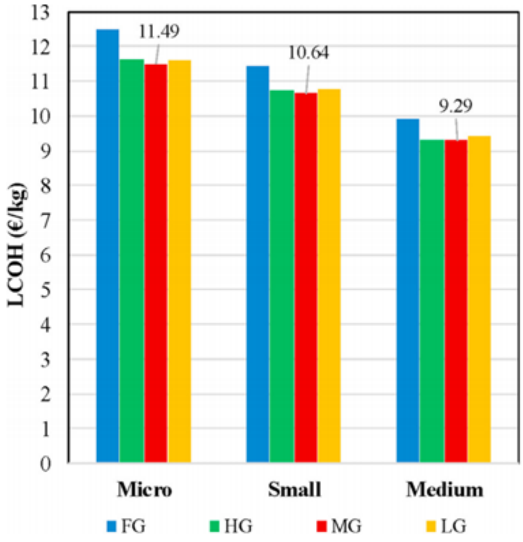


Figure 8: LCOE based on different scenarios, FG is full grid supply, HG is high grid supply MG is medium grid supply and LG is low grid, referring to renewable supply [44]

Adolf et al. (2017) in a study about hydrogen technologies, presented HRS's costs in California between 1.6€ and 2.4€ million with the difference of values mostly attributed to daily dispensing capacity and type of HRS. The authors also take a different approach to comparing on-site and off-site HRS's by computing system costs: for a small HR with on-site production system cost is around 22000 €/kgH_2/day while for an off-site HRS the cost is reduced to 13400 €/kgH_2/day. These costs are considerably lowered when considering a large HRS with distribution in liquid from, approximated in 3400 €/kgH_2/day, although study conclusions found that these costs could be up to 50% lower in 2025 [35].

In Table 6, presented below, we can see the costs of the different components of an off-site HRS, and their variation with size, according to Mayyas et al (2015) [47]. In their study, they consider that a medium sized HRS with a capacity of 500 kg/day costs around 1.2 million euros and a Large HRS, with 1000 kg/day of capacity around 1.6 million euros.

Table 6: HRS sizing and components costs [48][47]

HRS Component	Medium HRS	Large HRS
	Cost (thousand €)	Cost (thousand €)
Compressor	324	480
Chiller	162	200
Electrical	40	40
Storage Tanks	171	240
Dispenser	162	280
Piping-Control-Safety	16	16
Labour-Other Expenses	320	350

As Table 6 shows, the most of expensive component is by far the compressor, followed by storage tanks, the dispenser, and the chiller.

As it can be verified, the costliest components of the HRS are the compressor, the labour and other expenses associated with the installation costs. In case this was an on-site HRS, therefore PV modules would be necessary, or alternatively other sources of energy to supply the electrolyser, raising costs to between 2 million and 4.5 million, according to different sources [48], [49].

A study conducted by Philipp K. Rose (2020) took a different approach to others, analysing the implementation of on-site HRS along with the investment and possible developments in the existing power system. It focused on Germany and was comprised of two different scenario forecasts for 2050: In the first scenario the investment in the HRS network was optimized, and only later the electricity grid was optimized. Comparatively, in the second scenario both HRS investment and electricity systems investment were made simultaneously. Results showed that scenario 2 had much higher electrolyser capacities when compared to scenario 1 (165 MW compared 60 MW) mainly to due to the electricity systems optimization and higher flexibility of scenario 2. Another interesting result was that HRS infrastructure costs were significantly higher (+ 560 million Euros per year) compared to scenario 1, specifically due to electrolyser and low-pressure storage cost increases. However, power consumption was drastically lower in scenario 2, costing 940 million less per year, and compensating the difference in infrastructure costs. From this, the authors concluded: the costs of electricity generation are the most determining in estimating hydrogen production costs, and thus investing in electricity network for cheaper supply, and oversizing on-site electrolysers is a reasonable business decision. The authors also predict that the average LCOH for both scenarios varies between 4.83 €/kg and 5.36 €/kg with and operational expenditure of around 80% [50].

Conclusions were that co-optimization of the various sectors is very important as simulations show that by optimizing the electricity system, a great reduction in costs is possible, along with a high level of flexibility in the production. Therefore, the article provides us, with a good insight with the way the power systems and the HRS investment interact.

2.4 Acceptance of Hydrogen Powered Vehicles

2.4.1 Early Adopters of Hydrogen Powered Vehicles

Like with any technological innovation in the past, there are several steps between the invention of a new concept or method and its widespread use of the public. In this case, hydrogen is no different, and for a successful implementation in Portugal and in the EU, it is necessary to have a group of people, and especially companies, to be willing to invest and to be the first adopters of fuel cell technologies. While there are several studies that aim to understand who are the first early adopters of Fuel cell vehicles [51]–[54], Hardman (2019), in its analysis concludes that FCEV buyers will be typically male, middle aged, high income, highly educated and with more than one vehicle [51]. This can be expected, as the costs and handicaps associated with investing in a FCEV are still considerable. For example, the lack of a sufficient HRSs infrastructure in the EU means that an individual that requires the use of a car for travelling might not be able to do so in a FCEV, as some regions have very few hydrogen refuelling stations. If this is taken into consideration, plus the still considerable costs of purchasing a FCEV, it is understandable that FCEV are bought by early adopters, and mainly as a secondary vehicle.

As for FCEBs and FCET, the situation is different, as most of these vehicles are owned by companies. Bus companies are often regarded as the best candidates for early adopters, due to the fact that they usually have medium small/medium sized fleets, have their own maintenance shops and crews, and can be served by a single HRSs. This can be seen in multiple cities in Germany and Japan, where bus companies are increasingly growing small FCEB fleets [50], [53], [55], [56]. As for Heavy-duty truck companies, the adoption might take longer, as there aren't enough HRSs yet to allow for long distance travels as is the case with many trucking companies [55], although smaller trucks or local fleets, like garbage disposal and maintenance, might implement hydrogen vehicles earlier. That said, it can be expected that Bus companies contribute significantly to the implementation of hydrogen in Portugal, with the deployment of one or more HRSs that would firstly serve to supply the local fleets of FCEBs. These refuelling stations would then be also accessible to the public, allowing for privately owned FCEVs to use them, thus inducing growth in the hydrogen fleet.

2.4.2 Hydrogen powered vehicles acceptance

Social acceptance has been an important factor for the discussion of hydrogen as a technology. Since hydrogen started to be seen as an alternative to fossil fuel in the beginning of the 21st century, several studies have been conducted to understand the role hydrogen will have in the transportation sector. One of the major focus points is the level of acceptance it will have with companies and people, as it is imperative for a technology in adoption phase to be viewed as safe, reliable, and advantageous. Looking at a study developed in 2004 called AcceptH2Public [56] that studied public opinion of hydrogen in London, Perth and Luxembourg, results showed that people were already strongly supportive of hydrogen and fuel cell . However, in the enquiries there was a considerable number of persons that said they required more information, demonstrating that although people were in fact open to the H_2 implementation, they lacked information to have a conscious opinion on it.

A study conducted in Spain by Diego Iribarren in 2015 [57] based on 1005 enquires also showed that overall people are willing to accept hydrogen as a key player in the transportation sector and also on the energy market. Firstly, results show that around 30% answered that they weren't familiar with the concept of hydrogen, which shows that there is still a large portion of the population that doesn't understand the applications for hydrogen, not even its existence. Secondly, around 60% found an affordable tax to develop hydrogen to be a good idea. The main barriers for H_2 implementation found by most people in the study were the cost of vehicles, the availability of hydrogen stations and lastly vehicle features. Overall, the conclusions were that more policy, industrial and research efforts are necessary to overcome obstacles in the path of hydrogen implementation.

Another article , written by Manuela Ingaldi in 2020 [58] focused on three European countries that had an underdeveloped Hydrogen network, in this case Poland, Czechia and Slovakia, that had a total of 350 respondents. The results demonstrated that respondents lack information about hydrogen and its technologies, for example, most were unaware about the benefits of generating electricity from hydrogen. Another important aspect was that around 40% were unsure about the safety of H_2 use in our society.

Christian Oltra et al. (2017), wrote an article evaluating the public acceptance of fuel cell applications in European countries. The study was based on a questionnaire, distributed in seven countries and had approximately 1000 answers per country. Results regarding the view of respondents on HFCEVs was positive, with 63% considering it a good, or very good option. Moreover, 78% also supported the substitution of conventional buses with FCEB, although at the same time participants reported a low likelihood of buying a HFCEV. The authors found that public acceptance for hydrogen technologies was high and that less than half of the of participants weren't aware of the possibilities of hydrogen in energy production and storage.

Gregory Trencher et al (2021) published a study focusing on identifying barriers and drivers of fuel cell technologies for passenger vehicles in Germany [59]. However, and contrary to other studies, this study focused only on interviewing and enquiring experts in industry, research institutes, government, or public organizations. Results showed profitability was still an issue hindering acceptance from companies towards the technology, namely of the refuelling stations. Experts highlighted that the lack of profitability of hydrogen refuelling stations at the moment, stating there are more than 90 HRSs in Germany, that could support a fleet of 40,000 vehicles while there were only 1016 FCEVs in circulation. This meant that although the number of refuelling stations is set to grow in the next years, the low utilization level might prove an obstacle for companies that would invest in infrastructure. The authors also expressed concern that with the success of BEV in recent years, and with the rapid developments this type of vehicle has seen in the last years, such as significant ranges increase and decreasing charging times, companies might see hydrogen, and the necessary investments related to its implementation and development as a lesser priority compared to BEVs. Conclusion were that further policy, industry and research efforts are required to overcome current obstacles hampering the success of hydrogen.

2.5 Hydrogen Production, Storage and Comsuption

2.5.1 Analysis of the current development of H2 technologies considering its three phases: production, storage, and consumption

2.5.1.1 Hydrogen Production and storage techniques

At this moment, there are 3 main ways to produce hydrogen which are Steam Methane Reforming (SMR) (grey hydrogen), coal gasification (brown hydrogen) and lastly via water electrolysis (green hydrogen). Steam methane reforming is the most used method, with 48% of all production in the world [60], and involves reacting Natural Gas, or Ethanol, with steam, producing H_2 and carbon dioxide, as can be seen in Figure 9. The hydrogen produced by this technique is commonly referred as grey hydrogen.

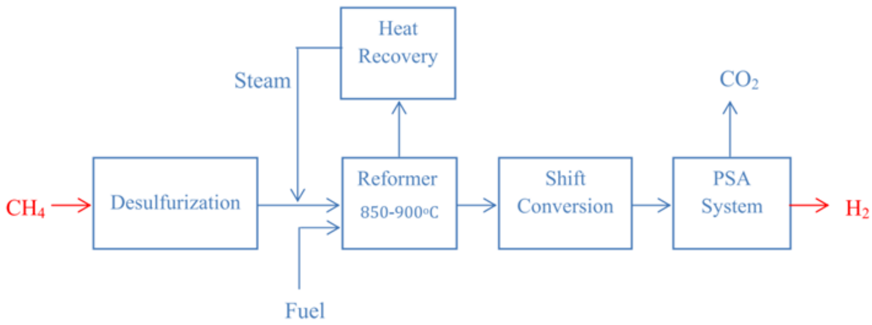


Figure 9 : Steam methane Reforming diagram [61]

The main advantages associated with this technique are the high thermal efficiency of the process (80%) and the high purity of the hydrogen produced (99,95%) [62]. Main drawbacks are high operation costs and high level of emissions, with 8 ton of CO_2 released by each ton of H_2 produced [60].

The Coal gasification involves the use of steam, coal and oxygen to produce Hydrogen and CO_2, and the described process can be observed in Figure 10. Main advantages are moderate thermal efficiency (52%) [63], cheap raw material, economic viability, making it favourable for large productions and disadvantages are high level of GHG and high reactor costs [62]. The hydrogen produced using this method is commonly referred as brown hydrogen.

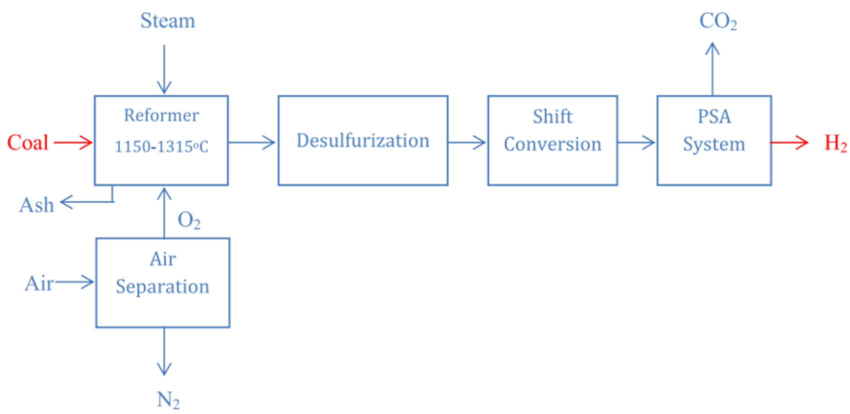


Figure 10: Coal Gasification diagram [61]

The third method is Water electrolysis, which consists of a cathode and an anode immersed in an electrolyte, then electrical current is applied to the water, that then splits into hydrogen at the cathode and on the anode side (See Figure 11) [61].

The hydrogen produced in the water electrolysis, also known as green hydrogen, is currently the most positively regarded technique in recent years, as its production releases nearly no emissions and requires only water and electricity, contrary to the SMR (grey hydrogen) and coal gasification (brown hydrogen) which are both emissions heavy. Adding to that, if the source of electricity is renewable, then this solution becomes one of the most sustainable fuel options in the market. However green hydrogen represents only 4% of the worldwide production [60], as at the moment, it is still significantly more expensive to produce and requires being fed by renewable sources to be truly emission free, although technological developments are expected to reduce the gap in the future.

For the water electrolysis method there are three main electrolyser technologies being used to produce green hydrogen: Alkaline Electrolysis (AEL), Polymer Electrolyte Membrane (PEM) and Solid oxide Electrolysis (SOEC) [64].

The first one, Alkaline Electrolysis is the most used and mature of the three (See Figure 11). Being in service now for several decades these electrolysers have proven to be affordable and have also shown a great flexibility in its production window, with variations in its capacity window from 20% up 150% according to [64]. This makes them ideal for situations where there are fluctuations in the energy supply, a recurring case with renewable sources where the production of energy varies considerably with the weather and hour.

The second one, Polymer Electrolyte Membrane (PEM) is a newer technology, that was first introduced in 1966 to improve over the problems the AE presented. Its main advantages are the ability to operate at colder temperatures, high efficiency, and high current density. Its main drawback is its production cost, although recent developments in technology have been reducing this price and thus pushing its commercial use [78][79]. In Figure 12**,** the reaction for the PEM electrolysis can be seen.

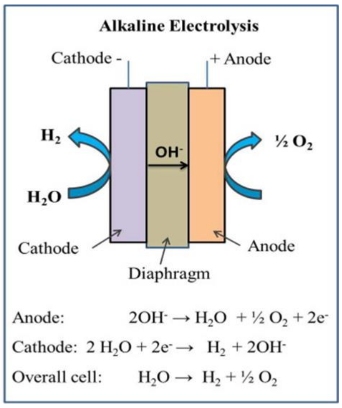


Figure 11:Alkaline Electrolysis operation principle and redox reactions [78]

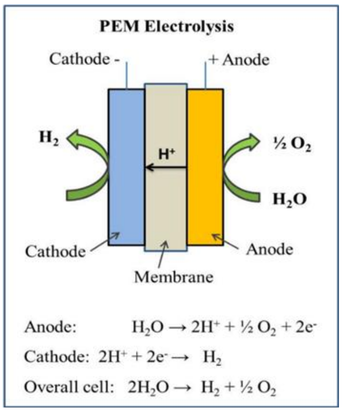


Figure 12: Polymer Electrolyte Membrane electrolysis operation principle [78]

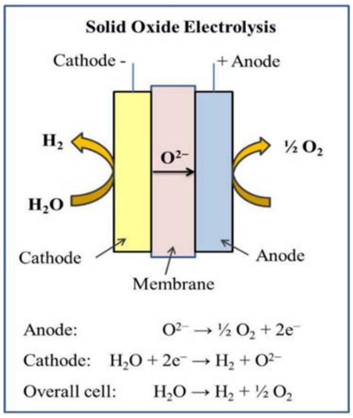


Figure 13: Solid Oxide electrolysis operation principle [78]

The Solid oxide electrolysis (SOEC), as presented in Figure 13, is the most recent technology of the three, is still considered to be in laboratory stage, and in the SOEC process, ZrO_2 doped with 8 mol% Y_2O_3 is used as the electrolyte [64], operating at high temperatures. The biggest advantage is the low electricity demand, and the biggest disadvantage is the fast degradation of components, gas leakage issues and lack of long term stability due to its high operation temperature [64].

2.5.1.2 Storage Electricity: Batteries vs Hydrogen Fuel Cells

When comparing electric to hydrogen fuel cell vehicles the first major difference is the fact that batteries store the energy directly and hydrogen fuel cells store H_2 that will be converted to electricity only when needed.

Battery life depends on working conditions, and lithium batteries, that are the most commonly used, have a maximum lifespan of 10 years, depending on battery size and number of cycles in usage [65]. Hydrogen fuel cell have a greater energy density than batteries, which in turn leads to a greater driving range of FCEVs. However, in terms of efficiency, electric vehicles are quite superior, having an overall efficiency of 86% where the FCEV only reach 54% in tank-to-Wheel efficiency [66].

It is also found that only when the CAPEX (Capital expenditure) of electrolysers drops to 25% of current price, the hydrogen storage system can have similar SSR with battery storage system under high NPV.

2.5.1.3 H_2 Refuelling Stations (HRS)

There are two main types of refuelling stations. The first one is off-site production where hydrogen is delivered from a central plant where it is produced, using either road transportation or pipelines. For road transportation, specialized heavy trucks are used and H_2 is transported as compressed gas, with pressures above 180 bar or can be transported in liquid form (LH_2)[67], but cryogenic tanks are necessary to keep its temperature bellow -253ºC. Compared to the transport in Gas form, LH_2 has the advantage that it is not necessary to be compressed , as H_2 is produced at 30 bar in offsite facilities meaning it needs to be pressurized to 180 bar for transport[48][67]. On the other hand, LH_2 is much more costly, as it requires a lot of energy for its liquefication, and as such it is not usually used. As to the pipelines, these are a much more cost effective alternative than road transportation, they can be used to reach much greater distances and significant portion of the existing natural gas pipelines can be adapted for this purpose. However, this alternative has some disadvantages: firstly, the initial costs for new pipelines is very high, which means it is often disregarded as a viable option and secondly, hydrogen requires specific materials and equipment to handle due to its inherent properties.

The second type of HRS is On-site production. On-site production has the same systems for the refuelling of vehicles, but the hydrogen supplied is produced at the same place as the station has an incorporated electrolyser. Currently the two of the most common production techniques used for this effect are Steam Methane reformation and water electrolysis.

In what concerns the refuelling process there are two main pressure values used to store hydrogen at HRS in gaseous form: 700 bar for light duty vehicles and 350 bar for heavy duty vehicles, generally [83]. In comparison the 700-bar system is more costly and energetically demanding, although the stored H_2 occupies less volume. Alternatively, it is possible to store hydrogen in liquid form, as stated before, but this requires maintaining it at very low temperatures(-253ºC) in cryogenic tanks. This option is less used, as these require a sophisticated freezing system, and known to have boil of problems [51].

As of 2021 there were 153 HRS stations installed in the EU, according to the Fuel Cell and Hydrogen Observatory [37] while Germany is the country that has the most installed, with 87 HRS's that service its more than 800 Hydrogen vehicles. However, of the 153, 135 are 700 bar HRS's, suited for passenger cars, and only 19 are 350 bar stations suited for heavy duty vehicles (Buses, trucks, medium sized commercials). The growth in number of HRS's in recent years, divided by each country can be seen in Figure 14.

