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Evaluation of Levelized Cost of Hydrogen (LCOH) produced by wind electrolysis: Argentine and Italian production scenarios

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Abstract

The work done in this thesis shows the methodology for evaluating the Levelized Cost of Hydrogen (LCOH) starting from production till delivery at Italian Hydrogen Refueling Stations (HRS), by means of PEM (*Proton Exchange Membrane* or *Polymer Electrolyte Membrane*) electrolysers. The energy exploited for electrolysis is wind energy (i.e. a renewable source), so it ensures the production of hydrogen actually green, differently from conventional production categories such as steam methane reforming and coal or biomass gasification. It was decided to size the study by assuming a national demand for hydrogen needed to meet a market penetration of 1% hydrogen cars. Respected sources have estimated that Italy will reach 1% of hydrogen powered vehicles shortly after 2030[1,2]

Two macro-scenarios have been analysed: a first scenario of Argentinian production, in Patagonia region, where a huge wind potential at low-cost can be exploited[3,4], and a second production scenario directly in Italy, saving of ocean transport expenses but with a higher cost for wind production energy.
Three kinds of storage and transport methodologies were evaluated: hydrogen in the compressed gaseous state (CGH2), hydrogen liquefied by cryogenics at -253 °C (LH2) and hydrogen bound to a Liquid Organic Hydrogen Carrier (LOHC), which allows to transport hydrogen at room temperature and pressure. Sensitivity analysis were also carried out for all scenarios analysed.

Results obtained show that the total cost of hydrogen is lower in the Argentine production scenario. Low production costs due to low wind energy costs and high capacity factors make it more competitive despite ocean transport.
The final levelized cost of hydrogen [€/kgH_2] obtained from scenarios allowed to assess the fuel economy convenience of a hydrogen FCEV (Fuel Cell Electric Vehicle) with respect to cars of the same segment with gasoline or hybrid (gasoline/electric) motorization.

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Chapter 1

INTRODUCTION

1.1 Background

Global energy related CO_2 emissions peaked in 2018 despite international climate targets. Air pollution is an urgent problem to solve. About 3 million people die for this reason every year.[5]

In the field of energy and climate the leaders of the European Union (EU) have set ambitious targets for 2020 and the EU is the first region in the world to have adopted binding rules to ensure that they are achieved. The fight against climate change is one of the five main themes of the global Europe 2020 strategy for smart, sustainable and inclusive growth.[6] In particular, the strategy aims to ensure that, by 2020, EU greenhouse gas emissions are reduced by 20% compared to 1990, 20% of energy comes from renewable sources and there is an increase in energy efficiency of 20%.

In October 2014, EU leaders intensified their commitment to making the Union's economy more competitive and to strengthening the security and sustainability of its energy system by adopting the 2030 energy and climate framework.[7] A central element of the framework is the binding target of reducing the EU's domestic greenhouse gas emissions by at least 40% below 1990 levels by 2030, and the increasing in energy efficiency of

32.5%. EU leaders agreed on the target of increasing the share of renewable energy to at least 32% of EU energy consumption by 2030.[8]

In the long-term, in addition to limiting global warming to less than 2 °C, the EU has committed itself to reducing emissions by 80-95% compared to 1990 levels by 2050.[9] By the middle of the century, energy should be almost 100% carbon-free, ensuring the technological neutrality of the solutions adopted, including the use of traditional energy sources with carbon capture technologies.

Italy is the country in the European Union with the most premature deaths due to air pollution. In Italy in 2015 60,600 premature deaths are attributable to fine particulate matter (PM 2.5), 3,200 to ozone (O_3) and 20,500 to nitrogen dioxide (NO_2).[10]

The air quality report published by Legambiente[11] shows that in Italy the problem of air pollution is widespread and has reached a chronic level. The report analysed pollution levels in 90 Italian cities. It has emerged that during 2015 in more than half (53%) the level of PM10 exceeded the limit, set by law at 50 micrograms per cubic meter not to exceed more than 35 times in a year. Italy leads the sad European list of deaths from nitrogen dioxide, even on ozone is first in Europe, while on fine particles, also emitted by the combustion of biomass, it shares the first position with Germany.[12]

1.2 Hydrogen: a key role in the future

The use of hydrogen as an energy carrier is beginning to emerge worldwide. Hydrogen is an energy carrier and not an energy source: although hydrogen as a molecular component (for example in water such as H_2O or methane such as CH_4) is abundant in nature, it is necessary to use energy to generate pure hydrogen (H_2). Hydrogen is a flexible energy carrier with potential applications in all energy sectors. In addition, it is one of the few potentially zero-emission energy carriers, along with electricity and advanced biofuels. In addition, the production of hydrogen from electricity and its storage is a valid option to increase the flexibility of the energy system, allowing the integration of high shares of non-programmable renewable sources such as photovoltaic and wind.[2]

Hydrogen is a promising long-term technology in many sectors: industrial applications, transport, building heating, cooling and electricity could potentially exploit hydrogen if production and use costs become profitable compared to other alternatives. The power sector could use hydrogen or hydrogen-rich fuels such as ammonia to produce electricity.

The competitiveness of FCEVs depends on the costs of fuel cells, the deployment of refueling stations and the cost of hydrogen storage on board. The reduction of the cost of delivery of hydrogen impacts more on the competitiveness of hydrogen trucks.[5]

Thanks to its versatility, it is reasonable think that hydrogen will play a leading role in a low-carbon global economy. Today's technologies already allow hydrogen to produce, store, move and use energy in different ways. Its production is possible with a wide variety of sources: natural gas, oil, coal, nuclear and even renewable sources. It can be transported in gaseous, liquid form, bound to other organic compounds. Transport can take place via pipelines, or on trucks, ships, such as other fuels such as natural gas, LNG, gasoline, diesel.[5]

To accelerate the growth and spread of hydrogen, governments need to work in a coordinated way. This will stimulate investment in infrastructure, increase knowledge and reduce costs. Hydrogen trade will benefit from common international standards.[5]

1.3 How is hydrogen produced?

Every year about 70 million tonnes of hydrogen are produced on our planet. Around 275 Mtoe of energy are used to produce hydrogen today (2% of global total primary energy demand).[5,13] Hydrogen is almost entirely used as a raw material in the refining and chemical industries. In Italy the demand for hydrogen represents about 0.9 % of world demand, about 0.448 Mt per year of hydrogen [Freedonia Group, 2011].

There are various technologies capable of separating hydrogen from the other chemical elements with which it is naturally associated. Hydrogen can be produced from different primary or secondary energy sources. Primary energy sources useful to produce hydrogen include renewable sources, such as biomass, but also fossil fuels, such as natural gas and coal. Electricity can be used to produce hydrogen, through the electrolysis process that allows the separation of water (H_2O) into its hydrogen and oxygen components.

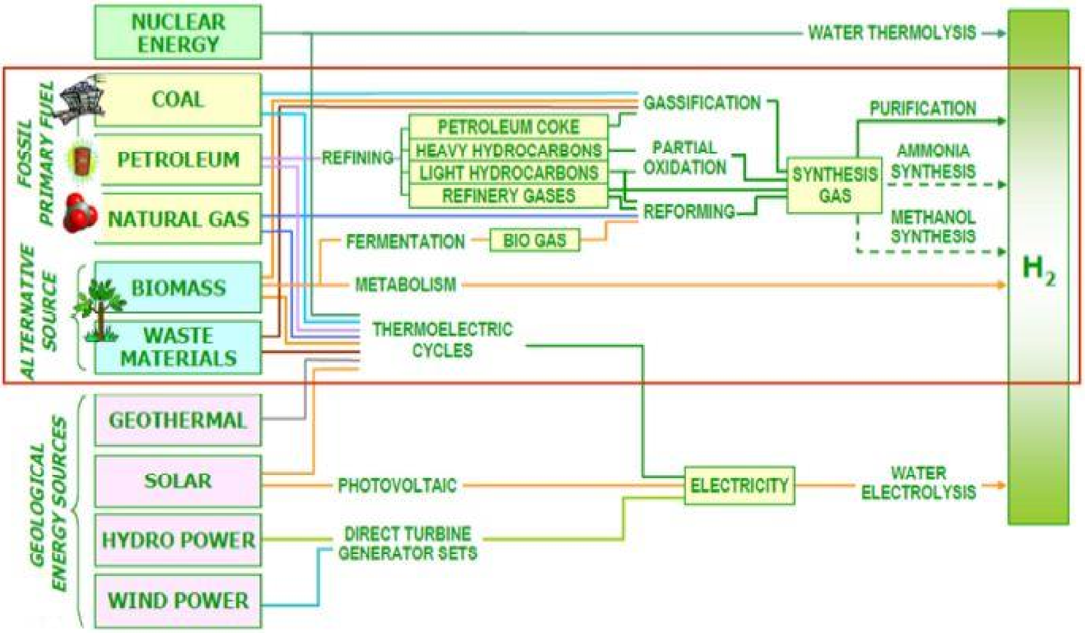


Figure 1: Sources and production paths of hydrogen [14]

About three-quarters of the total hydrogen produced come from natural gas and almost all the rest (23%) from coal. The annual production of hydrogen therefore consumes 6% of the global use of natural gas and 2% of the global use of coal, with the latter mainly used in China. As a result, 830 Mt CO_2/year are produced corresponding to the annual carbon dioxide emissions of the United Kingdom and Indonesia combined.[5]

Hydrogen can be produced from natural gas by SMR (Steam Methane Reforming), from coal by coal gasification and reforming, from biomass by gasification and reforming and finally from electric energy by electrolysis.

Around 48% of the world's hydrogen used in the refining, raw material and industrial gas industry is currently produced from natural gas through the Steam Methane Reforming Process (SMR).[15] This process is based on a reaction between methane and high temperature water vapour in the presence of a catalyst.[16] The concentration of CO_2 in the exhaust gases is high, for this reason SMR plants are promising candidates for the application of CCS (Carbon Capture and Storage) technology, which could lead to an 80% reduction in carbon emissions.
The share of hydrogen produced worldwide by electrolysis amounts to 2%, which is expected to rise in the future. As costs fall, more and more hydrogen will be produced from renewable sources in regions of abundance of cheap resources.[5]

Hydrogen itself does not contain carbon, when used in a fuel cell, water vapor is the only exhaust. However, considering the entire life cycle, hydrogen can have a significant environmental impact, its carbon dioxide emissions are determined by the primary energy source and the process used to produce hydrogen. These emissions must be considered when selecting the most appropriate production methods to meet the increasingly stringent environmental and climate objectives.[2]

Nowadays, to distinguish the different resources used to produce hydrogen, colours are used. Black hydrogen is hydrogen produced from coal, grey from natural gas and brown from lignite. Blue hydrogen refers to hydrogen produced from fossil fuels and subsequently subjected to CCUS to reduce CO_2 emissions. When production is from renewable sources, hydrogen is green. There is no colour association to indicate hydrogen produced from biomass, nuclear or grid mix electricity.[5]

1.4 Hydrogen from electrolysis

1.4.1 Overview

Electrolysis is a process of splitting water into hydrogen and oxygen, applying a direct current it is possible to convert electrical energy into chemical energy. Currently, the worldwide installed capacity is around 20 GW in 2018[17].

Production of hydrogen by electrolysis costs two to five times more than production by SMR.[13] However, a further aspect must be considered: the possibility of producing hydrogen in a completely renewable and carbon-free way (green hydrogen if produced by renewable electricity such as hydroelectric, photovoltaic, wind).

Electricity from renewable sources is a viable sustainable alternative to using grid electricity to produce hydrogen. Both photovoltaics and wind are facing a decrease in costs, therefore exploiting these resources in places where there is great availability and foreseeing the construction of electrolyser systems could represent an economic and clean method to obtain hydrogen also considering the transmission and distribution costs of the latter from remote locations where green production takes place towards end uses.[5]

The production of hydrogen from electricity with the possibility of transporting and storing it could be a valid option to increase the flexibility of the energy system, allowing the use of high shares of non-programmable renewable sources (photovoltaic, wind).[2]

In different areas of the globe, projects are being carried out or are being launched to produce hydrogen from renewable sources. Promising areas exist, for example, in Patagonia, New Zealand, Northern Africa, the Middle East, Mongolia, most of Australia, and parts of China and the United States.[5]

Argentina has one of the highest wind potentials in the world, estimated in over 2000 GW. In the provinces of Buenos Aires and Cordoba, there is a good potential for wind energy production but is very well known that Patagonia is the windiest region of the country.[4] Precisely for this reason, as will be seen later, one of the macro-scenarios of this thesis, will provide to produce green hydrogen by electrolysis with wind energy in Argentine Patagonia.

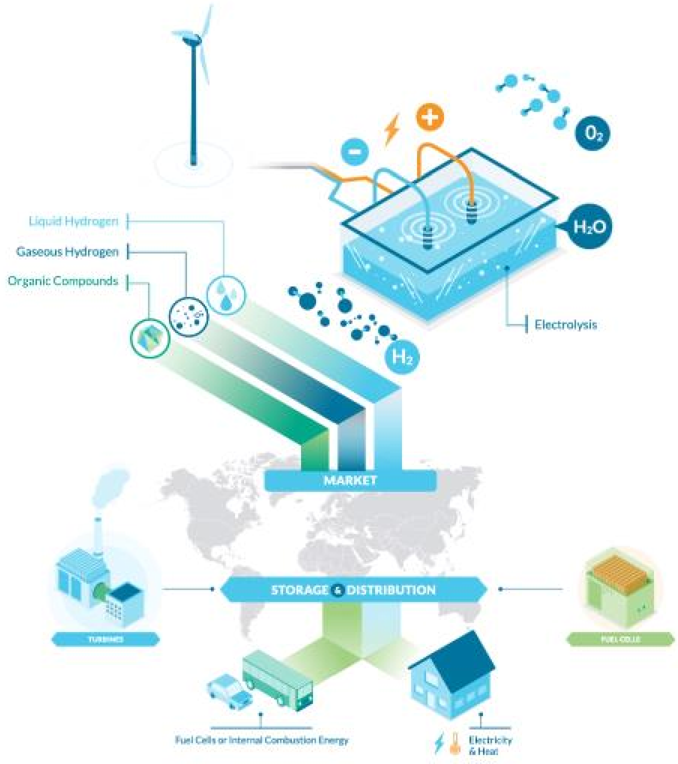


Figure 2: Wind to Hydrogen scheme [Hychico] [18]

Hydrogen-based technologies are suitable for large-scale energy storage applications. This approach is referred to as *Power to Power* (P2P) where the electric carrier is transformed into hydrogen by electrolysis, stored and re-electrified when necessary by fuel cell. However, the *power to power* paradigm is not the only one possible, you may have:[2]

- *Power to Gas*: the electric energy is transformed into hydrogen by electrolysis, it is then mixed in the natural gas network or transformed into synthetic methane;

- *Power to Hydrogen*: electricity is transformed into hydrogen used as a fuel for FCEV in the transport sector or used directly as a raw material, for example in the refining industry or in the chemical industry.

Different types of electrolysers are distinguished by their electrolyte and charge vector, and can be grouped into alkaline electrolysers, PEM electrolysers and solid oxide electrolysers (SOEC). Alkaline electrolysers are currently the most mature technology and investment costs are significantly lower than other types of electrolysers. However, the PEM and SOEC electrolysers have a higher future potential for cost reduction and efficiency improvements. In the last ten years there has been an increase in installations of electrolysis systems with the aim of producing hydrogen, with the PEM technology that has become the protagonist of great steps forward.[5]

1.4.2 PEM Electrolyser

Below is a brief description of the structure and operation of a PEM electrolyser.[19]
PEM electolyzer is composed of a series of electrolytic cells. An electrolytic cell (Figure 3) is an electro-chemical cell in which a not spontaneous reaction (with $\Delta G > 0$) is driven by electrical power. Electrical energy is transformed into chemical energy associated to a chemical element/compound, in this case hydrogen.

Water is supplied at the *anode*, the positive charged electrode, where with the help of the catalyst, OER (oxygen evolution reaction) occurs. Water is oxidized to oxygen and reacts delivering protons (ions H^+) and electrons (e^-).

$$H_2O^{(l)} \rightarrow 2H^+ + \frac{1}{2}O_2^{(g)} + 2e^- \tag{1.1}$$

H^+ ions cross the proton exchange membrane and reach the cathode, the negative charged electrode. Electrons reach the cathode as well, but they pass into the external electric circuit.
At the *cathode*, thanks to another kind of catalyst, reduction of H^+ happens and hydrogen is formed. This is HER (hydrogen evolution reaction):

$$2H^+ + 2e^- \rightarrow H_2^{(g)} \tag{1.2}$$

It can be written the total reaction:

$$H_2O^{(l)} \rightarrow H_2^{(g)} + \frac{1}{2}O_2^{(g)} \qquad (1.3)$$

The proton exchange membrane or polymer electrolyte membrane (PEM, Figure 4) let ions H^+ pass through it, while it is impermeable to molecules of hydrogen and oxygen, therefore electrolyte layer should be characterized by very low molecular diffusivity, very high capability to conduct ions. Moreover, it should be a good electrical insulator to avoid the conduction of electron which must go through the electrical circuit.
The electrolyte of a PEM is usually a material called Nafion®. It is obtained by adding to the molecule of Teflon a lateral branch which ends with a hydrogen sulfite (HSO_3^-). In this chemical group there is a very weak bond linking H^+ ions and SO_3^-. This give rise to high mobility of H^+ in the electrolyte layer.

Gas Diffusion Layer (GDL) is a porous layer constructed from graphite with a porosity of about 70%. Its function is to transport the water to the reaction site (catalyst layer or active layer) and remove products (hydrogen and oxygen) from it. In addition, GDL collects and transports electrons towards the external circuit thus its material needs to have good electrical conduction.

The electrolyte and two electrodes are sandwiched between two bipolar plates, which transport water to them, transport product gases, H_2 and O_2, away from the cell, conduct electricity, and circulate a coolant fluid to cool down the process.[20]

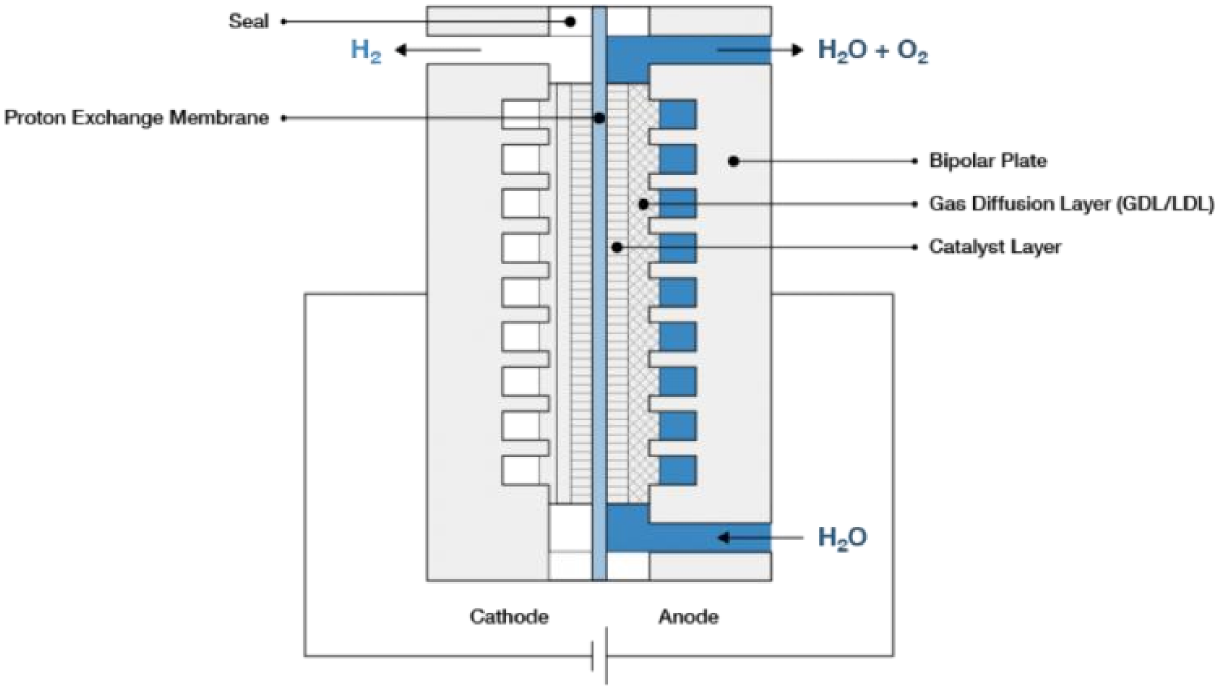


Figure 3: PEM Electrolyser Cell [20]

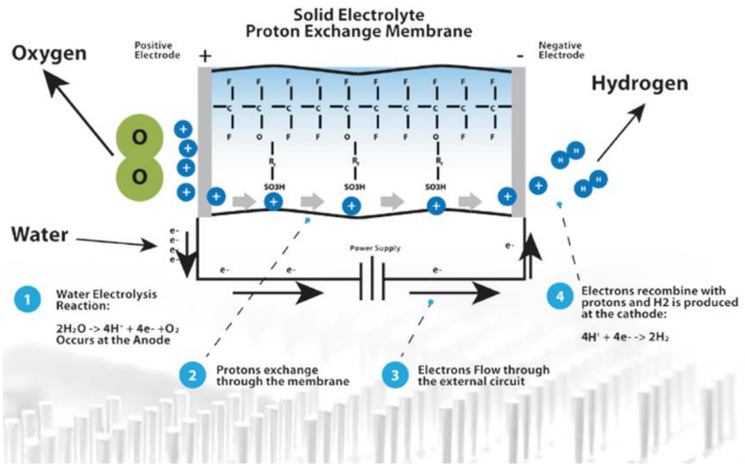


Figure 4: Solid Electrolyte Proton Exchange Membrane [21]

1.5 Towards a sustainable mobility

In the transport sector, supporting innovation and efficiency, curbing dependence on oil imports and driving the switch to domestic and renewable energy sources is the way forward to achieving the key European objectives: stimulating economic growth, increasing employment and mitigating climate change.

Transport in the European Union is heavily dependent on fossil fuels, in 2014 oil-derived fuels accounted for about 96% of the sector's total energy supply, 86% of which were imported.[22] Europe is a major importer of oil, nearly 8 billion barrels of crude oil were imported in 2018.[23] Italy has a degree of energy dependence among the highest in Europe, 76.9% in 2013, in continuous decline up to 74% in 2018.

Achieving the EU's climate change targets will require a drastic reduction in transport emissions, the production of which currently accounts for at least 30% of EU greenhouse gas emissions, 72% of which are attributed to road transport.[24]

In this context, to reduce global greenhouse gas emissions by 80% and thus contain climate change within safety limits, the transport sector must cut emissions by 60% by 2050 (compared to 1990 levels).[9]

Reducing transport emissions is therefore a key element of EU policy, supported by numerous projects and initiatives, including developing and encouraging the use of alternative non-petroleum fuels. A quarter of the EU's greenhouse gas emissions from transport are produced in urban areas, so large and small cities play a key role in mitigating climate change. Many of them also have to deal with congestion and improve air quality, which is currently unsatisfactory.

The European objectives of reducing fossil fuel energy consumption, reducing CO_2 emissions and improving air quality and reducing noise can be achieved through three key actions:[2]

1. avoiding private transport, for example through better urban planning and a significant increase in telework;
2. shifting demand for transport to more efficient modes, such as public transport and rail freight;

3. improving transport technologies
    a. increasing the efficiency of traditional technologies
    b. promoting the rapid deployment of alternative vehicles including BEV, FCEV, PHEV and biofuels including biomethane in both liquid and gaseous forms of mobility.

Historically, Japan and the European Union have led the reduction of emissions in the transport sector, it is expected that this leadership will continue in the future. This must be achieved through several strategic initiatives, including through the development of a sustainable alternative fuel strategy and related infrastructure. Electricity, hydrogen, biofuels, natural gas and liquefied petroleum gas (LPG) have now been identified as the main alternative fuels with long-term potential in terms of an alternative to oil also in view of their possible simultaneous and combined use by, for example, systems using dual-fuel technology.[2]

The coordination of the policy frameworks of all Member States should ensure the long-term safety necessary to encourage public and private investment in alternative vehicle and fuel technologies and for infrastructure construction, in order to pursue the dual objective of minimising dependence on oil and mitigating the environmental impact of transport. Hydrogen-powered vehicles currently have very low market penetration rates; the construction of sufficient hydrogen refuelling infrastructure is therefore essential to enable them to be widely disseminated.[2]

1.6 Hydrogen mobility

1.6.1 Overview

Hydrogen can play a decisive role in the future of road transport and related urban air quality: electric fuel cell vehicles (FCEV) emit neither CO_2 nor other pollutants that are particularly harmful to human health (NO_2, fine dust). To these important benefits is added an effect, albeit minor, purification of the air sucked by fuel cell systems. The latter is in fact equipped with extremely selective filters to avoid the entry of dust and all types of contaminants into the fuel cells.

In the field of light transport, FCEV vehicles can provide a transport service comparable to today's vehicles, in terms of refuelling times and range: currently, for cars, the efficiency on the road is about 1 kg of hydrogen per 100 km travelled, with autonomies from about 500 km to 750 km and fuel times less than 5 minutes. For buses the daily autonomies arrive up to 450 km, with consumption efficiencies of about 8-9 kgH_2/100 km, the refuelling times are less than 10 minutes. Despite the high costs to date, it is expected that these converge by 2030 with that of other power technologies thanks to economies of scale. As a confirmation of interest, the world's leading car manufacturers have already integrated hydrogen fuel cell technology into their strategic plans.[2]

Even in mass public transport there are interesting applications with more than 300 FCEV buses already operating and with strong development potential (China, USA, and Europe).[25]

In the field of heavy transport, vehicles will be responsible for an increasing share of greenhouse gas emissions. In the rail sector too, fuel cell powertrain locomotives are already competing with the existing diesel-powered locomotives in terms of performance and service guarantee. In some cases, they are even economically competitive, as reported and demonstrated by several European studies[5,26].

Within the maritime sector, fuel cells begin to show considerable potential in the field of electricity production, both for propulsive purposes and as APU (Auxiliary Power Units), despite there are serious barriers to overcome in terms of: power density requirements and reduced installation space on board.[2]

The alternative mobility to hydrogen includes types of vehicles even far from common use, such as “material handling”, also defined as industrial logistics. This represents a considerable proportion of the industrial equipment used to date in which hydrogen can play an important role.[2]

1.6.2 Fuel Cell

The fuel cell is the generator capable of converting the chemical energy of hydrogen into electricity and heat. This reaction occurs within a system consisting of two electrodes, the anode and the cathode, separated by an electrolyte. Among the different types of fuel cells currently existing, the PEMFC (Proton Exchange Membrane Fuel Cell) offer the most promising performance (Figure 5). PEMFCs are composed of layers of membranes, each of which is inserted between two conductive plates. At the anode the hydrogen molecules come in contact with the membrane and the electrochemical reaction is activated by a catalyst consisting of nano platinum particles. The molecules are then decomposed into two protons and two electrons. While protons can pass through the membrane and pass to the cathode electrons cannot and enter an electric circuit (which in an FCEV car feeds the electric motor). At the cathode, protons react with oxygen and electrons to generate electricity and water, the only substance released by the system.[2]

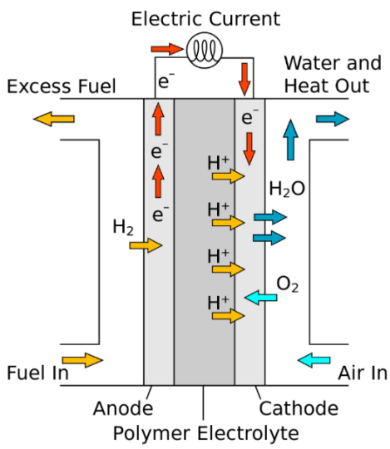


Figure 5: Diagram of a PEM Fuel Cell [27]

Although fuel cells have developed significantly over the past decade, high investment costs and relatively limited lifetimes remain the main obstacles to their wider application.

Investment costs depend heavily on production costs and could be significantly reduced with economies of scale. According to the US DOE 2012, the PEMFC systems for FCEVs show the greatest potential for reducing high production volume costs.[28]

Polymer membrane fuel cells (PEMFC) are the most widely used type of fuel cells in transport, thanks to their many advantages: no pollutant emissions and CO_2, high compactness, fast start-up times. Another point of interest concerns the development of high temperature fuel cells, in particular solid oxides (SOFC): this type of cell, although it has not yet reached the maturity of PEMFC in transport, has some important potential benefits, such as increased efficiency, especially when used in cogeneration systems, and the possibility of being fuelled by fuels other than pure hydrogen (such as natural gas or biomethane): for this reason, they can be an important solution for the near future.[2]

1.6.3 Light Duty FCEV

FCEVs are essentially electric vehicles that use hydrogen stored in a pressurised tank and a fuel cell for on-board power generation. FCEVs are also hybrid cars in which the braking energy is recovered and stored in a battery. The battery power supply is used successively to reduce peak fuel cell demand in acceleration and to optimize operational efficiency. FCVEs are usually refuelled with gaseous hydrogen at pressures between 350 bar and 700 bar. However, the 700 bar tanks allow much higher autonomies at acceptable volumes, the latest vehicles are in accordance with this technological choice. Currently, for cars, the fuel economy is about 1 kg of hydrogen per 100 km travelled, with autonomies from about 500 km to 750 km and refuelling times less than 5 minutes.

Although the costs of FCEV vehicles are now high (about 60,000 € the average price), the cost is expected to converge by 2030 with that of other power technologies (Figure 6), thanks to economies of scale.[29]

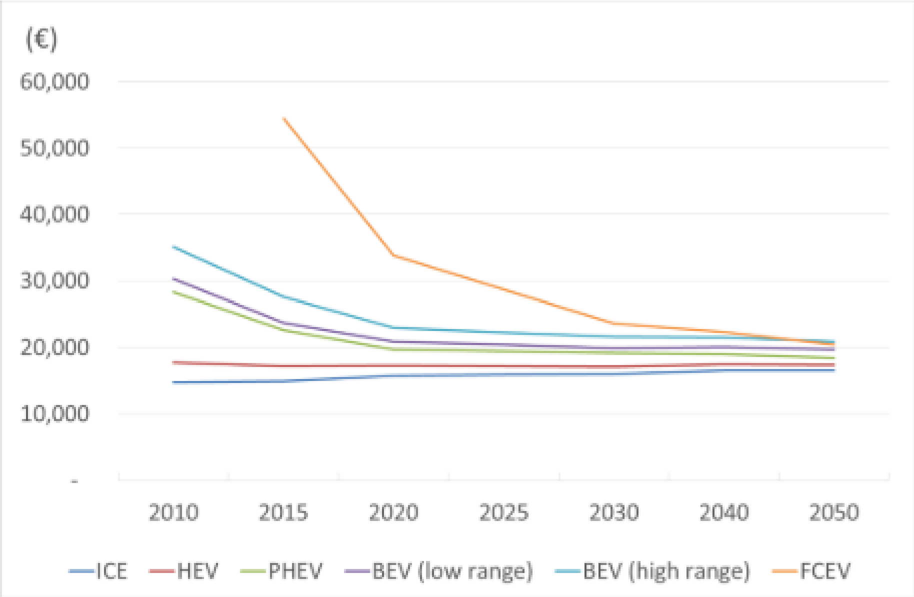


Figure 6: Car cost forecast by fuel technology in Europe [29]

Confirming the interest in FCEV technology, the world's largest automotive companies have already integrated hydrogen fuel cell technology into their strategic plans. Most of these manufacturers have started to invest in research and development in the last twenty years, from the first prototypes has passed quickly, in the last few years, to production on a commercial scale. Asian manufacturers, Honda, Hyundai, Toyota deserve attention.[2]

In terms of diffusion, IEA sources count as in circulation about 12,952 fuel cell vehicles in the world in 2018 (cars, buses, trucks, etc.) distributed as follows: 42% in North America, 43% in Asia (2926 in Japan, 900 in Korea and 1791 in China) and the remaining 11% in Europe (487 in Germany, 324 in France and the remaining divided among the other countries of the community).[30] It should be noted that although in the rest of the world fuel cell vehicles are generally used for passenger transport, in China, the main application is for commercial vehicles.

Honda FCX Clarity is a hydrogen FCEV car produced by Honda. Production began in June 2008, being the first hydrogen fuel cell vehicle available to retail customers. In 2013, Honda and General Motors signed an agreement for the shared development of fuel cell technology. In the first months of 2016 Honda introduced a new model on the international market, with a range of 750 km, a figure better than the previous version 30%.[2]

Hyundai has realized the first plant in the world for the series production of hydrogen vehicles, inaugurated in January 2013 for the production of 1000 *Hyundai ix35 Fuel Cell*. Hyundai aims to sell more than 10,000 FCEVs vehicles in South Korea by 2025.[2]

Toyota launched its *Mirai* model at the end of 2014 (which in Japanese means "future"). As of 2019, 9,685 were sold worldwide, of which 3,183 in Japan and 6,502 in the rest of the world. In North America, 5,888 and 599 in Europe. Six units were marketed in Italy. In 2020, the second generation of Mirai was launched: thanks to the improvement of the fuel cell system and the use of larger hydrogen tanks, increased its autonomy by 30%. It passed from two tanks with a total capacity of 4.4 kg to three tanks with a total capacity of 5.6 kg, which provide a range of 650 km.[2,31]

Regarding the European companies, Mercedes presented in November 2018 the new *Mercedes GLC F-Cell* that has two carbon fiber tanks with a capacity to store 4.4 kg of hydrogen and that can be filled in just 3 minutes.[2]

On the Italian side, FCA also has experience in the FCEV sector. The *Fiat Panda Hydrogen* is an FCEV prototype, built by the Turin company in 2005 with the support of the Ministries of Research and the Environment. The advanced development of this model took place within the "Zero Regio" project, funded by the European Commission, in implementation of the "VI Programma Quadro", with the aim of promoting mobility with low environmental impact.[2]

The number of FCEV cars proposed in the Scenario Mobilità H2IT is shown in Figure 7 for the Italian context. The sale scenario in Italy of FCEV cars aims to reach a stock of about 27,000 to 2025 (0.1 % of the Italian fleet), about 290,000 to 2030 (0.7 % of the Italian fleet) and about 8.5 M (20 % of the Italian fleet) to 2050. The economic barriers linked to the higher cost of hydrogen vehicles compared to conventional vehicles and the creation of production and distribution infrastructure need adequate funding, where specific national funds will have to accompany European funds.[2]

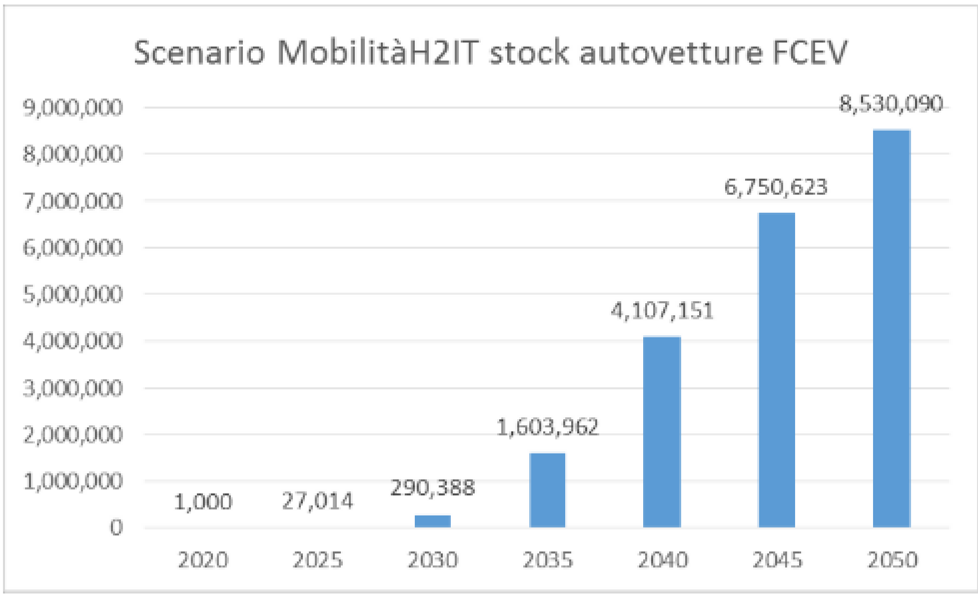


Figure 7: Stock FCEV cars up to 31/12/2050 [2]

1.6.4 Hydrogen Refueling Stations (HRS)

The advantages of hydrogen in the supply of vehicles are also evident in terms of refuelling infrastructure. Ensuring a minimum density of hydrogen refuelling stations and satisfying demand are two basic prerequisites for achieving consumer interest and ensuring a broad market for fuel cell vehicles and vehicles. The design characteristics of a hydrogen refuelling station are determined by the daily hydrogen demand, hydrogen storage mode in vehicles (such as pressure at 350 bar or 700 bar) and the way hydrogen is delivered or produced at the station. For passenger cars, very small stations with a capacity of 50-100 kg/day of hydrogen may be needed in the early stages, in a mature market stations up to at least 500 kg/day will be required.[2]

There are, however, strong economies of scale. The IEA argues that increasing the capacity of a station from 50 to 500 kgH_2/day can lead to a reduction of the specific cost of production of the kg of hydrogen (and consequently the cost of sale) by 75%. The use of the refueling infrastructures is another determining factor for the future competitiveness of the FCEVs. The risk of underused hydrogen refueling stations underlines the importance of ensuring high usage to cut costs in the early stages of FCEVs deployment. Only private industries can implement the necessary supply infrastructure, and car manufacturers will only be able to develop and market FCEVs if a minimum distribution network is planned and implemented. However, private industries alone, without public support, cannot assume the full financial risk. Finally, governments will have to clearly introduce the role of hydrogen in national energy strategies, underlining its potential to reduce greenhouse gas emissions, air quality benefits, and decrease in energy dependency.[2]

Hydrogen stations are currently in a phase of market introduction. The main elements of a hydrogen refuelling station are a compressor, hydrogen storage, pre-cooling/refrigeration equipment, and distributors. Currently, 3 hydrogen refuelling stations are operating in Italy: Bolzano (the only station with a 700-bar plant for car refuelling), Milan and Catania, the latter suitable for the supply of public transport with facilities at 350 bar. In addition, three other stations have been built in Rome, Mantua, Livorno and Sanremo but are not yet operational.[2]

Figure 8 shows the filling stations currently present on Italian territory (in operation, in green and not active, in red), those planned for 2020 (blue) and for 2025 (yellow).