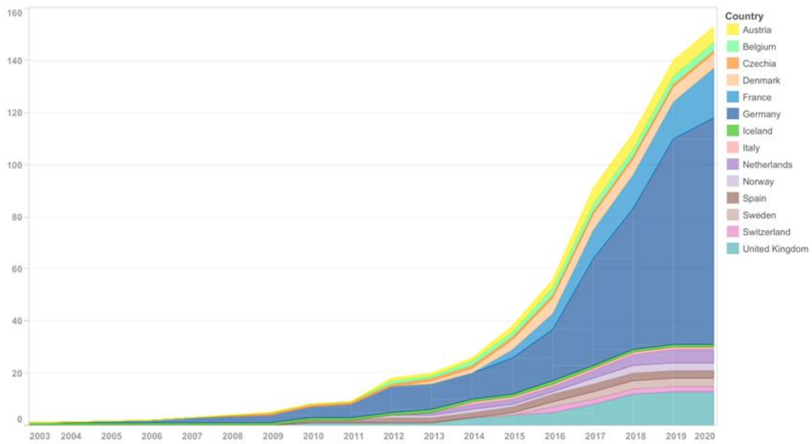


Figure 14: Number of HRS installed in EU by country and year [37]

Although these numbers are still low, they are expected to grow rapidly in the coming years, with several countries investing in EU, as ICE engines come under more pressure due to new emission regulations and the European commission allocates more funding to H_2. Portugal, for example has just installed its first HRS in Cascais , and several other are expected to open the next year [24].

2.5.1.4 Comparing On-site production with Off-site

When comparing these two types of HRS the main difference is the capacity of daily refuelling, as On-Site HRS´s have ranges between 100 kg/day and 550 kg/day when compared to the theoretically unlimited capacity of Off-Site HRS [67]. This means that Offsite HRS can adapt more easily the demand curve, whereas the On-site is limited to its capacity of production and the cost of reenforcing the electrical grid.

In terms of financial costs, On-site HRS are more costly to install, due to the components for the localized production and It is also worth considering that this cost is even higher when water electrolysis is used, as this technique is still more expensive than SMR.

2.6 Portuguese Hydrogen Market

2.6.1 Analysis of the current state of H2 technologies deployment in Portugal

Hydrogen is an upcoming alternative in the bid to find alternatives GHG emission heavy fuels and Portugal, being the first country in the world to commit to carbon neutrality targets for 2050 (2016), has kept interested in solutions that could help in this process of decarbonization [68]. As such, it has developed a road map for hydrogen [69], in an ambitious bid to reduce emissions by investing in alternatives to fossil fuels. At this moment there are ongoing plans to start hydrogen production on an industrials scale as soon as it is possible. Portugal possesses very good conditions for the installation of green hydrogen projects: low price solar power, with great solar exposition and the installed capacity of solar PV growing greatly in the last years and being expected to increase from 1GW in 2020 to 9.3 GW in 2030 [68]. Secondly, the existence of deep-water harbours is ideal for this kind of production, with the first projects expected to be installed in Sines. The Portuguese government predicts an investment of around 7 to 9 billion euros in hydrogen projects in the coming years which is estimated to translate into 2-2.5 GW of installed capacity in the next decade [68], [69]. Accompanying this growth in capacity are predictions of 50 to 100 HRS installed and 450-750 heavy duty vehicles in the same period of time [70]. This will contribute to the decarbonization targets of 2030 that Portugal is poised to achieve, of 55% reduction in Green House gases (GHG) and approximately 50% of energy production coming from renewable sources [68], [70]. It is also worth noting the objective of having 10 to 15% of H_2 injected in the natural gas grid.

Another important issue in the implementation of a hydrogen network in Portugal is the strategy for production and delivery, with the question pending between on-site production and off-site production as presented before. There are several studies conducted in Europe focusing on this subject that equate all the various possibilities: Centralized production centres with delivery via trucks, centralized production with delivery via pipelines, decentralized production , or even other alternatives such as production and supply directly at a dam for example [71]. Taking for example the study conducted by Øystein Ulleberg in Norway, he concluded that there are significant economic advantages associated with centralized hydrogen power plants, as Off-site production has a high investment cost, and offsite HRS electrolysers are much more expensive when combined than having a large electrolyser. However, the results of his study also showed that if the Hydrogen plants are not fully used then it becomes much less advantageous to choose On-site production instead of Off-site. Moreover, the costs of transporting hydrogen are still very high, so in some cases it might be justified to choose On-site production as it allows for greater flexibility to the demand. He concludes by stating that On-site production is a justifiable choice in the Norwegian market, especially in an ideal scenario where relatively large electrolyser serves a fleet of heavy-duty trucks dimensioned to absorb the HRS´s capacity (Figure 15).

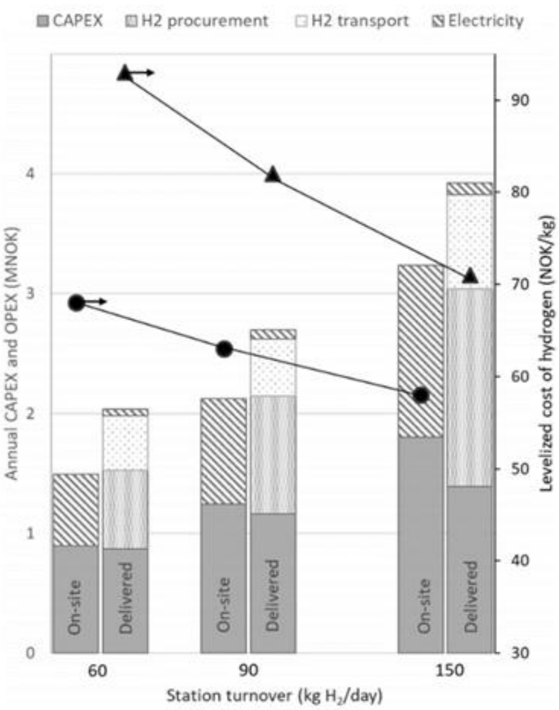


Figure 15: Comparison of costs between off-site and on-site alternative in Norway for various production turnovers [71]

Having this in mind, in a market where hydrogen is being implemented as a technology for transport, localized production in a small scale might just be the ideal choice, considering initial hydrogen vehicles will be few and as such centralized production would have lower system utilization rate overall.

Therefore, it is likely that the first refuelling stations will be small On-site localized production HRS´s, initially in the urban centres or heavily industrialised areas such as Sines [70].

To analyse where the first refuelling stations will be, one can take as an example the expansion of EV chargers from the beginning of the last decade, where the chargers where first installed in municipalities that pushed more for the energetic transition and where keen on investing in a more sustainable alternative, that is, early adopters. Figure 16 and Figure 17 present two different maps: the first one made in 2010 shows the municipalities that adhered to the pilot EV charging grid development program(Figure 16), and the second one is the Ultra-fast and fast EV charger available as of 2022 (Figure 17). Both maps were published by MOBI.E, a public entity that focuses on the development and management of EV chargers [72]. Currently, there are 4583 charging points in Portugal, of which 1706 are either for fast or ultra-fast charging.

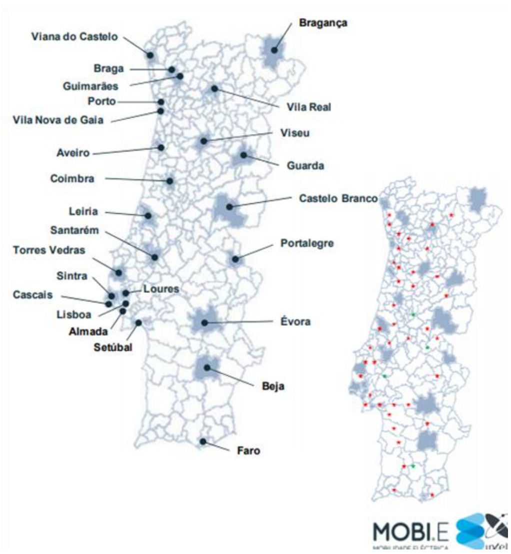


Figure 16: Municipalities that adhered to the pilot EV chargers Grid (2010) [31]

From these maps the expansion of EV chargers since 2010 is undeniable, and it is clear that in 12 years it was possible to establish a grid that covered most regions of the country. This is an important information because it might help understand where the first hydrogen refuelling stations might be located. The most evident aspect is the fact that chargers were installed in every district capital and other major cities in order to ensure that small fleets of EV´s could be viable choices for people in these places. Secondly chargers along major routes like Porto-Lisboa and Lisboa-Faro where also installed to provide conditions for travelling.

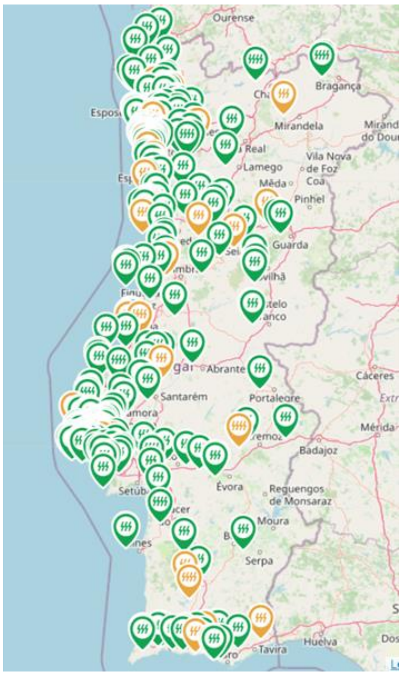


Figure 17: EV Ultra-fast and Fast Charger locations in 2022 [73]

When comparing this situation with hydrogen, a similar situation might occur as well, although there are some major differences: first, initial H_2 vehicles will be most commonly Buses and medium sized trucks, such as fleets for waste gathering from municipalities. As such, some of the first electrolysers will be installed for supply of small fleets of municipalities or small trucking companies and might not be fully available to the public for some time. Secondly hydrogen transport it quite expensive, as discussed before, and thus, having refuelling stations where its production occurs is likely to happen, such as the example of Sines, a maritime industrial port where the centralized production of hydrogen is expected to start soon. Lastly, the energy supply network was already implemented when EV chargers where installed which is not the case for hydrogen. Although Portugal might have a developed natural gas grid that could be used to help in distribution, it is adapted for the transport of hydrogen gas, with some minor component modifications, but it would be insufficient to cover the entire territory. This presents a major difference to the EV charger situation, as it will be necessary to either transport produced hydrogen from Centralized Production sites to Off-site HRS´s or to install HRS´s with On-site production, either way increasing the complexity of the investment.

As of 2021 the first hydrogen refuelling station has been announced in Cascais [25] and will feature localized H_2 production and have the capacity of 1MW, enough to supply the fleet of H_2 buses in the local municipality, but also other private users of hydrogen cars. Other stations are expected to be announced throughout the year in the country. Other projects, like the H2rail, that aims to convert regional diesel locomotives into hydrogen powered vehicles are also ongoing [74].

A study conducted by Silva in 2014 that analysed the impacts of hydrogen in transport in Portugal showed that hydrogen was likely to become economically viable by 2050. Also included, are projections for the penetration of hydrogen vehicles in the Portuguese market, considering a maximum penetration of 22% in an optimistic scenario. This was one of the three scenarios considered: one of the others was a pessimistic scenario, that predicted 1.3% of the vehicle fleet to be hydrogen powered, and the third one that considered that hydrogen wouldn't have an expression in this market by 2050 (~0%), a prediction that current trends in the market point to be likely incorrect [3]. The number of fuel cell vehicles in the country will increase significantly in the coming years with the introduction of new models, and with the cost of fuel cells dropping rapidly, with a price reduction of 65% in the last 10 years [75].

2.6.2 Assessment of risks and barriers associated to H2 implementation

Taking into consideration that financial costs are not the only factor in the implementation and that the utilisation of hydrogen as a direct or indirect fuel in heavy road transportation (passengers and freight), this barrier will be greatly focused on this chapter, while still analysing other barriers that are relevant for this study, such as safety and infrastructure.

2.6.2.1 High production costs

One of the greatest barriers the expansion of hydrogen has faced is its price of production. Most significantly this is a problem of green hydrogen as its technology is still in maturing phase, and as such its production prices are still significantly higher than grey or blue hydrogen. According to the Hydrogen Council (2021) grey hydrogen to cost around 0.7 to 1.15 €/kg to produce and green hydrogen between 3.3 and 4.5 €/kg as of 2020 while others estimates suggest that these values are closer 2 €/kg for grey H_2 an 7 €/kg for green hydrogen [3], [60]. As one could verify, the price varies a lot not only from source to source, but also in terms of range. This can be explained by the fact that the variables included in the prices vary greatly when coupled with different technology or geographical location. For example, the price of natural gas varies significantly from region to region, as producing countries have a lower price per kilogram, and as such, can produce grey hydrogen at a lower price than importing countries. Another aspect that could explain this difference is the fact that different sources consider different parts of the value chain of hydrogen production, opting to include or not the cost of electricity production for green hydrogen in its costs. Although the current price (2022 March) of natural gas methane is unusually high (6 times higher) than the average price of the last 10 years. This makes grey hydrogen more expensive than green hydrogen at the moment.

Green hydrogen production price is expected to drop 60% until 2030, to a possibly 1.5 USD/kg. This depends on a variety of factors, including the reduction of Capex costs, the investment on renewable sources and significant technological improvements [3].

There are however ways of estimating the price of green H_2, such as the one presented in (1).

$$\boldsymbol{H_2 cost}(\text{€}/\boldsymbol{kg}) = \left(\frac{\boldsymbol{ELECTR}}{\mathbf{1000}} + \frac{\boldsymbol{CPX}}{\mathbf{10}} \times \frac{\mathbf{1}}{\boldsymbol{FLH}}\right) \times \boldsymbol{\varepsilon} \qquad (1)$$

In this case ELECTR is the cost of renewable energy €/MWh, CPX is the electrolyser CAPEX €/kW, FLH is the operational time of the electrolyser in hours and ε the electrolyser power consumption kWh/kg.

Influencing the costs also is the costs of electrolysers: as of 2020 the Hydrogen council estimated that electrolyser systems cost to be around 1200USD/kg which makes it a considerable investment. However, as this is a technology that is still in development, these costs are expected to drop significantly in the next year as this technology matures [3].

As an emerging technology, hydrogen faces numerous barriers to a successful and widespread implementation in the market. These barriers have been continuously identified by different authors over the years, and while some have been reduced due to technology maturing, new legislations and other factors, others have remained relevant throughout the years. While some of the studies concerning this issue tend to have a global perspective on the existing barriers, others focus more in either the technological aspects or social aspects.

Manuela Ingaldi et al (2020) focused on the social aspect of the question and used a model where H_2 barriers were divided in three different categories: Mental, Social and Economic (see Figure 18). Main results of the study showed there was a general lack of information about hydrogen, with most people being unaware of the safety levels, storage capabilities and the concept of hydrogen as an energy source. Other results, show there is lack of availability of hydrogen powered cars and refuelling stations, as respondents didn't see the technology as available, and that it was not financially beneficial to use.

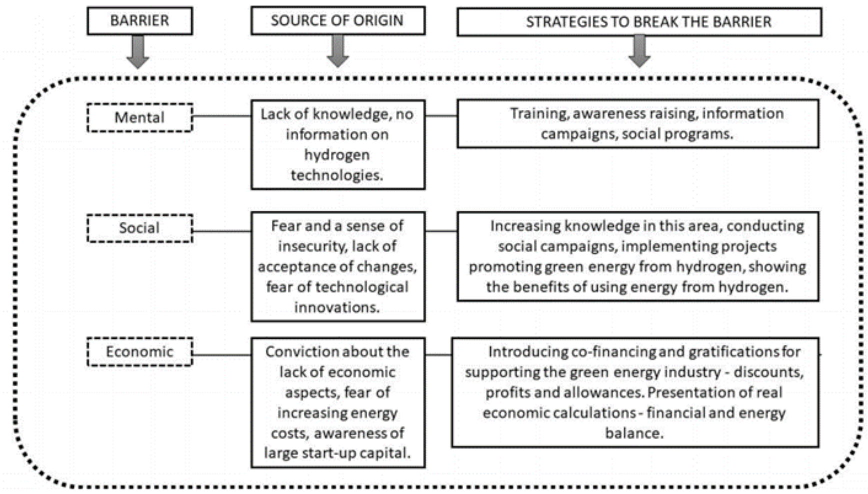


Figure 18: Barriers to the implementation of H_2 technologies and how to combat them [58]

Other authors, such as Cesar Delgado(2012), focused more on the technical and political barriers, and reached the conclusion that there was a need for more agents investing in H_2 in order to unlock other possibilities in hydrogen investment and development [76].

In his study about drivers and barriers of FCEV and FCEB (fuel cell electric buses) in Germany, Trencher et al (2021) [59] takes a different approach by enquiring only experts in hydrogen technologies, about the factors hindering and pushing hydrogen as a technology for the future in transport [59]. He classified the different factors in four different categories: supply, Infrastructure, demand and institutional, and then, he computed the average of several answers to understand what was considered a barrier and a driver.

In the supply side, major barriers identified were the costs of producing vehicles, current and future supply capacity, along with the lack of personnel or networks maintenance. In terms of infrastructure barriers, the authors found it to be the area where most barriers were considered to exist, mainly in costs of fuel and infrastructures, availability of HRS and most importantly profitability. The author noted that there was a clear lack of profitability of HRS stations in Germany, with around 11 FCEV per station at this moment, making it harder to justify the planned expansions of the HRS grid in the country. However, the scenario for FCEB was much more positive since they are operated in fleets and as such HRS have a much greater utilization rate.

In summary, most analysis showed that there are still various barriers hindering the implementation of hydrogen technologies and FCEV. For instance, the generalized lack of knowledge by the public, and the insecurities about the general safety of hydrogen technologies were pointed as the main social barriers. These can be eliminated or reduced, via training, information, social campaigns promoting green hydrogen, which could improve the level of knowledge and trust the public has about hydrogen. Another great barrier is the lack of HRS available in the EU to support the growth of a FCEV fleet, as most people don't see the technology available to them, except for a few regions in Germany, Netherlands, and France. As HRS are quite expensive to operate, government funding, and favourable tax policies will be required to combat this. Finally, almost every study considered the cost to be the biggest barrier, with both vehicle cost and fuel costs considered to be a major downside to the adoption of the technology. However, as hydrogen as a technology is still in a development phase, one can expect that in coming years costs decrease significantly, as both fuel and vehicles will be produced more efficiently with the evolution of the technology.

2.6.2.2 Hydrogen Safety

Hydrogen safety is a topic that brings concern to a lot of people, including possible investors, users, and workers. According to Moradi et al.(2019) [22], hydrogen has a high level of public concern, due to accidents like the Hindenburg disaster in 1937 and more recently the hydrogen explosion in the Fukushima nuclear plant (2011). Therefore, they believe that even minor accidents in the future, for example in fuel stations or storage facilities, might hinder its development and acceptance in the market. Thus, having safe and reliable operations of hydrogen infrastructures is considered key in the next years of implementation. Previous studies that approached hydrogen acceptance found that the implementation of the charging posts of electric vehicles could influence positively that of HRSs. According to Silva et al. (2014), the growing acceptance of EV charging points might facilitate the introduction of infrastructures for hydrogen refuelling, as it demonstrates people's ability to adapt to new technologies and systems

[77]. An example of how much the use of hydrogen concerns people is the Navibus H_2 project in Nantes, where a small navette ship powered only by H_2 serves as a means of transportation between two neighbourhoods [78], where in an enquiry resulting from the project implementation, 35% of the respondents expressed fear of explosion of the possible storage tanks near the pier. This shows that a large portion of people still fear this technology and associate it with danger and hazards.