Figure 8:Map of HRS in Italy at 31/12/2025 [2]

Hydrogen filling stations can be supplied in two different ways:

1. On-site hydrogen production directly at the refueling station;
2. Production of hydrogen in centralised plants and transport to the refuelling station.

Every approach has its advantages and compromises. While centralized hydrogen production offers economies of scale to minimize the cost of generating hydrogen, the need to distribute hydrogen entails transport costs. The exact opposite is true of decentralized hydrogen generation. With a view to increasing electricity production from renewable sources, it seems strategic to locate the production of hydrogen from electrolysis near production sites from renewable energy sources (RES).[2]

1.6.5 H_2 storage in the FCEVs

Among the energy carriers, hydrogen has a high energy content per unit mass (120 MJ/kg), equal to about two and a half times the methane (50 MJ/kg) and almost three times the diesel (44,4 MJ/kg) and petrol (43,6 MJ/kg)[32]. However, referring to the volumetric content, the situation is reversed because hydrogen, due to its low density (it is the lightest element), has a reduced energy content in terms of volume: this is one of the major disadvantages if hydrogen is to be used as a fuel for mobile transport applications.

To try to overcome this problem, storage systems aimed at increasing the volumetric density of hydrogen have always been studied. The most commonly used methods are storage in high pressure cylinders (up to 700 bar or more), or in the form of liquid. The storage of cylinders allows to obtain good energy densities per unit volume, which can be further increased in case of storage in liquid form. So-called LOHC (Liquid Organic Hydrogen Carriers) are also a family of technologies, currently under study experimentation, promising to limit the problems of pure hydrogen storage. However, as shown in Figure 9, the energy density of hydrogen in terms of volume is still lower than that of other fuels, whether in the form of gas (methane) or in liquid form (LNG, methanol, diesel).[2]

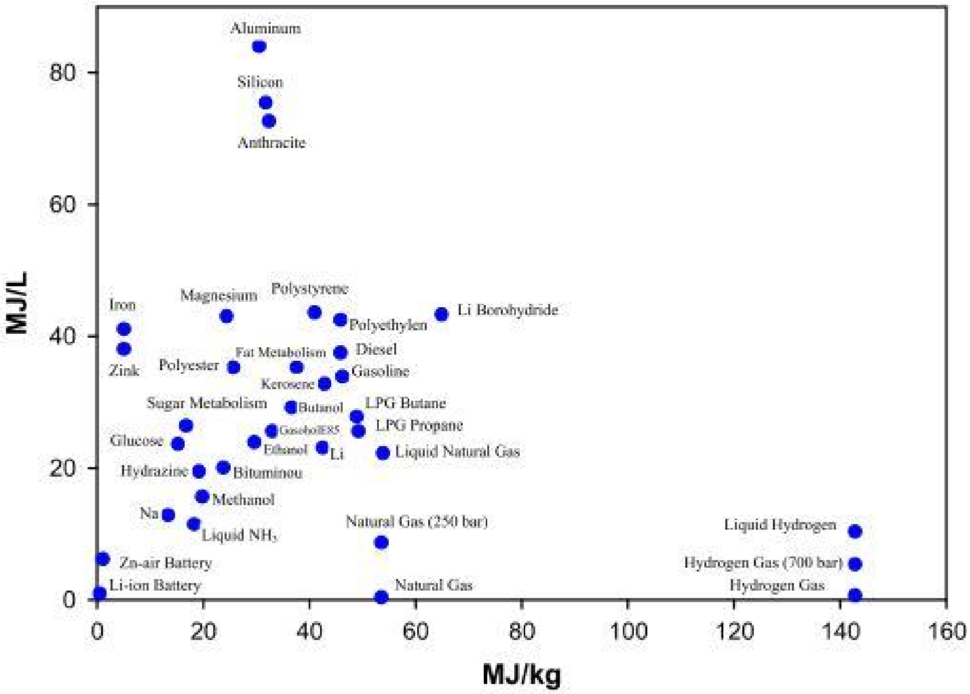


Figure 9: Volumetric vs Gravimetric energy density of a group of materials and technologies [33]

Hydrogen can be stored in gaseous form at constant temperature. The easiest way to decrease its volume is to increase its pressure, this process requires energy (with efficiencies usually between 80 and 91% for compression at 70 MPa). The current preference for automotive applications is 70 MPa compression, at this pressure hydrogen has a density of 42 kg/m^3.[2]

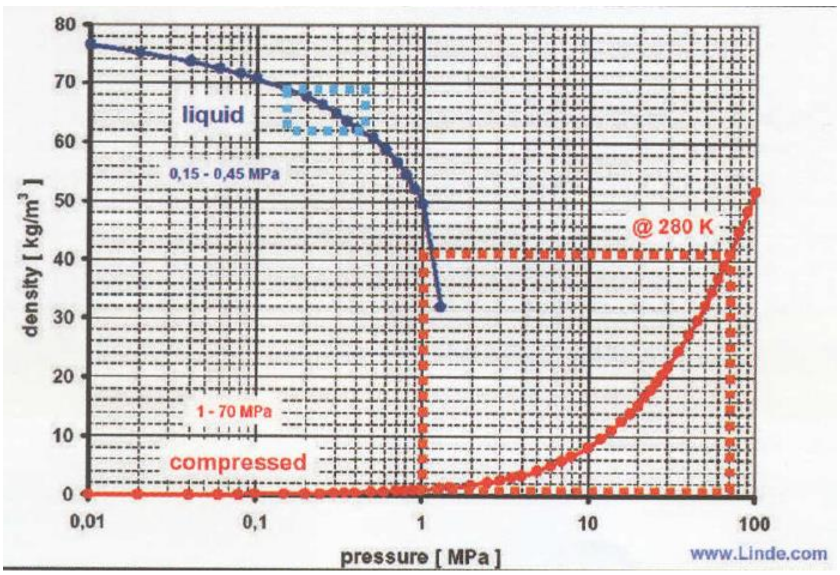


Figure 10: H_2 Density vs Pressure [34, from Linde.com]

Even at very high pressure, gaseous hydrogen has a density much lower than liquid hydrogen which is about 71 kg/m^3 at ambient pressure and -253 °C (hydrogen liquefaction temperature).

Hydrogen storage performance in terms of energy density (kWh/m^3) and specific energy (kWh/kg) are far better than those of electrochemical storage, namely batteries.[2]

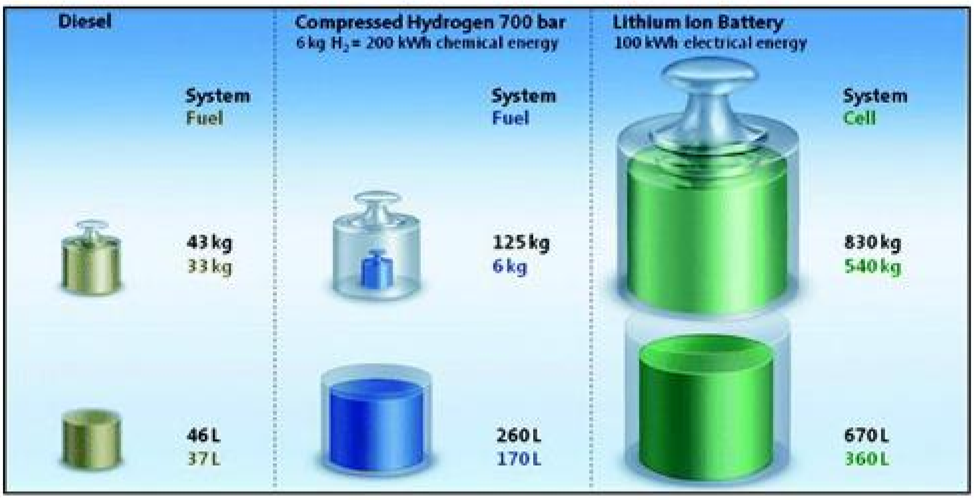


Figure 11: Comparison of energy storage for mobility [2]

It is possible to store 6 kg of hydrogen (about 200 kWh) compressed at 700 bar in a tank with a total weight of 125 kg and a volume of 260 litres. To store half of this energy (100 kWh) 830 kg of weight and 670 litres of volume are required in lithium-ion electric batteries. A 260-litre tank can fit perfectly into the necessarily small volume of a vehicle, offering a range of 600 km, comparable to that offered by petrol-powered vehicles and clearly superior to the reduced autonomies of BEVs (Battery Electric Vehicle) currently on the market. Finally, unlike batteries, the storage performance of a hydrogen tank does not deteriorate with the number of charges and discharges or exposure to extreme temperatures.[2]

Chapter 2

ARGENTINE PRODUCTION SCENARIO

2.1 Sizing of the project

The project of production of green hydrogen in Patagonia region in Argentina from wind energy is dimensioned to meet the demand for hydrogen mobility of FCEV cars in Italy assuming a market penetration of 1%.

Population of Italy:[35] 60,238,522

Number of cars:[36] 39,018,070

The number of vehicles per inhabitant according to this ratio is 0.65. As the percentage tends to rise[37] it has been chosen to approximate excess to 0.7 vehicles per inhabitant. Thus, the number of hydrogen cars on national soil corresponding to the market penetration of 1% is:

FCEV cars = 60,238,522 inhabitants * 0.7 cars/inhabitants * 1% = **421,670**

The average daily demand (on an annual basis) for total hydrogen in the country (kgH_2/day) was calculated from the Excel model *HDSAM* (*Hydrogen Delivery Scenario Analysis Cost Model*) of the National Laboratory of Argonne (USA):

Annual H_2 demand per vehicle = 222 kgH_2/year·car

Daily average H_2 demand per vehicle = 222/365 = 0.61 kgH_2/day·car

Daily average H_2 demand in Italy =
0.61 kgH_2/day·car * 421,670 cars = 256,793 kgH_2/day

Annual H_2 demand in Italy =
256,793 kgH_2/day * 365 days = 93,729,328 kgH_2/year = 93,729 tH_2/year

Considering HRS with a maximum capacity of 500 kgH_2/day, and thus providing an average of 400 kgH_2/day (HDSAM assumption), the number of HRS in Italy is obtained by rounding up the ratio between the daily average hydrogen demand and 400 kg H_2/day dispensed from the single station on average. This results in:

Hydrogen Refueling Stations necessary in Italy = 642

The technical and economic values of the PEM electrolyser system have been learned by consulting different sources in the scientific literature.[38–40]

The lifetime of the plant was considered to be 20 years.[38]

The consumption of PEM electrolysers in 2020[39] is between 5.2 kWh/Nm^3 and 4.7 kWh/Nm^3. Dividing by 0.0899 kg/Nm^3 (H_2 density in STP conditions), results in a consumption between 58 and 52 kWh/kgH_2 produced. As default value has been chosen 58 kWh/kgH_2, then in the sensitivity analysis will also be considered lower consumption values such as up to 52 kWh/kgH_2.
The water consumption considered is 15 l/kgH_2 produced.[38]

Regarding the lifetime of the stack, the statistically most relevant range is between 40000 and 60,000 hours[39], therefore 50,000 hours is considered as default value.
A CAPEX Total System Equipment of 1200 €/kW has been chosen: the graph of cost projection for PEM electrolyser is shown below:[40]

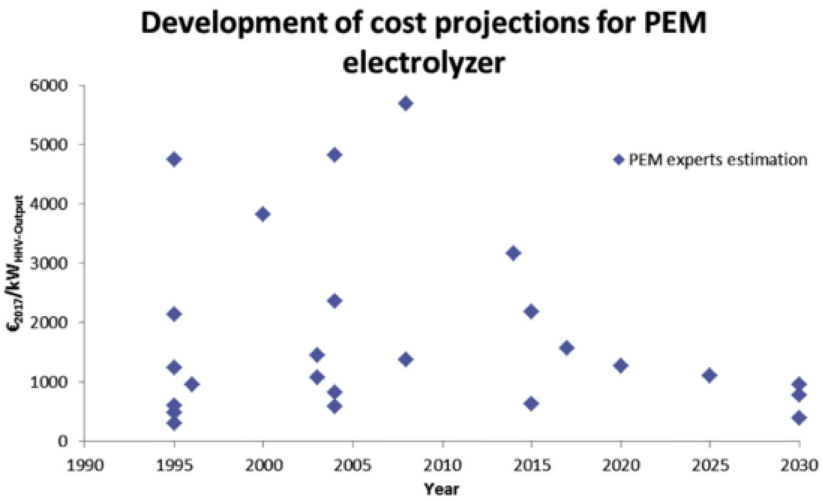


Figure 12: Cost projections for PEM electrolyser [40]

At the end of the stack's lifetime, the stack must be replaced. CAPEX Stack replacement for large units is considered equal to 420 €/kW.[38]

Annual Energy Demand = Electrolyser Consumption * Annual H_2 demand Italy
= 58 kWh/kgH_2 * 93,729,328 kgH_2/year =
5,436,301,034 kWh/year = 5,436,301 MWh/year = 5,436 GWh/year

At this point, we get the size of the plant through the Capacity Factor. In strongly windy regions such as Patagonia average capacity factor of 50% can be reached, with peaks of 60-70%. For example, the Diadema Wind Park, locate approximately 20 km northwest of Comodoro Rivadavia City (Chubut Province, Argentina) had a CF = 54.9% in 2017.[18]
A CF = 50% has been considered as default value.

Plant Size = Annual Energy Demand / (CF * 8760) =
= **1,241,165 kW = 1,241 MW = 1.24 GW**

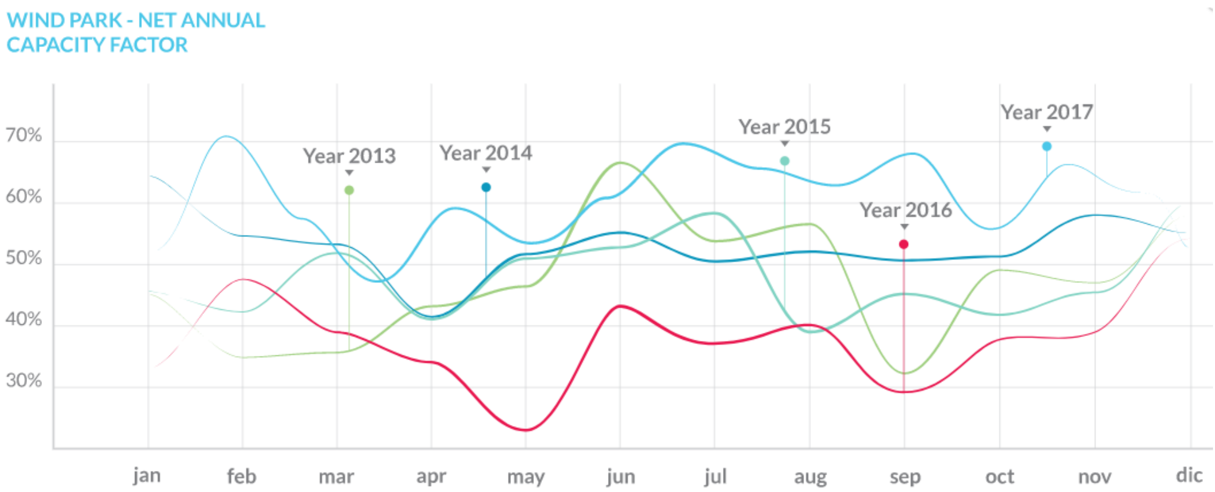


Figure 13: Net annual Capacity Factor - Diadema Wind Park [18]

Population of Italy	60,238,522 inhabitants
Cars/people ratio	0.7
H_2 market penetration	1%
FCEV cars	421,670 cars
Annual H_2 demand per vehicle	222 kgH_2/year
Daily Average H_2 demand per vehicle	0.61 kgH_2/day
Daily Average H_2 demand in Italy	256,793 kgH_2/day
Annual H_2 demand in Italy	93,729 tH_2/year
HRS necessary in Italy	642
Annual Energy Demand	5,436 GWh/year
Plant Size	1.24 GW

Table 1: Project Data Recap

2.2 Production Cost

For the economic assessment, Levelized Cost Of Hydrogen ($LCOH$)[41] is calculated. The main cost components are capital expenditures ($CAPEX_{stack}$ and $CAPEX_{aux}$), operating cost including maintenance ($OPEX$) and consumable expenditures like *Electricity (E)*, *Water (W)*, which are set into relation to the annual amount of *Supplied Hydrogen (H)*. All cost components are levelized over the plant lifetime *n.* A Weighted Average Cost of Capital ($WACC$) of 5% is assumed as discount rate.[38] It is denoted with *r*.

$$LCOH = \frac{\sum_{t=0}^{n}(CAPEX_{stack} + CAPEX_{aux} + CAPEX_{other} + OPEX + E + W)_t \cdot (1+r)^{-t}}{\sum_{t=0}^{n} H_t \cdot (1+r)^{-t}} \qquad (2.1)$$

A lifetime of 20 years has been considered for the overall system. All CAPEX are sustained at the beginning of the operation of the plant, in year zero. The stack must be replaced every 50,000 hours, so its investment cost ($CAPEX_{stack}$) is faced again in the year when it reaches the end of lifetime, which depends on CF.
For example, in the case of CF = 50% there is only one stack replacement that occurs in the twelfth year of life plant, hence the cost will be discounted with the discount rate to the twelfth year.

In the cost of H_2 production are considered:

- **CAPEX Stack**
- **CAPEX Auxiliary**: obtained by subtracting CAPEX Stack from CAPEX Total System Equipment: includes the investment cost of the various auxiliary equipment of the electrolyser.
- **OPEX Electrolyser System**
- **Water**
- **Electricity for Production**
- **CAPEX Civil Works**
- **Other Costs**

CAPEX Stack [€] = CAPEX Stack [€/kW] * Plant Size [kW]

CAPEX Stack [€] = 420 €/kW * 1,241,165 kW = **521,289,140 €**

CAPEX Auxiliary [€/kW] = CAPEX Total System Equipment [€/kW] – Capex Stack [€/kW]

CAPEX Auxiliary [€/kW] = 1200 €/kW – 420 €/kW = 780 €/kW

CAPEX Auxiliary [€] = CAPEX Auxiliary [€/kW] * Plant Size [kW]

CAPEX Auxiliary [€] = 780 €/kW * 1,241,165 kW = **968,108,403 €**

OPEX Electrolyser System [€/year]

OPEX Electrolyser System are assumed equal to 2% of the CAPEX Total System, thus equal to 2% of 1200 €/kW hence 24 €/(kW*year).

These are not investment costs consequently they are faced every year, with respective discounting of r=5%.

OPEX Electrolyser System [€/year] = OPEX [€/kW·year] * Size Plant [kW]

OPEX Electrolyser System [€/year] = 24 €/kW·year * 1,241,165 kW =

29,787,951 €/year

Remember that this is the OPEX in year zero of the plant, in the following years will be gradually updated according to the factor $(1+ r)^{-t}$.

Water

Unit Cost Water[38] = 3.8 €/m^3 = 0.0038 €/l = 0.0038 €/kgH_2O

Water consumption in rated conditions[38] = 15 l/kg H_2

Hourly H_2 production [kgH_2/h] = Daily average H_2 demand [kgH_2/day] / 24 = [256,793 kgH_2/day] / 24 = 10,700 kgH_2/h

Hourly water mass flow rate in rated conditions [kgH_2O/h] =

10,700 kg H_2/h * 15 l/kg H_2 = 160,495 l/h = 160,495 kgH_2O/h

Water [€/year] = Unit Cost Water [€/kgH_2O] * Hourly water mass flow rate in rated conditions [kgH_2O/h] * 8760 h/year * CF [%]

= 0.0038 €/kgH_2 * 160,495 kgH_2O/h * 8760 h/year * 50% CF = **2,671,286 €/year**

Electricity for Production

According to data from the Argentine Ministry of Energy (Ministero de Energìa y Minerìa)[42], the average cost of kWh of electricity produced from wind power in the province of Chubut in Patagonia is 0.04 €/kWh.

Unit cost of electricity produced from wind energy = 0.04 €/kWh

Annual Electricity Cost for Production [€/year] =

0.04 €/kWh * Size Plant [KW] * 8760 h/year * CF [%] =

0.04 €/kWh * 1,241,165 kW * 8760 h/year * 50% = **217,452,041 €/year**

Remember that this annual cost must be discounted year by year according to the factor $(1+r)^{-t}$.

CAPEX Civil Works [€]

These are the costs related to construction work. This includes foundations, industrial buildings, lighting, fences, security. A cost function has been used:[38]

$$CAPEX_{civil\ works} = (A + B) \cdot (S_{adjust} \cdot Area_{equipments}) \tag{2.2}$$

The coefficients are:

A = 950 €/m^2	Base Cost
B = 150 €/m^2	Additional Cost for greenfield
S_{adjust} = 150 %	Surface adjustment

For PEM electrolyser:[38]

$Area_{equipments}$ = 0.05 €/kW

It is obtained:

CAPEX Civil Works [€] = 102,396,081 €

Other Costs [€]

Below, the description of what is included in the item "Other Costs":[38]

Engineering Costs:

Costs of engineering, architecture, studies, permits, legal fees and other pre and post construction expenses.

Distributed Control System (DCS) and Energy Management Unit (EMU):

Costs of components that allow safe operation and optimisation of the production plant.

Interconnection, Commissioning and Start-Up Costs:

Expenditure related to piping, interconnection, inspection, testing, commissioning and start-up.

"Other costs" generally represent 45% of the *CAPEX Total System Equipment* (in this case *CAPEX Stack* and *CAPEX Auxiliary*) for a small 2.5 MW plant. In order to reflect the economy of scale on larger projects an equation model is proposed to adapt costs:[38]

$$Other\ Costs = 10\% \left(\frac{2.5\ MW}{Plant\ Size\ [MW]}\right) + 35\% \tag{2.3}$$

In this case with a size plant of 1241 MW, the percentage to be considered is 35.02%.

Other Costs [€] = 35.02 % * (CAPEX Stack [€] + CAPEX Auxiliary [€]) = **521,589,140 €**

It was chosen to bring together *CAPEX Civil Works* and *Other Costs* under a single item:

CAPEX Civil Works & Other Costs [€] = 623,985,221 €

Below is a summary table of the LCOH Production partition, with all related cost items

Year	Hours stack [h]	CAPEX Stack [€]	CAPEX Auxiliary [€]	OPEX System [€]	Electricity for Production [€/year]	Water [€/year]	CAPEX Civil Works & Other Costs [€]	Total Cost [€/year]	Actualized H_2 produced [kgH_2/year]
0	0	521289140	968108403	29787951	217452041	2671286	623985221	2363294043	93729328,17
1	4380	0	0	28369477	207097182	2544082	0	238010741	89266026,83
2	8760	0	0	27018550	197235412	2422935	0	226676896	85015263,64
3	13140	0	0	25731952	187843249	2307557	0	215882758	80966917,76
4	17520	0	0	24506621	178898333	2197673	0	205602627	77111350,24
5	21900	0	0	23339639	170379364	2093022	0	195812026	73439381,18
6	26280	0	0	22228228	162266061	1993355	0	186487643	69942267,79
7	30660	0	0	21169741	154539106	1898433	0	177607280	66611683,61
8	35040	0	0	20161658	147180101	1808031	0	169149790	63439698,68
9	39420	0	0	19201579	140171525	1721935	0	161095038	60418760,65
10	43800	0	0	18287218	133496690	1639938	0	153423846	57541676,81
11	48180	0	0	17416398	127139705	1561846	0	146117948	54801596,96
12	52560	290273299	0	16587046	121085433	1487472	0	429433250	52191997,10
13	56940	0	0	15797186	115319460	1416640	0	132533287	49706663,91
14	61320	0	0	15044939	109828057	1349181	0	126222178	47339679,91
15	65700	0	0	14328514	104598150	1284934	0	120211598	45085409,44
16	70080	0	0	13646204	99617286	1223747	0	114487236	42938485,18
17	74460	0	0	12996384	94873605	1165473	0	109035463	40893795,41
18	78840	0	0	12377509	90355815	1109974	0	103843298	38946471,82
19	83220	0	0	11788104	86053157	1057119	0	98898379	37091877,92
20	87600	0	0	11226765	81955387	1006780	0	94188932	35325598,02
Cumulated[€] or [kg]		811562439	968108403	401011660	2927385120	35961412	623985221	5768014256	1261803931
Impact [%]		14,07%	16,78%	6,95%	50,75%	0,62%	10,82%	100,00%	
Portions / LCOH [€/kg H_2]		**0,64**	**0,77**	**0,32**	**2,32**	**0,03**	**0,49**	**4,57**	

Table 2: Scenario ARG – Production Cost (a)

Production Cost Items	**€/kgH_2**	**Impact [%]**
CAPEX Stack	0,64	14,1%
CAPEX Auxiliary	0,77	16,8%
OPEX System	0,32	7,0%
Electricity for Production	2,32	50,8%
Water	0,03	0,6%
CAPEX Civil Works & Other Costs	0,49	10,8%
LCOH Production	**4,57**	

Table 3: Scenario ARG - Production Cost (b)

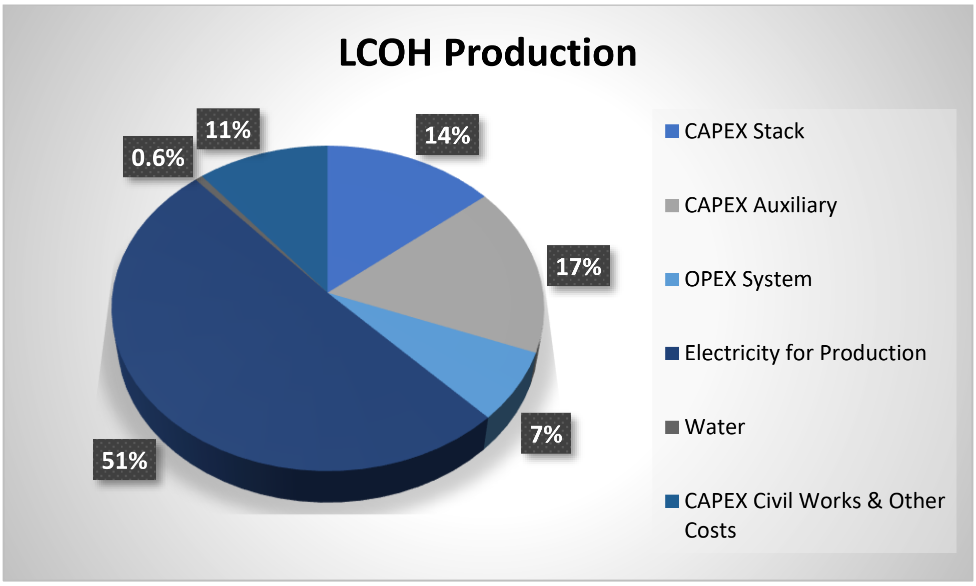


Figure 14: Scenario ARG - Production Cost

The production of hydrogen by wind energy in Argentina has an impact on the hydrogen cost of **4.57 €/kgH_2**. The main contribution is due to the cost of energy, in fact it constitutes 51% of the entire production cost. It can be realized the importance of exploiting low wind electricity cost in Patagonia. As we will see, in the production scenario in Italy, this cost being higher, will contribute in a higher overall production cost.

2.3 Transmission from production site to naval port

The analysis of the hydrogen value chain goes on to assess of the cost component that concerns the transmission of hydrogen from the production site to the naval port, in this case, the Puerto Comodoro Rivadavia located in the extreme south of the region. It was considered a distance of 100 km.

Concerning ocean shipping, transport of hydrogen in the compressed gaseous state is not taken into account because it is not attractive because of its low energy density.[5,43] On the other hand, storage methodologies and transport of hydrogen liquefied by cryogenics (LH2), then at a temperature of -253 C or hydrogen at room conditions linked to a Liquid Organic Hydrogen Carrier (LOHC) such as Toluene or Dibenzyltoluene, have been studied and are considered feasible.
Therefore, in this production scenario in Argentina we will assess the costs incurred since hydrogen is produced by electrolysis until the embarkation of:

- *LH2: Liquefied Hydrogen*
- *LOHC: Hydrogen bound to a Liquid Organic Hydrogen Carrier*

Before to continue, it is good to briefly describe the instrument that has allowed the estimates of transmission, liquefaction, terminals and distribution costs by tractor-trailers (in the case of LH2) or compressed H_2 truck-tube trailers (methodology feasible in the case of GH2, as we will see in the Italian scenario, as there is no shipping constraint).

HDSAM: Hydrogen Delivery Scenario Analysis Cost Model

HDSAM is an Excel model of the National Laboratory of Argonne (USA): it provides the cost estimates listed above from input data including the main:

- Market penetration of hydrogen vehicles
- Population
- Area
- Transmission mode
- Distribution mode
- Refueling Station Capacity
- Storage for plant outages and peaks
- Energy and feedstock prices
- Modality and pressure dispensing hydrogen to the vehicle

2.3.1 LH2 – Liquefied Hydrogen

Liquefaction is a standard pre-treatment for hydrogen transport. The advantage is that 1 bar liquefied hydrogen has a density of 71 kg/m^3 compared to 0.0899 kg/Nm^3 under STP conditions. The same mass of hydrogen in the liquid state occupies a volume almost 800 times smaller than it would occupy under ambient conditions. The problem, however, is that hydrogen needs to be cooled below 21 K (-253 °C) in order to be able to obtain it in the liquid phase: this requires a complex process based on different compression and pre-cooling phases. As a result, the entire process is characterized by high energy expenditure and electricity demand is between 8 and 12 kWh/kgH_2[41], or even between 12 and 15 kWh/kgH_2 as reported by this other source.[44] Storage at -253 °C is obtained by means of a vacuum-insulated internal pressure vessel with an outer casing.[45] Any container containing liquefied hydrogen needs to be very well insulated to prevent the opposite state from passing to the gaseous state.[41]

The pathway up to the port rated with HDSAM is as follows:

LH2: Liquefaction -> LH2 Terminal at Production site (with cryogenic storage of 6-days demand) -> Transport to port by tractor-trailers (100 km) -> LH2 Terminal at Argentine Port (with cryogenic storage of 1-day demand)

Liquefied Hydrogen - LH2		
Items	**€/kgH_2**	**Impact [%]**
Liquefier	1,93	83,9%
LH2 Terminal at Production site (storage 6 days)	0,20	8,7%
Tractor-Trailer (Transmission to Port)	0,12	5,2%
LH2 Terminal at Argentine Port (storage 1 day)	0,05	2,2%
Total Cost from Production site to Argentine port	**2,30**	

Table 4: LH2 ARG - From Production site to Argentine port

The cost contribution of this section is **2.30 €/kgH_2**. It is clear that the vast majority of the impact is given by Liquefier, because of the considerable investment costs and energy required by liquefaction.

The LH2 Terminal at the production site, presents a cryogenic storage that stores an amount of LH2 equal to the national demand of six days (to decide the number of days to set on HDSAM was consulted a report by Argonne[46] in which 40 tH_2/day from wind energy are produced). The number of days chosen seems a reasonable value, to cope with unplanned interruptions of the plant, and with the variability of wind power as a source. HDSAM results have an impact of 0.20 €/kgH_2.

The cost due to truck trailers (0.12 €/kgH_2) over a distance of 100 km that comes out of the simulation HDSAM finds confirmations in the literature.[5] (Figure 15)

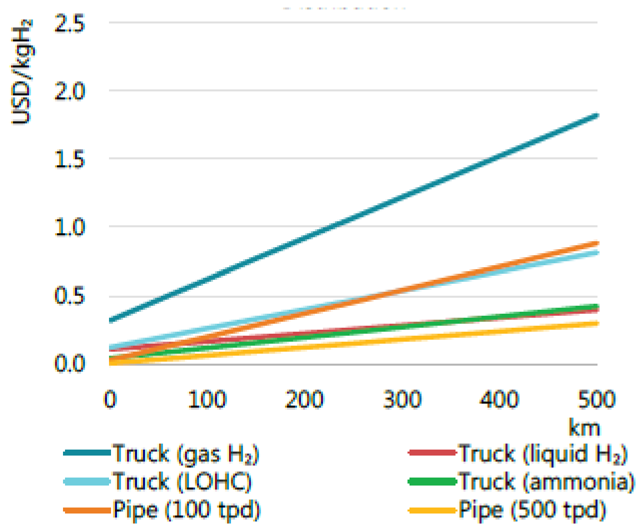


Figure 15: H_2 transport cost [5]

It was planned an LH2 Terminal located at the Port of Argentina to ensure that hydrogen is stored temporarily before being loaded into the tank of the ship via pumps and loading arms.[47] The storage of the port terminal was sized for the demand for a single day (1-day storage). Its cost is 0.05 €/kgH₂.

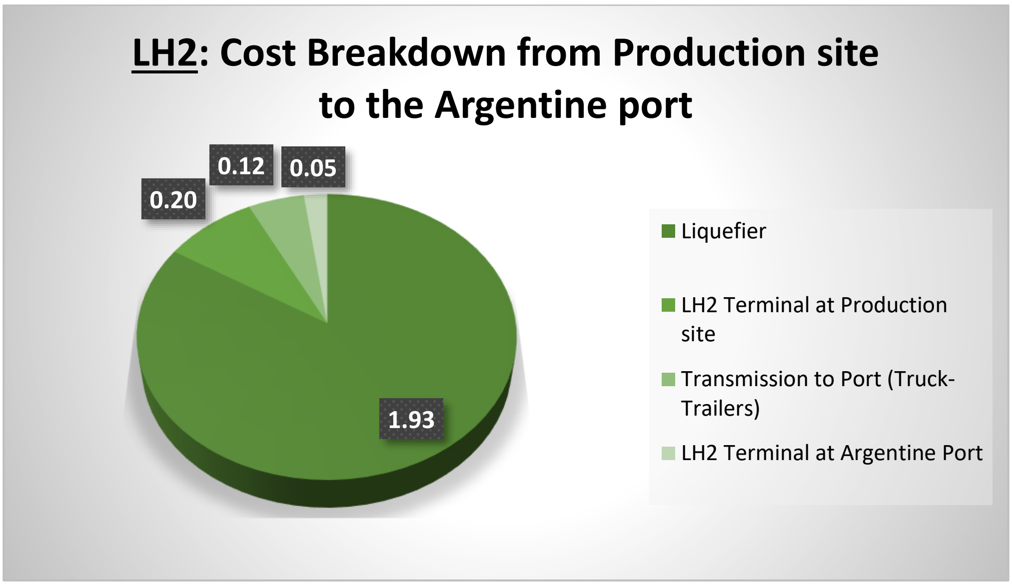


Figure 16: LH2 ARG - Cost Breakdown from Production site to the Argentine port

2.3.2 LOHC – Liquid Organic Hydrogen Carriers[41]

A viable alternative for long-distance hydrogen transport is the Liquid Organic Hydrogen Carriers (LOHC) method. These are aromatic carbohydrates that allow storage between 5.8 and 7.3% hydrogen mass fraction depending on the LOHC used. 630 Nm^3 of hydrogen can be stored in 1 m^3 of LOHC (equivalent to about one tonne).[48]

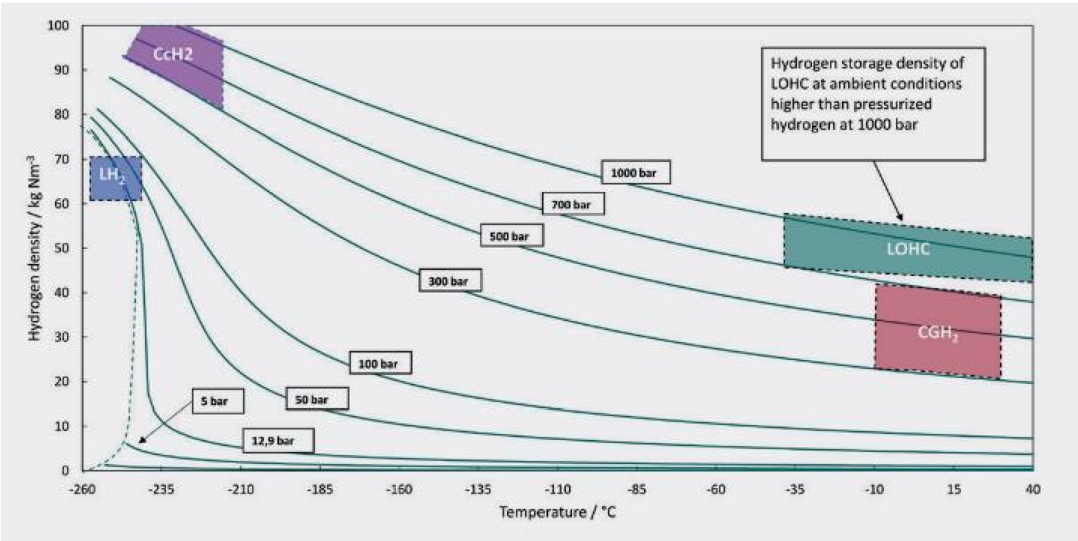


Figure 17: Hydrogen density as a function of pressure and temperature for different storage methods [48]

During transport and distribution, LOHC-bonded hydrogen can be held at room pressure and temperature, which allows for easier handling than compressed hydrogen at very high pressures or hydrogen liquefied by cryogenics. The best-known and promising organic compounds are Toluene (C_7H_8) and Dibenzyltoluene ($C_{21}H_{20}$). Dibenzyltoluene is preferable for its lower toxicity, Toluene is cheaper: 0.72 €/kg instead of 4€/kg of Dibenzyltoluene.