One of the negative aspects of hydrogen is the fact that it has a colourless flame [79], [80], which means that it is considerably harder to spot fire accidents. Although this type of accidents is rare, there are still some occurrences that demonstrate this technology is still maturing and evolving in what concerns safety, such as the 2019 fire at Sandvika HRS [81], where a leak in the high pressure storage system was reported.

Due to this aspect it is indispensable to include sensors in vehicles and storage units to detect any possible leaks [79].

Another important safety aspect of hydrogen is the embrittlement of materials. As hydrogen molecules are very small, leakage trough materials and corrosion are important factors that must be addressed with the right choice of metals for pipes and storage units [80]. The embrittlement is caused by the appearance of cracks, initiated by the combination of hydrogen diffusion and residual stresses [82], [83]. That said, several studies on the effects of hydrogen on steel pipes have shown that embrittlement is a current concern. These studies , such as the one of Abdulah (2005), Hardie et al. (2006), Nanninga et al.(2012) on the embrittlement of carbon steel, stainless stell and nickel alloy, have concluded that hydrogen embrittlement increases with two factors, which are pressure and alloy strength [84]–[86]. Therefore, the right materials to store and transport hydrogen are chosen in order to reduce the probability of embrittlement [82]. For example, one way to solve this problem is to use other materials, less likely to suffer such damage, such as Fiber Reinforced Polymers (FRP) which can last up to 50 years of service and pressures up to 170 bar [22].

In terms of dispersion, hydrogen has a density of 0,0838 kg/m^3 while air has a density of 1,205 kg/m^3, at normal temperature and pressure conditions (NTP), meaning hydrogen it is 14,5 times lighter than air [87] and therefore, in case of a leak, it will rise and disperse rapidly in an open environment [80]. H_2 is the most buoyant gas of the four options, and around 57 times lighter than petrol vapour, the heaviest. This is a considerable safety advantage, as it will disperse rapidly in the air in case of a release, contrary to what happens to petrol vapour and propane, which will stay close to the ground due to being denser than the air. However, it must be taken into consideration that when hydrogen is stored in cryogenic temperatures (<-73 ºC) the same effects of buoyancy do not apply, and as saturated hydrogen vapour is heavier than the air, it will therefore remain on the ground before temperature increases [88].

Vladimir Molkov (2012) in his book, “Fundamentals of Hydrogen Safety Engineering I”[88] includes an analysis to hydrogen fire and explosion indices, that can be analysed in Table 7.

Table 7 : Comparison of fire and explosion indices between several fuels [88]

Fuel	Flashpoint (ºC)	Auto-ignition Temperature (ºC)	Flammability range (%vol)	Maximum pressure of deflagration (Kpa)	Minimum Ignition Energy (mj)
Hydrogen	<-253	510	4.-75	730	0.017
Methane	-188	537	5.28-15	706	0.28
Propane	-96	470	2.2-9.6	843	0.25
Gasoline	34	230-480	0.79-8.1	-	0.23-0.46
Diesel	37-110	210-370	0.6-6.5	-	-
Methanol	6	385	6-36.5	620	0.14

As it can be verified in Table 7, hydrogen has the widest flammability range of all fuels, meaning it can be ignited if its concentration in the air is between those values. Moreover, as the optimal combustion condition is a 29% hydrogen-to-air ratio [87], and hydrogen has a very small Minimum Ignition Energy, a small spark may be enough to ignite it. Therefore, in order to maintain safety it is of extreme importance that possible ignition sources are removed or isolated, as even small aspects such as lighting near vent stacks, overheating equipment, electrostatics discharges and other small aspects may ignite it [22], [88], [89].

Auto-ignition is also considerably high for hydrogen (510 ºC) especially when compared with other fuels. This means that it is unlikely for heat to ignite hydrogen mixed with air, contrary to gasoline, where this situation is possibility, due to its low auto-ignition temperature [90].

In Table 8, values for the octane number for several fuels are presented. The octane number, or performance of hydrocarbon, is a measure of resistance to knock in ICE, that is, resistance to auto-ignition during compression. In this case the higher the octane number, the higher the resistance to auto-ignition. Comparing with other fuels hydrogen has the highest-octane number, and therefore is more resistant to auto-ignition than other fuels. That said, it is important to refer these values are not relevant for fuel cell vehicles, as it only applies in ICE vehicles [90]. However, it still demonstrates that hydrogen is in fact a safe fuel when compressed which might provide useful when refuelling, transporting, and handling it.

Table 8: Octane number comparison between different fuels [90]

Fuel	Octane Number
Hydrogen	130+ (lean burn)
Methane	125
Propane	105
Octane	100
Gasoline	87
Diesel	30

Although the public might, in general, associate hydrogen with explosions and disasters, this idea is not actually correct, as safety is one of the positives arguments for its use. For instance, the idea that Hydrogen explodes when in contact with oxygen and heat is wrong, as it requires a set of specific conditions for explosions to occur. In fact, only when it is reaches a certain level of confinement and dispersion associated with the presence of oxygen and heat there may be reunited the conditions for such an accident

Although there are some safety concerns related to the use of hydrogen, it is important to understand that current technological advances and proper regulation makes hydrogen as safe to use as any other fuel. Measures like proper ventilation, highly sensible leakage sensors, choosing embrittlement resistant materials and defining safety regulations to ensure the safety in using hydrogen are aspects industry stakeholders have taken into consideration to reduce as much as possible the risk of accidents [91].

FCEV manufacturers also acknowledge that people are worried about the safety levels of their vehicles, and as such, have conducted several marketing campaigns and strategies to help them understand that hydrogen vehicles are indeed safe. For example, Toyota states that their multi-layered hydrogen tanks for vehicles are able to withstand a bullet shot from close range [92]. Renault, on a small article, states that its FCEVs have a system that dilutes and disperses hydrogen stored in the vehicle in less than a minute, in an effort to demonstrate that their hydrogen vehicles are as safe to operate as any other fuel type [93]. Although these measures might seem small or insufficient, they show that manufacturers take seriously customers insecurity towards FCEV and are willing to change their perception on the technology.

2.6.2.3 Infrastructure

One of the major challenges in adopting hydrogen powered vehicles is creating the necessary infrastructure to accommodate hydrogen. Since hydrogen is very different from any other fuel in use before, being made of very small molecules and lighter than air [23] developing the necessary technology to provide adequate, efficient, and safe refuelling's is a great challenge for manufacturers. HRS are technologically complex and use a variety of components and materials that are specific to hydrogen handling, with many of those still in a development phase.

In Figure 19, a simplified scheme of a HRS is presented, where main components are included.

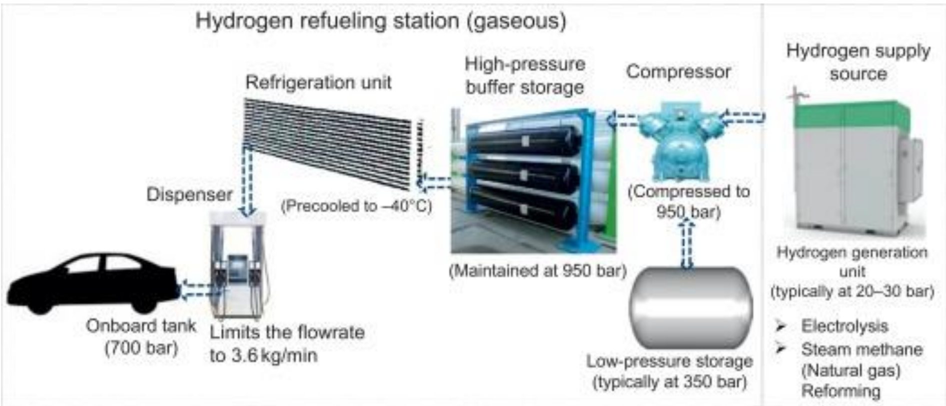


Figure 19: HRS diagram of components [94]

2.7 Assessment of advantages and motivators associated to H_2 implementation

There are many positive points to be made about the implementation of hydrogen. For instance, the fact that hydrogen can be produced using only clean energy and water and that once consumed it has nearly zero emissions [56], is probably one of the strongest points for its investment. However, other factors such as the energy storage capabilities and the wide range of applicability will also be analysed in the chapter.

A clean fuel produced from clean sources

As analysed in chapter 2.5.1, it is possible to produce hydrogen using the water electrolysis technique, meaning that only water and electricity are required to produce H_2. Moreover, the fact that it produces a negligible quantity of emissions when consumed in a fuel cell is a considerable advantage when compared to other fuel options, that are emission heavy, either in production, consumption, or both. In a moment when Europe and Portugal have taken a decisive shift towards decarbonization and sustainability, hydrogen presents itself as a decarbonization opportunity, that could significantly reduce global emissions in the future and help achieve emissions goals.

2.7.1.1 Hydrogen as a Battery

One to the great advantages associated with the production of H_2 is that one can convert energy into hydrogen, meaning that the production and storage of H_2 can be viewed as of storing energy, comparable to how a battery works. This process is called Power to Gas, or PtG. The power to gas process is used to convert the surplus power in the grid into H_2 via water electrolysis or even to convert the H_2 into methane, using CO and CO_2 (Figure 20).

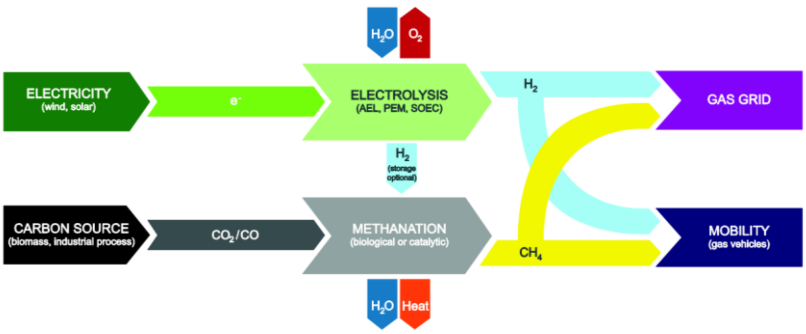


Figure 20 : Power to Gas process chain [64]

This aspect is of great importance, as it allows for the utilization of excess energy in the grid to be stored, instead of going to waste or being exported, it can be used during peak hours, when consumption is higher. As about 60% of all electricity produced in Portugal comes from renewable sources, there is a high variability on the supply side, with wind, solar and hydropower sources being heavily reliant on the weather. Figure 21 presents the production versus demand of electricity for the 25 of Mars 2022, according to the Portuguese national electricity grid manager REN [95], representing the supply of energy by source. The dark line represents the demand, the dark blue (hydropower), green (wind power), yellow (solar), grey (natural gas) and orange (imported energy).

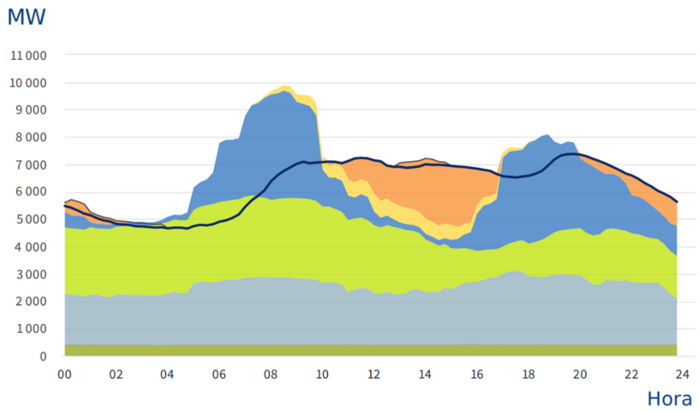


Figure 21: Energy production vs consumption on the 25.03.2022 in Portugal [95]

As it can be verified, there is a significant difference between the demand line, in black, and the supply from the various sources, as there are several hours where the supply surpasses the demand and others where the production is insufficient, and energy must be imported from abroad (orange). One of the best solutions is to store energy either in batteries on through hydropower dams although the second is also quite dependent on the weather or the season. It is in this situation that hydrogen production may also be a solution, by increasing the flexibility of the supply curve and helping to match it with the demand, thus reducing energy waste and improving system efficiency.

Energetic independence from oil producing countries

Another great motivator for the investment in hydrogen is the fact that it can decrease the energetic dependence from oil producing countries. Since it is possible to produce H_2 using only water and electricity 8green hydrogen), it opens the possibility that countries can produce their own needs of fuel for transportation, and reduce greatly oil imports, provided they produce enough electricity to sustain the electrolyser's demand. That said, many European countries have sought to reduce their energetic dependence on other countries, especially oil producing countries, thought investments in renewable energies, emission reducing and improving energetic efficiency of systems, as is the case of Portugal [8], [70].

2.8 Hydrogen Literature Gap

With the rise of popularity of hydrogen as a clean alternative and possible substitute for derivate fuels in the long-term, the number of published articles, papers, dissertations, and scientific papers has seen a very rapid increase in the last years as the need for information regarding the subject rose. In terms of acceptance studies, there are multiple studies that analyse public opinion, knowledge and acceptance towards the technology as described before, [56], [58], [96], [97], with some focusing on specific countries [57], [59], [98] and other on multiple cities or countries [56], [58], [97] while others studies took a different approach by analysing public reaction to implemented hydrogen projects [78]. There were also some studies where the authors chose a different path and decided to analyse the level of acceptance and willingness to invest in companies, targeting industry key stakeholders, that could be major promotors and investors in such technology [55].

Studies evaluating hydrogen from the economical point of view are also frequently published [43], [76], with a significant focus on infrastructure costs and investments [44], [55], [99].

As for Portugal there are relatively few studies regarding hydrogen, mainly focused on an assessment of its life-cycle in the country [100], an economic impact study [101], a technological analysis [69], and a study forecasting the implementation level and its effects long-term [77]. That said, studies regarding hydrogen acceptance in Portugal were found to be very scarce, particularly in what regards acceptance of hydrogen in companies, which is a clear gap in terms of literature analysis. Acceptance studies are an essential point, as people's opinions and views towards a technology define the likelihood of adoption of new technological solutions. Therefore, this study will focus on analysing the acceptance and the implementation possibilities of hydrogen in the Portuguese road transport market, contributing to the literature, and to enrich and complement other studies on the subject. Moreover, since the technology is still in an initial implementation phase and there is still relatively low knowledge of the subject, a decision was made to focus the study on road transport companies, as various studies analysed in the early adopters section (2.4.1) confirmed this type of companies to be the best candidates to be the first adopters and investor of H_2. This analysis was performed through interviews with decision makers in transport companies and also via questionnaires to workers of those companies, therefore providing a complete overview on the likelihood to invest but also acceptance from company workers.

3 METHODOLOGY

The goal of this thesis is to provide an analysis on the potential of hydrogen in Portugal in the road transport sector. In order to achieve these objectives, the analysis was supported by three different elements: A set of interviews targeting decision makers in key companies of the Portuguese transport industry, and a questionnaire that surveyed workers in those companies, who may or do already work with hydrogen directly, were conducted. Furthermore, an economical comparison of the different powertrain options available in the market, through a Total Cost of Ownership (TCO) analysis was performed. The results will provide an overview of the acceptance of hydrogen in the Portuguese transport sector and the economic impacts of investing in the technology for its deployment. An overview of the methodology is presented in Figure 22.

Evaluating the status of the technology, understanding current market tendencies, quantifying risks and impacts of the implementation of hydrogen technologies and understanding companies' interest in this technology was key to fully understand the level of acceptance and engagement of Hydrogen of the Portuguese transport industry and market. With this knowledge, a survey and interview guide were developed specifically for the transport sector industry to address the willingness to accept hydrogen and decision-making process for the future implementation of hydrogen in the transport sector.

The interviews outcome helped provide a solid picture of the challenges that the implementation of hydrogen in the Portuguese Transport industry creates at a top management level. This approach allows for a better perception of social, economic, technical, political, and financial barriers for the future deployment of hydrogen in the transport sector. The questions ranged from sustainability, commitment, knowledge of hydrogen technologies and its application, views of positive and negative sides of its adoption and possibilities of adoption in their companies.

The survey results provided an insight of workers' knowledge, perception, and willingness to accept hydrogen FCEVs, as well as their concerns and past experiences with similar deployments of other technologies. The results enabled to collect information about the willingness to work with this technology, providing an overview on what still needs to be done in terms of awareness and acceptance and serve also as means of informing people of hydrogen technologies and its availability.

In the survey respondents were also enquired if they felt comfortable to have refuelling stations in their workplace, if they would consider buying a hydrogen vehicle in the future, and if they though their company would be ready to invest in hydrogen powered vehicles or not.

Finally, a TCO analysis was performed, providing a solid techno-economic comparison between the different powertrain options available in the market for different ownership periods. Fuel costs, maintenance costs, acquisition costs, insurance, tax policies, depreciation and a series of other factors were used as inputs to provide simulations as close to reality.

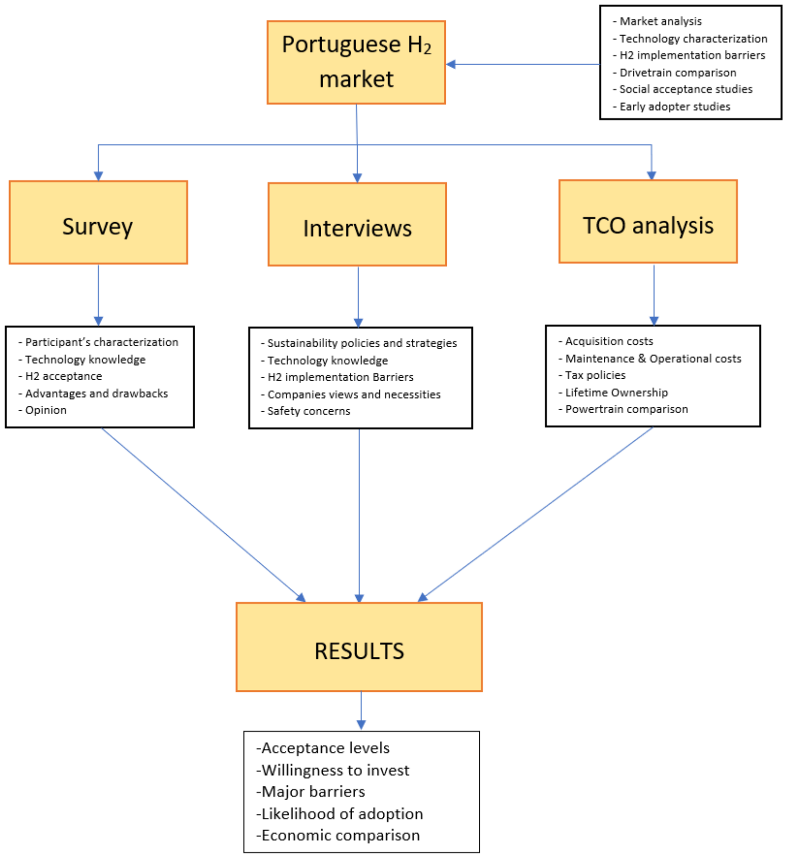


Figure *22: Thesis Methodology chart*

3.1 Case Study

For the purpose of data gathering, eight companies were part of the study, collaborating both in the realization of the interviews to the decision-makers of companies of the Portuguese road transport sector and in the questionnaire of workers of the same companies. The companies were all directly or indirectly linked to the Portuguese transport sector and were chosen based on parameters such as company fleet size, market share, visibility, innovation and funding capabilities and location, which were seen as the main requirements for a company to be a possible early adopter of H_2, as was verified in the early adopters' studies analysed in the literature review. As to the method in which the enquiries and interviews occurred, companies were offered the option to realize both remotely and in person. Most companies opted for remote interactions not only because of practical reasons, but mainly due to the COVID-19 pandemic, which strongly reduced in person interactions. All remote interviews were recorded, apart from three, where this was not possible due to technical problems. Interviews were then transcribed and organized by themes. In Table *9* are presented the companies the collaborated in this study.

Table 9*: Companies interviewed categorized by city and mobility sector, type of interview, type of questionnaire.*

Interview #	Organization	City	Interview	Questionnaire
	National Association of transportation of goods			
1	ANTRAM	Lisboa	Remotely	Remotely
	Passenger transport companies			
2	STCP	Porto	Remotely	Remotely
3	Carris	Lisboa	Remotely	Remotely
4	Cascais Próxima	Cascais	Presencially	Remotely
5	Rodoviária de Lisboa	Lisboa	Remotely	Remotely
	Trucking companies			
6	Patinter	Mangualde	Remotely	Presencially
7	Luís Simões	Loures	Presencially	Remotely
	Infrastruture			
8	PRF Gas solutions	Leiria	Remotely	Remotely

The impacts of COVID-19 in this dissertation were very significant. Contacting companies proved to be a very difficult task, as pandemic measures implicated that many interviews and enquiries had to be conducted remotely reducing the quality of the data obtained and narrowing the channels of communication. Moreover, several of the companies that were targeted by this study didn't respond to appeals for collaboration or didn't respond in time for the processing of data, reducing, unfortunately, the amount of data from which conclusions and results were drawn. However, the pool of data obtained had a satisfactory dimension and was sufficiently diverse to represent the various segments of the market, with the exception of vehicle manufacturers, which unfortunately weren't possible to include.

3.2 Questionnaire

The target public of the questionnaire was defined taking into consideration the objectives of this thesis, which was to evaluate the acceptance levels of hydrogen in the transport industry. Therefore, instead of designing a questionnaire targeting the public, the decision was made to focus on workers of transport and mobility industries, as they are or will be the early adopters of this technology. This included heavy-duty vehicle drivers, mechanics, hydrogen refuelling station employees, vehicle warehouse staff among others. That said there was an effort to include companies from various points of the hydrogen value chain such as equipment manufacturers, fuel producers, passenger vehicle companies, trucking companies and even vehicle manufacturers.

3.2.1 Questionnaire Design

The survey was composed by a total of 28 questions, split into four different sections: participant socio-economic characterization, knowledge on hydrogen technologies, opinion towards H_2 and main advantages/disadvantages of the technology. The questionnaire took on average 6 minutes to fill and started with an introduction text that explained the goal of the study, basic principles of the technology and motivations.

In the first section, respondents' socio-economic characterization consisted in four different questions regarding age, gender, educational level, and environmental consciousness.

The "knowledge about hydrogen technologies" section was focused on understanding the level of knowledge participants had regarding hydrogen and had a total of 9 questions and started with an Initial question that asked if respondents were familiarized with the topic of hydrogen. Questions in this section ranged from the familiarization and association with hydrogen to previous work experiences with the technology, as well with previous formations. A sub-section was made available for those who said that had previously received formation about hydrogen before, in order to assess the information taught, the quality of the formations and its usefulness according to the respondent.

The third section had the objective of analysing the attitude of participants towards H_2 and was composed by 7 questions. In the first questions participants were asked to classify various types of powertrains to indicate how safe they viewed them. A set of questions evaluated the concerns relating to work near an HRS, such as safety, acceptance of the instalment, and level of regulations regarding H_2, which allowed to understand whether participants were comfortable to work with hydrogen or considered it too unsafe. In the final question of the section participants were asked if they agreed with different options of vehicle transportation and other applications of hydrogen.

The last section had 5 questions, and respondents were asked to identify the main advantages and disadvantages of the use hydrogen in transportation. Participants were also asked in a third question to identify the main barriers for the implementation of hydrogen in the Portuguese market, and if they would consider buying a hydrogen car in the future, or for their company.

The quantity and content of the questions to be included in the questionnaire was thoroughly analysed and, the final questions were found to be the ones that were most adequate for the scope of the questionnaire.

Every question was subject of thorough analysis and consideration before integrating the final version of the questionnaire. There was an effort for questions to be as clear and direct as possible, so that the process of filling the questionnaire was as effortless and simple as possible.

3.2.2 Questionnaire format and data analysis

The questionnaire was carried out online via google forms and 109 valid answers were collected between the $16^{th\ of}$ September and 26^{th} November 2021, with only one invalidated answer. In most cases, the survey link was first sent by email to companies and then distributed internally upon requisition, with one exception where it was possible to conduct the questionnaire in person.

Since the goal of the study was to measure the level of acceptance on the transportive market in Portugal, and as such only companies operating in Portuguese territory were chosen for the survey, respondents were likely all Portuguese.

The data was collected and transferred to excel where it was possible to organize and analyse it, creating relevant graphs, tables, and correlate data from different questions when necessary.

The quantity and content of the questions to be included in the questionnaire was thoroughly analysed and, the final questions were found to be the ones that were most adequate for the scope of the questionnaire. It is also important to mention that answers were all anonymous and therefore it was not possible to identify to which company the answers belonged.

3.3 Interviews

The interviews were a fundamental part of this study. While the questionnaire provided an insight on worker's views and opinions towards hydrogen, providing valuable information regarding barriers for the implementation of the technology, the interviews with major companies of the transport sector helped understanding the acceptance of the technology, the willingness to invest in hydrogen related technologies and measure the probability of a successful implementation to occur in Portugal.

As hydrogen is still in an early development stage in Portugal, with very few vehicles and infrastructure available, it became clear it was important to interview companies that had the capability to become early adopters. For this, parameters like company fleet size, market share, visibility, innovation and funding capabilities and location were used to define which companies had an adequate profile.

In total 8 interviews were made during this study including three passenger transportation companies, two freight truck companies, one company that produces and instals hydrogen equipment and a national trucking association. While other companies could be included in this study, the companies in question were identified as the most likely to be early adopters due to the aforementioned reasons. In Table *10* are listed the companies interviewed categorized by sectors, location, company type and date of the interview.

Table 10*: Companies interviewed, categorized by sectors, city, type, and date*

Interview #	Organization	City	Company Type	Date
	National Association of transportation of goods			
1	ANTRAM	Lisboa	Public	17/10/2021
	Passenger transport companies			
2	STCP	Porto	Public	15/10/2021
3	Carris	Lisboa	Public	20/09/2021
4	Cascais Próxima	Cascais	Public	27/09/2021
5	Rodoviária de Lisboa	Lisboa	Private	22/09/2021
	Trucking companies			
6	Patinter	Mangualde	Private	09/10/2021
7	Luís Simões	Loures	Private	03/11/2021
	Infrastruture			
8	PRF Gas solutions	Porto	Private	20/10/2021

A general script for the interviews was also created to improve efficiency of data collection and analysis. The script was composed of 26 open answer questions divided in 4 categories: Company sustainability, hydrogen technology knowledge, hydrogen in the transportation sector and adoption and implementation by the company. The script is available in Annex 2. However, it is important to refer that the script only provided the general guidelines for the interviews, and as such, other questions were asked depending on company and adequacy of such increments, that will be included in the interview analysis. Interviewees were also free to provide any other information or opinions regarding the implementation of FCEVs. Interviews had an average duration of 60 minutes and were made in Portuguese only.

3.4 Hydrogen deployment Total Cost of Ownership analysis (TCO)

While the emergence of new technologies in the automotive market may bring forward several positives in terms of emissions, different power sources among others, it also means more decisions have to be made when the moment to buy a new vehicle comes. The amount of powertrain options, fuel types, accessibility of refuelling/recharging points and future market trends may prove to be a challenge for business owners and private users to fully grasp and understand. As such, it is important to analyse the various costs that are associated with the different powertrains, to balance the advantages and disadvantages each one has, and to understand what the most economic option is, as this remains one of the main deciding factors for vehicles owners. That said, a comparison of the TCO of the different powertrain options available in the market will be made, for buses, trucks and light passenger vehicles for 5 and 12 year ownership periods. Several assumptions were made in the process that are explained in the sections bellow. It is also important to refer that the values used fit the Portuguese market and its tax system. To enrich the analysis, a comparison with the cost per kilometre was also added.

When buying a new vehicle one of the most important decision factors for buyers is how much it costs. No matter what type of vehicle a person buys, it is always a considerable financial effort to buy and own one, with costs usually increasing with size and luxury level. Since it is difficult to compare costs between different vehicles other than its price, it is possible to use the total cost of ownership (or TCO) equation to analyse all the other costs involved such as licensing, maintenance, fuel cost among others, thus allowing for a better comparison between cars with different fuel types from a financial perspective. Therefore this thesis will use the TCO equation utilized by Desreveaux et al(2020), presented in Equation 2 and others such as 3 and 4, to compute and compare the TCO of several heavy duty and light duty vehicles [42].

$$\boldsymbol{TCO = CC - SV + \sum_{i=0}^{n} \left(\frac{AC}{(1+\sigma)^i}\right)} \quad (2)$$

In this case, CC is the capital cost, comprised of cost of vehicles plus the cost of registration, minus tax policy increases or decreases, depending on the fuel type (plus for diesel and less for EV’s for example). SV is salvage value and was calculated using vehicle depreciation $\boldsymbol{A_{dep}}$, the tax policy as well as vehicle costs $\boldsymbol{C_{veh}}$, discount rate $\boldsymbol{\sigma}$ and the number of years until resale $\boldsymbol{n}$, presented in equation 3.

$$\boldsymbol{SV = (1 - A_{dep})(C_{veh} - P_{veh})(1 + \sigma)^{-n}} \quad (3)$$

AC represents the annual costs, which is the sum of energy costs (EC), maintenance costs (C_m) and insurance costs (C_{ins}).

However, after receiving some input from the several companies that were interviewed, the SV formula was simplified to be half of the AC, as these values were found to be much closer to reality than the ones computed using the formula presented

$$\boldsymbol{AC = (EC + C_m + C_{ins})} \quad (4)$$

In essence these are the factors commonly used for TCO estimations of vehicles. There are some other authors, such as Giles L.Bourque et al (2020), that go even further and incorporate other aspects like driving license costs, domestic electric charger and plate licensing, but since these don't affect the TCO in a significant manner, they won't be included in this study [102].

The investment costs associated with the necessary Electric chargers, HRSs and Natural gas refueling stations were not included in this analysis, as they were out of the scope of this work. Furthermore, comparing investments in infrastructure was found to be a complex endeavor, as some of the powertrains compared do already have an implemented grid, such as EV and diesel vehicles, therefore requiring few investments or no investments at all. A future work, analyzing the required investment in infrastructure to implement a HRS in Portugal and comparing the costs with other powertrain options would be a considerable complement to this study.

3.4.1 Assumptions for the calculations

The parameters and prices used were based on the Portuguese market. While some of the values used could be obtained directly, such as electricity and diesel prices, others, such as maintenance values, had to be defined using external inputs and there were some values that were defined as assumptions. (See Table 11)

Diesel, LPG and LNG prices were obtained from the Portuguese general management of Energy and Geology office [103] along with the electricity prices, which I verified using invoices of my house from previous months. As for hydrogen there was a significant difficulty in defining the value at which it would be sold, since there aren´t yet any HRSs open to public use and since the production units of green hydrogen in the country are still under construction and as such there is still very little information regarding the fuel cost. Therefore, for the purpose of this analysis the value of 10 €/kg will be used as an approximation, which was referred by some of the interviewed companies as plausible initial market value.

The maintenance and insurance for buses and trucks, as well as the annual distance values were obtained during the interviews through data shared by some of the interviewed companies. As for light duty passenger vehicles these values were obtained using insurance company's simulations and speaking with car maintenance workshops. The interest rate used was the same used in similar projects [42], [50] and the annual distance was the average distance made in average by in car, according to a local study from ACP [104]. An incentive for the purchasing of vehicles with reduced emissions, such as BEVs and FCEVs was also included in the analysis of light duty passenger vehicles, as the Portuguese government provides an incentive of up to 3000€ [30], [105]. For Trucks and Buses however, it was not possible to confirm the existence of such incentive, nor the value available and therefore the option was made to not include the incentives in the analysis.

Other factors, such as tax costs and exemptions for each powertrain, were excluded from the computation for buses and trucks since it was not possible to gather sufficient data regarding this topic. The "Other taxes Diesel" and "Other taxes LPG" values represent the sum of the Portuguese tax over vehicles (ISV) and circulation tax (IUC) that vehicles in this powertrain category must pay. These values were obtained through official legislation on the internet [106], [107], with IUC and ISV of diesel equal to 340€ and 500€ respectively and the IUC and ISV of LPG equal to 330€ and 200€ respectively. EV's, at this moment, enjoy an exception from these two taxes a due to their contribution towards sustainable mobility. Since hydrogen vehicles have only recently been introduced in Portugal, the legislation isn't still clear on this subject, and as such it was assumed that these vehicles will benefit from the same tax exceptions.

Table 11: Parameters used for the techno-economic calculations of Trucks, Buses and light duty passenger vehicles [42], [50], [104],[106], [107]

Trucks		Buses		Light duty vehicles	
Parameters	Values	Parameters	Values	Parameters	Values
Diesel (€/L)	1,4	Diesel (€/L)	1,4	Diesel (€/L)	1,4
Electricity (€/Kwh)	0,17	Electricity (€/Kwh)	0,17	Electricity (€/Kwh)	0,17
LNG (€/L)	1,11	LNG (€/L)	1,11	LPG (€/L)	0,81
H2 (€/L)	10	H2 (€/L)	10	H2 (€/L)	10
DV maintenance (€)	2000	DV maintenance (€)	1500	DV maintenance (€)	600
EV maintenance (€)	2000	EV maintenance (€)	1500	EV maintenance (€)	500
LNG maintenance (€)	2000	LNG maintenance (€)	1500	LPG maintenance (€)	600
H2 maintenance (€)	2000	H2 maintenance (€)	1500	H2 maintenance (€)	550
DV insurance (€)	1500	DV insurance (€)	1500	DV insurance (€)	700
EV insurance (€)	1500	EV insurance (€)	1500	EV insurance (€)	600
LNG insurance (€)	1500	LNG insurance (€)	1500	LNG insurance (€)	700
H2 insurance (€)	1500	H2 insurance (€)	1500	H2 insurance (€)	600
Interest rate (%)	4,5	Interest rate (%)	4,5	Other taxes Diesel (€)	840
Annual mileage (Km)	120000	Annual mileage (Km)	50000	Other taxes LPG (€)	530
				Interest rate (%)	4,5
				Annual mileage (Km)	9000

3.4.2 TCO for Heavy Duty passenger vehicles

The TCO calculations for Buses were conducted using four different vehicles representing the different powertrains options available in the market:

- Mercedes Benz Citaro – Diesel (Estimated price 200 000 €)
- Caetano Bus eCity Gold– Electric (Estimated price 500 000 €)
- Caetano Bus/Toyota H2.City Gold – FCEB (Estimated price 500 000 €)
- Mercedes Benz Citaro – LNG (Estimated price 220 000 €)

The models representing each powertrain were chosen based on their popularity and number of vehicles on the road in Portugal and were used to collect data on several aspects such as fuel consumption, price, driving range among others. In this case, comparisons were made using only 12 years, as it is unusual for bus companies to sell vehicles before this time and 12 years is commonly considered the average lifetime of a heavy-duty passenger vehicle [108].

3.4.3 TCO for Heavy Duty vehicles

The economic comparison for heavy duty vehicles, as with heavy duty passenger vehicles, was conducted analysing four different models sold in Portugal representing four different powertrains available in the Portuguese market:

- Renault Truck T – Diesel (Estimated price 70 000 €)
- Volvo FH Electric (Estimated price 216 000 €)
- Nikola – FCET (Estimated price 230 000 €)
- Volvo FH LNG (Estimated price 90 000 €)

The diesel and the LNG models were chosen because of their popularity and number of vehicles circulating in Portugal. As for electric trucks, there are still very few circulating in Portuguese roads, and as such, the Volvo FH Electric was considered as one of the few being sold at this moment. Regarding hydrogen trucks, there are no FCETs operating in Portugal at this moment, and with none being sold, commercially the Nikola FCET was chosen as it had the most complete information that could be found.

3.4.4 TCO for passenger vehicles

For the passenger vehicles analysis, four different options were considered, a Tesla Model 3 as an Electric vehicle, a Volkswagen Golf as a Diesel option, a Dacia Duster representing GPL cars and lastly a Toyota Mirai II as a Hydrogen FCEV. In the choice of vehicles, it was intended that all options were in the same price range and vehicle class, however that was not always possible as there isn’t an LPG option in the market that has a similar cost to the other alternatives. The simulation was dimensioned for first-hand ownerships of 5 years and 12 years respectively. While five years represents a relatively small period for owning a car, a twelve-year ownership was also used as a lifetime ownership calculation.

4 RESULTS AND DISCUSSION

4.1 Survey analysis

4.1.1 Participant characterization

Participant characterization was focused on general data about respondents, such as age, gender, and level of studies. In Table *12*, participant's age and corresponding gender are presented.

Table 12*: Participant's gender and corresponding age*

Gender	18-25	25-40	40-60	+60	Total (%)
Female	0,9	2,7	8,0	0,0	11,6
Male	1,8	33,0	48,2	4,5	87,5
I prefer not to say	0,0	0,0	0,9	0,0	0,9
Total (%)	2,7	35,7	57,1	4,5	100,0

As it can be seen, most of the respondents were male, which is common in this market. In terms of age, the majority were between 40 and 60 years old, which indicates a high level of career longevity. The second most common age was 25-40.

As one could verify, more than half of the participants (57/112) had a level of studies higher than high school (12^{th} grade), of which around 37 % had a degree. On the other hand, 26 % of the participants had only completed the 9^{th} grade or lower. This is not uncommon, as this market provides job opportunities that don't require a high level of educational studies from the participants. (Table *13*)

Table 13*: Participant's level of studies*

Level of studies	%
Completed 4th grade	1,8
Completed 6th grade	7,1
Completed 9th grade	17,0
Completed Highschool	22,3
Degree	36,6
Degree Pre-Bologne	0,9
Doctorate	0,9
Master	8,0
Tecnical/Professional/Artistic course	5,4
Total	**100**

In order to evaluate the level of consciousness of the respondents about environmental issues and forms of combating them, participants were asked to rate by level of agreement four different statements on this subject.