To bind hydrogen to the LOHC it is necessary to make a reaction called *Hydrogenation*, which is exothermic and releases heat at a temperature of 150 °C.
Hydrogenation process takes place downstream of the electrolyser, then at the production site, so it can be assumed to use the electricity produced by the wind farm then at 0.04 €/kWh. What's this power for? Hydrogenation is a pressurized process, LOHC needs to be compressed first, at a pressure of 50 bar and this is the main reason for the

total demand for electricity by hydrogenation which amounts to 0.967 kWh/kgH_2. The heat made available at 150 °C by hydrogenation is often not usable, so it is not considered.

Once arrived at the Italian HRS, it is necessary to make the hydrogen again available, then to release it from its carrier: it is necessary the *Dehydrogenation*. For both Toluene and Dibenzyltoluene, temperatures above 300 °C are required, so the process needs heat supply, it's endothermic. To produce this heat, you can use the combustion of natural gas that is widely available and cheap or burn some of the hydrogen transported. In this work, natural gas combustion was chosen. Downstream from dehydrogenation there is gaseous hydrogen, not pressurized (GH2). A catalyst is needed for both hydrogenation and dehydrogenation, e.g. Pt/C.

The following chemical reaction is a typical Dehydrogenation in which Hydrogen (H_2) and Toluene (C_7H_8) are separated from Methyl-Cyclohexane (C_7H_{14}), the product of the previous Toluene Hydrogenation:

$$C_7H_{14} \xrightarrow{heat} C_7\,H_8 + 3H_2 \tag{2.4}$$

As regards dehydrogenation, a total of 9.5 kWh/kgH_2 are required for dibenzyltoluene, including 0.5 kWh/kgH_2 for preheating and 9 kWh/kgH_2 for actual dehydrogenation. As toluene has a higher reaction enthalpy, in total it needs 10 kWh/kgH_2 of heat.
In addition to heat, electricity is needed for pumps and auxiliary components, for a total of 0.367 kWh/kgH_2.
The size of the dehydrogenation plant is much smaller than that of hydrogenation because the process is carried out at individual refuelling stations (HRS), so a dehydrogenation plant is foreseen at each refuelling station in Italy. It will be used natural gas (at the industrial level, the cost varies depending on that range of consumption) and electricity drawn from the network to the Italian industrial cost always dependent on the consumer range. A consultation of two tables from EUROSTAT was carried out. In any case it will be better discussed, when we deal with dehydrogenation, now we are still studying the cost between the Production site and the Argentine Port.

The hydrogen from dibenzyltoluene is pure enough to be used in a FC (Fuel Cell), in fact meets the demand a purity of 99.999%, instead if toluene is used as a carrier, is not yet clean enough and requires additional electricity (0.2 €/kgH_2) and additional investment cost to purify it to the optimal level.
These reasons, together with its lower toxicity, led to choose as LOHC Dibenzyltoluene ($C_{21}H_{20}$), which is increasingly considered the future of hydrogen storage.[49]

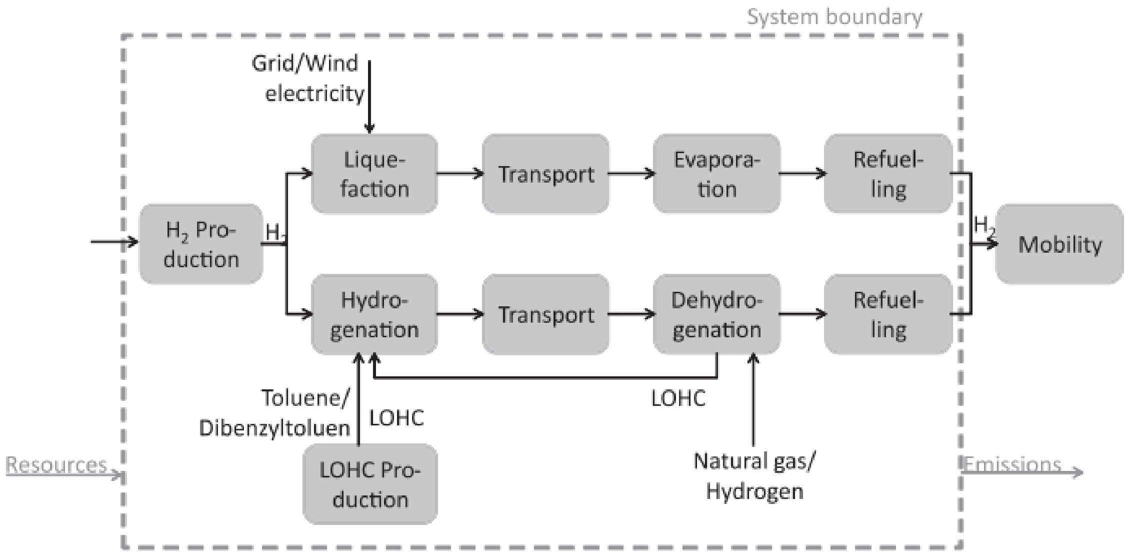


Figure 18: LOHC vs LH2: From Production to Mobility [41]

Following this overview of the LHOC technology, the procedure that allowed to estimate the cost of hydrogenation, which as mentioned, takes place downstream of the electrolyser plant, is shown below. LOHC used is Dibenzyltoluene ($C_{21}H_{20}$).
Basic data are summarised:

Daily average H_2 demand in Italy	256,793 kgH_2/day
Annual H_2 demand in Italy	93,729,328 kgH_2/year
Production Plant Size	1,241 MW
Unit cost of electricity produced from wind energy	0.04 €/kWh
Lifetime system	20 years
Discount rate	5%

- **CAPEX Hydrogenation [€]**

  The paper on which the technology has been studied refers to a plant with a hydrogenation capacity of 50 tH_2/day and the CAPEX is equal to 1.9 million €.[41] In this case study we have to hydrogenate 5 times more hydrogen, therefore it has been chosen to assume a cost of installation 5 times greater that is: 9,500,000 €

- **OPEX Hydrogenation [€/year]**

  It is considered a 3% per annum of CAPEX[44], so you have at zero year: 285,000 €/year, which will be discounted with the discount rate.

- **CAPEX LOHC – Dibenzyltoluene [€]**

  It is necessary to consider the contribution of the cost of capital due to the material used as carrier, dibenzyltoluene, which is permanently bound in the plant. 6.8 kg LOHC per kW of installed power with an economic value of 4€/kgLOHC.[43]

  1,241,165 kW * 6.8 kgLOHC/kW * 4€/kgLOHC = **33,759,678 €**

  The cost of the catalyst should be added, but considering that it is enough 1 kg per 500,000 kg of LOHC and its cost is 150€/kg,[43] it is a contribution that can be overlooked.

- **Electricity for Hydrogenation [€/year]**

  Electricity required for Hydrogenation = 0.967 kWh/kgH_2
  Annual Electricity required for Hydrogenation =
  0.967 kWh/kgH_2 * 93,729,328 kg H_2/year = 90,636,260 kWh/year

  Annual Electricity Cost for Hydrogenation [€/year] =
  0.04 €/kWh * 90,236,260 kWh/year **= 3,625,450 €/year**

The investment costs are carried out in year zero of the plant and the annual electricity costs and OPEX are discounted year by year with the factor $(1+r)^{-t}$.

The following table shows a summary: the columns related to hydrogenation are highlighted in light blue. The others related to dehydrogenation, will be highlighted when we focus on the latter.

Year	CAPEX Hydrogenation [€]	OPEX Hydrogenation [€/year]	CAPEX Dibenzyltoluene [€]	CAPEX Dehydrogenation [€]	OPEX Dehydrogenation [€/year]
0	9500000	285000	33759678	16168000	485040
1	0	271429	0	0	461943
2	0	258503	0	0	439946
3	0	246194	0	0	418996
4	0	234470	0	0	399044
5	0	223305	0	0	380042
6	0	212671	0	0	361944
7	0	202544	0	0	344709
8	0	192899	0	0	328294
9	0	183714	0	0	312661
10	0	174965	0	0	297772
11	0	166634	0	0	283593
12	0	158699	0	0	270088
13	0	151142	0	0	257227
14	0	143944	0	0	244978
15	0	137090	0	0	233313
16	0	130562	0	0	222202
17	0	124345	0	0	211621
18	0	118423	0	0	201544
19	0	112784	0	0	191947
20	0	107414	0	0	182806
Cumulated [€] or [kg]	9500000	3836730	33759678	16168000	6529711
Impact [%]	9,91%	4,00%	35,20%	7,63%	3,08%
Portions LCOH Hyrogenation [€/kgH_2]	**0,008**	**0,003**	**0,027**	-	-
Portions LCOH Dehydrogenation [€/kgH_2]	-	-		**0,05**	**0,02**
LCOH Hydrogenation+Dehydrogen. [€/kgH_2	0,01	0,003	0,027	0,05	0,02

Electricity for Hydrogenation [€/year]	Electricity for Dehydrogenation [€/year]	Heat for Dehydrogenation [€/year]	Total Cost [€/year]	Hydrogenation of national annual H_2 demand [kgH_2/year]	Dehydrogenation of annual H_2 distributed in the AREA [kgH_2/year]
3625450	1599100	12456183	77878450	93729328	25070309
3452810	1522952	11863031	17572165	89266027	23876484
3288390	1450430	11298125	16735395	85015264	22739509
3131800	1381362	10760119	15938471	80966918	21656675
2982667	1315583	10247732	15179496	77111350	20625405
2840635	1252936	9759745	14456663	73439381	19643243
2705367	1193273	9294995	13768251	69942268	18707850
2576540	1136450	8852377	13112620	66611684	17817000
2453848	1082334	8430835	12488209	63439699	16968572
2336998	1030794	8029367	11893533	60418761	16160544
2225712	981708	7647016	11327174	57541677	15390995
2119726	934960	7282872	10787785	54801597	14658090
2018786	890438	6936069	10274081	52191997	13960086
1922654	848037	6605780	9784839	49706664	13295320
1831099	807654	6291219	9318894	47339680	12662209
1743904	769194	5991637	8875137	45085409	12059247
1660861	732566	5706321	8452512	42938485	11484997
1581772	697682	5434591	8050011	40893795	10938093
1506450	664459	5175801	7666677	38946472	10417231
1434714	632818	4929335	7301597	37091878	9921172
1366394	602684	4694604	6953902	35325598	9448736
48806576	21527415	167687753	307815863	1261803931	337501767
50,89%	10,16%	79,13%	**LCOH [€/kgH_2]**		
0,039	-	-	**0,08**		
-	**0,06**	**0,50**	**0,63**		
0,04	0,06	0,50	**0,70**		

Table 5: Liquid Organic Hydrogen Carrier Hydrogenation - Impact on LCOH

The contribution of hydrogenation on the LCOH is **0.08 €/kgH_2** produced, of which about 50% is given by the cost of electricity to enable the process, electricity very cheap, because it is that produced by the wind farm in Patagonia at 0.04 €/kWh. One third of the impact of the process is due to the cost of Dibenzyltoluene.

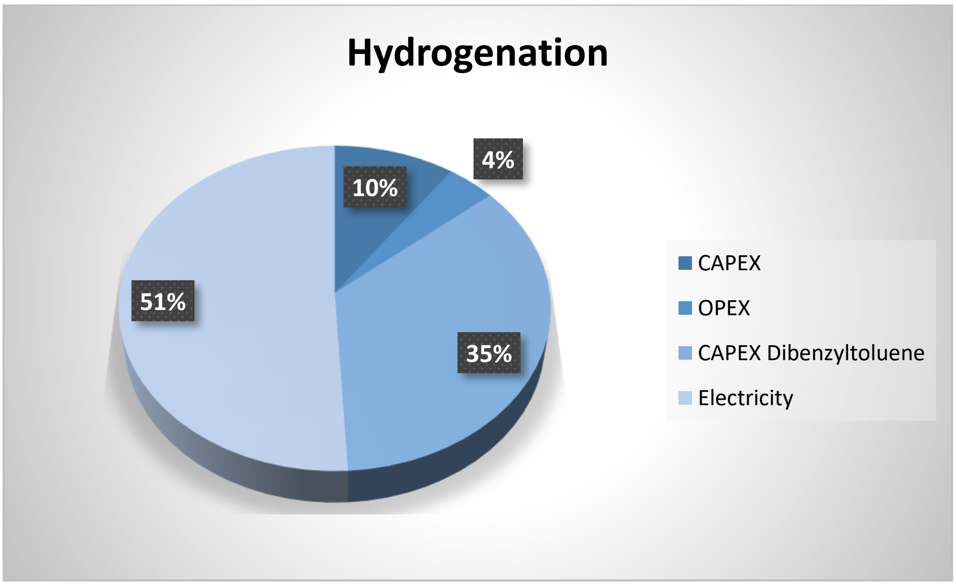


Figure 19: LOHC Hydrogenation - Cost allocation

LOHC: Dibenzyltoluene		
Items	**€/kgH$_2$**	**Impact [%]**
LOHC Hydrogenation	0,08	33,6%
LOHC-H2 Terminal at Production site (storage 6 days)	0,04	17,7%
Tractor-Trailer (Transmission to Port)	0,10	44,2%
LOHC-H2 Terminal at Argentine Port (storage 1 day)	0,01	4,4%
Total Cost from Production site to Argentine port	**0,23**	

Table 6: LOHC ARG - From Production site to Argentine port

In HDSAM there is no transport setting with LOHC, however it can be estimate the cost of transport by tractor-trailers taking into account some considerations: the amount of liquefied hydrogen transportable by the single truck-trailer is about 4,000 kg, while for the hydrogen bound to the carrier, each truck can carry about 1,800 kg of hydrogen.[5,41] Thus certainly are needed more truck-trailers units with respect to LH2 case. It should also be noted that while for the single truck the investment cost is the same (160,000 €/truck), there is a considerable difference for trailer:[41] 80,000€/trailer for LOHC and

860,000€/trailer for LH2 due to the choice of tank with the most advanced technology to ensure maximum thermal insulation.[44] Input data discussed above have been manually modified on HDSAM.

Hence, there is a factor that would tend to increase the cost, namely the number of truck-trailers, and a factor that tends to decrease it, that is the investment cost much lower than the trailers for LOHC. HDSAM shows that these factors balance roughly, the cost of transmission to the port is very similar to LH2 scenario.

Tractor-Trailer (Transmission to the port) = 0.10 €/kgH_2

The reasoning is confirmed in the scientific literature. Below, a quote from the paper:[43]
"The costs and energy consumptions for the road transport of LH2 and LOHC are similar. Apparently the higher cargo of LH2 compensates for the higher capital investment."

Regarding the impact of the cost of the LOHC-H_2 Terminal, which HDSAM does not calculate, it is learnt from the literature[41] that the cost of the LOHC storage is one fifth of the cost of LH2 storage, so it is considered:
0.20/5 = 0.04€/kgH_2 for LOHC-H_2 Terminal at Production site
0.05/5 = 0.01€/kgH_2 for LOHC-H_2 Terminal at Argentine port

There are big cost savings faced from production site to the port with the storage of hydrogen in Dibenzyltoluene: the total value is **0.23 €/kgH_2**, exactly 10% compared to the LH2 scenario. Liquefaction is in fact very expensive. So far, the balance is in favor of LOHC.

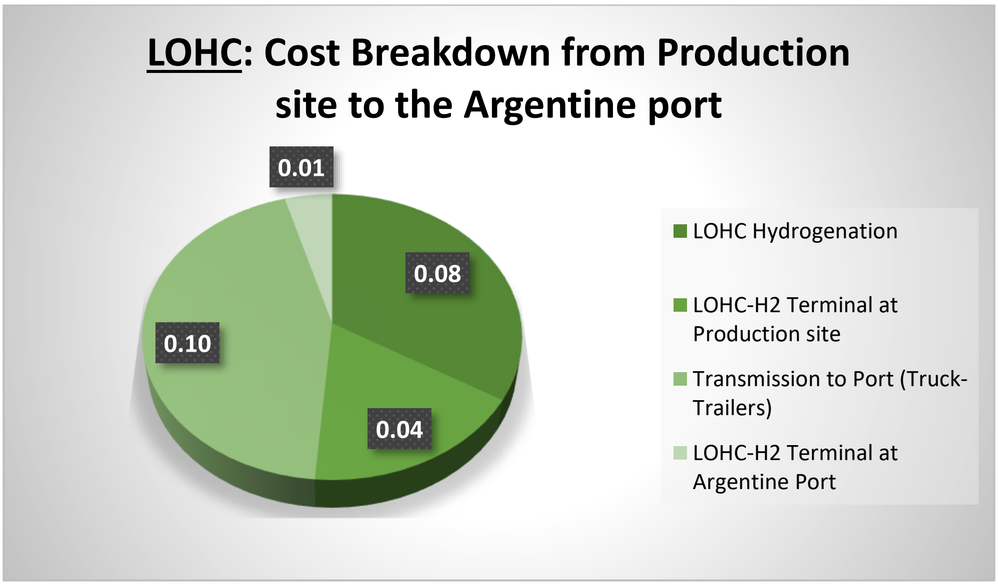


Figure 20: LOHC ARG - Cost Breakdown from Production site to the Argentine port

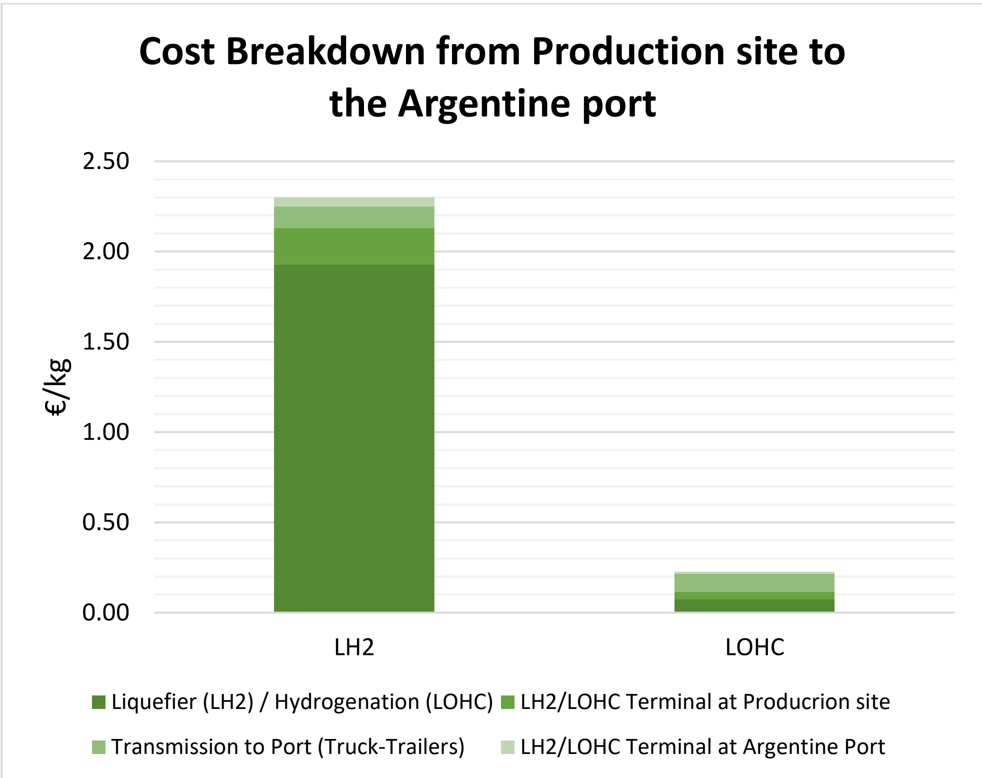


Figure 21: Scenario ARG - Cost Breakdown from Production site to the Argentine port: LH2 vs LOHC

2.4 From Argentine naval port to Italian HRS

2.4.1 Oceanic Transport

Once the hydrogen is at the terminal of Port of Comodoro Rivadavia, it is transferred to the ships. Before describing ocean transport aspects, a choice is justified: to make to arrive all the national hydrogen to an only Italian port, logistically is much dysfunctional in how much costs of distribution in all Italy through truck-trailers would be excessive, as each truck would travel too many kilometers and would need more trucks overall. This reasoning has been confirmed by the simulations on HDSAM: in fact, calculating the unique distribution throughout the Italian surface, it is an unreasonable distribution cost, with more than 1,800 km travelled on average. For this reason it has been decided to subdivide Italy in 7 areas: the more important commercial ports in proximity of every area have been considered, and one port has been previewed for every area: in that way, the distribution in every area is more versatile, with distances covered from the truck-trailers ranging from a minimum of 466 to a maximum of 722 km depending on the area considered and a cost of distribution per single area acceptable.

Obviously the amount of daily hydrogen demand arriving at the port of the single area and the number of HRS per single area, were calculated using HDSAM (its calculation procedure was reported at the beginning, only the data change), distributing proportionately the total population of the area concerned. A clear overview of this subdivision is shown in the following table:

Region/ AREA	Population [inhab.]	Area [km²]	Density [inh/km²]	N° of FCEVs	Avg H_2 demand [kgH_2/day]	N° HRS
Piemonte	4,340,934	25,387	171	30,387	18,505	47
Valle d'Aosta	125,488	3,261	38	878	535	2
Lombardia	10,102,943	23,864	423	70,721	43,068	108
Liguria	1,542,970	5,416	285	10,801	6,578	17
AREA 1	**16,112,335**	**57,928**	**278**	**112,786**	**68,686**	**172**
Veneto	4,907,206	18,345	267	34,350	20,919	53
Trentino-A.A.	1,074,710	13,605	79	7,523	4,581	12
Friuli-V.G.	1,211,234	7,924	153	8,479	5,163	13
AREA 2	**7,193,150**	**39,874**	**180**	**50,352**	**30,664**	**77**
Toscana	3,722,351	22,987	162	26,056	15,868	40
Emilia-Rom.	4,466,664	22,453	199	31,267	19,041	48
AREA 3	**8,189,015**	**45,440**	**180**	**57,323**	**34909**	**88**
Lazio	5,864,948	17,232	340	41,055	25,002	63
Abruzzo	1,305,637	10,832	121	9,139	5,566	14
Umbria	880,196	8,464	104	6,161	3,752	10
Marche	1,518,246	9,401	161	10,628	6,472	17
AREA 4	**9,569,027**	**45,929**	**208**	**66,983**	**40,792**	**102**
Molise	302,234	4,461	68	2,116	1,288	4
Campania	5,785,273	13,671	423	40,497	24,662	62
Puglia	4,007,889	19,541	205	28,055	17,085	43
Basilicata	556,877	10,073	55	3,898	2,374	6
AREA 5	**10,652,273**	**47,746**	**223**	**74,566**	**45,410**	**114**
Calabria	1,924,506	15,222	126	13,472	8,204	21
Sicilia	4,967,905	25,832	192	34,775	21,178	53
AREA 6	**6,892,411**	**41,054**	**168**	**48,247**	**29,382**	**74**
Sardegna	1,630,311	24,100	68	11,412	6,950	18
AREA 7	**1,630,311**	**24,100**	**68**	**11,412**	**6,950**	**18**
ITALY	**60,238,522**	**302,073**	**199**	**421,670**	**256,793**	

Table 7: Data for the 7 Italian areas

The arrival ports for each of the seven areas are as follows:

- ✓ AREA 1: Porto di Genova
- ✓ AREA 2: Porto di Venezia
- ✓ AREA 3: Porto di Livorno
- ✓ AREA 4: Porto di Civitavecchia

- ✓ AREA 5: Porto di Napoli
- ✓ AREA 6: Porto di Messina
- ✓ AREA 7: Porto di Cagliari

Sardinia was considered alone (AREA 7), because it is an island far from the rest of the country.

2.4.1.1 LH2 Oceanic Transport

Using the Google Maps distance meter, the distances of each Italian port from the Porto di Comodoro Rivadavia have been calculated.

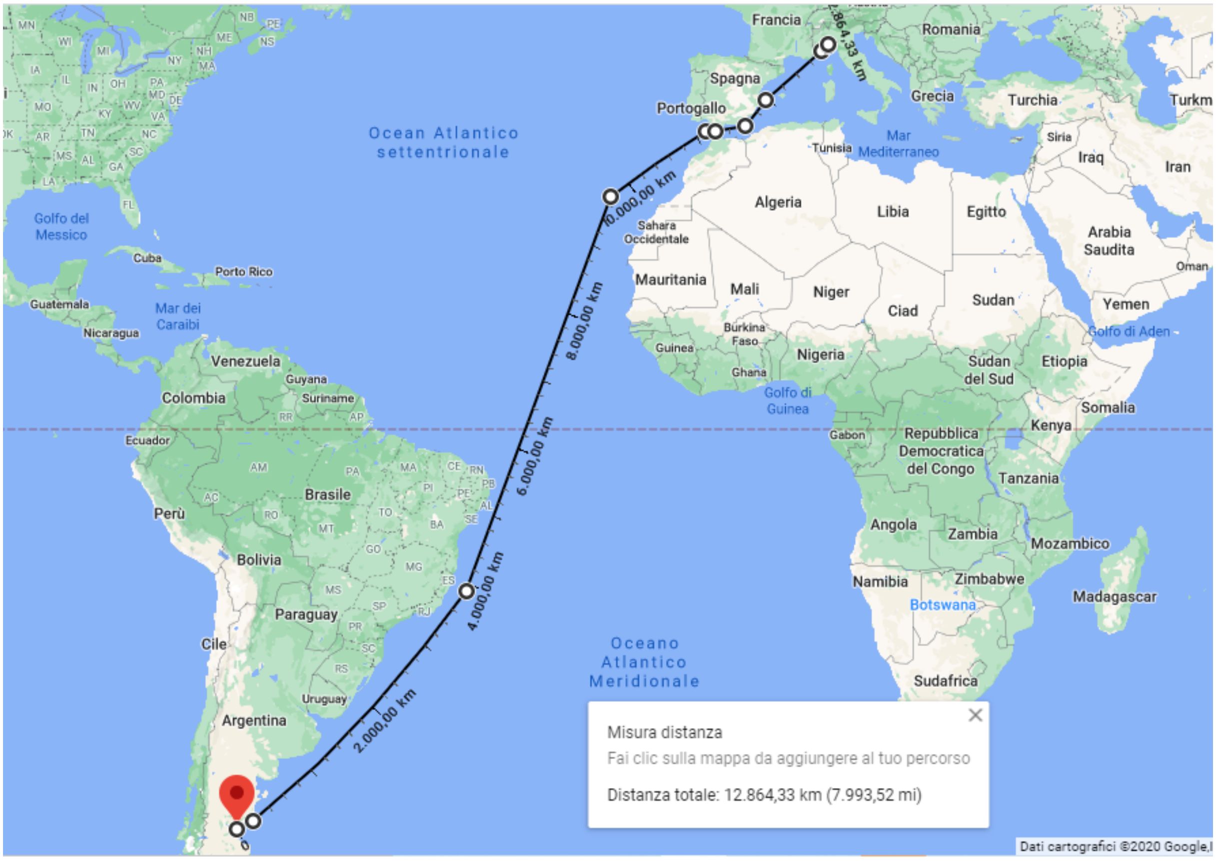


Figure 22: Oceanical distance: Puerto de Comodoro Rivadavia - Porto di Genova [Google Maps]

The distances of all seven Italian ports are available in the following table:

Area	Port of Arrival	Distance [km]
1	Genova	12865
2	Venezia	14490
3	Livorno	12900
4	Civitavecchia	13000
5	Napoli	13200
6	Messina	13160
7	Cagliari	12650

Table 8: Distance from Puerto de Comodoro Rivadavia

The cost of ocean transport ($/kgH$_2$) was learnt from literature:[5]

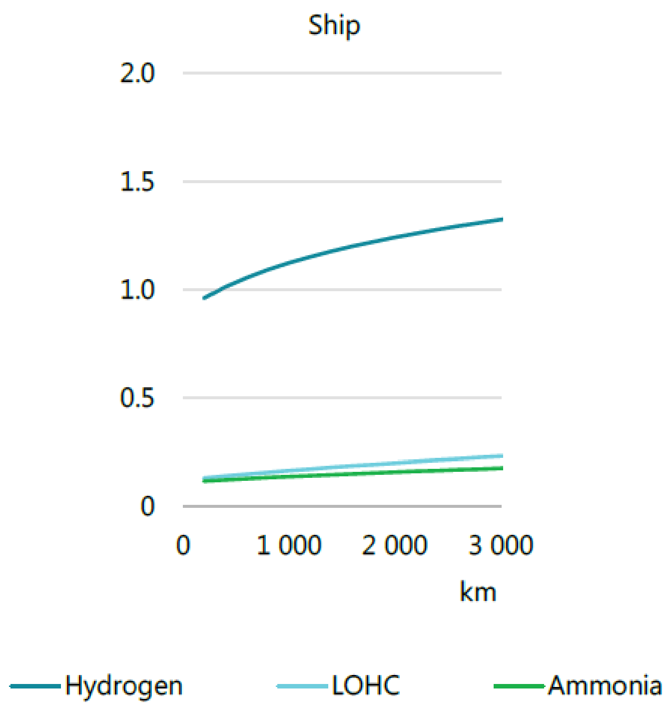


Figure 23: Cost of hydrogen transport by ship [5]

The LH2 curve is the blue one. The figure shows the trend up to 3,000 km. To derive the cost values for the distances of this case study has become necessary an interpolation. With the help of *Web Plot Digitizer*, it was possible, starting from the image, to trace the coordinates of a considerable number of points belonging to the curve. By importing these coordinates to MATLAB in the form of x and y vectors, and using *Curve Fitting Tool*, it was possible to find the function that best interpolates the curve. The two possible functions were exponential and power, both with two terms. Both have been plotted on MATLAB to see the trend up to the desired distances and choose the one with a better fitting.

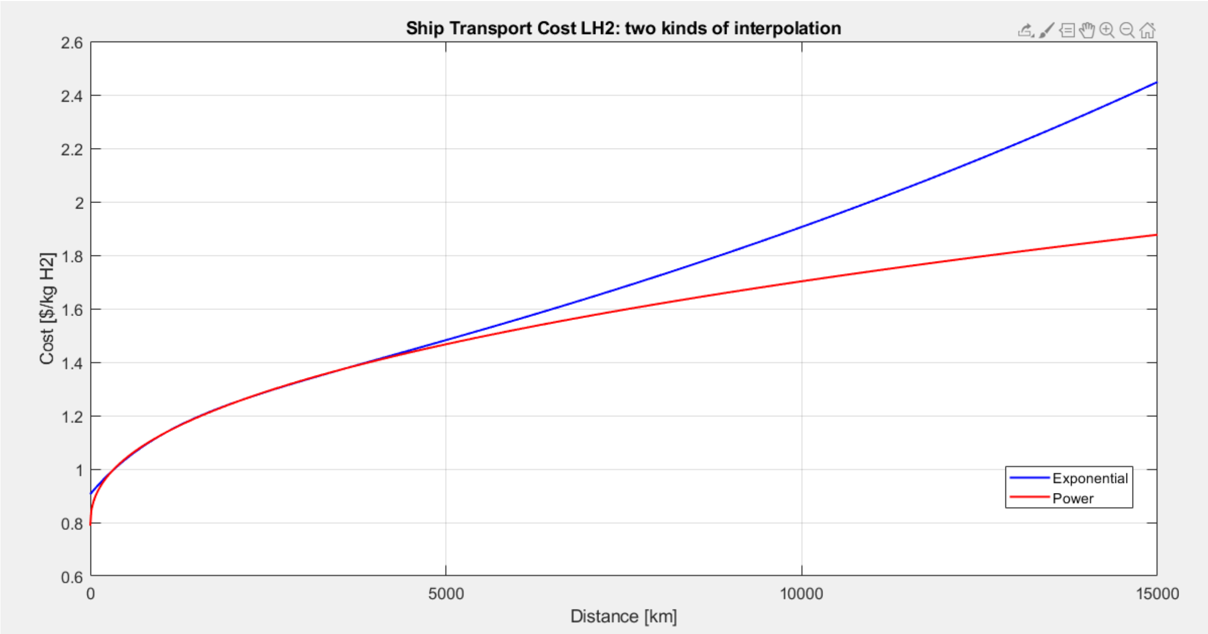


Figure 24: Interpolating functions of LH2 ship transport cost trend

The power function is more suitable to describe the trend:

$$Cost\left[\frac{\$}{kg}\right] = a \cdot x^b + c \tag{2.5}$$

a = 0.01742

b = 0.43

c = 0.7882

In the following table there are the costs for ocean transport of LH2 towards each of the 7 Italian ports, evidencing the values converted in €/kgH_2 with factor of conversion euro/dollar equal to 0.85.

Area	Port of Arrival	Distance [km]	Cost [$/kg]	Cost [€/kg]
1	Genova	12865	1,81	**1,54**
2	Venezia	14490	1,86	**1,58**
3	Livorno	12900	1,81	**1,54**
4	Civitavecchia	13000	1,81	**1,54**
5	Napoli	13200	1,82	**1,55**
6	Messina	13160	1,82	**1,54**
7	Cagliari	12650	1,80	**1,53**

Table 9: LH2 ship transport cost

2.4.1.2 LOHC Oceanic Transport

Refer again to Figure 23. It's clear that the cost of shipping hydrogen bound to a LOHC is far lower than the LH2 because it's a compound at room pressure and temperature. The complex technology for the insulation of the cryogenic tanks of LH2, which means that the investment cost is much higher is not necessary.[43]

The situation is similar to the previous case: in order to derive the cost, which is linear with the distance in the case of LOHC, the light blue line of Figure 23 has been interpolated by means of *Web Plot Digitizer* and MATLAB:

$$Cost\left[\frac{\$}{kg}\right] = p_1 \cdot x + p_2 \tag{2.6}$$

$p_1 = 3.726 \cdot 10^{-5}$

$p_2 = 0.1257$

In the following table there are the costs for ocean transport of LOHC towards each of the 7 Italian ports, evidencing the values converted in €/kgH_2 with factor of conversion euro/dollar equal to 0.85.