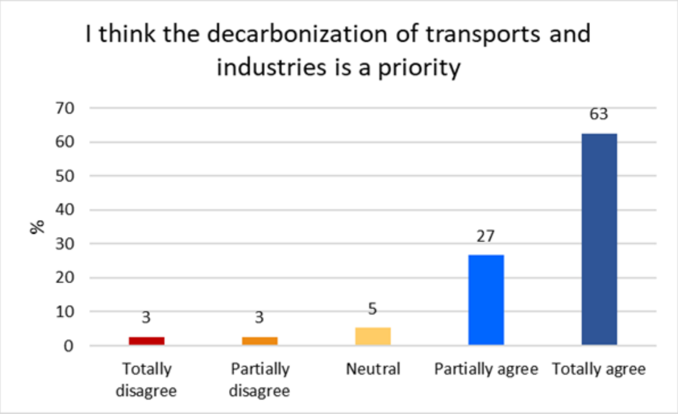


Figure 24: Decarbonization of transport and industry

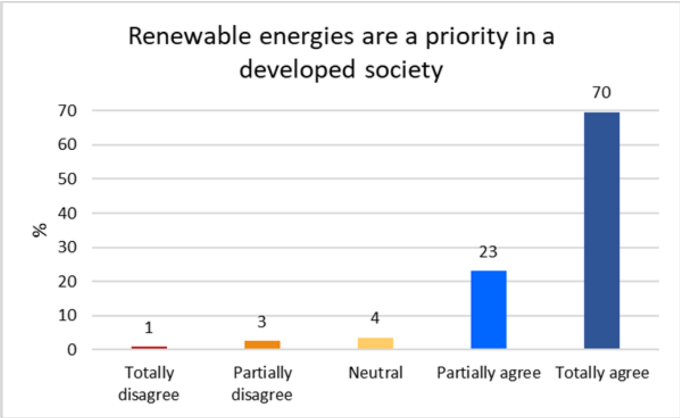


Figure 23: Priority of renewable energies

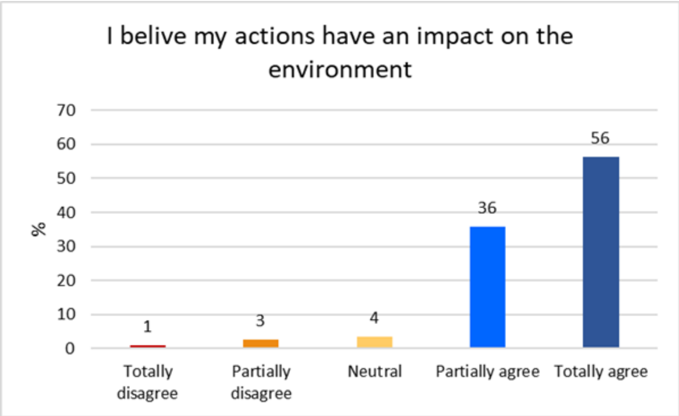


Figure 26: Personal impact on the environment

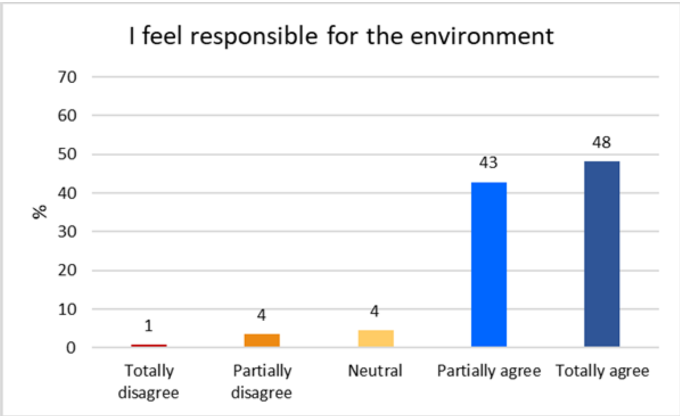


Figure 25: Responsibility for the environment

Responses demonstrate that participants understand the importance of preserving the environment and that their contribution is not negligible (Figure 26). Respondents recognize that decarbonizing transports and industries, with 63% stating they totally agree with this statement while 70% also fully agreed that investing in renewable energies is a priority in our society. (Figure 23). Most participants also considered that their actions have an impact in the environment with 92% saying they agree or totally agree with the statement and when asked if they felt responsible for the environment results were very similar with the difference that participants were more divided between “Partially agree” and “Totally agree” with around 43% and 48% respectively (Figure 26).

This suggests that while people understand their role in promoting a sustainable environment, they might not necessarily feel fully responsible for it, as their actions only have a limited impact.

4.1.2 Knowledge about hydrogen

To analyse the knowledge about hydrogen that each respondent possessed, the question: “Are you familiarized with the topic of hydrogen?” was made, and the results correlated with the level of studies of each respondent. In this way it was possible to verify not only the general knowledge about the subject, but also to evaluate if the level of studies influences the level of knowledge of hydrogen. Results can be observed in Figure 27 (1- Unfamiliarized;5 - very familiarized):

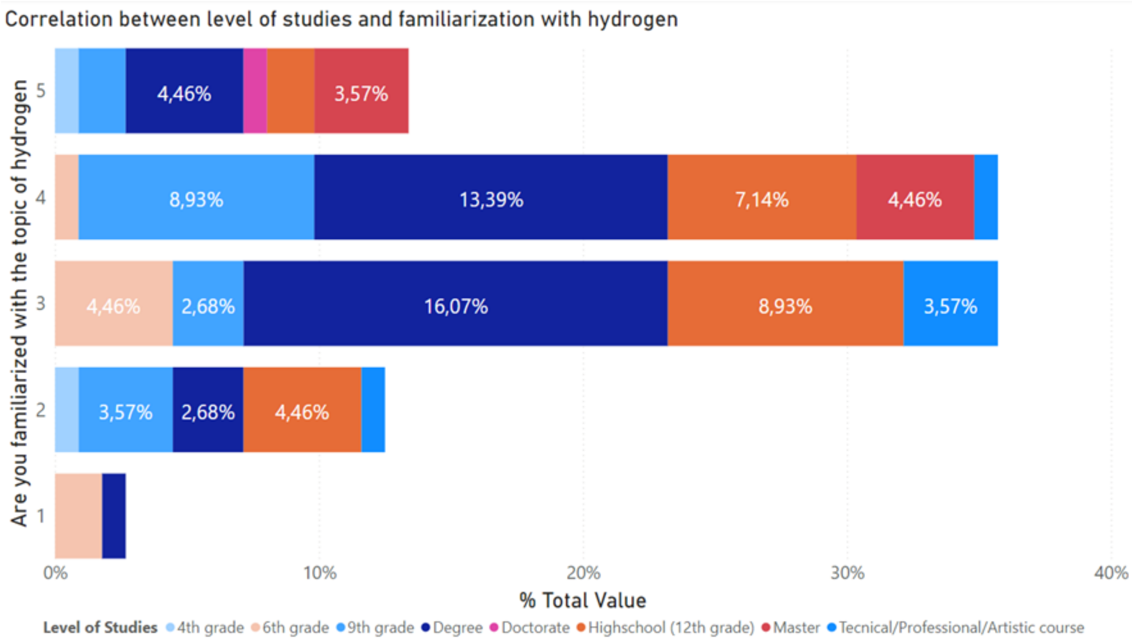


Figure *27: Question number 5 and 6: Are you familiarized with the topic of hydrogen/ Level of studies?*

As it can be seen, most respondents consider themselves to be somewhat familiarized to this topic, with more than 35% of the respondents considering themselves familiarized with H_2 (option 4) and around 13% stating they were very familiarized (option 5). This shows that while hydrogen is still a new technology, the media attention it has received in recent years has translated into a wider recognition of the technology’s existence, in tandem with a higher knowledge level of hydrogen. It is also important to refer that since transport companies are often responsible for the introduction of new technologies and alternatives in the market, such as natural gas for vehicles (GNV) in buses for example, the acknowledgement of newer fuels and alternatives tends to be higher in such companies.

Regarding the question: “In what context(s) have you heard of usage of hydrogen?”, results as displayed in Figure 28.

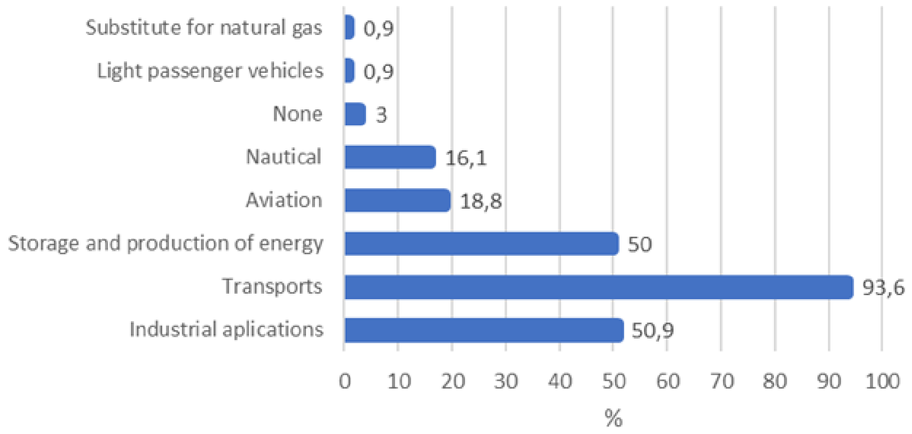


Figure *28: Question number 7: In what context(s) have you heard of usage of hydrogen?*

As shown, the most chosen option was transport, with more than 90% of the respondents having heard of hydrogen as a possibility in terms of mobility. Further analysis shows that more than 40 % have heard of its use in the industry, followed by energy storage and production and lastly aviation and nautical uses. Although transportation was the most recognized option, the fact that almost 60% of all respondents didn't recognize its industrial capabilities was unexpected and may indicate a low level of knowledge about hydrogen of a significant portion of the respondents.

Results to the question: "Do you consider hydrogen to be a clean fuel?" indicate that almost 75% of the respondents see hydrogen as a clean fuel, and only a small percentage disagrees. This is of great importance, as the idea that hydrogen is a clean fuel contributes strongly to a positive regard of the technology by the public, and even more so in a time where sustainability is so relevant.

In the following question, participants were asked: "What characteristics do you link with hydrogen in transportation, industry, and services?" and were presented with a selection of multiple-choice answers, as can be seen in Figure 29.

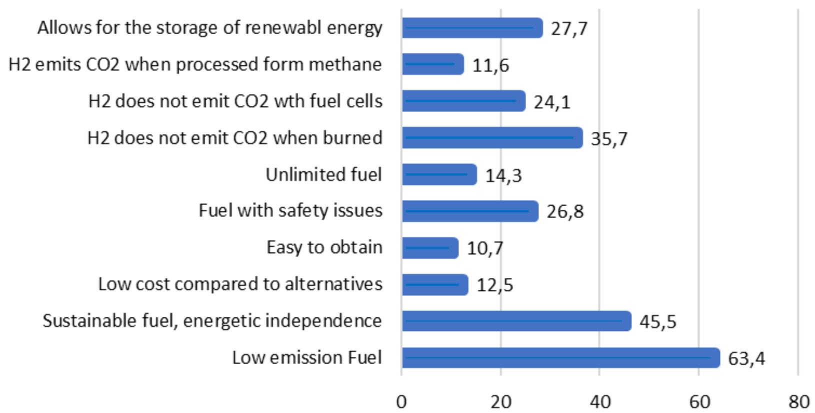


Figure *29: Question number 9: What characteristic do you link with hydrogen in transportation, industry, and services?*

Indeed, most respondents agree that hydrogen is a low emission fuel, with over 65% selecting this option. Similarly, around 50% view it as a sustainable fuel that will increase energetic independence, while more than 30% say they recognize the possibilities in energy storage. This shows that a significant portion of respondents are aware of the potential hydrogen has in terms of energetic storage and independence. Further analysis shows that safety is seen by around a third of respondents as potential hazardous, and then around the same percentage see it as not emitting CO_2.

Participants were also enquired if Portugal has an implemented hydrogen distribution infrastructure. Most respondents agree that there isn't an implemented distribution infrastructure in the country yet, with over 20% saying they don't know if that is the case or not. This indicates that most of the participants have at least a basic understanding of what hydrogen is, as they were able to confirm the inexistence of a distribution infrastructure.

In question 11 the respondents were asked if they worked or had worked with hydrogen before. Most respondents had never worked with hydrogen before. However, a quarter of respondents answered positively to this question, which is a clear indicator of the growing role of hydrogen in Portugal and can be expected as some of the companies that were targeted in this enquiry had hydrogen specific business plans or already used it. Another important conclusion was that 1 in each 3 respondents that said they never worked with hydrogen before but showed willingness to work with it in the future ("No, but I would like to"). This demonstrates that people are interested, and in some cases eager to know and work with this new technology.

In case of affirmative response, participants were asked what the context of their involvement with hydrogen technologies was, through an open answer question, with around 23 %, or 20 participants being eligible to answer. Main answers were the following:

- Public Transportation/Bus driver (50 % of answers)
- Infrastructure production and management (25% of answers)
- Investigation in the transportation sector (25% of answers)

The most chosen option was Bus driver.

In a next step, respondents were asked if they felt the necessity of having training about hydrogen at its possible applications. Results demonstrated that ~75% of participants feel they need more information about hydrogen and therefore regard training in a positive manner. The feedback from the enquiries, especially from the ones collected personally, also demonstrated that participants acknowledge that hydrogen may well become a widely used solution, and as such are willing to learn more about the technology and understand the importance of training.

In the next question respondents were asked if they had any training about hydrogen before or not. Results show that most participants never had any training about hydrogen and its uses. With only ~15% of respondents stating they have had formations regarding H_2 before, this result is a reflex of the early stage of implementation the technology is in Portugal, as many of the companies that are view as possible early adopters of hydrogen, aren't yet investing in training. However, one might expect this situation to change, as the appearance of hydrogen related projects in the future in such companies will certainly be accompanied by adequate training.

The following subsection was comprised of questions to participants that had trainings before, with the goal of evaluating the utility and contents of such trainings.

4.1.3 Hydrogen Training

In this subsection, participants that answered positively about having had training before were asked a set of questions regarding the nature and content of such trainings, with the goal of evaluating the quality and usefulness.

In the first question, respondents were asked about what they learned in their training, and were given the following options, being allowed to choose more than one. Results are presented in Figure 30.

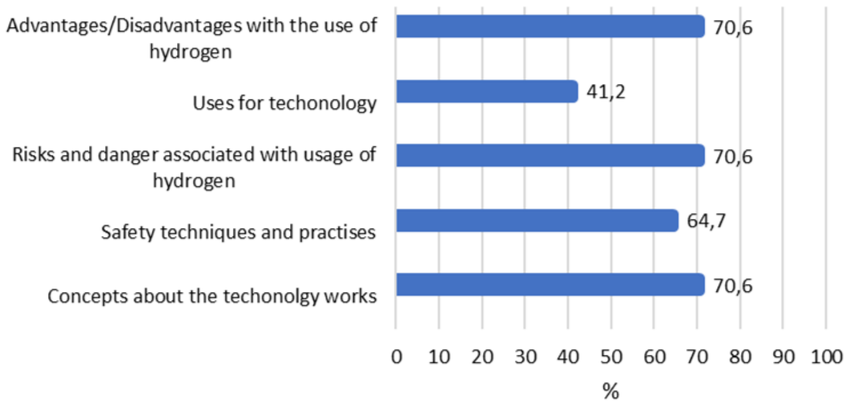


Figure *30: Question 15: What have you learned in your trainings about hydrogen and its uses?*

Respondents were also given the option to add another answer if they felt it wasn't represented in the option above. Most respondents chose all options, except for uses for the technology, which was a less focused topic.

In the next question, participants were asked if they considered the knowledge obtained in their trainings useful, in which case they were asked to rate the usefulness in a rank from 1 (Not Useful) to 5 (Very useful). As it can be seen (Figure 31), most respondents agree that trainings were useful for their work. This shows that trainings about hydrogen have a positive impact on the working capabilities of workers in the transportation sector and provide them with tools they could use afterwards.

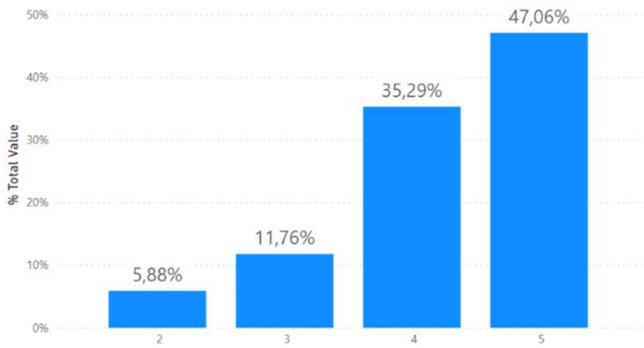


Figure *31: Question 16: Do you consider useful the knowledge obtained in such trainings?*

In the last question of this subsection participants were asked if the trainings had altered their perception about hydrogen and its technologies, therefore providing a measure usefulness of the trainings according to the respondents. Most of the participants that had trainings about hydrogen felt their perception on the technology changed. However, a significant portion (~32%) considered it didn't change their previous perception on the subject.

Further analysis showed, by correlation of date with the previous question, as can be seen in Figure 32, that 50% of those responded negatively(~32%), found the knowledge they obtained useful, indicating that if training didn't affect their view about the technology it was because in most cases, they already had that knowledge before. Therefore, it is fair to conclude that trainings are in fact very useful for workers and recognized by them as a necessity to understand the technology, its capabilities and safety requirements.

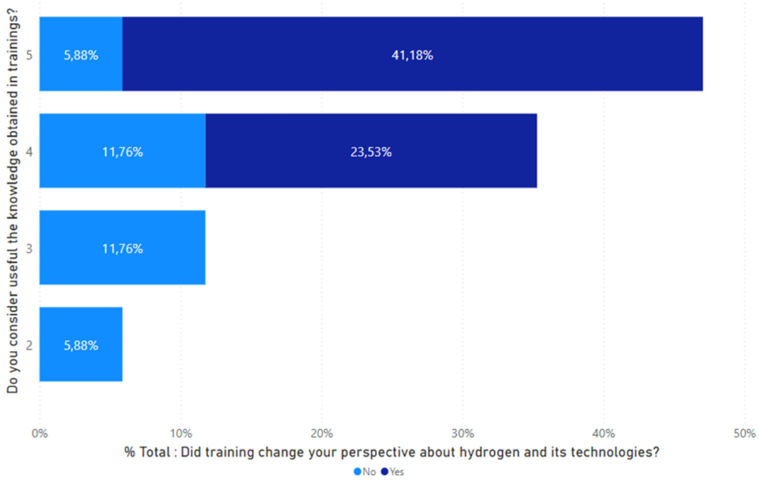


Figure *32: Correlation between usefulness of hydrogen trainings and the effects of the trainings*

4.1.4 Attitude towards hydrogen technologies

In this section, questions were focused on providing a general picture of the views and opinions participants had about H_2 technologies, with a focus on safety, comparisons, and implementation situations.

In a first step, participants were asked to rate a range of fuels and power sources for vehicles in terms of the level of safety they attribute to them. Results are presented in Table 14.

Table 14 : Question 18: Rate the level of safety you attribute to each powertrain option

Level of Safety	H2	Petrol	Diesel	LPG	LNG	Lithium Bateries	Etanol	
Very Unsafe	2,75	6,42	3,64	6,36	2,94	4,76	9,35	Percentage %
Unsafe	11,01	17,43	13,64	23,64	18,63	18,10	22,43	
Neutral	42,20	30,28	29,09	25,45	31,37	35,24	42,06	
Safe	38,53	40,37	41,82	40,91	42,16	37,14	22,43	
Very safe	5,50	5,50	11,82	3,64	4,90	4,76	3,74	
% Total	100	100	100	100	100	100	100	

As it can be verified, opinions were divided in this matter, with answers split into all five options for all powertrains. On average, LPG and Ethanol were considered the less safe options, with around 30% in both cases saying these options were unsafe and very unsafe, while Lithium batteries, Diesel and H_2 were considered the safest, with approximately 42%, 53% and 44% considering the technologies safe or very safe, respectively. Further analysis showed that in categories where participants could be less informed such as the case with hydrogen and ethanol, there was a tendency for people to choose the neutral option (42,20% and 42,06%), which may point towards a general lack of knowledge about these technologies, particularly in terms of safety.

In the next step, respondents were asked if they were aware of the implementation of hydrogen in their workspace or not.

While most respondents answered yes or no, 20,54% indicated they weren't aware if hydrogen was implemented in their work which indicates a lack of awareness about the technology. Furthermore, around 49% of all participants said there weren't any hydrogen infrastructures implemented in their workspace, underlining the fact that most companies haven't yet implement hydrogen.