Area	Port of Arrival	Distance [km]	Cost [$/kg]	Cost [€/kg]
1	Genova	12865	0,61	**0,51**
2	Venezia	14490	0,67	**0,57**
3	Livorno	12900	0,61	**0,52**
4	Civitavecchia	13000	0,61	**0,52**
5	Napoli	13200	0,62	**0,52**
6	Messina	13160	0,62	**0,52**
7	Cagliari	12650	0,60	**0,51**

Table 10: LOHC ship transport cost

2.4.1.3 Number of ships required

In December 2019 Kawasaki Heavy Industries, Ltd. launched at the shipyard in Kobe (Japan) the Suiso Frontier, the world's first ship for the transport of liquid hydrogen. Long 116 meters, it will be equipped with a double shell vacuum insulated tank produced by Harima Works, capable of containing 1,250 cubic meters of liquid hydrogen and stored at a temperature of -253 °C.
The owner of the unit is the Hystra (Energy and Hydrogen Supply-chain Technology Research Association), a society created from Kawasaki, Iwatani Corporation, Shell Japan and Electric Power Development Co. The union of these Japanese industrial realities gave rise to the pilot program NEDO that by 2020 will begin to transport liquid hydrogen from Australia to Japan.[50,51]

Taking into account the volume of the tank of this mentioned ship and consulting the literature on the speed and days required for loading/unloading at the port of a ship carrying hydrogen[43], the number of monthly loads required by each area to meet the respective hydrogen demand has been calculated. The density of hydrogen when bonded to LOHC is 43 kg/m^3 [45].

Data	LH2	LOHC
Ship Speed [kn]	18	15
Ship Speed [km/h]	33	28
Hydrogen Storage Tank [m^3]	1250	1250
H_2 Density [kg/m^3]	71	43
Mass of H_2 transported [kgH_2]	88750	53750
Loading/Unloading [days]	2	2

Table 11: Ship Transport data

LH2 Ship Transport					
Area	Port of Arrival	Length of round trip including loading/unloading [days/roundtrip]	Average Daily Demand [kgH_2/day]	Days between loads	Loads/Month required
1	Genova	34,2	68686	1,3	**24**
2	Venezia	38,2	30664	2,9	**11**
3	Livorno	34,2	34909	2,5	**12**
4	Civitavecchia	34,5	40792	2,2	**14**
5	Napoli	35,0	45410	2,0	**16**
6	Messina	34,9	29382	3,0	**11**
7	Cagliari	33,6	6950	12,8	**3**

Table 12: LH2 Ship Transport

LOHC Ship Transport					
Area	Port of Arrival	Length of round trip including loading/unloading [days/roundtrip]	Average Daily Demand [kgH_2/day]	Days between loads	Loads/Month required
1	Genova	40,6	68686	0,8	**39**
2	Venezia	45,5	30664	1,8	**18**
3	Livorno	40,7	34909	1,5	**20**
4	Civitavecchia	41,0	40792	1,3	**24**
5	Napoli	41,6	45410	1,2	**26**
6	Messina	41,5	29382	1,8	**17**
7	Cagliari	39,9	6950	7,7	**4**

Table 13: LOHC Ship Transport

2.4.2 Terminal at Italian port

2.4.2.1 LH2 Terminal at Italian port

Upon arrival in Italy, in the port of each area was provided an LH2 Terminal, sized to cope with interruptions for upstream maintenance of the production plant (Plant Outages). The default setting was left unchanged on HDSAM, 10 days scheduled. The reasoning finds confirmations in literature.[47]

In such way, to the Italian ports it will be able to have hydrogen on hand to be able to send to the row of distribution (that it will be treated more ahead) in order to satisfy the demand, even if upstream the production is stopped in those days and the ships do not arrive.

HDSAM provides the following results:

AREA 1: 0.29 €/kg

AREA 2: 0.37 €/kg

AREA 3: 0.36 €/kg

AREA 4: 0.34 €/kg

AREA 5: 0.33 €/kg

AREA 6: 0.38 €/kg

AREA 7: 0.81 €/kg

The cost per kg of Area 7 is higher than the others because Sardinia alone has a smaller population, hence it has a daily hydrogen demand of almost an order of magnitude less than the other areas (see Table 7). It follows that investment costs (which make up 75% of the cost item) have a greater impact on the single kilogram of H_2.

2.4.2.2 LOHC Terminal at Italian Port

Analogously to the assumptions made for the previous terminals, the costs of the LOHC-H_2 terminals to the Italian port are considered like a fifth of the LH2 terminals:

AREA 1: 0.06 €/kg

AREA 2: 0.07 €/kg

AREA 3: 0.07 €/kg

AREA 4: 0.07 €/kg

AREA 5: 0.07 €/kg

AREA 6: 0.08 €/kg

AREA 7: 0.16 €/kg

2.4.3 Distribution from Italian ports to HRS

At this point, the liquefied hydrogen (LH2) or the hydrogen bound to the LOHC, is loaded by pumping from the terminal to the track-trailers, which carry out the distribution in the HRSs of the respective area.

HDSAM provided the average roundtrip length travelled by single truck trailer:

AREA 1 (Piemonte, Val d'Aosta,Lombardia, Liguria):	722 km
AREA 2 (Veneto, Trentino-Alto Adige, Friuli-Venezia Giulia):	599 km
AREA 3 (Toscana, Emilia-Romagna):	640 km
AREA 4 (Lazio, Abruzzo, Umbria, Marche):	643 km
AREA 5 (Molise, Campania, Puglia, Basilicata):	656 km
AREA 6 (Calabria, Sicilia):	608 km
AREA 7 (Sardegna):	466 km

2.4.3.1 LH2 Distribution

By entering the input data for each area, and the appropriate costs of LH2 trucks and trailers, HDSAM provided the Distribution cost for each area:

AREA 1:	0.52 €/kg
AREA 2:	0.45 €/kg
AREA 3:	0.48 €/kg
AREA 4:	0.48 €/kg
AREA 5:	0.48 €/kg
AREA 6:	0.46 €/kg
AREA 7:	0.40 €/kg

Weighted average with the weight equal to the kilometers of each area: 0.47 €/kg

2.4.3.2 LOHC Distribution

Through the appropriate manual modifications on HDSAM as in the case of the Transmission to the argentine port, we obtain:

AREA 1: 0.45 €/kg

AREA 2: 0.39 €/kg

AREA 3: 0.41 €/kg

AREA 4: 0.41 €/kg

AREA 5: 0.42 €/kg

AREA 6: 0.40 €/kg

AREA 7: 0.33 €/kg

Weighted average with the weight equal to the kilometers of each area: 0.41 €/kg

The following table shows a summary of distribution costs:

Cost of Distribution from Port to HRS [€/kgH$_2$]			
Area	**Aveage roundtrip length single truck [km]**	**LH2**	**LOHC**
1	722	0,52	0,45
2	599	0,45	0,39
3	640	0,48	0,41
4	643	0,48	0,41
5	656	0,48	0,42
6	608	0,46	0,40
7	466	0,40	0,33

Table 14: Cost of Distribution from Port to HRS

2.4.4 Cost Breakdown

Liquefied Hydrogen - LH2	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7
Items	€/kgH_2						
Oceanic Transport Argentine / Italy	1,54	1,58	1,54	1,54	1,55	1,54	1,53
LH2 Terminal at Italian Port (storage for Plant Outages, 10 days)	0,29	0,37	0,36	0,34	0,33	0,38	0,81
Distribution (Tractor-Trailer) from Italian ports to HRS	0,52	0,45	0,48	0,48	0,48	0,46	0,40
Total cost from Argentine Port to Italian HRS	**2,35**	**2,40**	**2,37**	**2,36**	**2,35**	**2,38**	**2,74**

Table 15: LH2 ARG - From Argentine port to Italian HRS

LOHC: Dibenzyltoluene	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7
Items	€/kgH_2						
Oceanic Transport Argentine / Italy	0,51	0,57	0,52	0,52	0,52	0,52	0,51
LOHC-H2 Terminal at Italian Port (storage for Plant Outages, 10 days)	0,06	0,07	0,07	0,07	0,07	0,08	0,16
Distribution (Tractor-Trailer) from Italian ports to HRS	0,45	0,39	0,41	0,41	0,42	0,40	0,33
Total cost from Argentine Port to Italian HRS	**1,02**	**1,03**	**1,00**	**1,00**	**1,01**	**1,00**	**1,00**

Table 16: LOHC ARG - From Argentine port to Italian HRS

Having to deal with a liquid at room conditions instead of a liquid to be maintained at -253 °C is an important advantage in favor of LOHC storage: in fact, especially ocean long distance transport but also storage at terminals are much less expensive. There is a difference of more than 1.30 €/kgH_2 between the two storage, transport and distribution methodologies, regarding this cost section: **2.35 €/kgH_2** for **LH2** and **1.02 €/kgH_2** for **LOHC.**

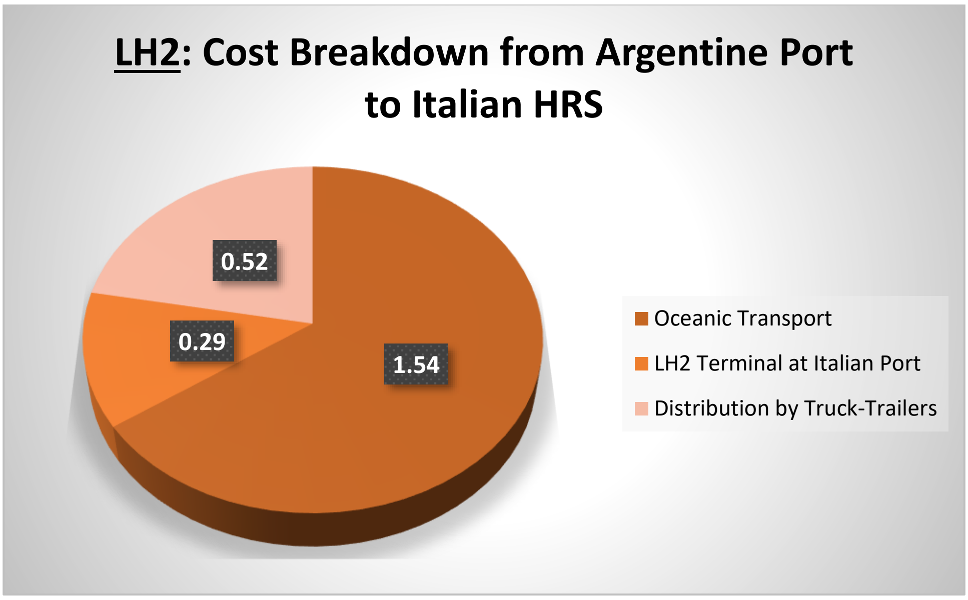


Figure 25: LH2 ARG - Cost Breakdown from Argentine port to Italian HRS

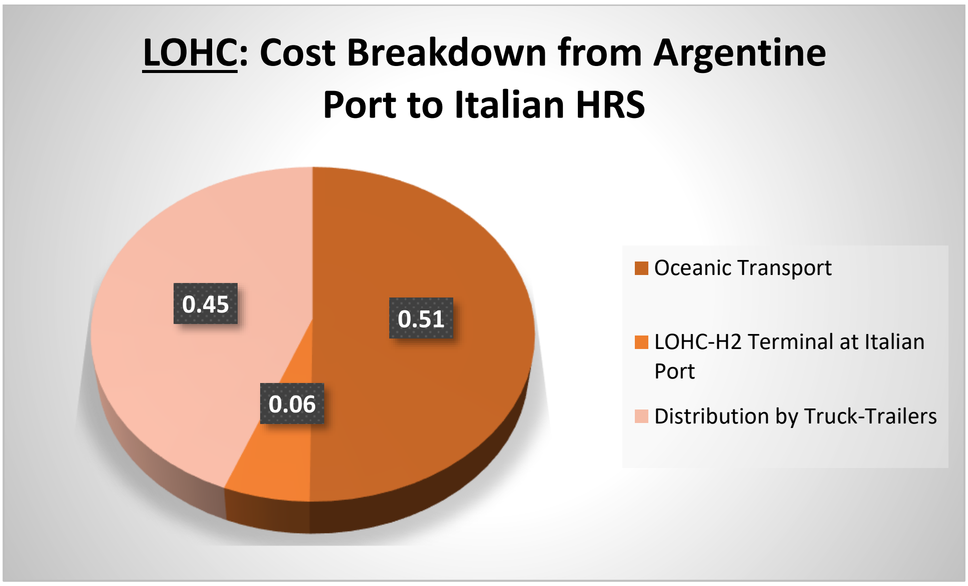


Figure 26: LOHC ARG - Cost Breakdown from Argentine port to Italian HRS

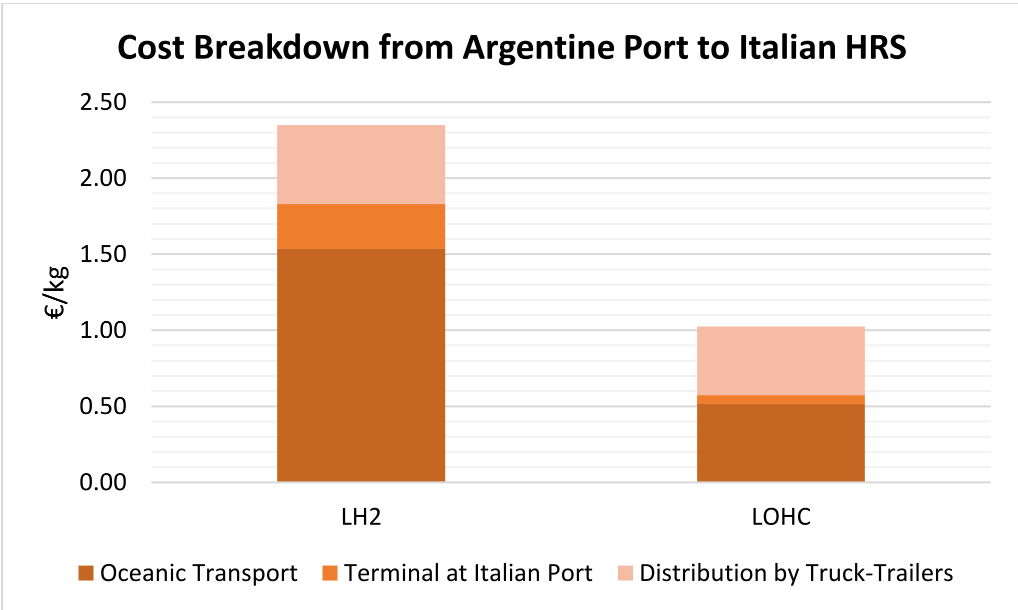


Figure 27: Scenario ARG - Cost Breakdown from Argentine port to Italian HRS: LH2 vs LOHC

2.5 Hydrogen Refueling Stations (HRS)

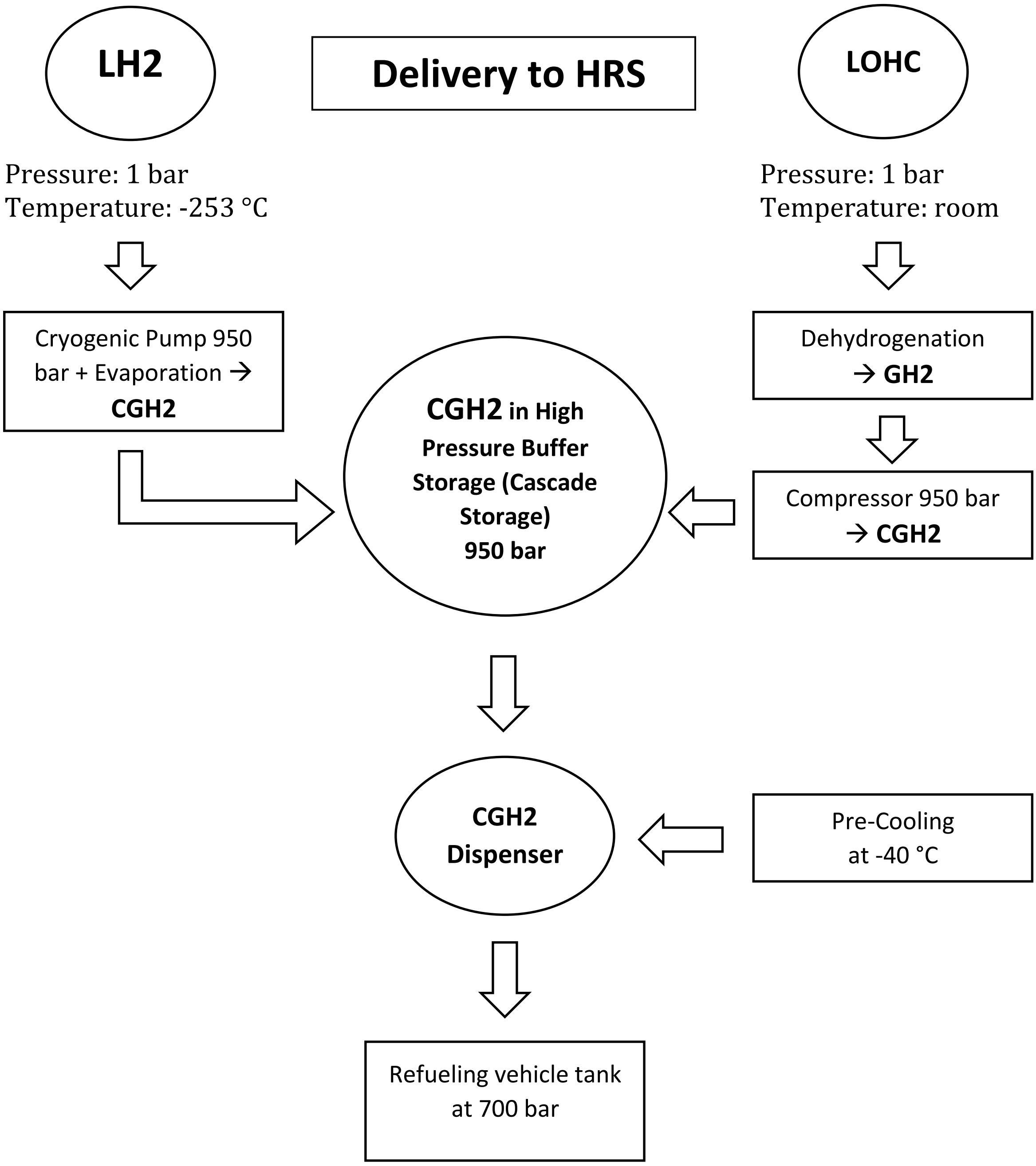
To have a similar amount of energy in the hydrogen vehicle to that of petrol or diesel vehicles, trying to be as contained as possible on the volume of the tank, the refuelling is carried out at very high pressures. With vehicles refueling at 700 bar, the refuelling time does not exceed the target of 3-5 minutes.

A decree published in the "Gazzetta Ufficiale" in January 2017, has provided for the increase of the maximum operating pressure of the supply pumps from the current 350 bar to 700 bar, a change necessary to meet the technical needs of the cars on the market. In doing so, the modern cars powered by fuel cells could start to refuel in a few minutes and in total safety.[52]

In addition, with higher pressures equal hydrogen masses can be stored in smaller volumes. To store hydrogen it was necessary to arrive (as in the case of the Honda Clarity) at pressures of 700 bar in the tank to ensure the sedan of 4.91 meters a maximum approved distance of almost 600 km.[53]

The hydrogen must be stored in the cascade storage and made available to the dispenser at very high pressure (875-950bar)[41,44,45] to refuel vehicles at 700 bar. Compression is done by compressors if we are dealing with gaseous hydrogen just dehydrogenated by LOHC, or by high pressure cryogenic pump if we are operating with LH2. In addition, it is essential to pre-cool hydrogen before it is dispensed to vehicles because during refuelling it expands. When hydrogen expands, it heats up (as opposed to other gases, due to the negative Joule-Thomson coefficient for hydrogen at those temperatures). To ensure that the temperature does not rise too much during refuelling, hydrogen is pre-cooled to -40 °C before it reaches the nozzle.[54]
The cooling system is placed between the 950 bar storage vessels and the dispenser.[55] The SAE J2601 refuelling protocol aims to ensure that the tank of a hydrogen vehicle does not exceed 85 °C.[56]

For clarity, here is a flow chart of the operations that are performed on hydrogen depending on whether LH2 or LOHC arrives at HRS. Depending on whether we are dealing with LH2 or LOHC, we start from left or right of the flow diagram:



Depending on whether you arrive at the station LH2 or LOHC, you will have in the first case the structure of an LH2 Hydrogen Refueling Station (LH2 HRS), in the second one a LOHC Hydrogen Refueling Station. (LOHC HRS).
LOHC fuelling stations are not available today and a demonstration of the combination of a dehydrogenation unit and a 700 bar refuelling compressor has yet to be conducted.[44]

2.5.1 LH2 Hydrogen Refueling Station

In the LH2 scenario, liquefied hydrogen arrives with truck-trailers at the HRS. Before it can be stored in the high-pressure storage buffer (cascade storage 950 bar) and sent to the dispenser from which the vehicles will be refuelled to 700 bar, it must be returned to the gas phase GH2. The liquid hydrogen is conveyed from the cryogenic tanks of the truck to the cryogenic storage tank of the station, then is compressed and vaporized by a cryogenic pump that has a consumption of 0.5 kWh/kgH_2[41], and an evaporator.

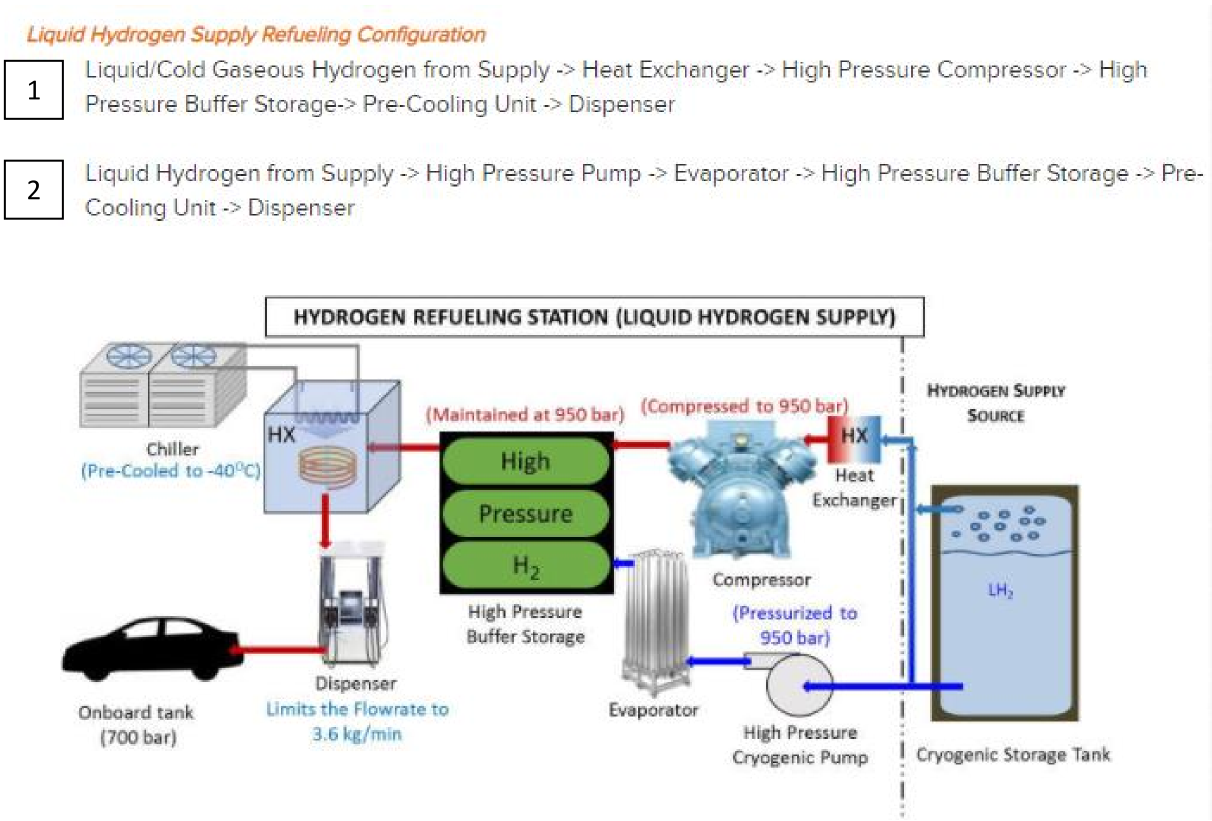


Figure 28: Configurations of LH2 Hydrogen Refueling Station [57]

In Figure 28 two configurations of HRS are shown when delivery of LH2 arrives. In this work the second one is described.

The cryo pump operates with liquid hydrogen (LH2) at -253 °C. At this temperature, however, hydrogen cannot be simply suctioned in. Hence the pump uses a two-chamber system which is completely immersed in the cryogenic liquid. In the first chamber, LH2 from the storage tank is compressed to 0.6 MPa. The compression to 100 MPa takes place in the second chamber. Subsequently, the temperature of the cryogenic gas is increased

up to the fueling temperature of -40 °C. During all of these process steps, the high purity level of the hydrogen is maintained.
In addition to its small footprint and high capacity, the cryo pump minimizes the energy required by the fueling station. It only needs 10–20% of the energy required by a conventional compressor. The cooling power of cryogenic LH2 also eliminates the need for an external cooling system for the supply line. And the low-maintenance design cuts operating costs further.[58]

The impact on the cost of hydrogen of an LH2 HRS is represented by the following items:

- **CAPEX LH2 Cryogenic Storage Tank**
- **CAPEX High Pressure Cryogenic Pump**
- **CAPEX Evaporator**
- **CAPEX Cascade Storage 950 bar**
- **CAPEX Dispenser 700 bar**
- **Land/Other CAPEX**
- **CAPEX Control/Safety Equipment**
- **OPEX LH2 HRS**
- **Electricity for Cryogenic Pump/Evaporation**

The value of the CAPEXs are obtained by consulting the Refueling Station LH2 section downstream of HDSAM simulations. It is considered AREA 1, composed of 172 refueling stations. The useful life is 20 years, except for the cryogenic pump[59] and evaporator[44], which have useful life of 10 years thus their investment will be supported again in the eleventh year. The values are converted from $ to €.

CAPEX LH2 Cryogenic Storage Tank

HDSAM sizes the storage for a capacity of 2,412 kg of LH2 for single HRS:

Single HRS:	**170,400 €**
Overall AREA 1:	**29,308,800 €**

CAPEX High Pressure Cryogenic Pump

Number of cryopumps:	1
Single HRS:	**391,786 €**
Overall AREA 1:	**67,387,192 €**

CAPEX Evaporator

Number of Heat Exchangers:	1
Single HRS:	**42,060 €**
Overall AREA 1:	**7,234,320 €**

CAPEX Cascade Storage 950 bar

Capacity [kg H_2]:	67
Single HRS:	**73,069 €**
Overall AREA 1:	**12,567,868 €**

CAPEX Dispenser 700 bar

Number of dispensers:	2
Single HRS:	**101,621 €**
Overall AREA 1:	**17,478,812 €**

Land/Other CAPEX

Single HRS:	**212,028 €**
Overall AREA 1:	**36,468,816 €**

CAPEX Control/Safety Equipment

Single HRS:	**85,000 €**
Overall AREA 1:	**14,620,000 €**

Total CAPEX LH2 HRS:

Single HRS:	**1,075,964 €**
Overall AREA 1:	**185,065,808 €**

OPEX LH2 HRS:

The percentage of annual OPEX costs for refuelling stations is 10% of the initial CAPEX.[44]

Single HRS: **107,596 €**

Overall AREA 1: **18,506,581 €**

Electricity for Cryogenic Pump/Evaporation

Electric Energy required: 0.5 kWh/kgH_2

The cost of electricity drawn from the Italian network for industrial activities is available on EUROSTAT. It depends on the annual consumption band. The last column presents the prices for the year 2020. It was considered the cost including taxes and taxes.[60]

Definition of annual consumption range of electricity per HRS:

Annual Electricity demand for Criogenic Pump/Evaporation =
0.5 kWh/kgH_2 * 25,070,309 kgH_2/year = 12,535,154 kWh/year

Annual Electricity demand for Criogenic Pump/Evaporation at the single HRS =
[12,535,154 kWh/year] / 172 stations = 72,879 kWh/(year*HRS) = *73 MWh/(year*HRS)*

In the case of LH2 HRS, the electricity consumption is in the range 20 MWh - 500MWh which corresponds to a tabulated cost (including taxes and duties) of:

Electricity Cost from the grid = 0.2057 €/kWh

Annual Electricity Cost for Cryogenic Pump/Evaporation [€/year] = 0.2057 €/kWh * 12,535,154 kWh/year = **2,578,481 €/year**

The following table shows a summary, highlighting the cost contribution by LH2 HRS:

Year	CAPEX LH2 Cryogenic Storage [€]	CAPEX Cryogenic Pump [€]	CAPEX Evaporator [€]	CAPEX Cascade Storage 950 bar [€]	CAPEX Dispenser 700 bar [€]	Land/Other CAPEX [€]
0	29308800	67387192	7234320	12567868	17478812	36468816
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	39399896	4229757	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
Cumulated [€] or [kg]	29308800	106787088	11464077	12567868	17478812	36468816
Impact [%]	5,72%	20,83%	2,24%	2,45%	3,41%	7,12%
Portions / LCOH LH2 HRS [€/kgH$_2$]	**0,09**	**0,32**	**0,03**	**0,04**	**0,05**	**0,11**

CAPEX Control/Safety Equipment [€]	Total CAPEX LH2 HRS [€]	OPEX LH2 HRS [€/year]	Electricity Cryopump/Evaporation [€/year]	Total Cost [€/year]	Annual H$_2$ demand of the AREA [kgH$_2$/year]
14620000	185065808	18506581	2578481	206150870	25070309
0	0	17625315	2455696	20081011,46	23876484
0	0	16786014	2338758	19124772,82	22739509
0	0	15986680	2227389	18214069,36	21656675
0	0	15225410	2121323	17346732,72	20625405
0	0	14500390	2020308	16520697,83	19643243
0	0	13809896	1924102	15733997,93	18707850
0	0	13152281	1832478	14984759,93	17817000
0	0	12525982	1745218	14271199,94	16968572
0	0	11929507	1662112	13591618,99	16160544
0	0	11361435	1582964	12944399,04	15390995
0	43629653	10820415	1507585	55957651,67	14658090
0	0	10305157	1435795	11740951,51	13960086
0	0	9814435	1367424	11181858,58	13295320
0	0	9347081	1302308	10649389,12	12662209
0	0	8901982	1240294	10142275,35	12059247
0	0	8478078	1181232	9659309,861	11484997
0	0	8074360	1124983	9199342,725	10938093
0	0	7689867	1071412	8761278,786	10417231
0	0	7323682	1020393	8344075,034	9921172
0	0	6974936	971802	7946738,128	9448736
14620000	228695461	249139483	34712057	512547001	337501767
2,85%	44,62%	48,61%	6,77%	100,00%	
0,04	**0,68**	**0,74**	**0,10**	**1,52**	

Table 17: LH2 HRS - Impact on LCOH

LH2 Hydrogen Refueling Station		
Items	**€/kgH$_2$**	**Impact [%]**
LH2 Cryogenic Storage Tank	0,09	5,7%
High Pressure Cryogenic Pump (950 bar)	0,32	20,8%
Evaporator	0,03	2,2%
Electricity for Cryogenic Pump/Evaporation	0,10	6,8%
Cascade Storage (950 bar)	0,04	2,5%
Dispenser CGH2 (700 bar)	0,05	3,4%
Land / Other Capital Costs HRS	0,11	7,1%
Control / Safety Equipment	0,04	2,9%
Operation & Maintenance LH2 HRS	0,74	48,6%
Total LH2 Hydrogen Refueling Station	**1,52**	

Table 18: LH2 HRS - Cost detail

LH2 HRS contribution to LCOH is **1.52 €/kgH_2**: about half of this is due to Operation and Maintenance (OPEX) costs. These costs impact more because they are faced each year with an estimated amount of 10% of the initial investment. Another considerable part of the cost (20.8%) is given by the Cryogenic Pump, whose investment cost is really important. The considerable investment is however compensated because of the lower energy absorbed for compression with respect to conventional compressors (only 0.5 kWh/kgH_2): it follows that the share of energy in the total cost is quite modest: 0.10 €/kgH_2, which represents 6,8% of the cost attributable to the entire HRS.

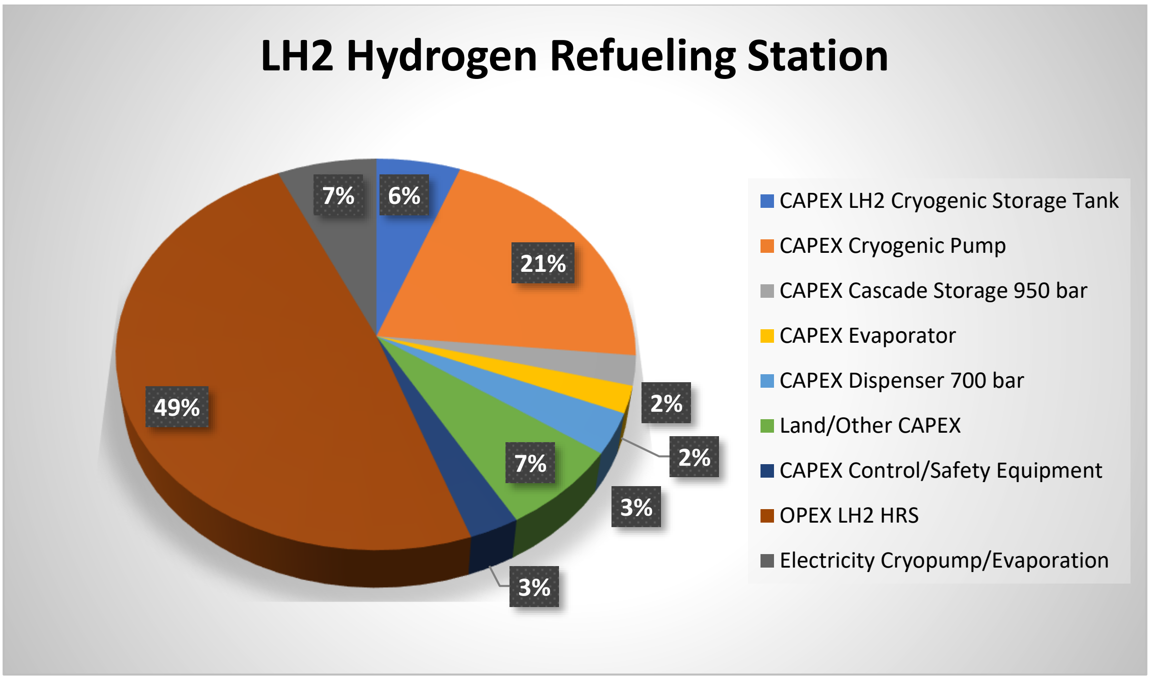


Figure 29: LH2 HRS - Cost allocation

2.5.2 LOHC Hydrogen Refueling Station

At the arrival of LOHC truck trailers to the HRS, it is stored in the HRS tank. At this point the LOHC dehydrogenation must be carried out so that hydrogen can be freed from the mixture with dibenzyltoluene that is used to transport it. The state of the hydrogen once separated is in the gaseous state (GH2),[44] then is compressed to 950 bar, conveyed in the cascade storage and at that point, through the dispenser, FCEVs can be refueled at a pressure of 700 bar. The structure of a LOHC HRS is similar to CGH2 HRS with the addition of dehydrogenation. Another difference is that compression of hydrogen downstream of dehydrogenation starts from the pressure of 1-2 bar,[44] while in the CGH2 HRS as we will see in the Italian scenario, the high pressure compression starts from a higher pressure, as the hydrogen coming from the distribution with truck tube trailers is already compressed to 200-250 bar,[43–45] or even 500 bar in more recent times.[59] For this reason, the energy expenditure for compression and pre-cooling will be higher in this case (as already mentioned 4.36 kWh/kgH_2) compared to the case of CGH2 HRS in which you need 1.9 kWh/kgH_2 (1.5 kWh/kgH_2 for compression plus 0.4 kWh/kgH_2 for pre-cooling).[44]

The electrical and thermal energy required for the dehydrogenation process are summarised:

- Electric Energy: 0.367 kWh/kgH_2
- Thermal Energy from Natural Gas: 9.5 kWh/kgH_2

The cost of thermal kilowatt-hour from natural gas for industrial activities is available on EUROSTAT. It depends on the annual consumption band. The last column presents the prices for the year 2020. It was considered the cost including taxes and taxes:[61]

Definition of annual consumption range of natural gas per HRS

AREA 1 is considered, but the results are the same for all areas because the daily hydrogen demand and the number of HRSs are proportionate for each area:

Daily average H_2 demand in the AREA = 68,686 kgH_2/day

Annual H_2 demand in the AREA = 25,070,309 kgH_2/year

Number of HRS in the AREA = 172

Annual Thermal Energy demand for Dehydrogenation =
9.5 kWh/kgH_2 * 25,070,309 kgH_2/year = 238,167,931 kWh/year

Annual Thermal Energy demand for Dehydrogenation <u>at the single HRS:</u>
= [238,167,931 kWh/year] / 172 stations = 1,384,697 kWh/(year*HRS) * 0.0036 GJ/kWh = **4,985 GJ/(year*HRS)**

In the case of LOHC HRS, the electricity consumption is in the range 1000 GJ – 10000 GJ which corresponds to a tabulated cost (including taxes and duties) of:

Cost of Natural Gas = 0.0523 €/kWh

Definition of annual consumption range of electricity per HRS:

Annual Electricity demand Dehydrogenation =
0.367 kWh/kgH_2 * 25,070,309 kgH_2/year = 9,200,803 kWh/year

Annual Electricity demand for Dehydrogenation <u>at the single HRS</u> =
[9,200,803 kWh/year] / 172 stations = 53,493 kWh/(year*HRS) = *53,5 MWh/(year*HRS)*

At this point, it is necessary to make a clarification: for the decision of the annual consumption range of electricity at the individual HRS, it is not necessary to consider only the energy for dehydrogenation, as it also performs the compression of hydrogen at 950 bar at HRS, a process that absorbs much more energy than the dehydrogenation itself: 4 kWh/kgH_2 and the Pre-Cooling at -40 °C (0.36 kWh/kgH_2). There is therefore a total consumption for Compression + Pre-Cooling equal to 4.36 kWh/kgH_2.[41,44]
The calculations will be shown in more detail later, when compression and pre-cooling will be treated, for now take for good the total consumption for compression+pre-cooling of *635.5 MWh/year*HRS*.