The next question asked if participants considered to be safer charging a battery of an EV via high Voltage, with the associated risk of electrocution, or filling tank through pressurized hydrogen, with the risk of explosion or flames associated. As it can be verified in Figure 33, most respondents, 54,46% answered that they didn't know or didn't answer, indicating they that they lacked the information to formulate an opinion on the matter. On the other hand, the results also show that around 33% consider filling a tank through pressurized hydrogen gas safer, against 12% who consider charging an EV battery via high voltage a safer option. This result could be considered unexpected, as the electric technology has been implemented for more than a century, as is used nowadays in almost every possible application, whereas the hydrogen technology has seen very limited use in transport. From this, one might conclude that a significant portion of participants, consider hydrogen as at least reasonably safe, as was confirmed in Table 14.

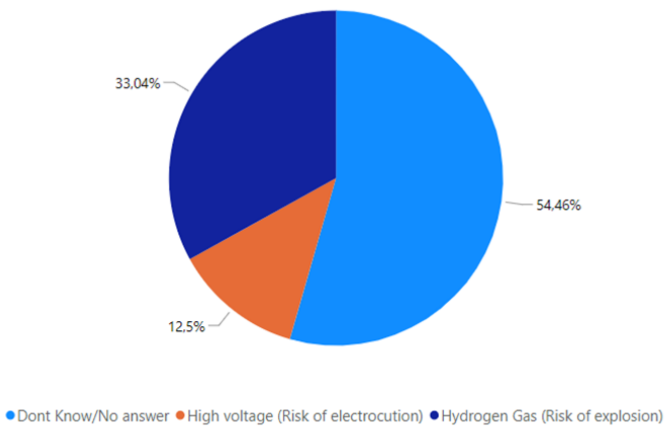


Figure *33: Question 20: Which do you think is safer: high voltage charging (EVs) or high-pressure hydrogen refuelling (FCEVs)?*

In the following question, respondents were asked if there are enough safety regulations at this moment so that hydrogen could be used safely. Using a scale from 1 to 5, with 1, insufficient regulation and 5 sufficient regulations, participants rated the affirmation, with results are visible in Figure 34.

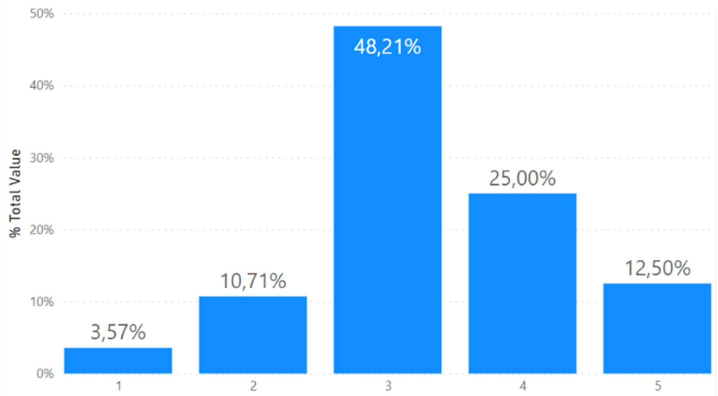


Figure *34: Question 21: I think there are enough safety regulations so that hydrogen can be used without great risks*

As it is possible to see in Figure 34, 47,5% of all answers have the focus on options 4 or 5, meaning that the regulations and norms in place were sufficient and adequate for a safe use of H_2. Further analysis shows that the most chosen option was number 3, which might indicate that people are unsure about the adequacy of the regulations regarding this technology.

The next step, respondents were questioned if the idea of having hydrogen stored in their workplace worried them. Options ranged from a scale of 1 (It doesn't worry me) to 5 (I am very concerned) with results in display in Figure 35.

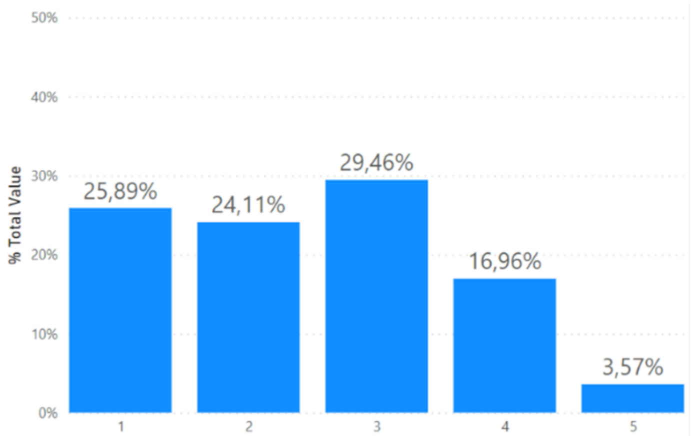


Figure *35: Question 22: Does the idea of having hydrogen stored in your workplace worry you?*

As it can be verified, most respondents say they are worried about HRS safety in various degrees. Although the average is lower than 3, with 50% choosing either 1 or 2, meaning most aren't much worried about this, it does still indicate that 1 in 5 does not consider hydrogen as a safe fuel (options 4 and 5).

Question 23 asked participants if they would accept the installation of an HRS in their workplace or company. Most people said responded positively to this question, with a small portion being unsure about this question.

The fact that no one fully rejected the idea of having an HRS is a demonstration that even if some people consider hydrogen as unsafe (Table 14) or aren't comfortable with the idea of having hydrogen stored in their workplace (Figure 35) they trust safety measures will be enough to ensure their safety, and therefore are, for the most part, willing to accept an HRS in their workplace.

4.1.5 Advantages and disadvantages of hydrogen

The purpose of this section was to understand the advantages and disadvantages of hydrogen from the participants view.

The first question asked what the main disadvantages were. Respondents were given four different suggestions, while they could choose more than one option. The option to add a personalized answer was also included. Results are presented in Figure 36.

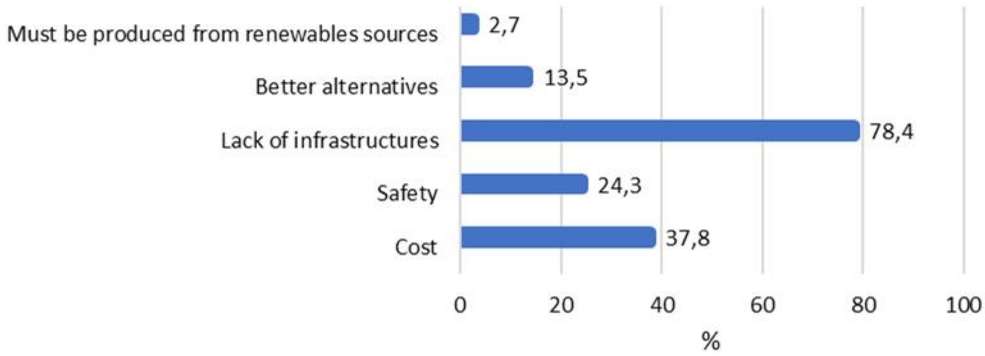


Figure *36: Question 24: What are the main disadvantages of hydrogen?*

As one can see, respondents in this enquiry chose as the main disadvantages the lack of infrastructures, with almost 80% selecting this option. The costs were the second most chosen disadvantage, as participants see the cost of vehicles and fuel as a major difficulty.

In the next step, participants were then asked about what they thought were the main advantages associated with the use of hydrogen. Similarly, to the disadvantages, five suggestions were provided, while participants could choose more than one, or add a personalized answer. In Figure 37 it is possible to analyse the results.

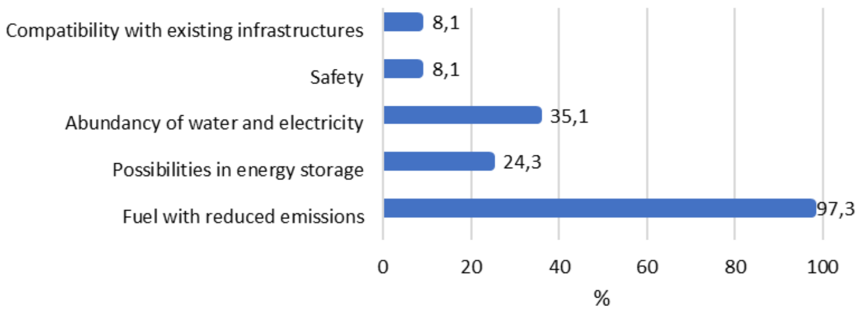


Figure *37: Question 25: What are the main advantages of hydrogen?*

As the figure shows, the most chosen option is “fuel with reduced emissions”, with most participants considering it the main advantage. Energy storage possibilities and abundancy of feedstock were the second and third most voted, although with less than 40% of votes each.

In question 26, respondents were asked what the main barriers to the implementation of hydrogen technology are. In this case five suggestions were provided, while participants could choose multiple options and could add other answers. Results can be seen in Figure 38.

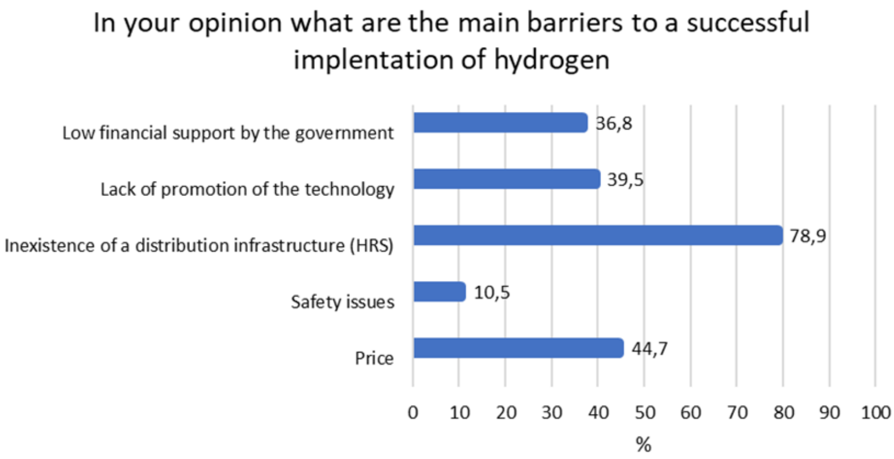


Figure *38: Question 26: In your opinion what are the main barriers to a successful implementation of hydrogen?*

Results show that the lack of infrastructure is the main barrier for a successful implementation with the majority choosing this option. Price, lack of financing from the government and lack promotion of the technology were also seen as major obstacles to an effective implementation of the technology.

Respondents were then asked if they would consider buying a FCEV in the future, with options ranging from 1 (Very unlikely) to 5 (Very likely). In Figure 39 results can be analysed.

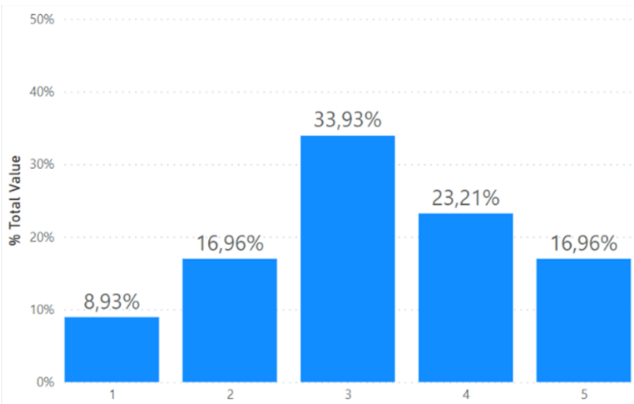


Figure *39: Question 27: How likely are you to buy a hydrogen powered vehicle in the future?*

In this case, respondents were very divided in their responses to the question, with a slight tendency to consider it a likely situation. The most chosen option was number 3, which translates to an indecision about the subject. This is an expected result, as there is still not much information about hydrogen vehicles, and as it is a recent technology.

The following question focused on the probability of the respondent's companies to buy hydrogen vehicles in the future, in a scale from 1 (Very unlikely) to 5 (Very likely). Results are presented in Figure 40.

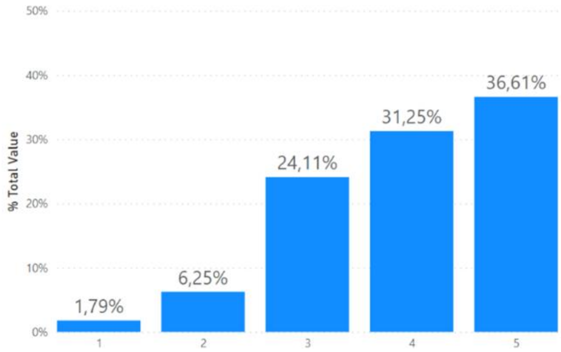


Figure *40: Question 28: How likely is your company to buy FCEVs in the future?*

In this scenario, most participants think that their companies will be buying FCEVs at some point, with most answers being 4 (Likely) and 5 (Very likely). This indicates respondents see transportation companies as the most likely adopters of this new technology, especially when compared to question 27 (Figure 39), where the same people were divided when it came to buying a FCEV as a personal vehicle. A reason for this could be the perception from participants that companies have the financial means to invest and efficiently use a small fleet of FCEV.

4.2 Interview analysis

In the analysis of the responses to the interviews, several recurring topics and thematics were identified around which the results were characterized. As such, this analysis will focus on seven different subsections, as these help to expose problems and necessities in a clearer way and help identify possible solutions according to the industry's decision makers. The sections are Environment and sustainability, Hydrogen's early adopter, Similarities with the electric situation, Views and opinions on hydrogen, Supporting the implementation of hydrogen in transport, Obstacles and Safety concerns. In Table 15 are presented the interviewed companies of this analysis

Table 15*: Companies interviewed, categorized by sectors, city, type, and date*

Interview #	Organization	City	Company Type	Date
	National Association of transportation of goods			
1	ANTRAM	Lisboa	Public	17/10/2021
	Passenger transport companies			
2	STCP	Porto	Public	15/10/2021
3	Carris	Lisboa	Public	20/09/2021
4	Cascais Próxima	Cascais	Public	27/09/2021
5	Rodoviária de Lisboa	Lisboa	Private	22/09/2021
	Trucking companies			
6	Patinter	Mangualde	Private	09/10/2021
7	Luís Simões	Loures	Private	03/11/2021
	Infrastruture			
8	PRF Gas solutions	Porto	Private	20/10/2021

4.2.1 Environment and sustainability

When enquired if companies had an essential role in promoting a sustainable environment, every interviewee responded in a positive affirmation regarding this question. One of the respondents highlighted the necessity of promoting the welfare and focusing on client needs (int.3), while another respondent pointed to the necessity of operating withing technology maturity (int.6).

Sustainable measures were also one of the topics of interviews, with companies presenting different solutions. Constant fleet renewals were the most referred aspect by enterprises (Int.1-7), with investment in less pollutant vehicles being continuous. One of the passenger vehicles companies (int.3), stated there was a large effort at the moment to substitute diesel vehicles in their company with less pollutant alternatives, and as such, their company had been investing in natural gas buses and electric buses in an attempt to reduce carbon emissions. Another company also concurred with this view (int.2) and further indicated that while 80% of their Bus fleet was powered by natural gas for vehicles and 5% was electrically powered, they would be reducing even further their diesel fleet in the next years. The trucking companies interviewed (int 6,7), were more sceptical to the immediate adaptation to natural gas although having already ran pilot projects using this technology. Main issues cited were the lack of refuelling infrastructure, which reduced the flexibility of the service, increased maintenance costs and required training.

Eco-driving was also a common measure in several interviews (int.4-6) with companies using systems in their vehicles that register driving patterns and behaviour. Using this information companies can then do workshops, educational sessions and counselling of drivers resulting in better fuel and tyre management, reduced maintenance costs and reduced emissions.

4.2.2 Hydrogen’s early adopters

Regarding the question “Do you consider companies may be the first adopters of new technology, before a wider adoption by our society?” the feedback was mainly positive (int.1-4,6-8) although there were several conditions for this to happen. The management of economic margins and not increasing costs significantly were essential aspects pointed by interviewees (Int.2,6,7) for companies to support new technologies, while for another company (int. 8), a hydrogen infrastructure supplier referred financial capability as another important factor, as industry stakeholders explained that having adequate financing was essential for companies to invest in more expensive technologies (int.4,5).

The difference between public and private companies mentioned in several interviews (Int.1,3-5) was a key subject, as most stakeholders pointed those public entities are more focused on public service, rather than having profit. Because of this, interviewees agree that funding for newer technologies is often more accessible in public companies. More than one public transportation company stressed that the use of public funding must be taken with increased responsibility and caution (int.3,4), as although these companies are government funded, they are still using taxpayers' money, and as such new investment must be financially viable.

4.2.3 Similarities with the electric situation

Electric vehicles were a recurring topic in interviews (int.1-4,8), as they were the most recent and comparable technology to be introduced in the transportation market, and as such, were often used as means of comparison with hydrogen. One of the Bus transport companies (int.2) pointed out that the adoption of EBs had several challenges such as the reduced autonomy presented by these vehicles, with first generation EBs only covering around 160 km (int.2) and the fact that considerable infrastructure investment to accommodate the charging of the vehicles was necessary (int.2,3).

That said, buses are still set to become progressively electric in the coming years, with fleet renewals and technological developments likely supressing the aforementioned problems in the coming years. However, trucking companies do not seem to share the same point of view (int 6,7) as the opinion was that ETs can't provide the same level of service as DTs. Driving range and low cargo capacity were cited as major problems, along with infrastructure needs and required immobilization due to recharging. For these reasons, the truck operating companies interviewed demonstrated a lack of interested and belief in the capabilities of ETs to substitute diesel trucks in the coming future.

4.2.4 Views and opinions on hydrogen

When questioned about hydrogen, every person interviewed considered themselves to be familiarized with the topic, demonstrating a minimum level of knowledge of the technology. This is a clear indicator that companies not only acknowledge that hydrogen has real potential of competing with other alternatives but also that it could well be adopted in Portuguese companies soon. One of the decision-makers/manager of the bus companies interviewed has the only hydrogen fleet working in Portuguese territory (int.4) at this moment, with 2 CaetanoBus Fuel Cell buses. The company also revealed further plans to expand the existing fleet to 10 buses next year, therefore increasing five times the actual size while further elaborating that this investment would also be accompanied by the construction of a new HRS to service the fleet.

When enquired about positive aspects of the use of hydrogen in transportation, most answers identified the fuel type as clean and non-pollutant (int.2-8). Another positive aspect of hydrogen that was often referred was the autonomy of Fuel cell vehicles. For example, one of the companies operating urban buses (int.2), indicated from a previous pilot experience with FCEBs in 2006 that their driving range was about 400 km at that time (int.2), and by comparison stated that electric buses they bought in 2018 where only capable of driving range of 160 km using 200 kWh batteries, although newer generations of buses are expected to improve on driving range to 400 km and have an increased battery capacity. In interview 4, the bus company that operates two FCEBs, said they were positively surprised by the high driving range of their two units, referring that they could sometimes reach 600 km before refuelling. One company operating buses (int.3) brought forward the interesting point that although FECBs have a similar operational model as EBs, they are better in several aspects with reduced refuelling time, which is comparable to diesel, reduced infrastructure costs required to support a fleet and reduced battery use, that are still a source of pollution, due to their production process, and have proven to be difficult to recycle.

As for disadvantages about hydrogen use, fuel and vehicle costs were pointed by all interviews (int.1-7) as the main disadvantages compared to its alternatives. PRF (int.8), a hydrogen electrolyser and infrastructure producer, said in their interview that although hydrogen is very expensive at this moment, in a close future one could expect the fuel price to be significantly lower, as there are several ongoing projects in Portugal that will significantly increase the production, and the CAPEX of hydrogen will be lower with technology developments. The lack of infrastructure was also referred in most interviews (int.1,2,6,7) as the perception is that hydrogen is not yet available to use. Compared to diesel buses and electric buses that already have an existing grid of refuelling stations and charging points, hydrogen, much like any new fuel, requires a new infrastructure to allow for its distribution, which is even more aggravated when taking in consideration it must be stored at high pressure and low temperature, requiring highly specialized equipment. Safety of the refuelling process and storage of hydrogen was pointed as a major concern of two companies (int.2,6), as the idea of storing and dealing with a high-pressure gas, such as hydrogen was referred companies as they could be unstable and dangerous.