Annual Electricity demand for Dehydrogenation + Compression/Pre-Cooling at single HRS = 53.5 + 635.5 = *689 MWh/year*HRS.*

In the case of LOHC HRS, the electricity consumption is in the range 500 MWh - 2000MWh which corresponds to a tabulated cost (including taxes and duties) of:

Electricity Cost from the grid = 0.1738 €/kWh

With the unit costs of grid electricity and natural gas, it is possible to calculate:

- **Annual Cost of Natural Gas for Dehydrogenation [€/year]** =
  0.0523 €/kWh * 238,167,931 kWh/year = **12,456,183 €/year**

- **Annual Cost of Electricity for Dehydrogenation [€/year]** =
  0.1738 €/kWh * 9,200,803 kWh/year = **1,599,100 €/year**

Below, CAPEX of HRS dehydrogenation plants and operation and maintenance costs (OPEX) are calculated:

- **CAPEX Dehydrogenation [€]**
  Literature considers an investment cost of 94,000 €. In this case study, in Area 1 there are 172 refueling stations, thus 172 dehydrogenation plants are considered:

  CAPEX Dehydrogenation [€] = 94,000 €/HRS * 172 HRS = **16,168,000 €**

- **OPEX Dehydrogenation [€/year]**
  The operation and maintenance costs amount to approximately 3% annual of the initial CAPEX.[44]
  OPEX Dehydrogenation [€/year] = 3%/year * 16,168,000 € = **485,040 €/year**

The investment cost is carried out in year zero of the plant and the annual electricity costs and OPEX are discounted year by year over 20 years with the factor $(1+r)^{-t}$.

The following table shows a summary: the columns related to dehydrogenation are highlighted in pink.

Year	CAPEX Hydrogenation [€]	OPEX Hydrogenation [€/year]	CAPEX Dibenzyltoluene [€]	CAPEX Dehydrogenation [€]	OPEX Dehydrogenation [€/year]
0	9500000	285000	33759678	16168000	485040
1	0	271429	0	0	461943
2	0	258503	0	0	439946
3	0	246194	0	0	418996
4	0	234470	0	0	399044
5	0	223305	0	0	380042
6	0	212671	0	0	361944
7	0	202544	0	0	344709
8	0	192899	0	0	328294
9	0	183714	0	0	312661
10	0	174965	0	0	297772
11	0	166634	0	0	283593
12	0	158699	0	0	270088
13	0	151142	0	0	257227
14	0	143944	0	0	244978
15	0	137090	0	0	233313
16	0	130562	0	0	222202
17	0	124345	0	0	211621
18	0	118423	0	0	201544
19	0	112784	0	0	191947
20	0	107414	0	0	182806
Cumulated [€] or [kg]	9500000	3836730	33759678	16168000	6529711
Impact [%]	9,91%	4,00%	35,20%	7,63%	3,08%
Portions LCOH Hyrogenation [€/kgH$_2$]	**0,008**	**0,003**	**0,027**	-	-
Portions LCOH Dehydrogenation [€/kgH$_2$]	-	-		**0,05**	**0,02**
LCOH Hydrogenation+Dehydrogen. [€/kgH$_2$	0,01	0,003	0,027	0,05	0,02

Electricity for Hydrogenation [€/year]	Electricity for Dehydrogenation [€/year]	Heat for Dehydrogenation [€/year]	Total Cost [€/year]	Hydrogenation of national annual H_2 demand [kgH$_2$/year]	Dehydrogenation of annual H_2 distributed in the AREA [kgH$_2$/year]
3625450	1599100	12456183	77878450	93729328	25070309
3452810	1522952	11863031	17572165	89266027	23876484
3288390	1450430	11298125	16735395	85015264	22739509
3131800	1381362	10760119	15938471	80966918	21656675
2982667	1315583	10247732	15179496	77111350	20625405
2840635	1252936	9759745	14456663	73439381	19643243
2705367	1193273	9294995	13768251	69942268	18707850
2576540	1136450	8852377	13112620	66611684	17817000
2453848	1082334	8430835	12488209	63439699	16968572
2336998	1030794	8029367	11893533	60418761	16160544
2225712	981708	7647016	11327174	57541677	15390995
2119726	934960	7282872	10787785	54801597	14658090
2018786	890438	6936069	10274081	52191997	13960086
1922654	848037	6605780	9784839	49706664	13295320
1831099	807654	6291219	9318894	47339680	12662209
1743904	769194	5991637	8875137	45085409	12059247
1660861	732566	5706321	8452512	42938485	11484997
1581772	697682	5434591	8050011	40893795	10938093
1506450	664459	5175801	7666677	38946472	10417231
1434714	632818	4929335	7301597	37091878	9921172
1366394	602684	4694604	6953902	35325598	9448736
48806576	21527415	167687753	307815863	1261803931	337501767
50,89%	10,16%	79,13%	**LCOH [€/kgH$_2$]**		
0,039	-	**-**	**0,08**		
-	**0,06**	**0,50**	**0,63**		
0,04	0,06	0,50	**0,70**		

Table 19: Liquid Organic Hydrogen Carrier Dehydrogenation - Impact on LCOH

The contribution of dehydrogenation on LCOH is **0.63 €/kgH$_2$** produced: a significant impact (79%) is given by the cost of natural gas provided, in fact it is a reaction that requires a lot of heat. Although cost of industrial electricity from the Italian grid is more than 4 times higher than cost of electricity from Argentine wind generation, a not very high content of electricity absorbed by the process (0.367 €/kWh), causes the share of electricity cost in the kilogram of hydrogen to be contained (0.06 €/kgH_2, about 10% of the total process). The remaining percentage is attributable to CAPEX (8%) and OPEX (3%).

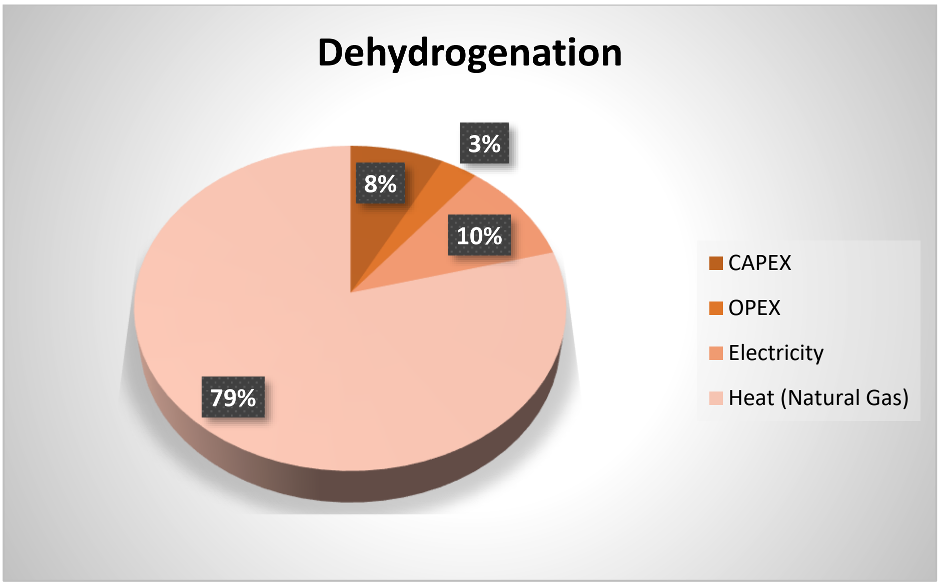


Figure 30: LOHC Dehydrogenation - Cost allocation

Hydrogen is in the gaseous state (GH2). At this point it can be compressed to 950 bar and stored in the cascade storage at 950 bar. Before refuelling the vehicle to 700 bar by means of the dispenser, it is sent to a pre-cooling circuit, so as to be expelled to the dispenser nozzle at -40 C.

The impact on the cost of hydrogen of an LOHC HRS is represented by the following items:

- **CAPEX LOHC Storage Tank**
- **CAPEX Compressor 950 bar**
- **CAPEX Cascade Storage 950 bar**
- **CAPEX Refrigeration Equipment**
- **CAPEX Dispenser 700 bar**
- **Land/Other CAPEX**

- **CAPEX Control/Safety Equipment**
- **OPEX LOHC HRS**
- **Electricity for Compression at 950 bar/Pre-Cooling**

The value of the CAPEXs are obtained by consulting the Refueling Station Gaseous H_2 section downstream of HDSAM simulations, except the LOHC Storage Tank since it is not calculated by HDSAM because it is not present in the CGH2 HRS architecture. It is considered AREA 1, composed of 172 refueling stations. The useful life is 20 years, except for the compressor which have useful life of 10 years[59] thus its investment will be supported again in the eleventh year. The values are converted from $ to €.

CAPEX LOHC Storage Tank

The same assumption made previously was considered: the cost of the tank for LOHC is one fifth of the cost of the cryogenic storage tank for LH2, the latter obtained from the HDSAM simulation for the previous case of LH2 HRS.

Single HRS:	**34,080 €**
Overall AREA 1:	**5,861,760 €**

CAPEX Compressor 950 bar

Number of compressors:	1
Single HRS:	**370,666 €**
Overall AREA 1:	**63,754,552 €**

CAPEX Cascade Storage 950 bar

Capacity [kg H_2]:	134
Single HRS:	**146,138 €**
Overall AREA 1:	**25,135,736 €**

CAPEX Refrigeration Equipment

Number of heat exchangers: 2

Single HRS: **136,669 €**

Overall AREA 1: **23,507,068 €**

CAPEX Dispenser 700 bar

Number of dispensers: 2

Single HRS: **101,621 €**

Overall AREA 1: **17,478,812 €**

Land/Other CAPEX

Single HRS: **209,005 €**

Overall AREA 1: **35,948,860 €**

CAPEX Control/Safety Equipment

Single HRS: **85,000 €**

Overall AREA 1: **14,620,000 €**

Total CAPEX LOHC HRS:

Single HRS: **1,083,179 €**

Overall AREA 1: **186,306,788 €**

OPEX LOHC HRS:

The percentage of annual OPEX costs for refuelling stations is 10% of the initial CAPEX.[44]

Single HRS: **108,318 €**

Overall AREA 1: **18,630,679 €**

Electricity for Compression at 950 bar/Pre-Cooling

Electric energy required = 4.36 kWh/kgH_2

Annual Electricity demand for Compression at 950 bar/Pre-Cooling =

4.36 kWh/kgH_2 * 25,070,309 kgH_2/year = 109,306,545 kWh/year

Annual Electricity demand for Compression at 950 bar/Pre-Cooling <u>at the single HRS</u> =

= [109,306,545 kWh/year] / 172 stations = 635,503 kWh/(year*HRS) =

635,5 MWh/(year*HRS)

Annual Energy Cost for Compression at 950 bar + Pre-Cooling [€/year] =

0.1738 €/kWh * 109,306,545 kWh/year = **18,997,478 €/year**

The following table shows a summary, highlighting the cost contribution by LOHC HRS:

Year	CAPEX LOHC Storage Tank [€]	Total Dehydrogenation [€/year]	CAPEX Compressor 950 bar [€]	CAPEX Cascade Storage 950 bar [€]	CAPEX Refrigeration Equipment [€]	CAPEX Dispenser 700 bar [€]
0	5861760	30708322	63754552	25135736	23507068	17478812
1	0	13847926	0	0	0	0
2	0	13188501	0	0	0	0
3	0	12560477	0	0	0	0
4	0	11962359	0	0	0	0
5	0	11392723	0	0	0	0
6	0	10850212	0	0	0	0
7	0	10333536	0	0	0	0
8	0	9841463	0	0	0	0
9	0	9372821	0	0	0	0
10	0	8926497	0	0	0	0
11	0	8501425	37275966	0	0	0
12	0	8096596	0	0	0	0
13	0	7711043	0	0	0	0
14	0	7343851	0	0	0	0
15	0	6994144	0	0	0	0
16	0	6661089	0	0	0	0
17	0	6343895	0	0	0	0
18	0	6041804	0	0	0	0
19	0	5754099	0	0	0	0
20	0	5480095	0	0	0	0
Cumulated [€] or [kg]	5861760	211912879	101030518	25135736	23507068	17478812
Impact [%]	0,62%	22,49%	10,72%	2,67%	2,50%	1,86%
Portions / LCOH LOHC HRS [€/kgH_2]	**0,02**	**0,63**	**0,30**	**0,07**	**0,07**	**0,05**

Land/Other CAPEX [€]	CAPEX Control/Safety Equipment [€]	OPEX LOHC HRS [€/year]	Electricity Compression 950 bar/Precooling [€/year]	Total Cost [€/year]	Annual H_2 demand of the AREA [kgH_2/year]
35948860	14620000	18630679	18997478	254643267	25070309
0		17743504	18092836	49684266	23876484
0		16898575	17231272	47318348	22739509
0		16093881	16410735	45065093	21656675
0		15327506	15629272	42919137	20625405
0		14597624	14885021	40875368	19643243
0		13902499	14176210	38928922	18707850
0		13240476	13501153	37075164	17817000
0		12609977	12858241	35309680	16968572
0		12009502	12245943	33628267	16160544
0		11437621	11662803	32026921	15390995
0		10892972	11107432	67777795	14658090
0		10374259	10578506	29049361	13960086
0		9880247	10074768	27666058	13295320
0		9409759	9595017	26348627	12662209
0		8961675	9138112	25093930	12059247
0		8534929	8702963	23898981	11484997
0		8128503	8288537	22760935	10938093
0		7741432	7893844	21677080	10417231
0		7372792	7517947	20644839	9921172
0		7021707	7159950	19661751	9448736
35948860	14620000	250810117	255748039	942053789	337501767
3,82%	1,55%	26,62%	27,15%	100,00%	
0,11	**0,04**	**0,74**	**0,76**	**2,79**	

Table 20: LOHC HRS - Impact on LCOH

LOHC Hydrogen Refueling Station		
Items	**€/kgH_2**	**Impact [%]**
LOHC Storage Tank	0,02	0,6%
LOHC Dehydrogenation	0,63	22,5%
Compressor (950 bar)	0,30	10,7%
Electricity for Compression/Pre-Cooling	0,76	27,1%
Cascade Storage (950 bar)	0,07	2,7%
Refrigeration Equipment	0,07	2,5%
Dispenser CGH2 (700 bar)	0,05	1,9%
Land / Other Capital Costs HRS	0,11	3,8%
Control / Safety Equipment	0,04	1,6%
Operation & Maintenance LOHC HRS	0,74	26,6%
Total LOHC Hydrogen Refueling Station	**2,79**	

Table 21: LOHC HRS - Cost detail

LOHC HRS contribution to LCOH is **2.79 €/kgH_2**, a much higher cost compared to LH2 HRS. This is mainly due to the presence of dehydrogenation, a process that requires a lot of heat, and which accounts for more than 20% of the cost. Another reason for the higher cost is the higher amount of electricity spent by the compressor with respect to electricity absorbed by the cryogenic pump in the LH2 case. There is a substantial difference: 0.76 €/kgH_2 instead of 0.10 €/kgH_2.

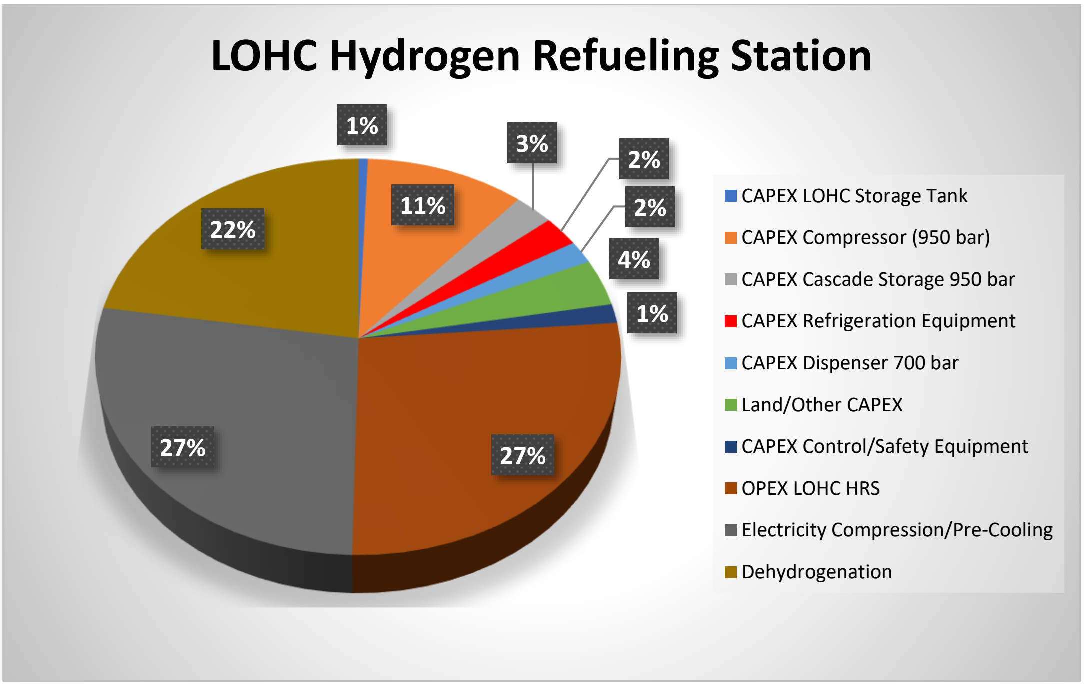


Figure 31: LOHC HRS - Cost allocation

2.6 Levelized Cost of Hydrogen (LCOH)

The analysis for both types of storage, transport and delivery of hydrogen (LH2 and LOHC) has been completed. It started from wind hydrogen production in Patagonia in the province of Chubut up to the Italian HRS. Two complete and summary tables with the final LCOH are then shown below:

	LH2						
Hydrogen Production from wind energy in Argentina [€/kg]	**4,57**						
Liquefier	1,93						
LH2 Terminal at Production site (storage 6 days)	0,20						
Tractor-Trailer (Transmission to Port)	0,12						
LH2 Terminal at Argentine Port (storage 1 day)	0,05						
Total Cost from Production site to Argentine port [€/kg]	**2,30**						
	Area 1	**Area 2**	**Area 3**	**Area 4**	**Area 5**	**Area 6**	**Area 7**
Oceanic Transport Argentine / Italy	1,54	1,58	1,54	1,54	1,55	1,54	1,53
LH2 Terminal at Italian Port (storage for Plant Outages, 10 days)	0,29	0,37	0,36	0,34	0,33	0,38	0,81
Distribution (Tractor-Trailer) from Italian ports to HRS	0,52	0,45	0,48	0,48	0,48	0,46	0,40
Total Cost from Argentine Port to Italian HRS [€/kg]	**2,35**	**2,40**	**2,37**	**2,36**	**2,35**	**2,38**	**2,74**
LH2 Cryogenic Storage Tank	0,09						
High Pressure Cryogenic Pump (950 bar)	0,32						
Evaporator	0,03						
Electricity for Cryogenic Pump/Evaporation	0,10						
Cascade Storage (950 bar)	0,04						
Dispenser CGH2 (700 bar)	0,05						
Land / Other Capital Costs HRS	0,11						
Control / Safety Equipment	0,04						
Operation & Maintenance LH2 HRS	0,74						
Total LH2 Hydrogen Refueling Station [€/kg]	**1,52**						
Levelized Cost Of Hydrogen [€/kg]	**10,74**	**10,79**	**10,76**	**10,75**	**10,74**	**10,77**	**11,13**

Table 22: Scenario LH2 ARG - Levelized Cost of Hydrogen

	LOHC: DibenzylToluene						
Hydrogen Production from wind energy in Argentina [€/kg]	**4,57**						
LOHC Hydrogenation	0,08						
LOHC-H2 Terminal at Production site (storage 6 days)	0,04						
Tractor-Trailer (Transmission to Port)	0,10						
LOHC-H2 Terminal at Argentine Port (storage 1 day)	0,01						
Total Cost from Production site to Argentine port [€/kg]	**0,23**						
	Area 1	**Area 2**	**Area 3**	**Area 4**	**Area 5**	**Area 6**	**Area 7**
Oceanic Transport Argentine / Italy	0,51	0,57	0,52	0,52	0,52	0,52	0,51
LOHC-H2 Terminal at Italian Port (storage for Plant Outages, 10 days)	0,06	0,07	0,07	0,07	0,07	0,08	0,16
Distribution (Tractor-Trailer) from Italian ports to HRS	0,45	0,39	0,41	0,41	0,42	0,40	0,33
Total Cost from Argentine Port to Italian HRS [€/kg]	**1,02**	**1,03**	**1,00**	**1,00**	**1,01**	**1,00**	**1,00**
LOHC Storage Tank	0,02						
LOHC Dehydrogenation	0,63						
Compressor (950 bar)	0,30						
Electricity for Compression/Pre-Cooling	0,76						
Cascade Storage (950 bar)	0,07						
Refrigeration Equipment	0,07						
Dispenser CGH2 (700 bar)	0,05						
Land / Other Capital Costs HRS	0,11						
Control / Safety Equipment	0,04						
Operation & Maintenance LOHC HRS	0,74						
Total LOHC Hydrogen Refueling Station [€/kg]	**2,79**						
Levelized Cost Of Hydrogen [€/kg]	**8,61**	**8,62**	**8,59**	**8,59**	**8,60**	**8,58**	**8,59**

Table 23: Scenario LOHC ARG - Levelized Cost of Hydrogen

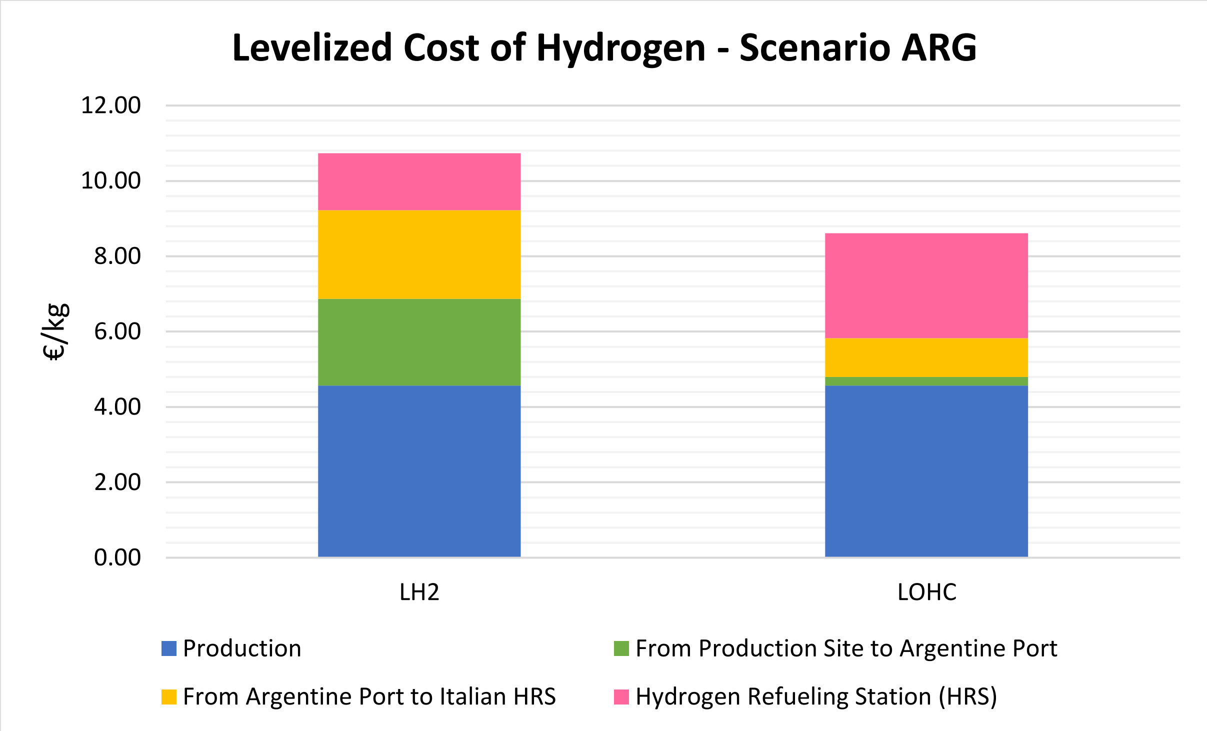


Figure 32: Scenario ARG: Levelized Cost of Hydrogen: LH2 vs LOHC

Between the two scenarios, the most advantageous in terms of LCOH is the storage with **Liquid Organic Hydrogen Carrier (LOHC)**. The final cost is **8.61 €/kgH$_2$**.

This technology allows to treat hydrogen at ambient conditions, thus avoiding expensive transformation processes such as Liquefaction (1.93 €/kgH$_2$), LH2 Terminals with cryogenic storages at -253 C (for a total of 0.44 €/kgH$_2$) and expensive ocean long-distance transport (1.54 €/kgH$_2$ for LH2 versus 0.51 €/kgH$_2$ for LOHC).

All these advantages can largely cover the disadvantage of a more expensive HRS (2.79 €/kgH$_2$ vs 1.52 €/kgH$_2$) due to dehydrogenation to make hydrogen available again and the compression of the GH2 from low pressure to very high pressure to refuel FCEVs.

Overall, the **LH2** cost is **10.74 €/kgH$_2$**, so there is more than 2 €/kgH$_2$ of difference between the two methodologies, which makes LOHC technology very attractive and the subject of much attention and study for the future.[62]

2.7 Sensitivity Analysis

The LCOH values obtained, 10.74 €/kgH_2 for LH2 scenario and 8.61 €/kgH_2 for LOHC scenario, are based on consumption values of the PEM electrolyser, wind energy cost and capacity factor considered as default, respectively equal to:

- PEM Electrolyser Consumption 58 kWh/kgH_2
- Wind Energy Cost 0.04 €/kWh
- Capacity Factor CF 50%

A sensitivity analysis was carried out to assess the impact on the final cost of the variation of one or more of the above parameters.

- *PEM Electrolyser Consumption*
  The source cited above[39] concludes that the electricity consumption for PEM electrolysers in the year 2020 can at most fall to 52 kWh/kgH_2.

- *Wind Energy Cost*
  The value of 0.04 €/kWh is an average value for the Province of Chubut in Argentina. According to the data of the Argentine Ministry of Energy (Ministero de Energìa y Minerìa)[42] it can be considered a range between 0.030 €/kWh and 0.055 €/kWh (30-55 €/MWh).

- *Capacity Factor – CF*
  Sensitivity analysis is carried out on typical CF values for a wind farm, reaching up to 70%, values that in some cases can be reached in Argentina.[18] Hence, the range 20-70% is analysed.

The sensitivity analysis was carried out on both the cost of production and the overall LCOH. A first procedure was to vary one parameter at a time by keeping the other two set at the default values.

Variable parameter: *Capacity Factor*

Wind Energy Cost 0.04 €/kWh

PEM Electrolyser Consumption 58 kWh/kgH_2

Capacity Factor CF [%]	Annual Equivalent Operating Hours [h/year]	CAPEX Stack	CAPEX Auxiliary	OPEX System	Electricity for Production	Water	CAPEX Civil Works & Other Costs	LCOH Production [€/kg]
20%	1752	1,03	1,92	0,79	2,32	0,01	1,24	7,31
30%	2628	0,95	1,28	0,53	2,32	0,02	0,82	5,92
40%	3504	0,76	0,96	0,40	2,32	0,02	0,62	5,08
50%	4380	0,64	0,77	0,32	2,32	0,03	0,49	4,57
60%	5256	0,69	0,64	0,26	2,32	0,03	0,41	4,36
70%	6132	0,61	0,55	0,23	2,32	0,04	0,35	4,10

Table 24: Scenario ARG - Production Cost as CF varies

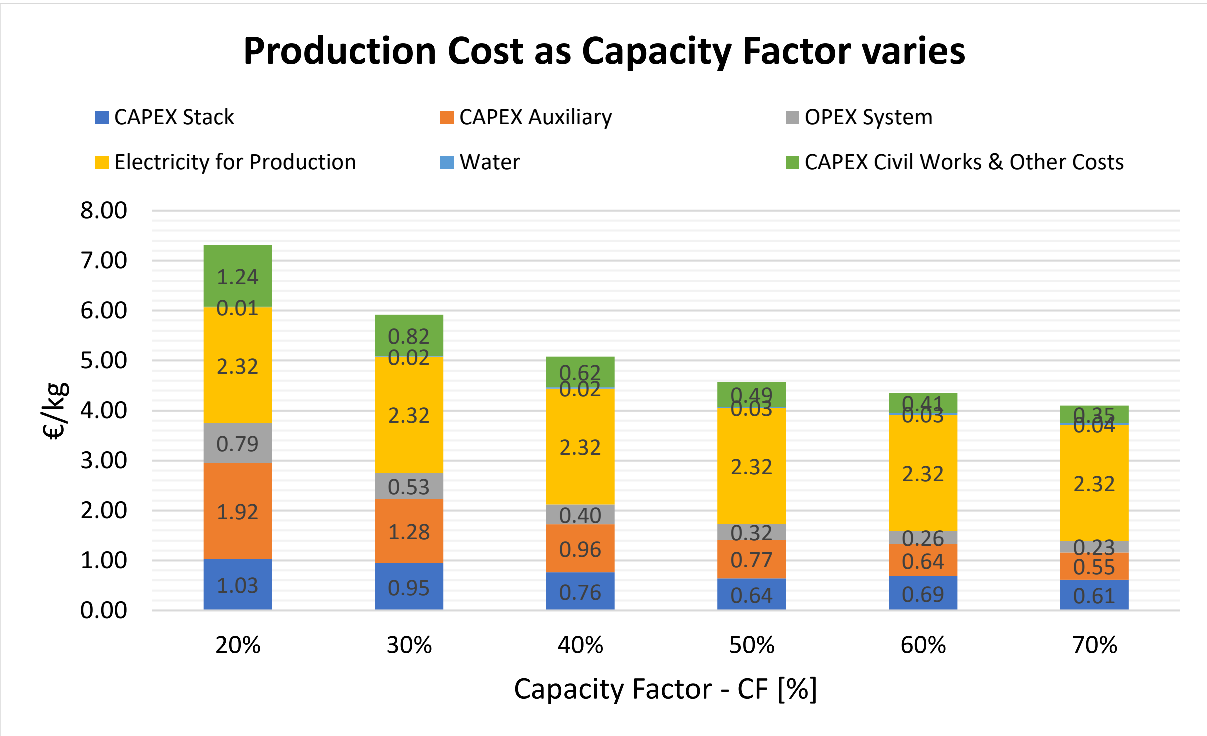


Figure 33: Scenario ARG - Production Cost as CF varies

Capacity Factor CF [%]	LCOH Production [€/kg]	Total LCOH - LH2 [€/kg]	Total LCOH - LOHC [€/kg]
20%	7,31	13,48	11,35
30%	5,92	12,09	9,96
40%	5,08	11,25	9,12
50%	4,57	10,74	8,61
60%	4,36	10,52	8,40
70%	4,10	10,27	8,14

Table 25: Scenario ARG - Levelized Cost of Hydrogen as CF varies

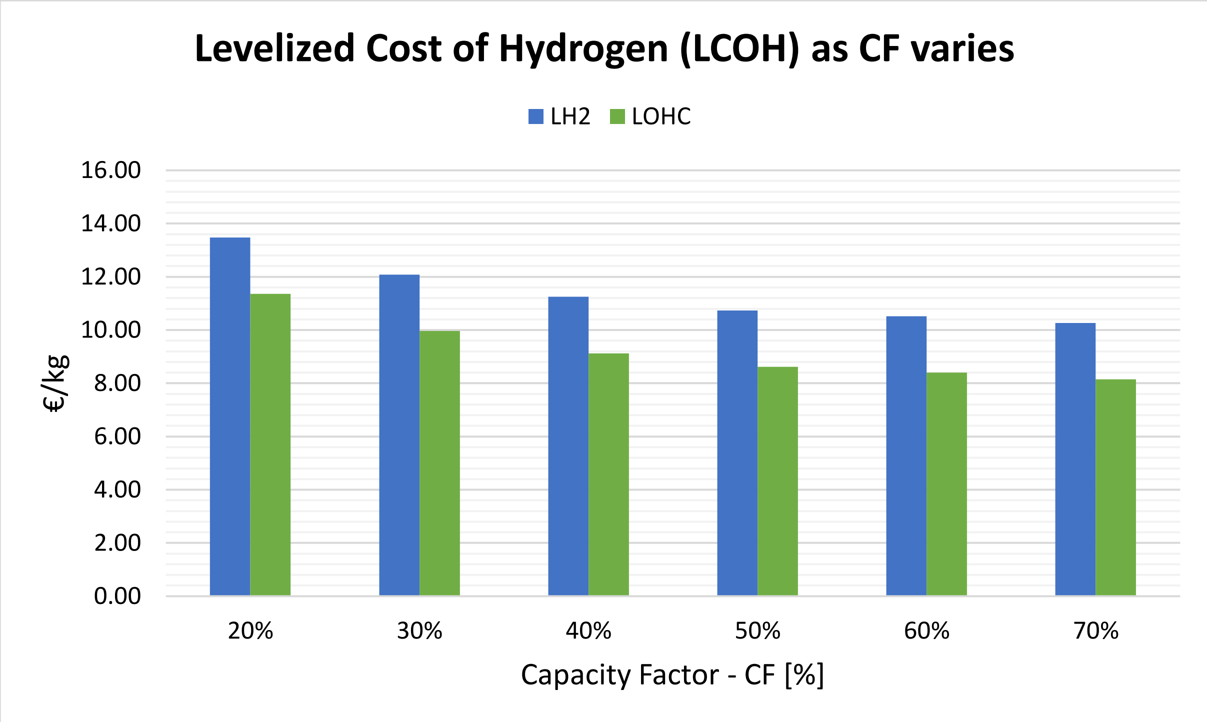


Figure 34: Scenario ARG - Levelized Cost of Hydrogen as CF varies

Overall, as CF increases, the cost of hydrogen decreases. Despite the negative effect of the frequency rise of stack replacement, the decrease of the size of the electrolyser system (same demand for hydrogen to be met with longer period of operation of the plant) causes a decreasing of investment costs of the stack and auxiliaries, the costs of civil works, the costs of operation and maintenance and all "other costs". It should be noted, however, that the magnitude of the change in cost becomes marked only for CF values below 40%. Arriving at a CF of 70% you have an additional saving of 0.47 €/kgH_2 compared to the cost with base case of CF = 50%: much less substantial than the savings that are obtained from 20% to 50%: 2.74 €/kgH_2.