4.2.4.1 Supporting the implementation hydrogen in transport

One of the questions (Annex 2) focused on what were the main factors that could contribute to a widespread use of H_2 in transportation. Demonstrations and information campaigns were considered important factors to improve public perception on the technology and convey the idea that hydrogen is available and safe fuel to use (int.3,7). One of the companies (int.7) also suggested that pilot projects are an essential factor to promote hydrogen use, and to demystify the dangers associated with refuelling stations, providing the example of Switzerland where a pilot project was running that led to a successful implementation in the country. The interviewee also added that these pilot projects are very important to ensure the commitment of companies, as once they test hydrogen vehicles and obtain the necessary infrastructure and requirements for the project, they are much more likely to invest in it. Another bus company (int.5) also stressed the importance of experimentation in achieving a more sustainable model for the use of hydrogen in terms of cost-benefit. Subsidization for reducing the costs involved with hydrogen such as infrastructure, fuel and vehicle costs was also a factor often referred by several companies as a major necessity to the implementation and growth of hydrogen use in transportation. One of the transportation companies (int.6) further said that subsidizing HRSs was essential to create a grid of refuelling points, in order to convince companies and car owners that hydrogen is an implemented solution and a logistically viable option, at least.

A concern brought forward by Cascais próxima (int.4), the company that owns the only FCEBs in Portugal, was the lack of legislation regarding hydrogen mobility at this moment in Portugal, with existing voids regarding refuelling and other safety procedures, and also the high level of bureaucracy necessary to deal with hydrogen, as some public and regulatory entities are yet to fully address issues related with the technology, making licensing and approval of H_2 related projects more complex. Ways of improving user confidence in hydrogen vehicles was a topic aborded in question 13 (Annex 2), with most answers pointing towards the need of experimentation and trainings, with companies highlighting that the tranquillity and confidence of users (int.7) are essential for the successful adoption of any technology.

In question 14, interviewees were asked whether their companies consider important the investment/adoption of hydrogen and why. As two of the companies operating buses indicated (int.3,5), the adoption of hydrogen in mobility reduces the use of fossil fuels, and thus improves air quality and reduces noise, as FCEBs much like electric vehicles are very quiet. This question provided the notion that there was a general sense of responsibility in these companies regarding not only the environment but also the welfare of users. PRF gas (int.8) added that companies have a key role in the development of new technologies, as when they start using a technology like hydrogen, they tend to develop it further, meaning they work as development Hubs.

4.2.4.2 Obstacles

One of the most important topics approached in the interviews was the obstacles companies see in the way of a successful national implementation of hydrogen. This allowed to understand their point of view and to clearly identify what are some of the points that are obstructing the implementation of hydrogen or could do so in the future if not solved. One of the trucking companies stated that maintenance and lack of technical knowledge would be a considerable challenge, as the technology is significantly different from diesel (int.6), the most used option in the company, and therefore it would be necessary for maintenance crews, drivers, and technical staff to acquire a significant amount of information. The company in question then provided the example of the introduction natural gas trucks (GNC) a few years before, were an increase of maintenance costs and time of repair was observed, leading sometimes to costs up to 15000€/day for every day the truck was immobilized. Trainings were also a difficulty noted (int.3,4), as companies' decision makers understand that the implementation of hydrogen will require workers to have considerable levels of knowledge of H_2 in order to safely operate vehicles and equipment without endangering others. In interview 8, with the company that produces hydrogen infrastructure, the respondent described the possibility of an accident involving hydrogen in the coming years as "tragic", as it would have grave repercussions in peoples trust in the technology and would likely scare some investors. However, the interviewee also added that while there is an associated risk with the use of hydrogen, his company followed European safety directives that designed to ensure the safety in the handling of H_2, and one could expect that future legislation will reduce even further the risk of hazard.

When enquired about workers feedback about the adoption of hydrogen answers were very positive, and as one company said in their interview, there is commonly a predisposition and enthusiasm of workers to try new products and to adapt to new technologies. The respondent from a truck company, while sharing the same opinion, added that people are sensibilized for the necessity of having cleaner and more sustainable technologies, and would therefore see it as a personal contribution to the decarbonization process and would be eager to collaborate. Another bus company stated their company tries to involve their workers as much as possible in the implementation of their growing hydrogen fleet, with the goal of making workers comfortable with the use of H_2 and to ensure their concerns are included and heard.

When asked if their companies were ready to accommodate hydrogen infrastructure responses were quite positive. While one of the interviewed companies already had a refuelling infrastructure (int.4) two other companies(int.6,3) affirmed they were ready to accommodate a hydrogen infrastructure with a trucking company suggesting it would be very easy to accommodate and adapt. While in technical terms there was a general agreement that it would be easy to install hydrogen infrastructure in their companies, companies often stressed that economically this wasn't as linear, as costs were still considered considerably high compared to alternatives. One decision maker, for example, stated that without financing and government support it would not be possible to invest in hydrogen infrastructure, as the cost-benefit of the solution is still too high, and would need to significantly drop for an investment justify an investment. Therefore, most companies consider hydrogen a viable option but only if there is political will and cost support for hydrogen implementation, as the investment costs are still significant (int.3,4,6).

When asked what kind of tests or services are required to support the usage of 100% hydrogen powered transport, the respondent from one of the bus companies (int.3) stated they would perform pilot tests in small scale, using one or two vehicles, and then based on an analysis of the results decide whether or not an implementation of hydrogen would be appropriate, a view shared by one of the truck operating companies (int.7).

Question 24 focused on the type of HRS installed and interviewees were asked if they would prefer their hydrogen to be originated from a centralized production unit (Off-site), or locally produced (On-site production). While some of the respondents didn't have an opinion on the subject, one of the bus companies stated that while both options were a possibility, the company had a slight preference for On-site production as it would be more fit to the company's dimension. However, in other interviews the choice would be decentralised production of H_2 (int.5,6), as it reduces the complexity of the implementation and allows for an easier management of the fleet (int.5) while another company (int.7) claimed to have no preference on the subject but would rather the less complex option.

4.2.4.3 Safety concerns

The safety of the refuelling was also aborded in one of the questions, and opinions were mixed regarding the subject. Respondents from one of the truck and bus companies expressed seeing this question as distant in the future, and not having enough information to answer respectively. One of the other Bus companies, on the other hand expressed concerns over this subject, stating there are multiple risks that must be thoroughly analysed and accessed first, and employees must then receive training to ensure acceptable levels of safety are achieved. The interviewee from another bus operating company had slightly different opinion, affirming current safety measures are sufficient and enough for refuelling to be conducted in a safe, controlled manner, and that the focus should be on ensuring workers have the appropriate training. PRF gas solution, as the only hydrogen infrastructure and fuel producer interviewed, defended the position that accidents with hydrogen are inevitable to occur from time to time, as there is a risk factor associated with the fuel, as is the case with any other fuel type. Therefore, the respondent considered it is important that risks are not neglected and are known and accepted.

The results for the interviews demonstrate that companies have moderate to very high level of awareness of hydrogen technologies, with 2 of the 8 companies interviewed already using hydrogen vehicles and or related infrastructure. All companies accepted hydrogen as a current or future option for investment, and companies perspective of hydrogen is that it is an emerging clean fuel, with a serious potential of growth in the Portuguese transport market. The main conclusions drawn from the interviews are presented in Table 16.

Table 16: Summary of the main conclusions of the interviews

Environment and sustainability	Hydrogen's early adopters	Similarities with the electric situation	Views and opinions on hydrogen	Implementation of hydrogen in transport	Obstacles	Safety concerns
• Companies recognize their role in promoting sustainable measures • Constant fleet renewals are a common measure • Substitution of diesel buses by natural gas and electric buses • Natural gas vehicles are a short-to-mid term solution for reducing emissions and electrics the future • Eco-driving and monitoring of driving beahavior is a common measure to imporve efficiêncy and reduce emissions	• The majority of the decision makers considers companies could be first adopters • Not increasing the costs and reducing economic margins would be key points • The difference between public and private companies in obtaining fuinding for newer technologies is considerable, and public companies having better acess	• Adoption of Electric buses required considerable infrastruture investments • ETs are not capable of providing the same level of service as DTs	• All interviewed decision-makers considered themselves to have a minimum level of knwoledge on hydrogen • One company operates two FCEBs, plans to expand to 10, and pointed the high autonomy of H2 buses • Most interviewees identified clean and non-plluant fuel type as positive aspect • Fuel and vehicle costs are the main disadvantages	• Demonstrations and information campaigns are important factors to improve public • Pilot projects would increase companies's commitment with the technology • Subsidizing HRSs is an essential step	• Maintenance and lack of technological knowledge is a considerable challenge • Possible accidents will have grave repercutions on people's trust in H2 • Political will and cost support are necessary factors for the expansion	• Companies lack information on safety and see it as a question for the future • Risk of accident must be recognized, analysed and accept as with other fuels • Trainings are very important

4.3 TCO Results and Discussion

The analysis to the TCO comparison was made in two different sections, first the results for heavy duty vehicles (trucks) and heavy-duty passenger vehicles (buses) were analysed and in the second section for light duty passenger vehicles.

4.3.1 TCO for Heavy Duty Passenger vehicles (buses) and Heavy-duty vehicles (trucks)

The results for the TCO comparison for Buses can be seen in Figure 41. As it can be seen, LNG buses are the most economically viable option at this moment, having a significantly lower ownership cost than all other three options, corresponding to a difference of around 141 000 € between LNG and diesel, the second less expensive option. Electric buses are the second less expensive option followed by hydrogen buses, which are still the costliest powertrain options in the market. As for heavy duty vehicles, LNG trucks are the most economic option of the four with an estimated TCO of approximately 429 000 €, followed by electric trucks, with a small difference for diesel trucks, and lastly hydrogen, the most expensive option of the four.

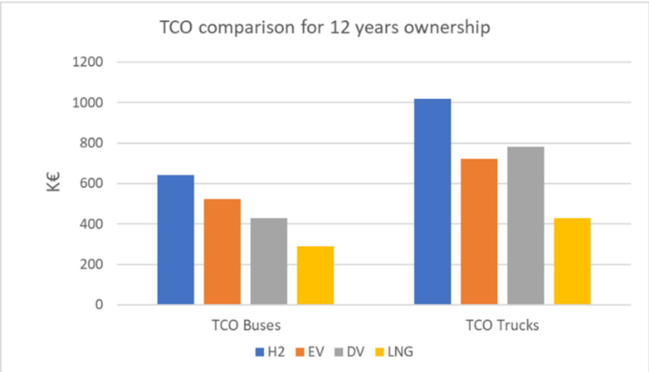


Figure 41: TCO comparison between powertrain options for buses and trucks

The comparison between the cost per kilometre of each powertrain can be observed in Figure 42 for both buses and trucks. The result shows that for buses, LNG is the cheapest option in terms of costs per kilometre, with 0,48 €/km, followed by diesel buses with a cost of 0,72 €/km, while electric buses have an estimated 0,87€/km and hydrogen buses 1,07 €/km. As for trucks, LNG has the lowest cost per kilometre, with 0,30 €/km, followed by electric trucks amounting for 0,50€/km, then diesel trucks, with a cost of 0,54 €/km and lastly hydrogen at 0,70 € per kilometre covered.

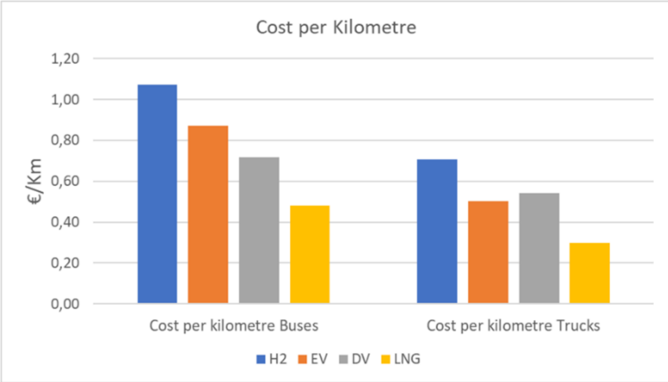


Figure *42: Cost per Kilometre between powertrain options for buses and trucks*

The results for the heavy-duty passenger vehicles were in line with what was expected for this analysis, with LNG buses and diesel buses being the most popular powertrains options in the Portuguese and European bus market (Table 2). The difference in cost per kilometre is also an important factor, with LNG buses costing an estimated 0,25 €/km less than DB, electric 0,15 €/km more than DBs and hydrogen an extra 0,35 €/km. In recent years, electric buses have seen a reduction in both acquisition and operational costs which in evident in Figure 41, as they are the third option in terms of economic viability. As for hydrogen buses, it's cost per kilometre is still significantly high, being more than the double of the LNG powertrain option.

For trucks the results of this analysis were not in line with was expected in this simulation, as the most popular choice in the Portuguese market, the diesel trucks, were found to have higher costs than LNG trucks and electric trucks. Results also demonstrate the economic advantage of LNG powertrain, itself costing 0,24 €/km less than the diesel option, electric costing 0,04 €/km less than diesel and hydrogen costing 0,16 €/km more, being the costliest of all powertrain options. Keeping this in mind, although diesel trucks are not the cheapest option of the powertrains option, they remain the remain largely the most popular option for companies, due to their flexibility, implemented infrastructures, knowledge of the technology and performance.

For both buses and trucks, the high hydrogen TCO results can be mostly attributed to the costs of hydrogen (10 €/kg), which was estimated to be a market entry price for green hydrogen and is likely to be considerably reduced in the coming years due to technological research and increased production. For comparison, and using the same formulas, a simulation was performed with hydrogen at 5 €/kg, which is a likely price to achieve in a few years as can be seen in Figure 43.

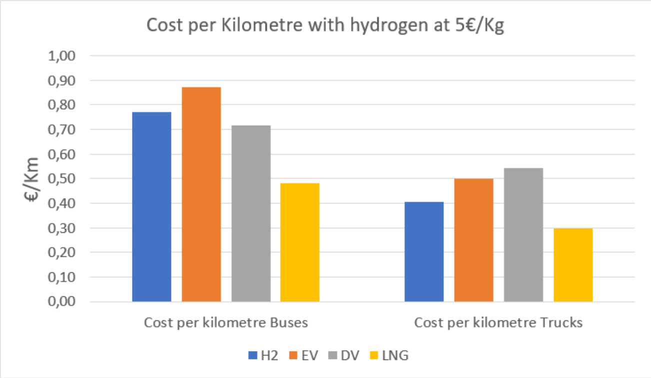


Figure *43: Cost per kilometre between powertrain options for buses and trucks, with H_2 costing 5 €/kg*

As can be seen in Figure 43, with hydrogen at 5 €/kg FCET and FCEB become much more cost competitive. For buses, H_2 powered vehicles become the third cheapest option after LNG and diesel vehicles, with a small cost gap to the second. As for trucks, Fuel cell trucks (H_2) become the second option in terms of costs, surpassing diesel trucks and electric trucks. This simulation proves that if there is a significant drop of price of hydrogen in the coming years, due to the development and expansion of the technology, hydrogen powered buses and trucks will become costs competitive with the other powertrain option in the market.

4.3.2 TCO for passenger vehicles

Results for the TCO comparison of passenger vehicles can be seen in Figure 44 and Figure 45 for the 5- and 12-year ownership periods respectively. For both ownership periods, the lowest TCO presented is for the LPG option, followed by electric vehicles, diesel vehicles and lastly hydrogen vehicles.

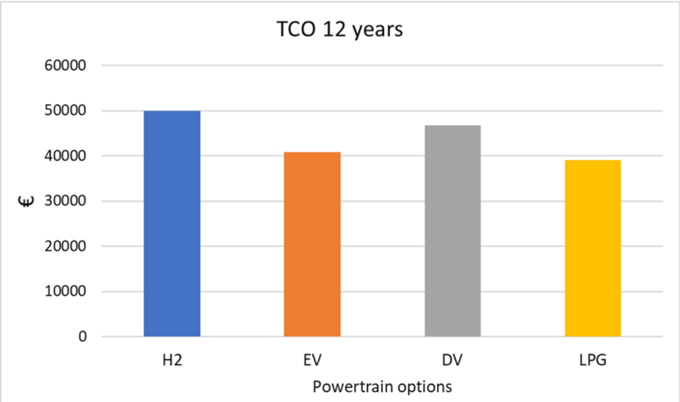


Figure 44: TCO comparison for 5 years of different powertrain options for light passenger vehicles

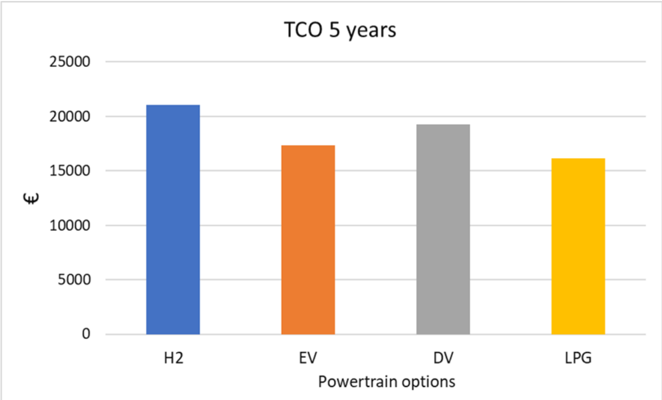


Figure 45: TCO comparison for 12 years of different powertrain options for light passenger vehicles

Although results for the two periods of ownerships are similar, when analysing the different cost differences if becomes clear that there are some differences, as can be seen in Table 17.

Table *17: TCO difference for 5- and 12-year periods of ownership*

	TCO difference		
5 year ownership		12 year ownsership	
LPG-D	-3117,0	**LPG-D**	-7630,9
EV-D	-1940,4	**EV-D**	-5791,8
H2-D	1760,5	**H2-D**	3189,9
	€		€

As one could verify in Table 17, LPG's TCO is considerably cheaper when compared to diesel or electricity, which may be attributed to the fact that it is priced at 0,81 € (Table 17) which are cheaper than its diesel counterparts. However, it is important to refer that adapting a petrol car to LNG bi-fuel in Portugal will cost an average 1500 € as well. Alternatively, there are a few models in the country that are sold with a bi-fuel system (LNG+Petrol), like the Renault Clio and the Dacia Duster, although the number of options is limited at this moment. As for electric vehicles, the results show surprisingly that their total costs are already less than diesel's, which one may attribute mainly due to the tax exemptions and government fundings for the purchase of EVs, and the increase in fossil fuel's costs in the last years. Hydrogen vehicles are the most expensive of the four powertrain options, which attributed mainly due to the estimated high entry price of hydrogen fuel (10 €/kg), and the low number of vehicles in offer. However, once production of hydrogen in Portugal increases, accompanied by technological development on electrolysers, it can be expected that this price will reduce significantly, reaching values close to 5 €/kg. In this situation, and using the same formulas for the TCO calculations, one could observe a much more favourable scenario for the hydrogen powertrain, as can be verified in the simulation presented in Figure 46

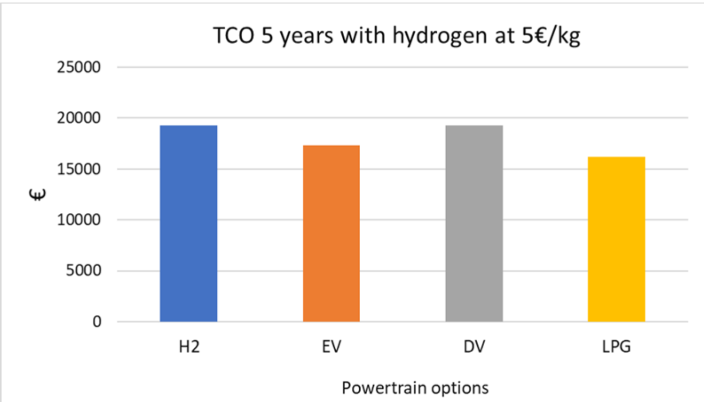


Figure *46: TCO for an ownership period of 5 years, with hydrogen costing 5€/kg*

4.3.3 Summary of the TCO analysis

Results for the TCO analysis varied significantly according to each powertrain. Overall, it is undeniable that diesel vehicles are no longer the cheapest in terms of ownership costs, with other powertrain options amounting to less costs in several situations.

Looking at the case for buses, results show there are evident advantages in operating LNG or CNG buses, as their costs are significantly lower than all other powertrain options available in the market. From the information collected from the interviews it was understood companies see natural gas-powered buses as a short-to-midterm solution, as they are less expensive to operate and significantly reduce emissions when compared to their diesel counterparts. Battery electric buses were also often quoted by companies as current investment targets for their fleets. Whilst this powertrain option still presents higher costs than diesel buses, the costs gap is minimum, and with technological developments and government funding it can be expected that this option will rapidly become cost competitive. Hydrogen buses, while having the highest costs, were also the subject of interest in the interviews, and were often considered to have at least an important role in the decarbonization of the industry. Moreover, the simulation ran with hydrogen at 5 €/kg (Figure 43), which can be expected in a few years, demonstrates this powertrain option will become cost competitive rapidly. With diesel no longer being the powertrain option with the lower costs, and with new emission regulations restricting even more the emissions allowed by each bus, one can expect bus companies to continue phasing out diesel buses, in favour of primarily LNG and CNG buses accompanied by a growth in investment in electric buses and later hydrogen buses, especially when hydrogen price drops.

Results for TCO analysis for trucks also showed that natural gas trucks have the lowest ownership costs of all options by a significant margin (Figure 41), with electric trucks and diesel trucks being the second and third most economic followed by hydrogen powered trucks. However, most companies in Portugal don't have significant LNG fleets in operation, which is mostly due to the lack of infrastructure available to support its growth. This was verified in several of the interviews, with interviewees pointing that LNG trucks often had to follow specific routes to ensure the necessary refuelling, therefore reducing the flexibility of the services and costing more money and time to the company. That said, it can be expected that in the next years the refuelling infrastructure will grow in Portugal and in Europe, which will contribute to the mitigation this problem. As for electric trucks, although being the second cheapest option, responses to the interviews demonstrated that companies don't yet see electric trucks as a fit substitution of diesel trucks, as they aren't able to haul heavy loads, require significant recharging times each trip, have a low driving range with a full charge and require significant infrastructure adaptations to allow for charging. As for hydrogen trucks, they are proved to be the most expensive option of the four. This can mostly be attributed to the high price of hydrogen assumed for these calculations (10 €/kg), which is estimated to be an entry market price that will likely drop to values closer to 5 €/kg in the coming years, which in turn will likely increase the competitiveness of this powertrain option, as can be observed in Figure 43. Although sharing a similar case with the bus market in terms of costs, it is likely that the transition from diesel trucks to alternative powertrains in Portugal will still take some years to occur, even if diesel trucks are more expensive to operate, as major trucking companies still consider that other powertrain options still hinder their service quality when compared to diesel due to their reduced flexibility, reduced capacity and/or higher costs.

The analysis for the TCO of passenger vehicles demonstrated owning a LPG is advantageous in terms of costs when compared to other powertrain options, with EVs being the second cheapest option followed by diesel and then hydrogen. While diesel and petrol vehicles are the dominant market options, electric vehicles have seen successive increases in sales in the last years, strongly promoted via newly implemented targets of decarbonization in Portugal and Europe. The charging grid has expanded significantly in the last ten years (as seen in Section 2.6.1) and affordable models have begun to appear which will further sales numbers. LPG vehicles on the other hand, haven’t seen a relevant increase in recent years, although having the lowest costs of all options and a decent refuelling grid in the country, as many of the regular refuelling stations also have LPG available. This can be explained by the fact that many people do not know the technology or how it works/how much it costs, which means there is a generalized lack of recognition from the population. Besides, as there aren´t many car manufacturers selling vehicles with an LPG installation, it is often required the installation of a kit to allow the combustion of this fuel. As for hydrogen vehicles, the TCO values demonstrate that costs associated with this powertrain are close enough to the other powertrain options that it could be considered competitive pricewise (Figure 46). Moreover, with production costs for green hydrogen expected to drop significantly in the next years, as explained before, and accompanied by a growth in the refuelling grid, one will likely see this option become a competitive one. Keeping this in mind, in the coming years it is predicted that diesel and petrol vehicles will be gradually substituted by electric vehicles in a first phase, and hydrogen at a later stage, with LPG seeing a small increase in percentage as well.

Initially, it was intended that the TCO analysis was made for various periods of time, so as to demonstrate the evolution of powertrain costs along the years and put in evidence the tendencies of cost variations. However, it was found that the data collected was insufficient for this type of analysis, and thus another approach was chosen to complete the study. That said, a future work could be developed on this topic, not only analysing powertrains ownership costs along the years, but also predicting future developments and TCOs.

5 CONCLUSIONS

The Goal of this study was to analyse the acceptance of hydrogen in the Portuguese transport market and to identify and understand what the major factors influencing it are, as well as perform an economic analysis of the deployment of hydrogen in companies of the transport sector.

In order to achieve this, a set of interviews and enquiries targeting major companies in the Portuguese transport segment was conducted, which allowed for a better understanding of companies' visions and strategy inclusion of the fuel type, to identify what are the main obstacles for a national adoption of the technology, should this implementation occur in the coming years, and to analyse workers opinions towards hydrogen.

As a technology, hydrogen brings forward several incredibly promising attributes that are likely to significantly impact our economy and society. As it can be produced using only water and renewable electricity, it is considered a virtually unlimited and truly clean fuel, with no emissions associated with its use either. Moreover, with an escalating demand for industries to decarbonize fleets and reduce emissions, the chances to capture interest and investment from companies on clean fuel sources such as hydrogen, couldn't be higher.

Research and development for hydrogen technologies over the last decade has been considerably high and is increasing with significant funding being allocated to hydrogen projects, and several countries are deciding to invest in this solution. Keeping this in mind, one could expect there will be a significant technological leap in the coming years, with a likely reduction in the CAPEX of infrastructures and parts, and the implementation and expansion of other electrolysis techniques such as PEM (Polymer Electrolyte Membrane) and SOEC (Solid Oxide Electrolysis), that have been proven to have a higher efficiency than Alkaline electrolysis.

Hydrogen will be a major asset in the country's energetic grid regulation, as the storage of energy in the form of fuel will reduce energy waste during peak hours of production, essentially using the energy production in excess to better adjust the supply to the demand needs, therefore increasing the efficiency and flexibility of the system. There are several ongoing energy storage projects being implemented in Portugal that are due to start working in this year [70], [109], [110].

The production of hydrogen has the potential to be a decisive step towards the energetic independence of the country, as identified in the interviews, as the country has the possibility to produce its own fuel instead of having to rely on oil producing countries. This aspect is of great importance, as fluctuations in fuel prices have had devastating effects to the economy in the past [111], [112], and left the country dependent on others.

Results from the enquiries demonstrate that workers from the transport sector have only a basic level of knowledge about hydrogen, and although they are generally weary of the safety risks it might pose to them, are willing and in many cases very interested to use the technology. This aspect was further confirmed in the interviews, where all company decision makers predicted their workers would have a very positive attitude for the adoption of the technology.

Interview results demonstrated that decision makers that participated had a reasonable level of knowledge about H_2 and its applications. Respondents were very collaborative and showed significant interest in acquiring new information about the subject, including technical specifications, production processes, transportation methods, refuelling systems and fuel and equipment costs. The potential of hydrogen as a green solution was widely recognized in every interview, although in many cases participants weren't aware of hydrogen's other possible applications, namely in energy storage. Information campaigns in the next years would be an important contribution to a successful implementation of hydrogen, as the number of companies aware that are fully aware of this solution and its characteristics will directly influence the chances of investing in it.

All companies showed willingness to invest in hydrogen vehicles at some point, demonstrating acknowledgement that hydrogen is in fact a possible solution to the inevitable decarbonization the transport sector will suffer. However, there was a generalized opinion that costs are still considerably high when compared to the other powertrain options, and that government funding is necessary to bridge the cost gap, and to convince companies that it is economically viable to invest in hydrogen.

Hydrogen safety was a topic that received considerable attention throughout this dissertation. The study shows that a considerable percentage of participants still associate hydrogen with danger and risk of explosion causing some discomfort and reluctance to use the technology, while some companies also raised some concerns about this topic. Having informative campaigns, creating small scale pilot projects, such as one of the interview bus companies has and ensuring a complete enforcement of the safety procedures are vital measures to mitigate as much as possible the risk of accidents and to make the public feel safe with the use of hydrogen vehicles.

The TCO analysis for a 12-year ownership showed a clear advantage in the investment in natural gas buses, with a cost per kilometre of 0,24 €/km compared to 0,72 €/km and 0,87 €/km of diesel and electric. The results were in line with the interviews, where bus companies affirmed to be conducting fleet renewals and switching from diesel buses to GNC and Electric buses, not only due to environmental motives but also because of economic competitiveness. Hydrogen buses are proven to be a reliable solution as reported by the company with H_2 buses in the fleet, and once the cost per kilogram lowers to reasonable values (~5 €/kg), one could expect hydrogen buses to be (Figure 43) considerably competitive. Companies are investing greatly in green technologies and implementing measures to reduce the emissions and costs as much as possible such as the use of eco-driving.

The TCO analysis for Trucks, for a 12-year ownership showed a clear advantage in the use of natural gas trucks, with a cost per kilometre of approximately 0,30 €/km compared to 0,5 €/km and 0,54 €/km of diesel and electric options. As for the hydrogen powertrain option results were

0,71 €/km with a fuel price of 10 €/kg and 0,41 €/kg with hydrogen at 5 €/kg, which means hydrogen trucks will become significantly competitive once the fuel price is reduced. However, although ET and GNC/LNG trucks had lower cost results, from the interviews it was clear that companies are not investing significantly in these technologies, most due to the lack of infrastructure, in the case of natural gas, and to the lack of capabilities, as electric trucks are not yet capable of the same performances as DTs. Therefore, it can be expected that diesel trucks will most likely dominate market sales in the next years, as other powertrain options do not have the required level of service yet. As for hydrogen trucks, companies understand its potential in the long term, and once there is infrastructure available will likely consider its use.

The scenario analysis provided a comprehensive prediction of the future of the transport market in Portugal, by considering electricity and fuel prices the main influencers of the market. The results demonstrate that hydrogen will be implemented in the future with various degrees of success, ranging from small, localized fleets to a dominant market position. LCOH will be a determining factor in the market outcome, and the CAPEX of electrolysers will strongly influence its variation.

Portugal is ready to receive hydrogen infrastructure. The first refuelling stations are being and will be built mostly around industrial areas, where electricity sources and all the required infrastructure are easily accessible. This will also serve to fuel several pilot projects, and to increase proximity with companies which may ultimately contribute to their commitment in use of hydrogen. In parallel one could expect major bus companies to start operating refuelling stations in cities, creating the first refuelling points near urban areas.

The Portuguese government and the European commission will have a major role in the future of hydrogen in the country, as the expansion of the infrastructure and the installation of electrolysers will require a strong political backing to provide assurance to possible investors their investments are viable.

Domestic companies that are developing hydrogen solutions like refuelling stations, electrolysers and transport and storage solutions will be key asset for the establishment of the technology, increasing the accessibility and reducing acquisition costs.

5.1 Messages for the industry

Infrastructure CAPEX will likely be reduced in the coming years, providing conditions for more HRSs to be constructed, especially for the support of companies’ fleets.

As verified in the questionnaire results, safety concerns regarding H_2 are limited, and with training and information campaigns, these concerns are reduced and for the most part addressed.

Pilot projects will be a very important step for the implementation of the technology in Portugal, as they will build trust with companies regarding FCEVs and allow for experimentation without a considerable investment. Creating the necessary conditions and ensuring funding for this type of projects would be a very important contribution towards implementation of the technology.

5.2 Future Work

An analysis focusing exclusively on a TCO for hydrogen would be a significant contribution to the current work developed on the subject. While this work does provide an analysis on this matter, a more in-depth study, including more variables and influencers would fill a gap on literature on the Portuguese hydrogen market.

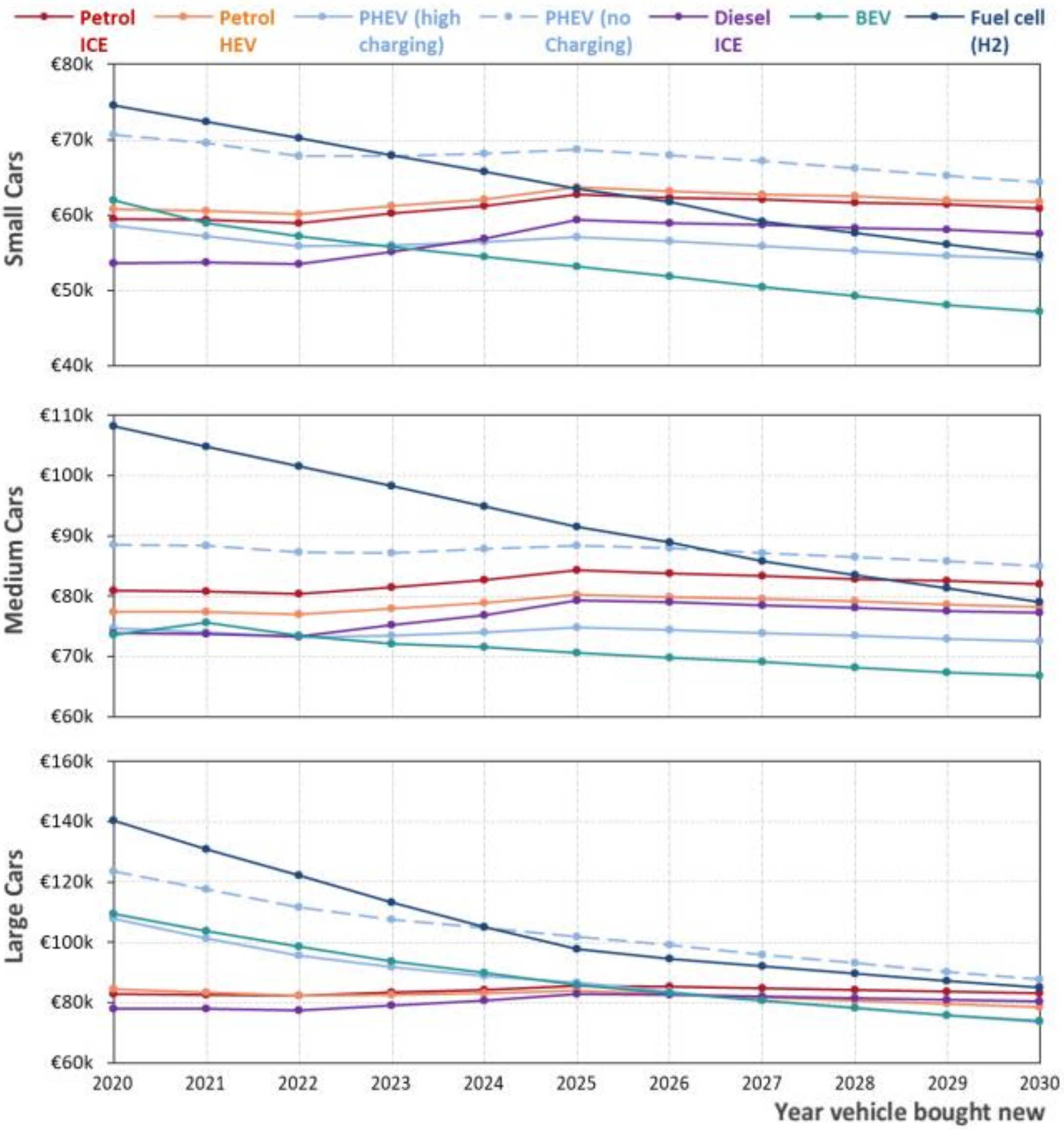
Infrastructure investment costs were also an important point identified along this study. Previous works have failed to analyse what would the costs of installing and implementing a HRS grid would be, especially when comparing with existing technologies in the market and their infrastructures

The impact of the COVID-19 pandemic on hydrogen projects and investments could also be subject a future work. The economic instability effects of the successive quarantines and the rise of component and construction costs could be analysed.

The effects of the Ukrainian-Russian war at the start of 2022 on the energy market could also be analysed, as the steep variations in the cost of oil and gas have generated increased commitments from governments and the EU for increased energetic independency and investment in carbon neutral solutions such has hydrogen. Therefore, a future analysis on the impacts of the war in the Portuguese and EU hydrogen policies would be a valuable literature addition.

An acceptance study targeting the users of the technology, that is, possible drivers of H_2 powered vehicles could provide an interesting addition to this study. It would also confirm the concerns and conclusions made in the enquiries.

6 APPENDIX



Annex *1: TCO predictions comparing different powertrains*

Interviews with key players of the Portuguese mobility industry

Company sustainability

1. Do you consider that companies have an essential role in promoting a more sustainable environment and eco-friendly technologies?
2. Can companies be the first promoters of a new technology, promoting its adoption by the public?
3. What sustainable measures has your company adopted in recent years, regarding the mobility sector?
4. Would you be willing to pay more so that your company would use environmentally friendlier technologies than the one at use, as of now? (Such as H2)

Hydrogen technology

5. Are you familiarized with H2 technology?
6. Which do you consider to be hydrogen's positive aspects?
7. Which do you consider to be hydrogen's negative aspects?
8. Do you think that hydrogen will contribute to a reduction in emissions?
9. Do you recognize hydrogen's potential in storing excess grid energy?
10. Can hydrogen, in certain situations, supply electricity to equipment's without being connected to the grid? Are you aware of this possibility?

Hydrogen technology in the transportation sector

11. Do you consider hydrogen that hydrogen is a viable solution when compared to its alternatives in the transportation industry?
12. In your opinion, what are the factors that would contribute the most to a more widespread use of H2 in the transportation sector?
13. What do you think could be done to improve user confidence in using H2 vehicles?

Technology adoption in the company

14. Do you consider important the investment/adoption of hydrogen technologies for your company? Why?
15. Do you anticipate/did you anticipate any difficulties or problems related to the adoption of hydrogen in your company?
16. How do you think will be managed the introduction of the technology in the company?
17. How will it be/was hydrogen introduced to the workers of the company? Will there be/was there any seminars? If yes, to what type of workers?
18. Regarding the feedback from your workers to technologies introduced in recent years in your company, how do you expect them to react to hydrogen by comparison?
19. What do you think that could be done to improve workers trust in in hydrogen powered vehicles?
20. Do you consider that your company is ready to accommodate hydrogen infrastructure?
21. What kind of tests or services do you require to support the usage of 100% hydrogen powered transport?
22. Is the investment necessary to buy and adopt H2 vehicles as well as to create the necessary refuelling infrastructure viable for your company at this moment?
23. Regarding hydrogen in general, what other professional areas that interest you the most?
24. In your opinion would you prefer that the hydrogen your company consumed to be originated from a centralized production unit (Off-site), or locally produced (On-site production)
25. Are you concerned with the safety of the refuelling process?
26. Are you aware of ongoing projects/investigations regarding hydrogen in the transportation sector? Which?

Annex *2 : Interviews with key players of the Portuguese mobility industry*

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