Variable parameter: *PEM Electrolyser Consumption*

Wind Energy Cost	0.04 €/kWh
Capacity Factor	50%

Electrolyser Consumption [kWh/kgH$_2$]	CAPEX Stack	CAPEX Auxiliary	OPEX System	Electricity for Production	Water	CAPEX Civil Works & Other Costs	LCOH Production [€/kg]
58	0,64	0,77	0,32	2,32	0,03	0,49	**4,57**
56	0,62	0,74	0,31	2,24	0,03	0,48	**4,41**
54	0,60	0,71	0,30	2,16	0,03	0,46	**4,26**
52	0,58	0,69	0,28	2,08	0,03	0,44	**4,10**

Table 26: Scenario ARG - Production Cost as Electrolyser Consumption varies

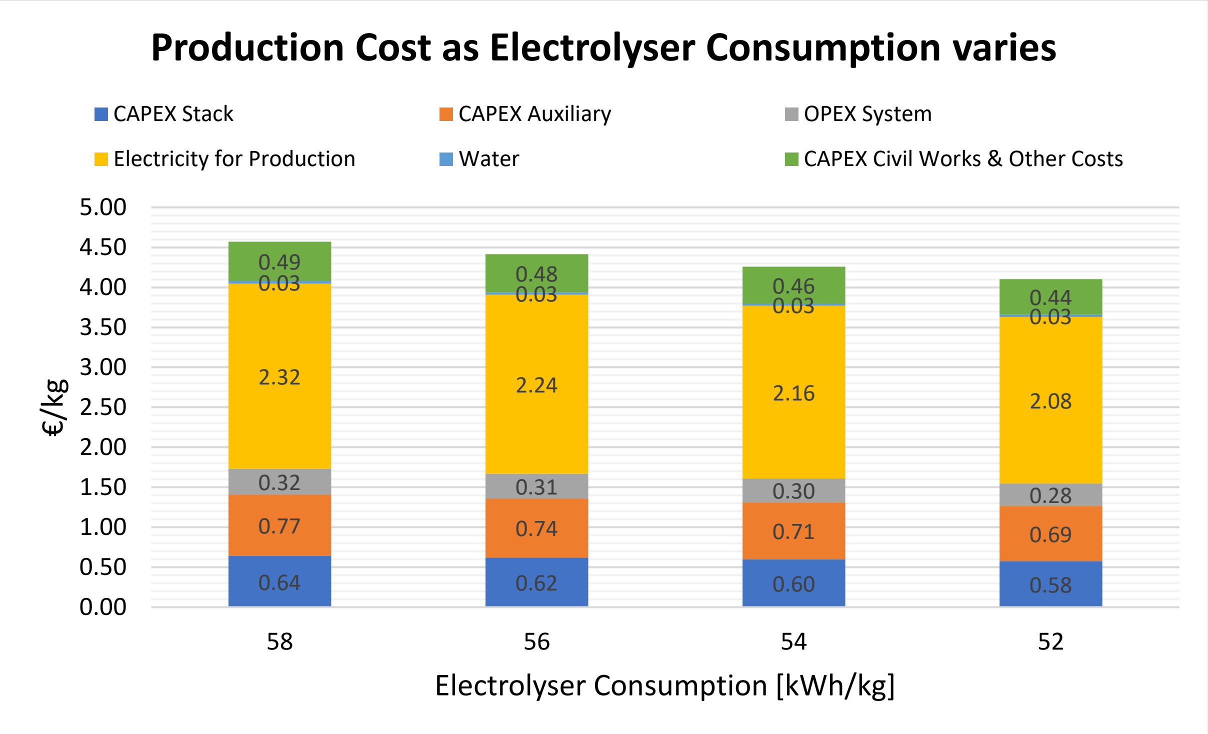


Figure 35: Scenario ARG - Production Cost as Electrolyser Consumption varies

Electrolyser Consumption [kWh/kgH$_2$]	LCOH Production [€/kg]	Total LCOH -LH2 [€/kg]	Total LCOH - LOHC [€/kg]
58	4,57	10,74	8,61
56	4,41	10,58	8,46
54	4,26	10,43	8,30
52	4,10	10,27	8,14

Table 27: Scenario ARG - Levelized Cost of Hydrogen as Electrolyser Consumption varies

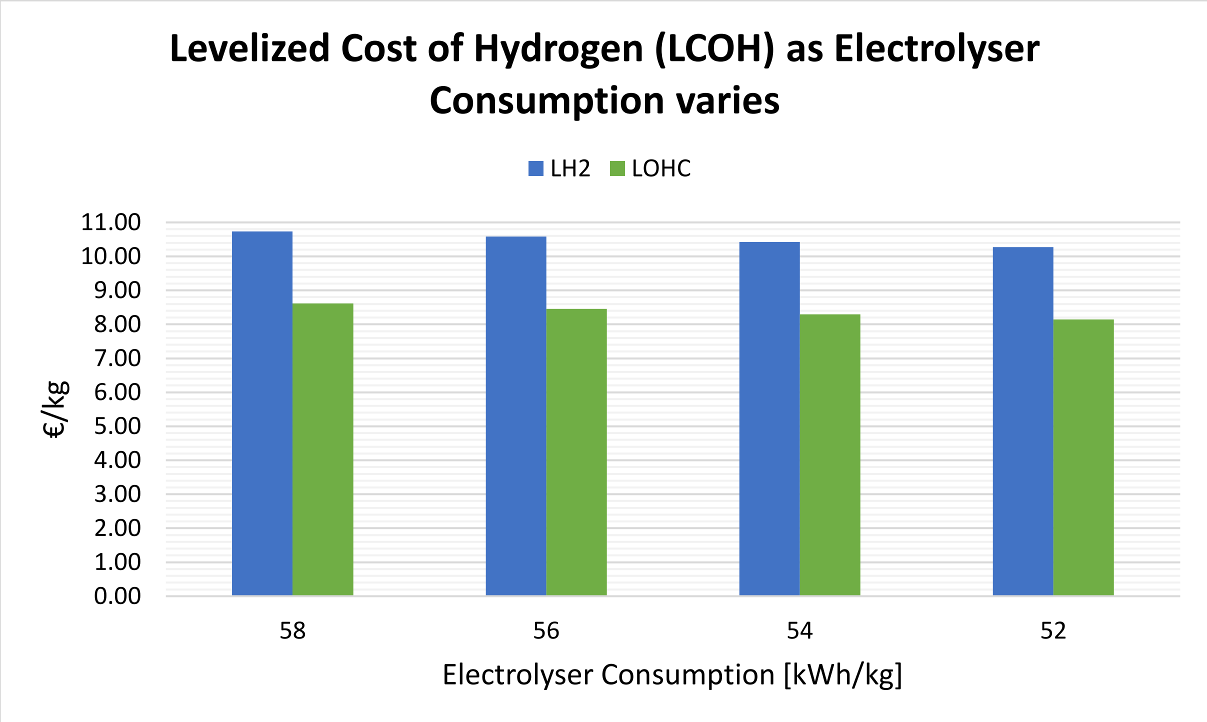


Figure 36: Scenario ARG - Levelized Cost of Hydrogen as Electrolyser Consumption varies

A more efficient electrolyser system results in a reduction of the electric energy consumption with the same hydrogen to be produced. In addition, a lower demand for electricity, with same CF, results in a slightly lower plant size: this involves other small cost reductions such as CAPEX stack, CAPEX auxiliary, OPEX, CAPEX Civil Works & Other Costs. If it were possible to reach a PEM electrolyser consumption of 52 kWh/kgH$_2$, the cost of producing green hydrogen from Argentine wind energy would decrease to 4.10 €/kgH$_2$, and the final LCOH would fall by a further 0.47 €/kgH$_2$, reaching 10.27 €/kgH$_2$ and 8.14 €/kgH$_2$ for scenario LH2 and LOHC respectively.

Variable parameter: *Wind Energy Cost*

PEM Electrolyser Consumption 58 kWh/kgH_2

Capacity Factor 50%

Wind Energy Cost [€/MWh]	CAPEX Stack	CAPEX Auxiliary	OPEX System	Electricity for Production	Water	CAPEX Civil Works & Other Costs	LCOH Production [€/kg]
55	0,64	0,77	0,32	3,19	0,03	0,49	**5,44**
50	0,64	0,77	0,32	2,90	0,03	0,49	**5,15**
45	0,64	0,77	0,32	2,61	0,03	0,49	**4,86**
40	0,64	0,77	0,32	2,32	0,03	0,49	**4,57**
35	0,64	0,77	0,32	2,03	0,03	0,49	**4,28**
30	0,64	0,77	0,32	1,74	0,03	0,49	**3,99**

Table 28: Scenario ARG - Production Cost as Wind Energy Cost varies

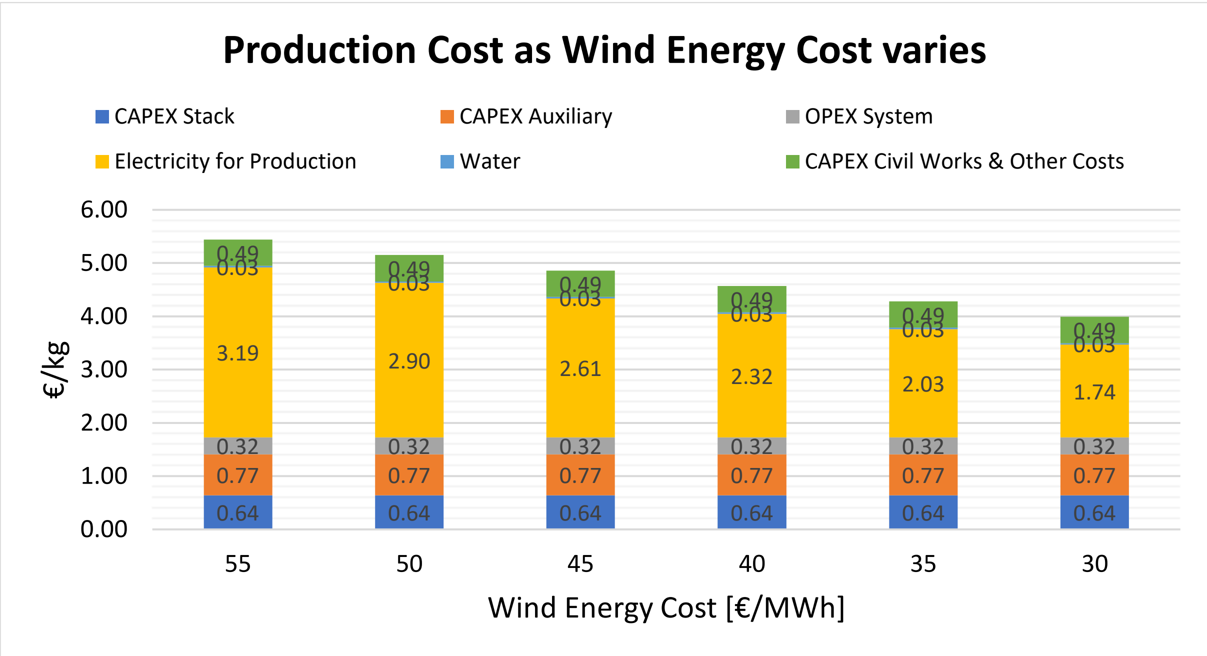


Figure 37: Scenario ARG - Production Cost as Wind Energy Cost varies

Wind Energy Cost [€/MWh]	LCOH Production [€/kg]	Total LCOH - LH2 [€/kg]	Total LCOH - LOHC [€/kg]
55	5,44	11,61	9,48
50	5,15	11,32	9,19
45	4,86	11,03	8,90
40	4,57	10,74	8,61
35	4,28	10,45	8,32
30	3,99	10,16	8,03

Table 29: Scenario ARG - Levelized Cost of Hydrogen as Wind Energy Cost varies

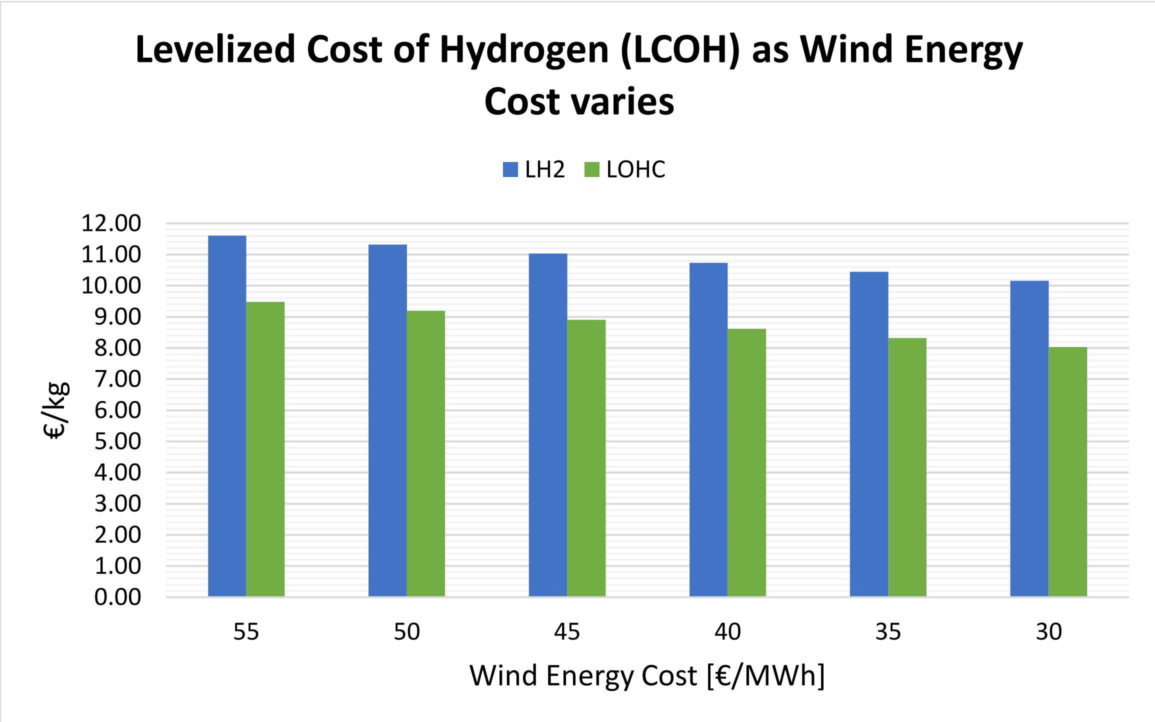


Figure 38: Scenario ARG - Levelized Cost of Hydrogen as Wind Energy Cost varies

The trend in the cost of hydrogen is linear with the wind energy cost. With a hypothetical average wind energy cost of 30 €/MWh, to produce 1 kilogram of green wind hydrogen would need 3.99 €, so 0.58 € less than the case of 40 €/MWh. The overall LCOH for LH2 scenario would fall to 10.16 €/kgH_2 while for LOHC scenario it would almost reach the threshold of 8 €/kgH_2.

A sensitivity analysis parameterizing two variables is carried out:

Variable parameters:

- ***Capacity Factor***
- ***PEM Electrolyser Consumption***

Wind Energy Cost = 0.04 €/kWh = 40 €/MWh

Production Cost

CF [%] / Consum. [kWh/kg]	20%	30%	40%	50%	60%	70%
58	7,31	5,92	5,08	4,57	4,36	4,10
56	7,06	5,71	4,91	4,41	4,21	3,96
54	6,81	5,51	4,73	4,26	4,06	3,82
52	6,56	5,31	4,56	4,10	3,91	3,68

Table 30: Scenario ARG - Production Cost as CF varies for different electrolyser consumptions

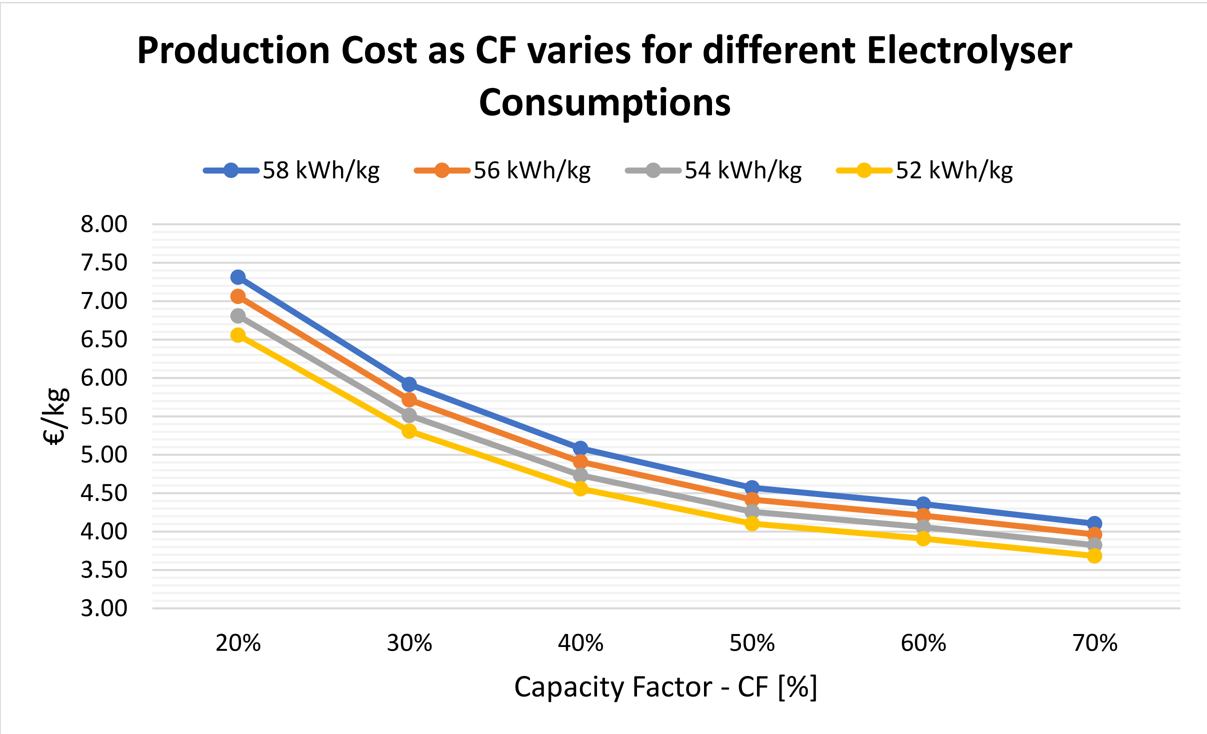


Figure 39: Scenario ARG - Production Cost as CF varies for different electrolyser consumptions

High plant uptime (CF = 70%) combined with the lower value of the electrolyser consumption range (52 kWh/kgH_2) would result in a hydrogen production cost of 3.68 €/kgH_2: 0.89 €/kgH_2 less with respect to base case.

Levelized Cost of Hydrogen – LH2 scenario

CF [%] / Consum. [kWh/kg]	20%	30%	40%	50%	60%	70%
58	13,48	12,09	11,25	10,74	10,52	10,27
56	13,23	11,88	11,08	10,58	10,37	10,13
54	12,98	11,68	10,90	10,43	10,23	9,99
52	12,73	11,47	10,73	10,27	10,08	9,85

Table 31: Scenario LH2 ARG - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

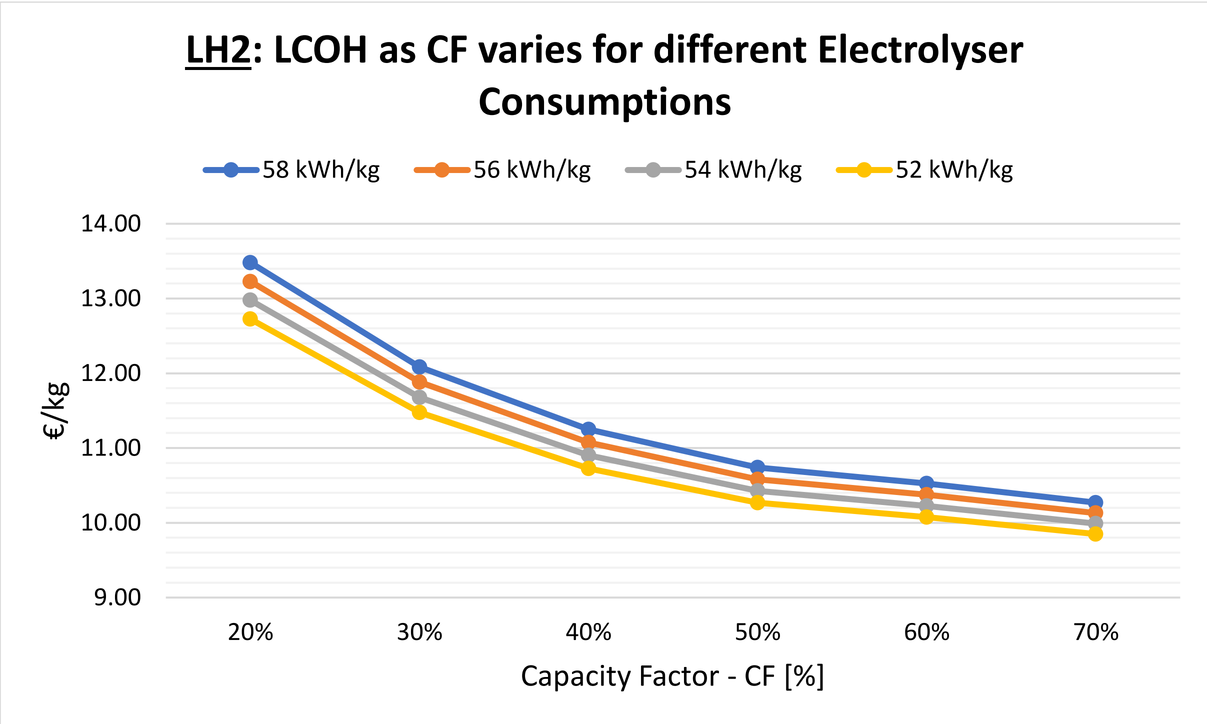


Figure 40: Scenario LH2 ARG - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

The final hydrogen cost in the best combination of LH2 scenario would go down to 9.85 €/kgH_2.

Levelized Cost of Hydrogen – LOHC scenario

CF [%] / Consum. [kWh/kg]	20%	30%	40%	50%	60%	70%
58	11,35	9,96	9,12	8,61	8,40	8,14
56	11,10	9,76	8,95	8,46	8,25	8,00
54	10,85	9,55	8,78	8,30	8,10	7,86
52	10,60	9,35	8,60	8,14	7,95	7,72

Table 32: Scenario LOHC ARG - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

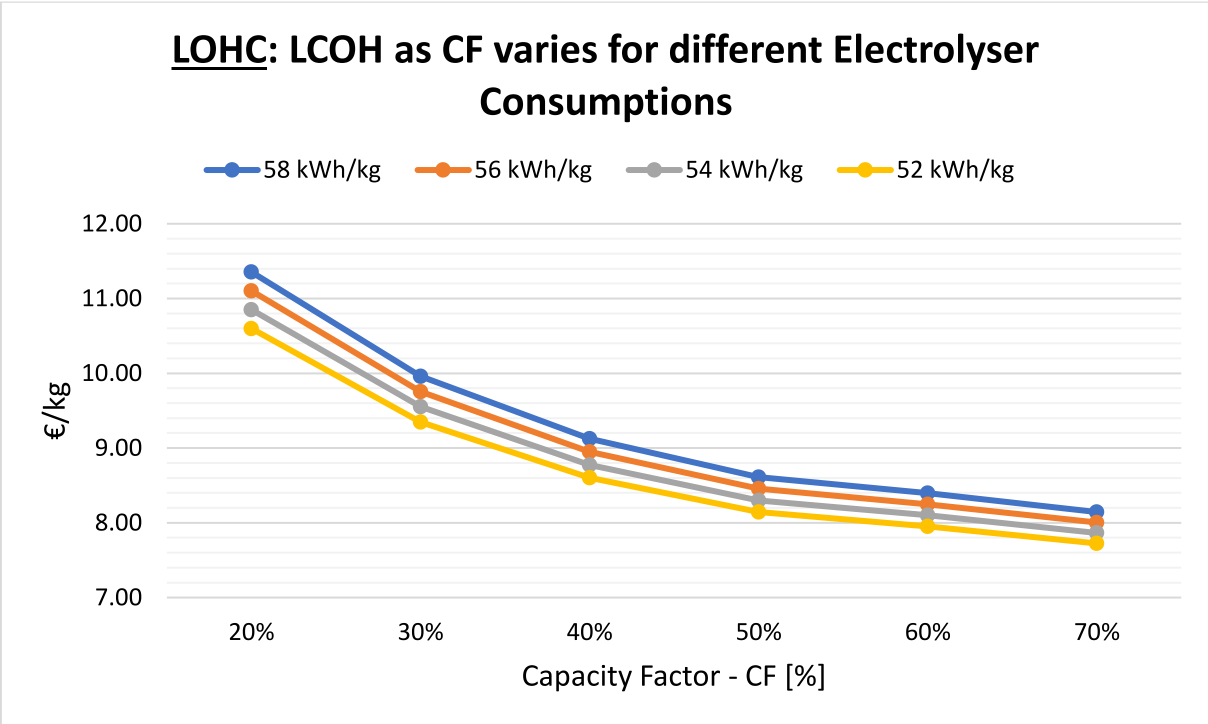


Figure 41: Scenario LOHC ARG - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

As regarding LOHC scenario, the final hydrogen cost in the best case would reach 7.72 €/kgH_2.

Variable parameters:

- ***Capacity Factor***
- ***Wind Energy Cost***

PEM Electrolyser Consumption = 58 kWh/kgH_2

Production Cost

CF [%] / Electricity [€/MWh]	20%	30%	40%	50%	60%	70%
55	8,18	6,79	5,95	5,44	5,23	4,97
50	7,89	6,50	5,66	5,15	4,94	4,68
45	7,60	6,21	5,37	4,86	4,65	4,39
40	7,31	5,92	5,08	4,57	4,36	4,10
35	7,02	5,63	4,79	4,28	4,07	3,81
30	6,73	5,34	4,50	3,99	3,78	3,52

Table 33: Scenario ARG - Production Cost as CF varies for different wind energy costs

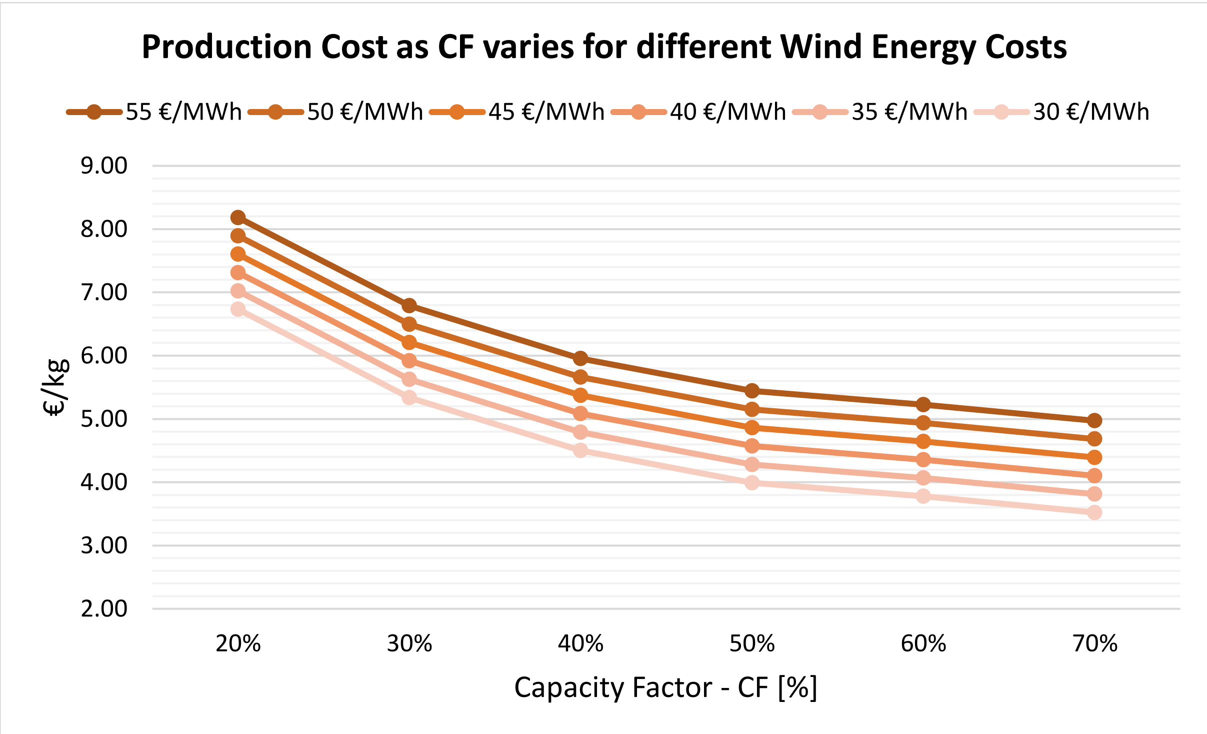


Figure 42: Scenario ARG - Production Cost as CF varies for different wind energy costs

High plant uptime (CF = 70%) combined with the lower value of the wind energy cost (30 €/MWh) would result in a hydrogen production cost of 3.52 €/kgH_2: 1.05 €/kgH_2 less with respect to base case.

Levelized Cost of Hydrogen – LH2 scenario

Electricity [€/MWh] \ CF [%]	20%	30%	40%	50%	60%	70%
55	14,35	12,96	12,12	11,61	11,39	11,14
50	14,06	12,67	11,83	11,32	11,10	10,85
45	13,77	12,38	11,54	11,03	10,81	10,56
40	13,48	12,09	11,25	10,74	10,52	10,27
35	13,19	11,80	10,96	10,45	10,23	9,98
30	12,90	11,51	10,67	10,16	9,94	9,69

Table 34: Scenario LH2 ARG - Levelized Cost of Hydrogen as CF varies for different wind energy cost

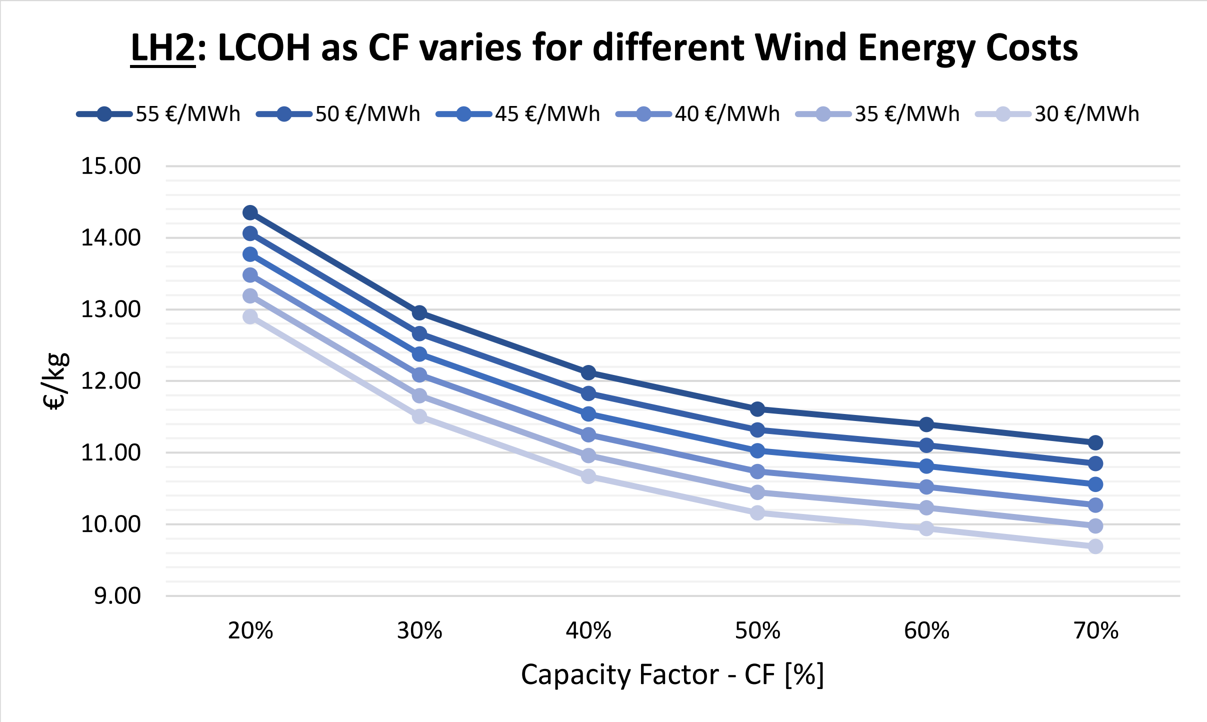


Figure 43: Scenario LH2 ARG - Levelized Cost of Hydrogen as CF varies for different wind energy costs

The final hydrogen cost in the best combination of LH2 scenario would go down to 9.69 €/kgH_2.

Levelized Cost of Hydrogen – LOHC scenario

CF [%] / Electricity [€/MWh]	20%	30%	40%	50%	60%	70%
55	12,22	10,83	9,99	9,48	9,27	9,01
50	11,93	10,54	9,70	9,19	8,98	8,72
45	11,64	10,25	9,41	8,90	8,69	8,43
40	11,35	9,96	9,12	8,61	8,40	8,14
35	11,06	9,67	8,83	8,32	8,11	7,85
30	10,77	9,38	8,54	8,03	7,82	7,56

Table 35: Scenario LOHC ARG - Levelized Cost of Hydrogen as CF varies for different wind energy costs

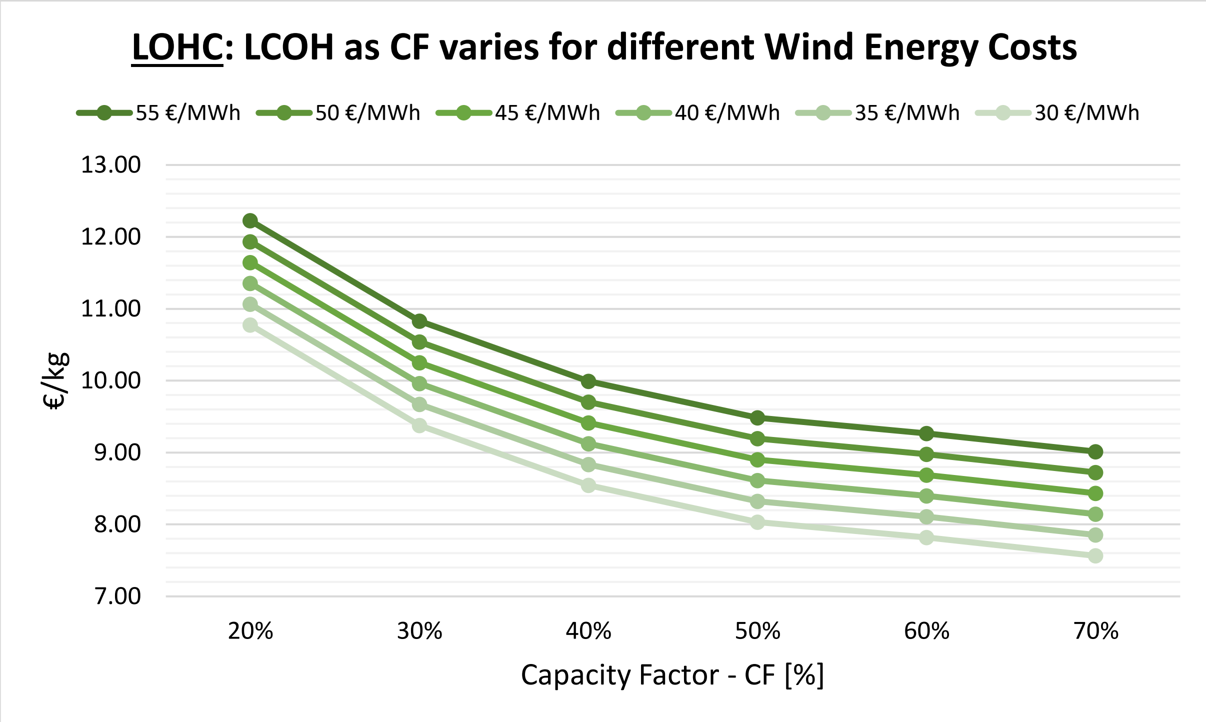


Figure 44: Scenario LOHC ARG - Levelized Cost of Hydrogen as CF varies for different wind energy costs

As regarding LOHC scenario, the final hydrogen cost in the best case would reach 7.56 €/kgH_2.

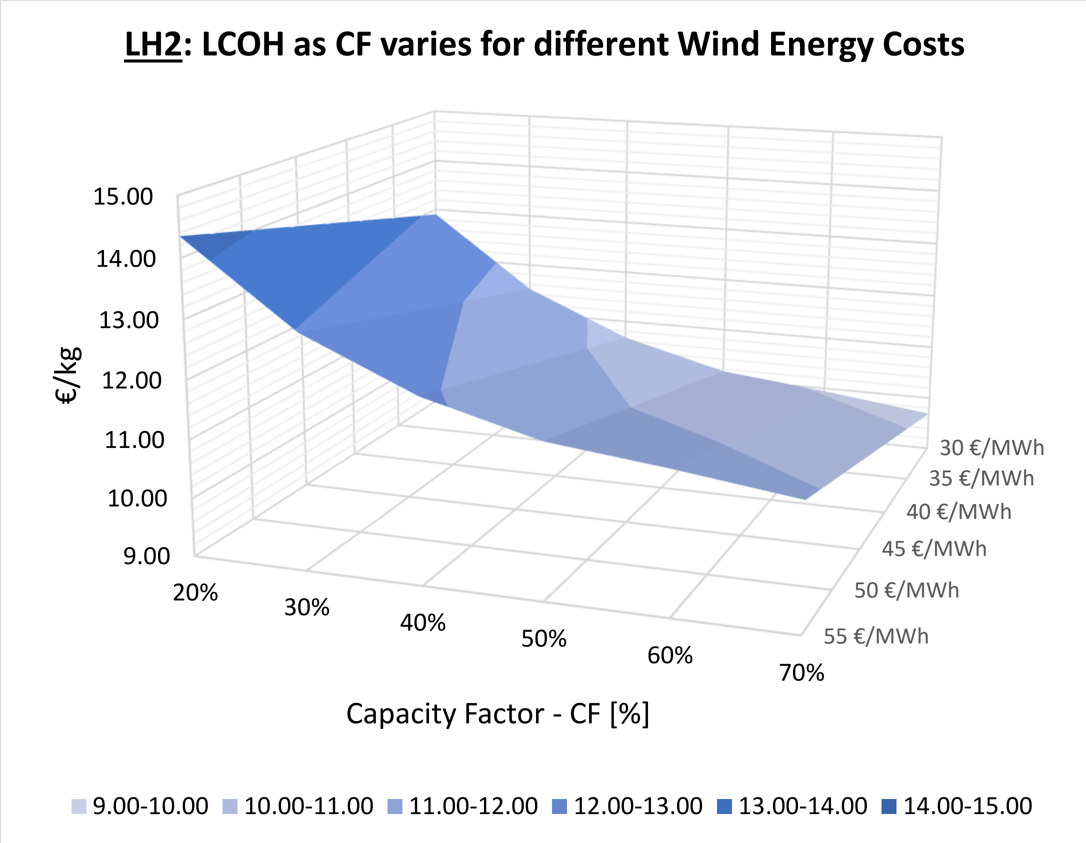


Figure 45: Scenario LH2 ARG - Levelized Cost of Hydrogen as CF varies for different wind energy costs (3D)

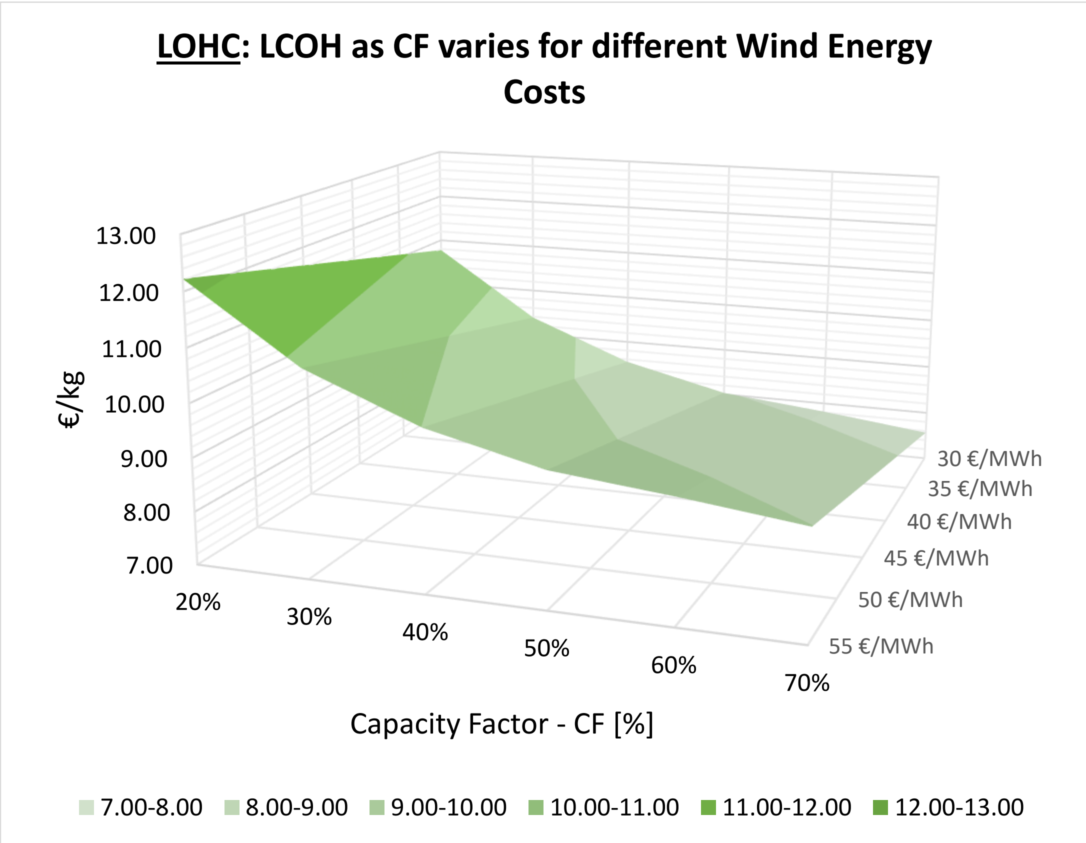


Figure 46: Scenario LOHC ARG - Levelized Cost of Hydrogen as CF varies for different wind energy costs (3D)

Chapter 3

ITALIAN PRODUCTION SCENARIO

3.1 Premise

The scenario of Production in Italy, in addition to the LH2 and LOHC scenarios also presents the storage and transport of compressed gas hydrogen (CGH2): in fact, there is no constraint of ocean transport that avoided to consider compressed gas.
The idea is to get to the LCOH for each of the three types of storage and compare the results with those of the Argentine scenario. One point in favour of the Italian scenario is the absence of ocean transport, while the points against are a higher cost of electricity from wind and a lower average capacity factor.

In Italy the current CF of the entire national wind farm is 25%, corresponding to about 2,200 hours per year of operation of the plants at the nominal power.[63]
At 2,200 hours of operation, the cost of wind energy is between 0.065 €/kWh and 0.080 €/kWh depending on the investment cost of wind turbines,[64] as can be seen from the following graph:

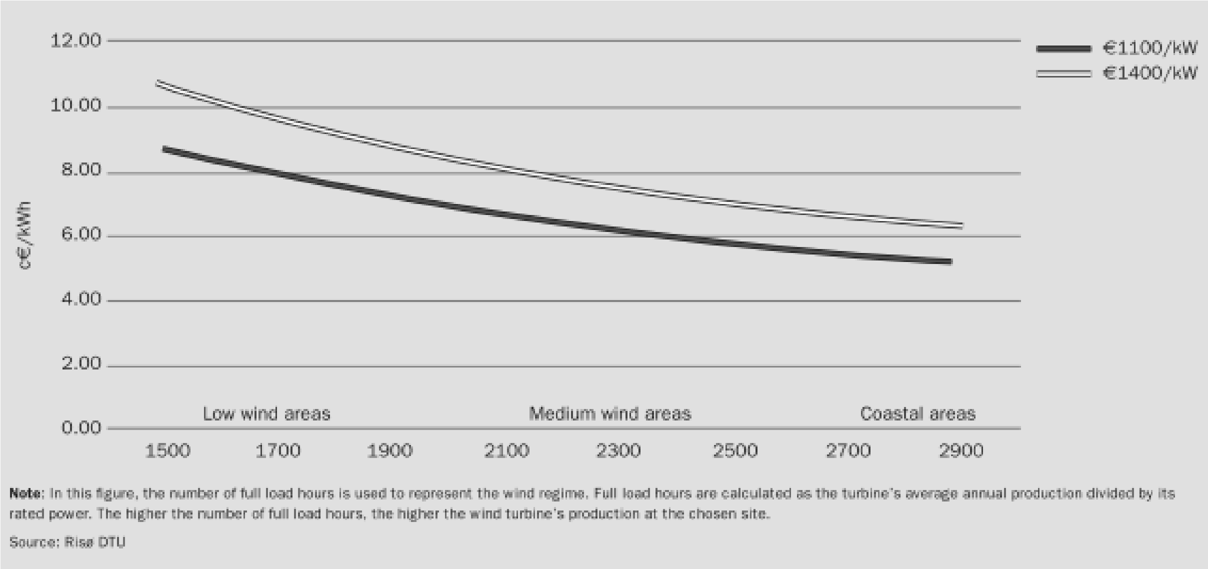


Figure 47: Cost of wind generated power as a function of the wind regime at the chosen site [64]

The installation costs of horizontal axis generators in Italy are around 900-1,300 €/kW.[65] The average value of the range is 1,100 €/kW so it can be considered the dark line of the previous chart, thus 0.065 €/kWh wind energy cost as default value for the Italian scenario.

Before going into detail in the Italian scenario it is necessary to make a premise: in the last report of 2020 of the National Wind Energy Association (ANEV),[66] the data of installed wind power in our country, region by region, are reported:

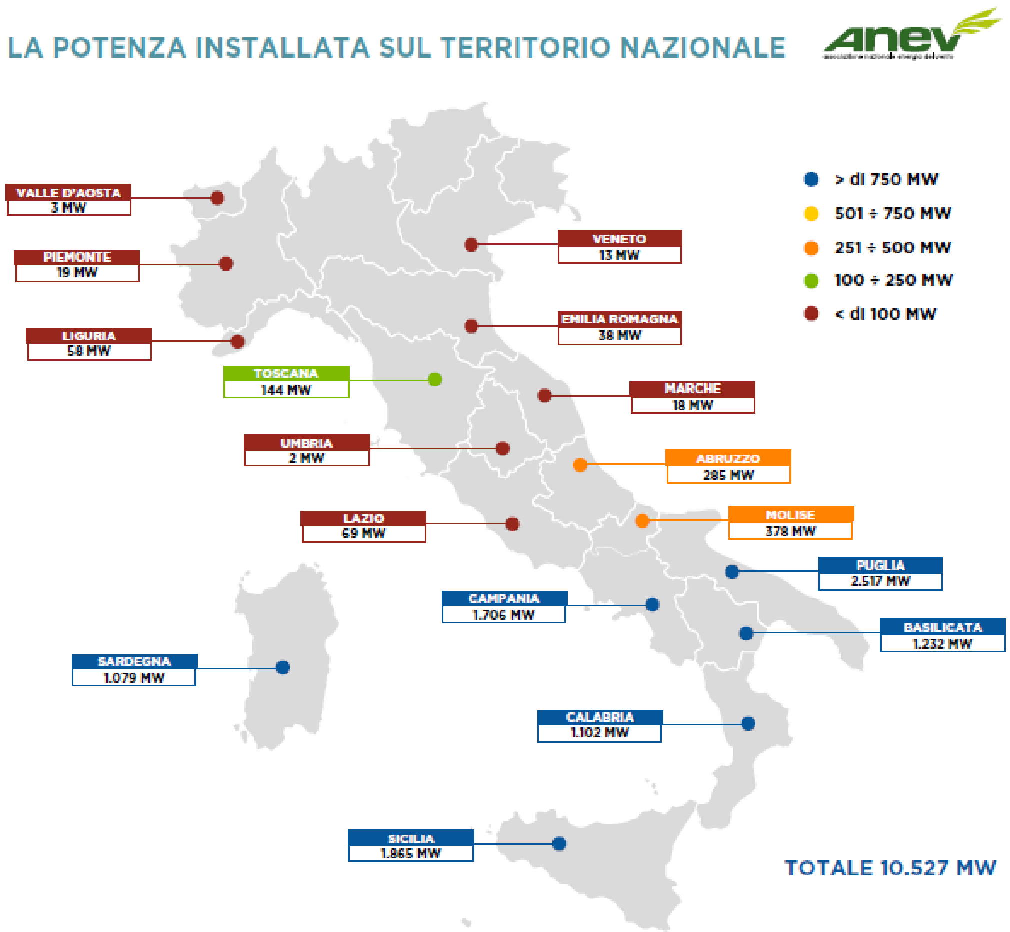


Figure 48: Installed Wind Power in Italy at 2019 [66]

The report of ANEV of 2020, provides the installed wind power in Italy updated to 2019, which amounts to 10,527 MW. The installed power is very unbalanced towards the regions of the South where there is higher availability of wind. There are 11 regions with less than 100 MW installed and even 3 in which wind power is not present: Lombardy, Trentino-Alto Adige and Friuli-Venezia Giulia. Apulia and Sicily are the two regions with the largest installed wind power, respectively with 2,517 MW and 1,865 MW.

When the Argentine scenario was analysed, once hydrogen arrives in Italy, 7 landing and distribution areas were considered:

AREA 1: Piemonte, Val d'Aosta, Lombardia, Liguria

AREA 2: Veneto, Trentino-Alto Adige, Friuli-Venezia Giulia

AREA 3: Toscana, Emilia-Romagna

AREA 4: Abruzzo, Marche, Umbria, Lazio

AREA 5: Molise, Campania, Puglia, Basilicata

AREA 6: Calabria, Sicilia

AREA 7: Sardegna

Assuming to produce hydrogen in each of these 7 areas (for the respective mobility demand at 1% market penetration) from wind energy with a capacity factor of 25%, the needs for each area considering the data in Table 7, is available in the second column of the following table. The third column reports the current availability by summing the wind power (MW) of the regions of the area in question:

AREA	Demand [MW]	Availability [MW] (2019)
1	664	80
2	296	13
3	337	182
4	394	374
5	439	5833
6	284	2967
7	67	1079

Table 36: Power required for H_2 car market penetration at 1% and availability of wind power for each area (2019)

With the current Italian wind power installed, it is not possible to meet the 1% of hydrogen car market in the areas of central-northern Italy because the availability is too low. The southern regions instead have greater potential, Area 5 reaches almost 6 GW wind.

ANEV has prepared a study on the potential wind achievable in our country until 2030 estimating what could be the contribution in terms of electricity production from renewable sources, employment and industrial development to achieve the objectives set by the European Commission.[67] The objectives to 2030 region by region are shown in the following table:

Region	Potential achievable [MW] (2030)
Puglia	2750
Campania	2000
Sicilia	2000
Sardegna	2000
Calabria	1750
Basilicata	1250
Lazio	750
Molise	750
Abruzzo	700
Marche	500
Toscana	500
Umbria	450
Liguria	250
Emilia-Romagna	250
Others*	300

Table 37: Wind potential achievable in Italy by 2030 [67]

*Others: Piemonte, Val d'Aosta, Lombardia, Veneto, Trentino-Alto Adige, Friuli-Venezia Giulia

The data were grouped according to the areas considered. It is clear that Northern Areas 1 and 2 will not be able to meet the needs even with the 2030 targets. For this reason, it has been chosen to join Areas 1,2 and 3 in a single macroarea (1+2+3) to evaluate the comparison demand/availability.

AREA	Demand [MW]	Target 2030 [MW]
1+2+3	1298	1300
4	394	2400
5	439	6750
6	284	3750
7	67	2000

Table 38: Power required for H_2 car market penetration at 1% and availability of wind power for each area (2030)

While combining the estimated 2030 availability of Areas 1-2-3, overall it would not be possible to meet all the demand for hydrogen mobility with market penetration 1%. It is unthinkable to use all the wind energy available, to produce hydrogen from electrolysis for mobility. Area 4 can be self-sufficient, as can areas in the South.

3.2 Production Cost

In the Italian scenario, hydrogen demand in Area 5 is taken into account to assess the costs because it is the area with greater availability of wind power.

Unit cost of electricity produced from wind energy = 0.065 €/kWh

Production Cost Items	**€/kgH_2**	**Impact [%]**
CAPEX Stack	0,83	10,6%
CAPEX Auxiliary	1,53	19,7%
OPEX System	0,64	8,2%
Electricity for Production	3,77	48,5%
Water	0,01	0,2%
CAPEX Civil Works & Other Costs	0,99	12,7%
LCOH Production	**7,77**	

Table 39: Scenario ITA - Production Cost

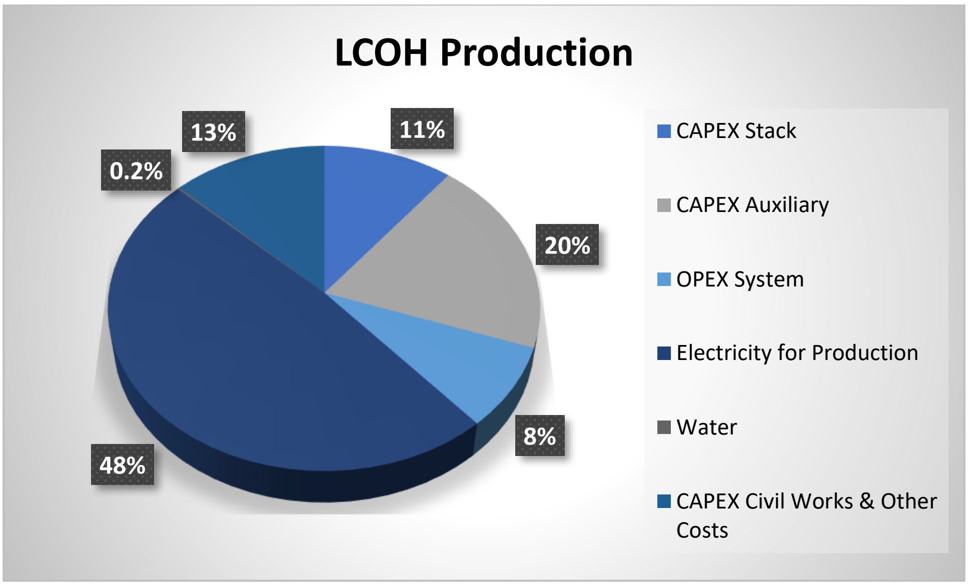


Figure 49: Scenario ITA - Production Cost

The cost of production amounts to **7.77 €/kgH_2**. There is an increase of 3.20 €/kgH_2 on the production cost in Italy compared to Argentina. The breakdown of the various contributions is similar to the Argentine production scenario.

3.3 From Production site to HRS

3.3.1 LH2 – Liquefied Hydrogen

In the Italian scenario we obviously do not have ocean transport, there is no storage at the naval ports, the layout provides a single LH2 Terminal at the production site, sized to cope with interruptions for maintenance (plant outages) considered as the previous scenario, thus for 10 days of production.

LH2: Liquefaction -> LH2 Terminal at Production site (with cryogenic storage for plant outages of 10-days demand) -> Distribution to HRS by truck trailers

A schematization is shown below:[68]

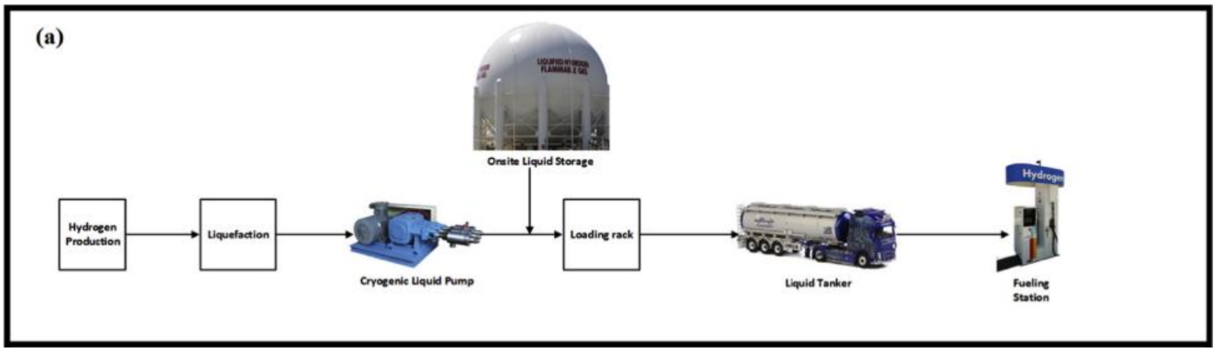


Figure 50: LH2 Storage and Delivery [68]

Liquefied Hydrogen - LH2	Area 1+2+3	Area 4	Area 5	Area 6	Area 7
Items	**€/kgH_2**				
Liquefier	1,95	2,41	2,36	2,56	3,38
LH2 Terminal (Storage for Plant Outages, 10 days)	0,28	0,34	0,33	0,38	0,81
Distribution to HRS (Truck-Trailers)	0,74	0,48	0,48	0,46	0,40
Total Cost from Production Site to HRS	**2,97**	**3,22**	**3,17**	**3,40**	**4,59**

Table 40: LH2 ITA - From Production site to HRS

Liquefaction cost is slightly higher than the Argentine scenario, which reached 2 €/kgH_2, a difference that is more accentuated for areas with lower demand. In fact, the investment costs of Liquefier, are distributed on a lower production (not corresponding to national demand, but to demand of the Area in question). The total cost from production site to the arrival at the HRS is **3.17 €/kgH_2**.

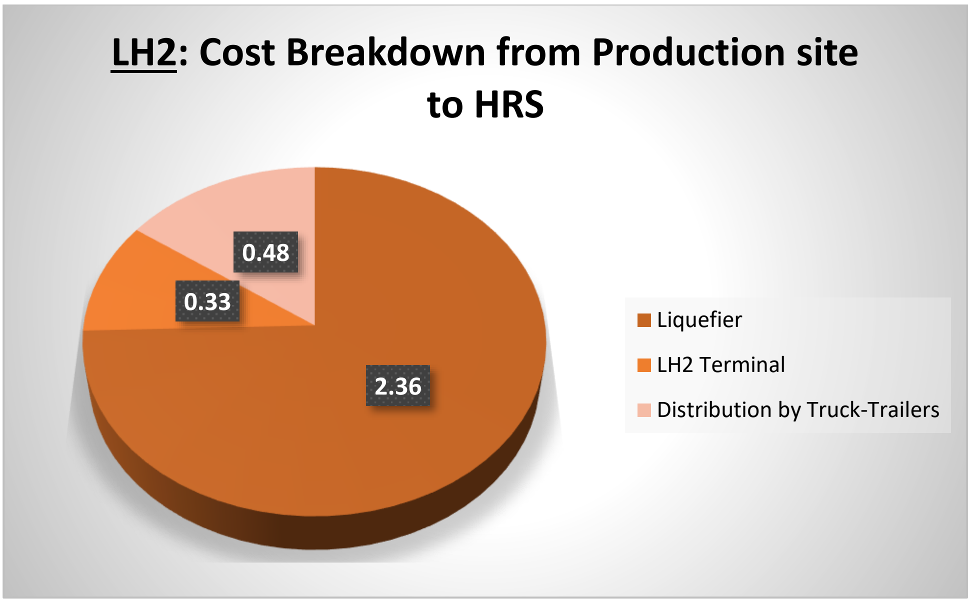


Figure 51: LH2 ITA - Cost Breakdown from Production site to HRS

3.3.2 LOHC – Liquid Organic Hydrogen Carrier

LOHC: LOHC Hydrogenation -> LOHC-H2 Terminal at Production site (with storage for plant outages of 10-days demand) -> Distribution to HRS by truck trailers

LOHC: Dibenzyltoluene	Area 1+2+3	Area 4	Area 5	Area 6	Area 7
Items	€/kgH_2				
LOHC Hydrogenation	0,13				
LOHC-H2 Terminal (Storage for Plant Outages, 10 days)	0,06	0,07	0,07	0,08	0,16
Distribution to HRS (Truck-Trailers)	0,65	0,41	0,42	0,40	0,33
Total Cost from Production Site to HRS	**0,83**	**0,61**	**0,61**	**0,60**	**0,62**

Table 41: LOHC ITA - From Production site to HRS

Compared to the Argentine scenario, the cost of hydrogenation, that occurs downstream of production, slightly increases, due to the higher cost of energy produced by the wind farm in Italy. It goes from 0.08 to 0.13 €/kgH_2. The total cost faced from the production site until the arrival at the HRS, stands at **0.61 €/kgH_2.**

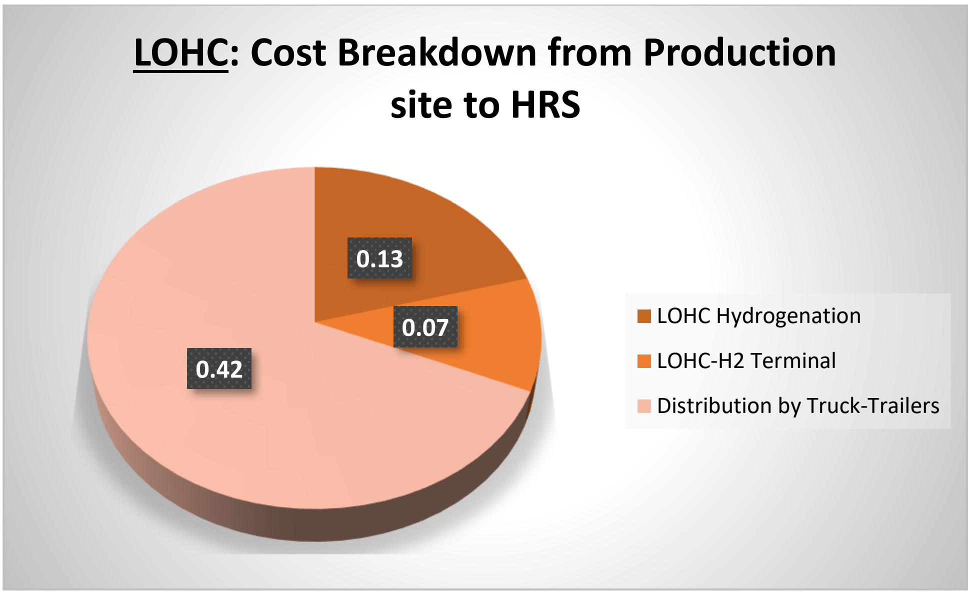


Figure 52: LOHC ITA - Cost Breakdown from Production site to HRS

3.3.3 CGH2 – Compressed Gaseous Hydrogen

In the production scenario in Italy, storage and delivery of compressed hydrogen was also analyzed. Downstream of production, hydrogen is further compressed and stored in a GH2 Terminal (200-500 bar), for an amount equal to the daily demand. Between the production and the Terminal is planned an underground geological cave able to store at a maximum pressure of 125 atm, an amount of compressed hydrogen that can cope with ten days of production interruption for maintenance (plant outages).

From GH2 Terminal, the trucks are loaded by tube trailers that transport compressed hydrogen to 500 bar, thus each truck has the capacity to carry about 1,000 kg of hydrogen.[5]

A schematization is shown below:[68]

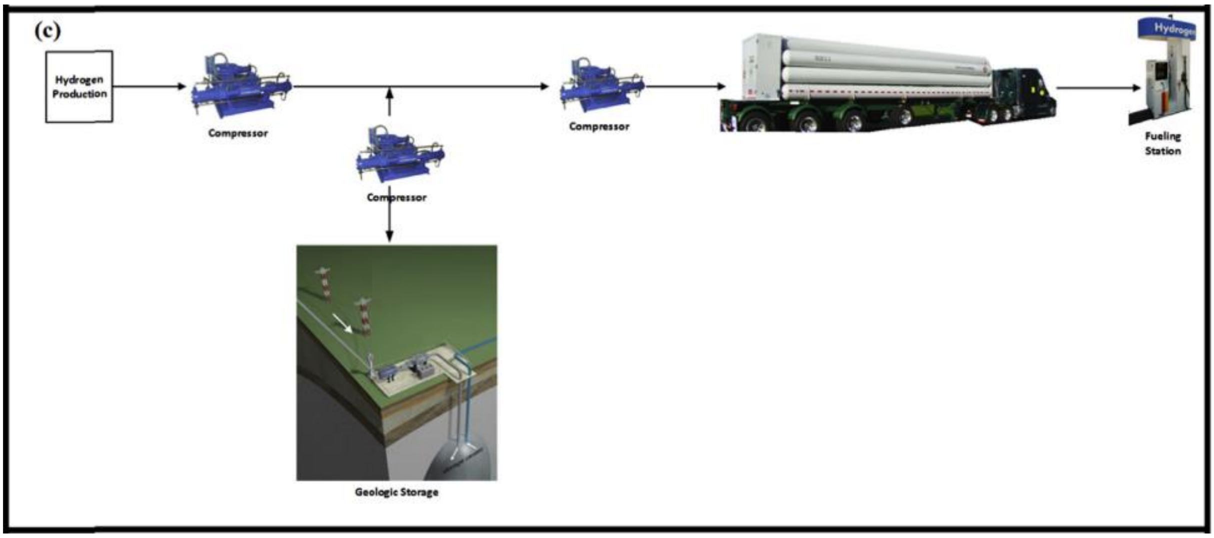


Figure 53: CGH2 Storage and Delivery [68]

Compressed Gaseous Hydrogen - CGH2	Area 1+2+3	Area 4	Area 5	Area 6	Area 7
Items	€/kgH$_2$				
H2 Gaseous Geologic Storage (for Plant Outages, 10 days)	0,07	0,11	0,11	0,13	0,23
GH2 Terminal	0,90	0,94	0,93	0,96	1,14
Distribution to HRS (CGH2 Truck Tube Trailers 500 bar)	2,24	1,38	1,40	1,35	1,25
Total Cost from Production Site to HRS	**3,21**	**2,44**	**2,44**	**2,44**	**2,61**

Table 42: CGH2 ITA - From Production site to HRS

The storage of large amounts of compressed hydrogen in underground caves is much more efficient, economical and flexible than storage in many small vessels.[45] In fact, the cost impact of Geologic Storage is modest (0.11 €/kgH$_2$).

The GH2 Terminal, on the other hand, accounts for much more, due to the costs of compression and compressed gas storage vessels, and the further compression of hydrogen to be charged in tube trailers of trucks (500 bar). It is almost 1 €/kgH$_2$.

The cost of distribution by truck tube trailers (between 1.25 and 1.50 €/kgH$_2$ depending on the area) is higher than in the case LH2 (as confirmed also by Figure 15). This is understandable, both because the volume of hydrogen transportable from the single GH2 truck is lower than that of LH2 truck (36 m^3 against 56 m^3, values available from the HDSAM results), and because the gaseous hydrogen, although it can be compressed at high pressure (500 bar), will never have the density of liquefied hydrogen: about 30 kg/m^3 against about 71 kg/m^3. They need more than double the trucks compared to LH2 as seen from HDSAM.

In conclusion, the total cost faced from the production site until the arrival at the HRS, stands at **2.44 €/kgH$_2$.**

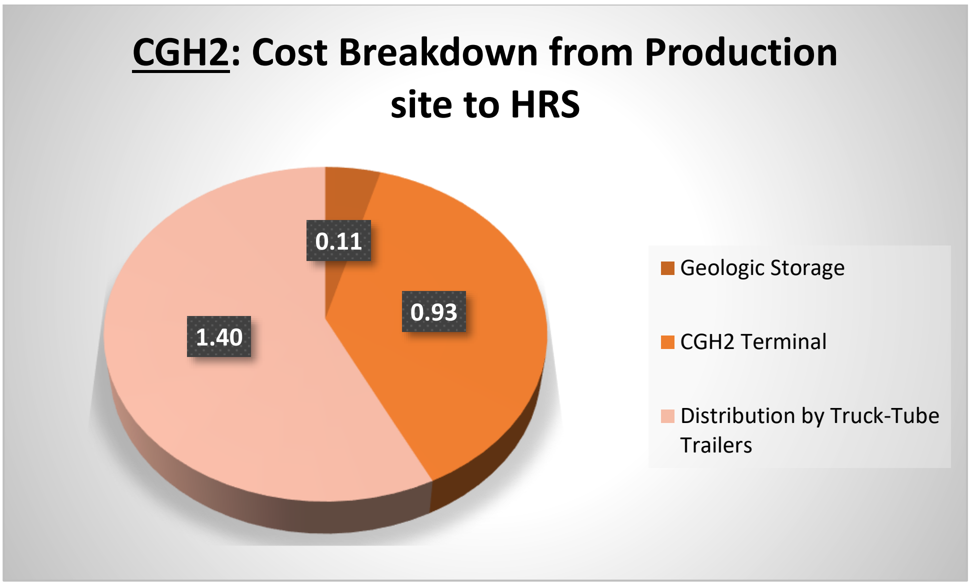


Figure 54: CGH2 ITA - Cost Breakdown from Production site to HRS

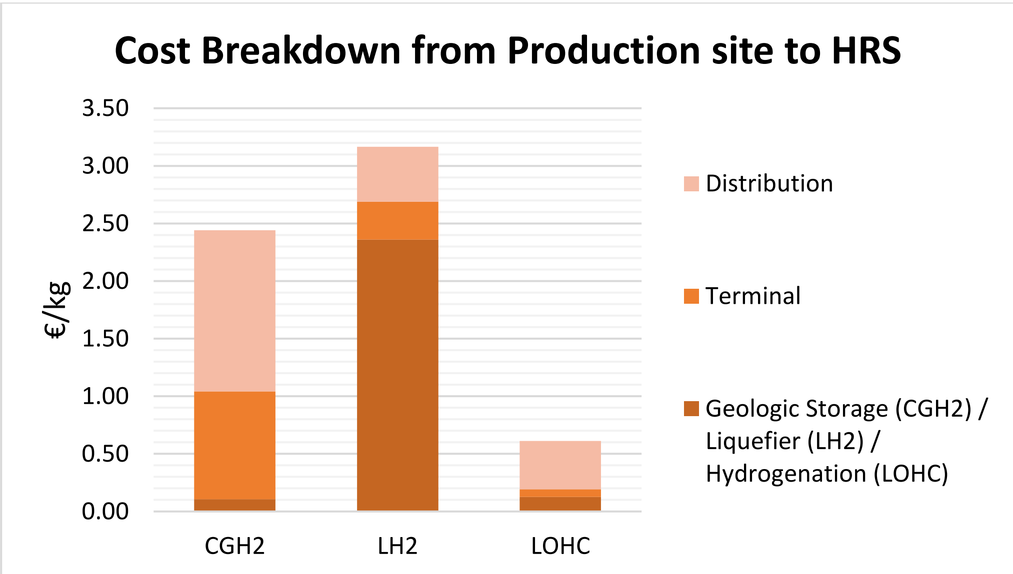


Figure 55: Scenario ITA - Cost Breakdown from Production site to HRS: LH2 vs LOHC

Comparing this cost section for the three types of storage, it is clear that the LOHC scenario is evidently the most advantageous. In fact, there is not an expensive liquefaction to face like in the scenario LH2, not even it is necessary to face high costs of distribution and terminals that are instead prerogative of the CGH2 scenario.

3.4 Hydrogen Refueling Stations

3.4.1 LH2 Hydrogen Refueling Station

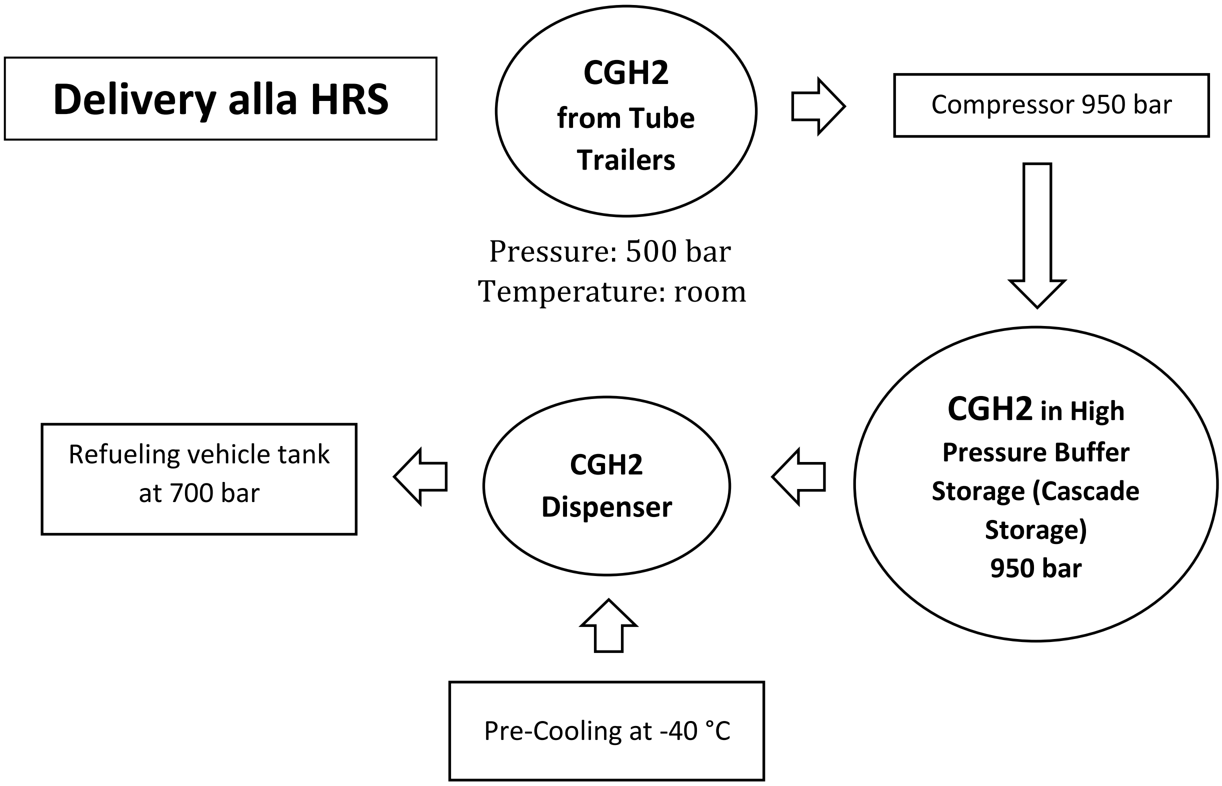
LH2 HRS have been already analysed in the Argentine scenario (see paragraph 2.5.1)

3.4.2 LOHC Hydrogen Refueling Station

LH2 HRS have been already analysed in the Argentine scenario (see paragraph 2.5.2)

3.4.3 CGH2 Hydrogen Refueling Station

Below, the CGH2 HRS scheme as shown for LH2 and LOHC scenarios:



The gaseous hydrogen that reaches the HRS is already compressed in the tube trailers, at 250-500 bar. Before it can be stored in the high-pressure storage buffer (cascade storage 950 bar) and sent to the dispenser from which the vehicles will be refuelled to 700 bar, it must be further compressed to 950 bar. This additional compression including the energy required by the pre-cooling circuit has a consumption of 1.9 kWh/kgH_2.[44] Instead, to compress at such pressures the hydrogen just released from the LOHC, then initially at pressures close to ambient pressure, and pre-cooling it to -40 °C, were needed more energy: 4.4 kWh/kgH_2.

Gaseous Hydrogen Supply Refueling Configuration

1	Gaseous Hydrogen from Supply -> High Pressure Compressor -> High Pressure Buffer Storage-> Pre-Cooling Unit -> Dispenser
2	Gaseous Hydrogen from Supply -> Medium Pressure Compressor -> Medium Pressure Buffer Storage-> Booster Compressor ->Accumulator -> Pre-Cooling Unit -> Dispenser

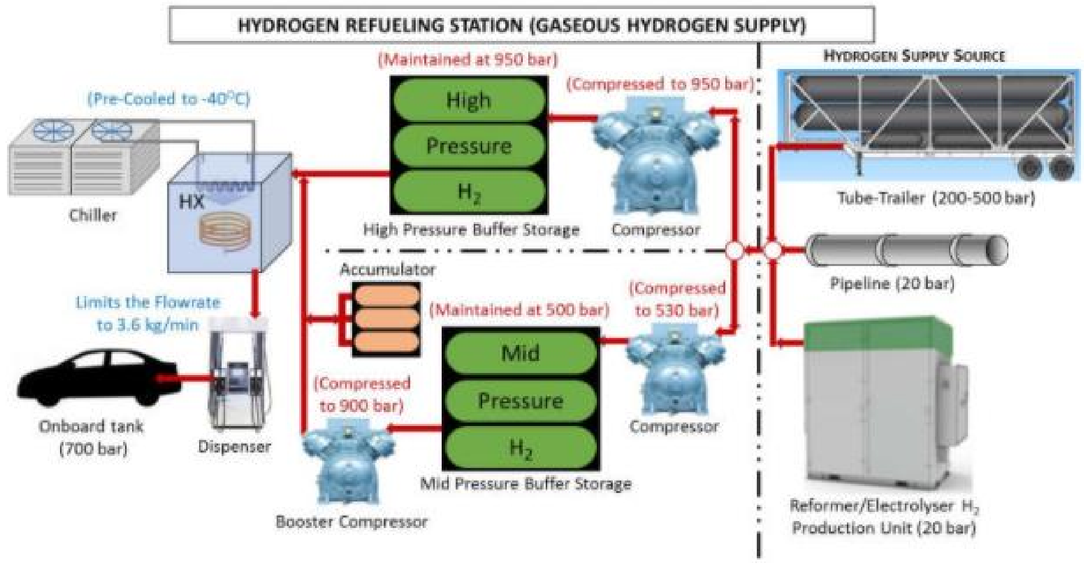


Figure 56: Configurations of CGH2 Hydrogen Refueling Station [57]

In Figure 56 two configurations of HRS are shown when delivery of CGH2 arrives. In this work the first one is described, with a 500 bar compressed hydrogen supply from tube trailers carried by trucks.

The impact on the cost of hydrogen of an CGH2 HRS is represented by the following items:

- **CAPEX Compressor 950 bar**
- **CAPEX Cascade Storage 950 bar**
- **CAPEX Refrigeration Equipment**
- **CAPEX Dispenser 700 bar**
- **Land/Other CAPEX**
- **CAPEX Control/Safety Equipment**
- **OPEX CGH2 HRS**
- **Electricity for Compression at 950 bar/Pre-Cooling**

The value of the CAPEXs are obtained by consulting the Refueling Station Gaseous H_2 section downstream of HDSAM simulations. It is considered AREA 5, composed of 114 refueling stations. The useful life is 20 years, except for the compressor which have useful life of 10 years[59] thus its investment will be supported again in the eleventh year. The values are converted from $ to €.

CAPEX Compressor 950 bar

Number of compressors:	1
Single Station:	**370,666 €**
Overall AREA 5:	**42,255,924 €**

CAPEX Cascade Storage 950 bar

Capacity [kg H_2]:	134
Single Station:	**146,138 €**
Overall AREA 5:	**16,659,732 €**

CAPEX Refrigeration Equipment

Number of heat exchangers:	2
Single Station:	**136,669 €**
Overall AREA 5:	**15,580,266 €**

CAPEX Dispenser 700 bar

Number of dispensers:	2
Single Station:	**101,621 €**
Overall AREA 5:	**11,584,794 €**

Land/Other CAPEX

Single Station:	**209,005 €**
Overall AREA 5:	**23,826,570 €**

CAPEX Control/Safety Equipment

Single Station:	**85,000 €**
Overall AREA 5:	**9,690,000 €**

TOTAL CAPEX CGH2 HRS:

Single Station:	**1,049,099 €**
Overall AREA 5:	**119,597,286 €**

OPEX CGH2 HRS:

The percentage of annual OPEX costs for refuelling stations is 10% of the initial CAPEX.[44]

Single HRS:	**104,910 €**
Overall AREA 5:	**11,959,729 €**

Electricity for Compression at 950 bar/Pre-Cooling

Electric energy required = 1.9 kWh/kgH_2

Annual Electricity demand for Compression at 950 bar/Pre-Cooling =
1.9 kWh/kgH_2 * 16,574,616 kgH_2/year = 31,491,771 kWh/year

Annual Electricity demand for Compression at 950 bar/Pre-Cooling <u>at the single HRS</u> =
= [31,491,771 kWh/year] / 114 stations = 276,244 kWh/(year*HRS) =
276 MWh/(year*HRS)

In the case of CGH2 HRS, the electricity consumption is in the range 20 MWh - 500MWh which corresponds to a tabulated cost (including taxes and duties) of:

Electricity Cost from the grid = 0.2057 €/kWh

Annual Energy Cost for Compression at 950 bar + Pre-Cooling [€/year] = 0.2057 €/kWh * 31,491,771 kWh/year = **6,477,857 €/year**

The following table shows a summary, highlighting the cost contribution by CGH2 HRS:

Year	CAPEX Compressor 950 bar [€]	CAPEX Cascade Storage 950 bar [€]	CAPEX Refrigeration Equipment [€]	CAPEX Dispenser [€]	Land/Other CAPEX [€]	CAPEX Control/Safety Equipment [€]
0	42255924	16659732	15580266	11584794	23826570	9690000
1	0	0	0	0	0	
2	0	0	0	0	0	
3	0	0	0	0	0	
4	0	0	0	0	0	
5	0	0	0	0	0	
6	0	0	0	0	0	
7	0	0	0	0	0	
8	0	0	0	0	0	
9	0	0	0	0	0	
10	0	0	0	0	0	
11	24706164	0	0	0	0	
12	0	0	0	0	0	
13	0	0	0	0	0	
14	0	0	0	0	0	
15	0	0	0	0	0	
16	0	0	0	0	0	
17	0	0	0	0	0	
18	0	0	0	0	0	
19	0	0	0	0	0	
20	0	0	0	0	0	
Cumulated [€] or [kg]	66962088	16659732	15580266	11584794	23826570	9690000
Impact [%]	17,06%	4,24%	3,97%	2,95%	6,07%	2,47%
Portions / LCOH CGH2 HRS [€/kgH_2]	**0,30**	**0,07**	**0,07**	**0,05**	**0,11**	**0,04**

Total CAPEX CGH2 HRS [€]	OPEX CGH2 HRS [€/year]	Electricity Compression 950 bar/Pre-Cooling [€/year]	Total Cost [€/year]	Annual H_2 demand of the AREA [kg H_2/year]
119597286	11959729	6477857	138034872	16574616
0	11390218	6169388	17559606	15785349
0	10847826	5875608	16723434	15033666
0	10331263	5595817	15927080	14317777
0	9839298	5329349	15168648	13635978
0	9370760	5075571	14446331	12986646
0	8924534	4833877	13758410	12368234
0	8499556	4603692	13103248	11779270
0	8094815	4384469	12479284	11218353
0	7709348	4175685	11885032	10684145
0	7342236	3976842	11319078	10175377
24706164	6992606	3787469	35486238	9690835
0	6659624	3607113	10266738	9229367
0	6342499	3435346	9777845	8789873
0	6040476	3271758	9312234	8371308
0	5752834	3115960	8868794	7972674
0	5478889	2967581	8446471	7593023
0	5217990	2826268	8044258	7231450
0	4969514	2691684	7661198	6887095
0	4732871	2563508	7296379	6559139
0	4507496	2441436	6948932	6246799
144303450	161004382	87206278	392514109	223130972
36,76%	41,02%	22,22%	100,00%	
0,65	**0,72**	**0,39**	**1,76**	

Table 43: CGH2 HRS - Impact on LCOH

CGH2 Hydrogen Refueling Station		
Items	**€/kgH_2**	**Impact [%]**
Compressor (950 bar)	0,30	17,1%
Electricity for Compression/Pre-Cooling	0,39	22,2%
Cascade Storage (950 bar)	0,07	4,2%
Refrigeration Equipment	0,07	4,0%
Dispenser CGH2 (700 bar)	0,05	3,0%
Land / Other Capital Costs HRS	0,11	6,1%
Control / Safety Equipment	0,04	2,5%
Operation & Maintenance CGH2 HRS	0,72	41,0%
Total CGH2 Hydrogen Refueling Station	**1,76**	

Table 44: CGH2 HRS - Cost detail

CGH2 HRS contribution to LCOH is **1.76 €/kgH_2:** a slightly higher cost with respect to LH2 HRS (1.52 €/kgH_2). About 40% is due to the Operation and Maintenance Costs (OPEX). These costs impact more because they are faced each year with an estimated amount of 10% of the initial investment. Another important part of the cost (17%) is the investment cost of the compressor, which still consumes less energy than LOHC HRS Compressor (0.39 €/kgH_2 instead of 0.76 €/kgH_2) because the gaseous hydrogen that arrives at the CGH2 HRS is already stored at 500 bar in tube trailers.

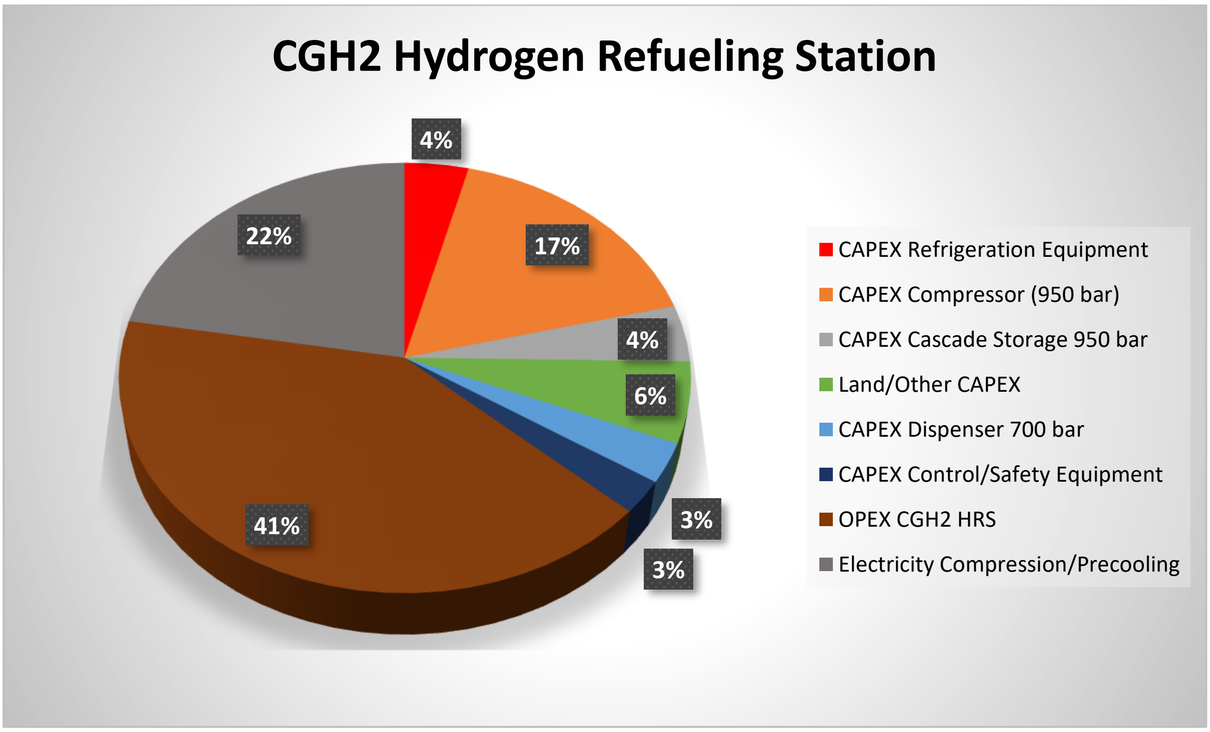


Figure 57: CGH2 HRS - Cost allocation

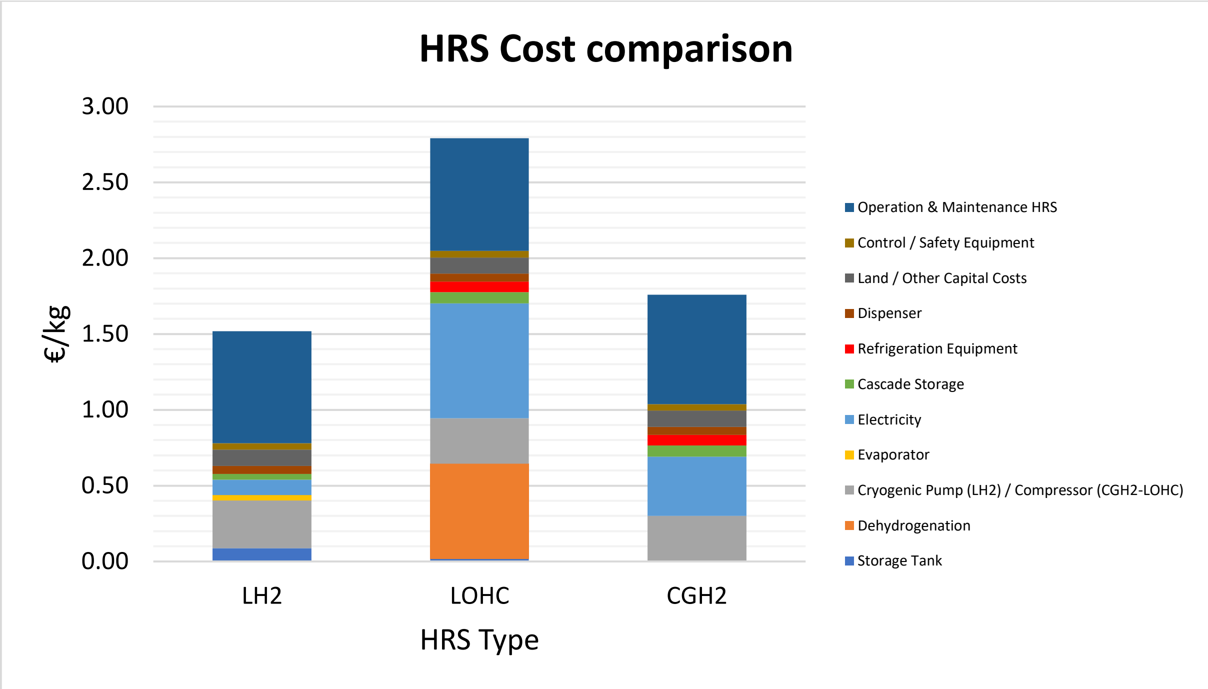


Figure 58: HRS Cost comparison

3.5 Levelized Cost of Hydrogen (LCOH)

The final result of the Levelized Cost of Hydrogen for the three methods of storage, transport and delivery of hydrogen is obtained: LH2, LOHC and, in this case also CGH2 scenario, which we had not discussed in the Argentine scenario for the constraint of ocean transport. Here are the three complete and summary tables:

	LH2				
Hydrogen Production from wind energy in Italy [€/kg]	**7,77**				
	Area 1+2+3	**Area 4**	**Area 5**	**Area 6**	**Area 7**
Liquefier	1,95	2,41	2,36	2,56	3,38
LH2 Terminal (Storage for Plant Outages, 10 days)	0,28	0,34	0,33	0,38	0,81
Distribution to HRS (Truck-Trailers)	0,74	0,48	0,48	0,46	0,40
Total Cost from Production Site to HRS [€/kg]	**2,97**	**3,22**	**3,17**	**3,40**	**4,59**
LH2 Cryogenic Storage Tank	0,09				
High Pressure Cryogenic Pump (950 bar)	0,32				
Evaporator	0,03				
Electricity for Cryogenic Pump/Evaporation	0,10				
Cascade Storage (950 bar)	0,04				
Dispenser CGH2 (700 bar)	0,05				
Land / Other Capital Costs HRS	0,11				
Control / Safety Equipment	0,04				
Operation & Maintenance LH2 HRS	0,74				
Total LH2 Hydrogen Refueling Station [€/kg]	**1,52**				
Levelized Cost Of Hydrogen [€/kg]	**12,26**	**12,52**	**12,46**	**12,69**	**13,88**

Table 45: Scenario LH2 ITA - Levelized Cost of Hydrogen

	LOHC: DibenzylToluene				
Hydrogen Production from wind energy in Italy [€/kg]	**7,77**				
	Area 1+2+3	**Area 4**	**Area 5**	**Area 6**	**Area 7**
LOHC Hydrogenation	0,13				
LOHC-H2 Terminal (Storage for Plant Outages, 10 days)	0,06	0,07	0,07	0,08	0,16
Distribution to HRS (Truck-Trailers)	0,65	0,41	0,42	0,40	0,33
Total Cost from Production Site to HRS [€/kg]	**0,83**	**0,61**	**0,61**	**0,60**	**0,62**
LOHC Storage Tank	0,02				
LOHC Dehydrogenation	0,63				
Compressor (950 bar)	0,30				
Electricity for Compression/Pre-Cooling	0,76				
Cascade Storage (950 bar)	0,07				
Refrigeration Equipment	0,07				
Dispenser CGH2 (700 bar)	0,05				
Land / Other Capital Costs HRS	0,11				
Control / Safety Equipment	0,04				
Operation & Maintenance LOHC HRS	0,75				
Total LOHC Hydrogen Refueling Station [€/kg]	**2,79**				
Levelized Cost Of Hydrogen [€/kg]	**11,40**	**11,17**	**11,18**	**11,17**	**11,19**

Table 46: Scenario LOHC ITA - Levelized Cost of Hydrogen

	CGH2				
Hydrogen Production from wind energy in Italy [€/kg]	**7,77**				
	Area 1+2+3	**Area 4**	**Area 5**	**Area 6**	**Area 7**
H2 Gaseous Geologic Storage (for Plant Outages, 10 days)	0,07	0,11	0,11	0,13	0,23
GH2 Terminal	0,90	0,94	0,93	0,96	1,14
Distribution to HRS (CGH2 Truck Tube Trailers 500 bar)	2,24	1,38	1,40	1,35	1,25
Total Cost from Production Site to HRS [€/kg]	**3,21**	**2,44**	**2,44**	**2,44**	**2,61**
Compressor (950 bar)	0,30				
Electricity Compression/Pre-Cooling	0,39				
Cascade Storage (950 bar)	0,07				
Refrigeration Equipment	0,07				
Dispenser CGH2 (700 bar)	0,05				
Land / Other Capital Costs HRS	0,11				
Control / Safety Equipment	0,04				
Operation & Maintenance CGH2 HRS	0,72				
Total CGH2 Hydrogen Refueling Station [€/kg]	**1,76**				
Levelized Cost Of Hydrogen [€/kg]	**12,74**	**11,97**	**11,97**	**11,97**	**12,14**

Table 47: Scenario CGH2 ITA - Levelized Cost of Hydrogen

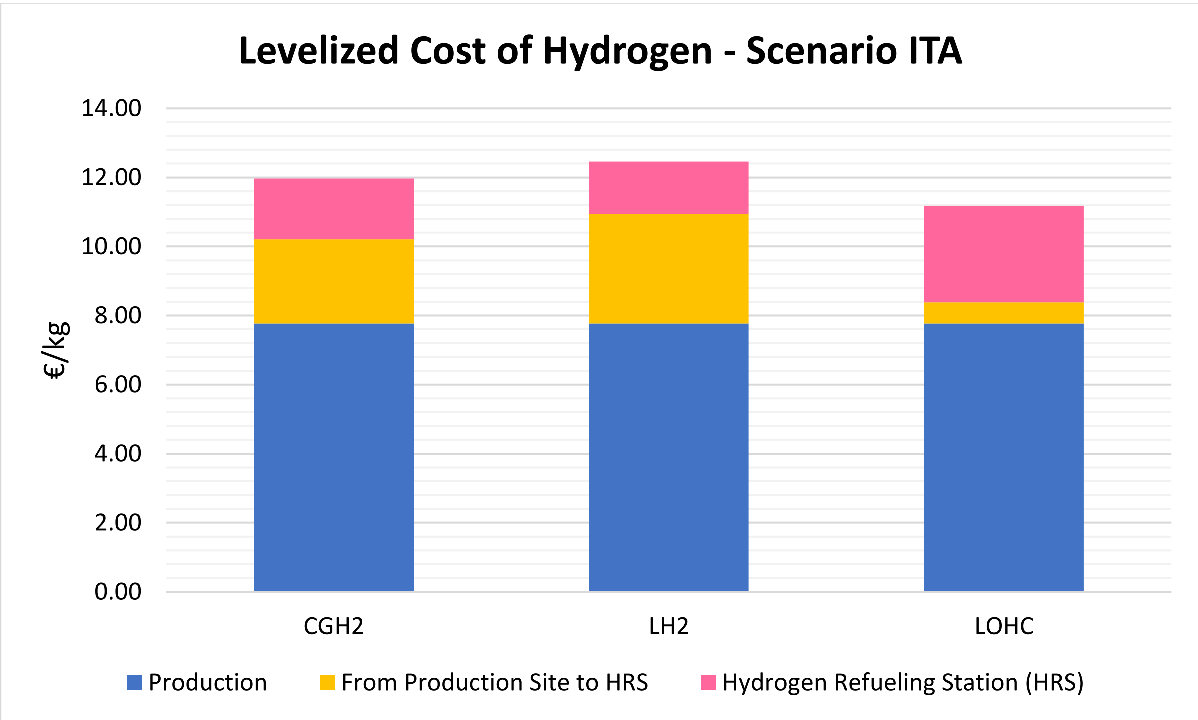


Figure 59: Scenario ITA - Levelized Cost of Hydrogen

Among the three Italian scenarios, the most competitive in terms of LCOH is the **LOHC** scenario. The Levelized Cost of Hydrogen for Area 5 amounts to **11.18 €/kgH$_2$**.

The absence of liquefaction or compression combined with a good energy density make it gain an advantage until distribution to HRS. This advantage is not entirely wasted despite a more expensive HRS due to dehydrogenation to make hydrogen available and usable again, and the compression of the GH2 from ambient pressure to very high pressures to refuel FCEVs at 700 bar.

Between the other two methodologies, the **CGH2** allows to obtain a lower cost: **11.97€/kgH$_2$** against the **12.46 €/kgH$_2$** of the **LH2**. Although the station of supply CGH2 is slightly more expensive, and the costs of GH2 terminal and transport considerably greater, it is once again the liquefaction to decree the greater total cost for the scenario LH2.

3.6 Sensitivity Analysis

The LCOH values obtained, 12.46 €/kgH$_2$ for LH2 scenario, 11.18 €/kgH$_2$ for LOHC scenario and 11.97 €/kgH$_2$ for CGH2 scenario are based on consumption values of the PEM electrolyser, wind energy cost and capacity factor considered as default, respectively equal to:

- PEM Electrolyser Consumption 58 kWh/kgH$_2$
- Wind Energy Cost 0.065 €/kWh
- Capacity Factor CF 25%

In the same way as for the Argentine scenario, in order to assess how the variation of one or more of the above parameters affects the final cost, a sensitivity analysis was carried out.

- *PEM Electrolyser Consumption*
  The source cited above[39] concludes that the electricity consumption for PEM electrolysers in the year 2020 can at most fall to 52 kWh/kgH$_2$.

- *Wind Energy Cost*
  The value of 0.065 €/kWh is an average value for Italy. It has been chosen a range between 0.05 €/kWh and 0.08 €/kWh (50-80 €/MWh).

- *Capacity Factor – CF*

  The range was chosen considering a variation of ±10% compared to the average value of CF for wind power in Italy, 25%.[63] Thus, 15-35% range is considered.

The sensitivity analysis was carried out on both the cost of production and the overall LCOH. A first procedure was to vary one parameter at a time by keeping the other two set at the default values.

Variable parameter: *Capacity Factor*

Wind Energy Cost 0.065 €/kWh

PEM Electrolyser Consumption 58 kWh/kgH_2

Capacity Factor CF [%]	Annual Equivalent Operating Hours [€/year]	CAPEX Stack	CAPEX Auxiliary	OPEX System	Electricity for Production	Water	CAPEX Civil Works & Other Costs	LCOH Production [€/kg]
15%	1314	1,38	2,56	1,06	3,77	0,01	1,65	**10,42**
20%	1752	1,03	1,92	0,79	3,77	0,01	1,24	**8,76**
25%	2190	0,83	1,53	0,64	3,77	0,01	0,99	**7,77**
30%	2628	0,95	1,28	0,53	3,77	0,02	0,83	**7,37**
35%	3066	0,85	1,10	0,45	3,77	0,02	0,71	**6,90**

Table 48: Scenario ITA - Production Cost as CF varies

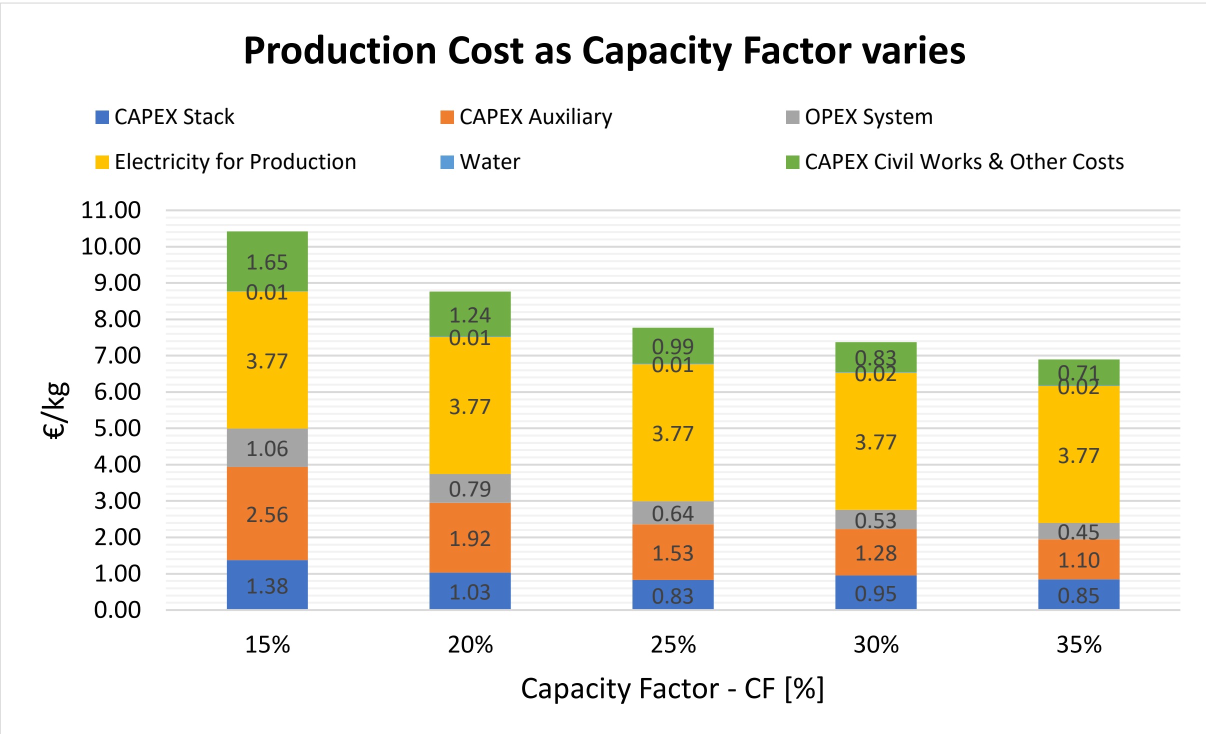


Figure 60: Scenario ITA - Production Cost as CF varies

Capacity Factor CF [%]	LCOH Production [€/kg]	Total LCOH - CGH2 [€/kg]	Total LCOH - LH2 [€/kg]	Total LCOH - LOHC [€/kg]
15%	10,42	14,62	15,11	13,83
20%	8,76	12,96	13,45	12,17
25%	7,77	11,97	12,46	11,18
30%	7,37	11,57	12,06	10,78
35%	6,90	11,10	11,58	10,30

Table 49: Scenario ITA - Levelized Cost of Hydrogen as CF varies

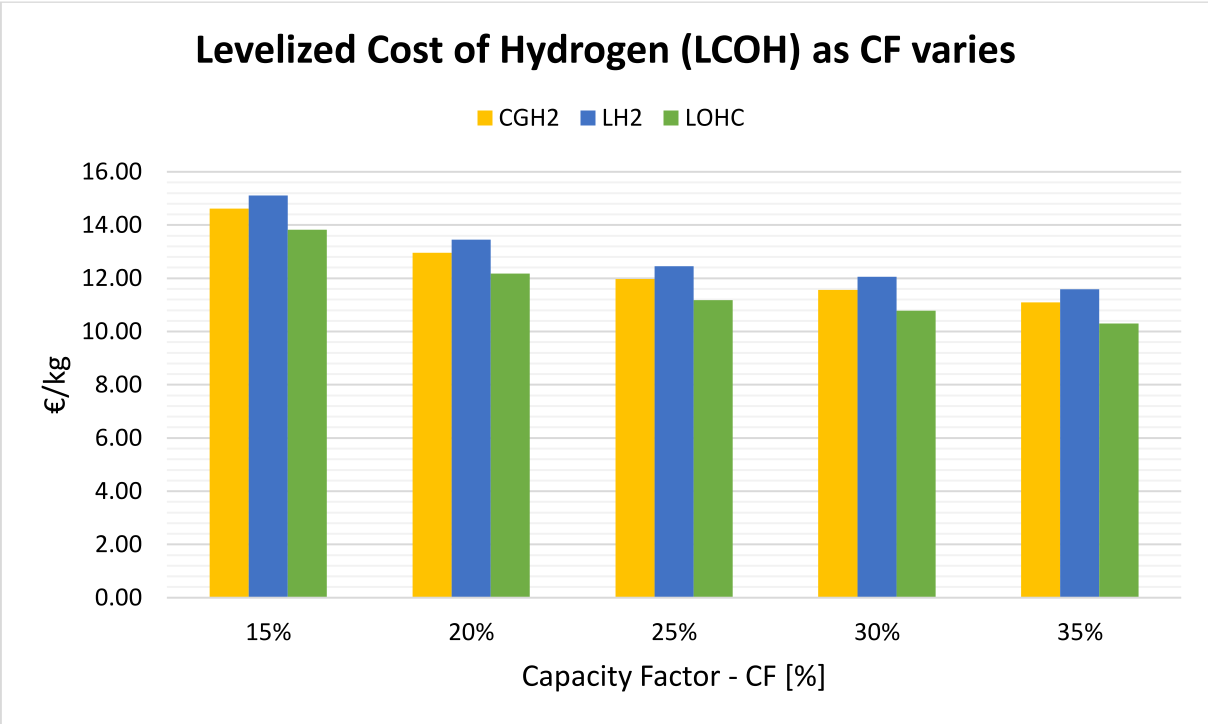


Figure 61: Scenario ITA - Levelized Cost of Hydrogen as CF varies

Variable Parameter: *PEM Electrolyser Consumption*

Wind Energy Cost 0.065 €/kWh

Capacity Factor 25%

Electrolyser Consumption [kWh/kg H_2]	CAPEX Stack	CAPEX Auxiliary	OPEX System	Electricity for Production	Water	CAPEX Civil Works & Other Costs	LCOH Production [€/kg]
58	0,83	1,53	0,64	3,77	0,01	0,99	**7,77**
56	0,80	1,48	0,61	3,64	0,01	0,96	**7,50**
54	0,77	1,43	0,59	3,51	0,01	0,92	**7,24**
52	0,74	1,38	0,57	3,38	0,01	0,89	**6,97**

Table 50: Scenario ITA - Production Cost as Electrolyser Consumption varies

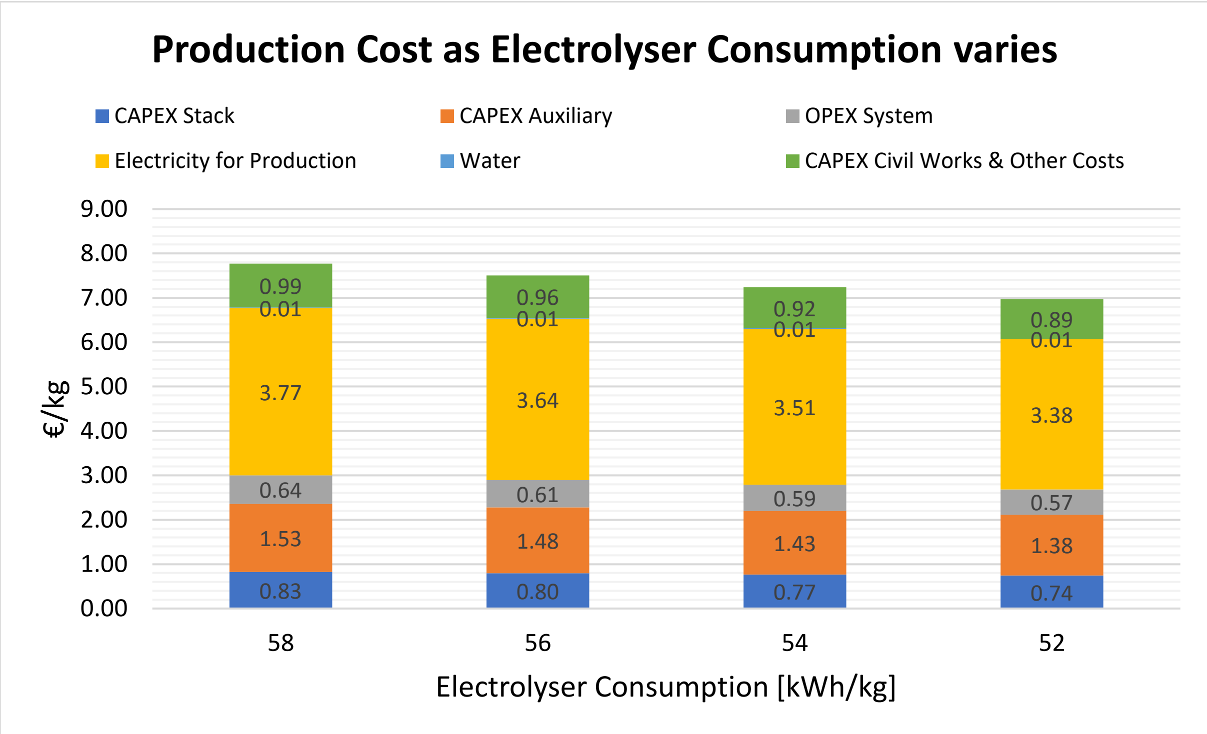


Figure 62: Scenario ITA - Production Cost as Electrolyser Consumption varies

Electrolyser Consumption [kWh/kg H_2]	LCOH Production [€/kg]	Total LCOH - CGH2 [€/kg]	Total LCOH - LH2 [€/kg]	Total LCOH - LOHC [€/kg]
58	7,77	11,97	12,46	11,18
56	7,50	11,70	12,19	10,91
54	7,24	11,44	11,92	10,64
52	6,97	11,17	11,66	10,38

Table 51: Scenario ITA - Levelized Cost of Hydrogen as Electrolyser Consumption varies

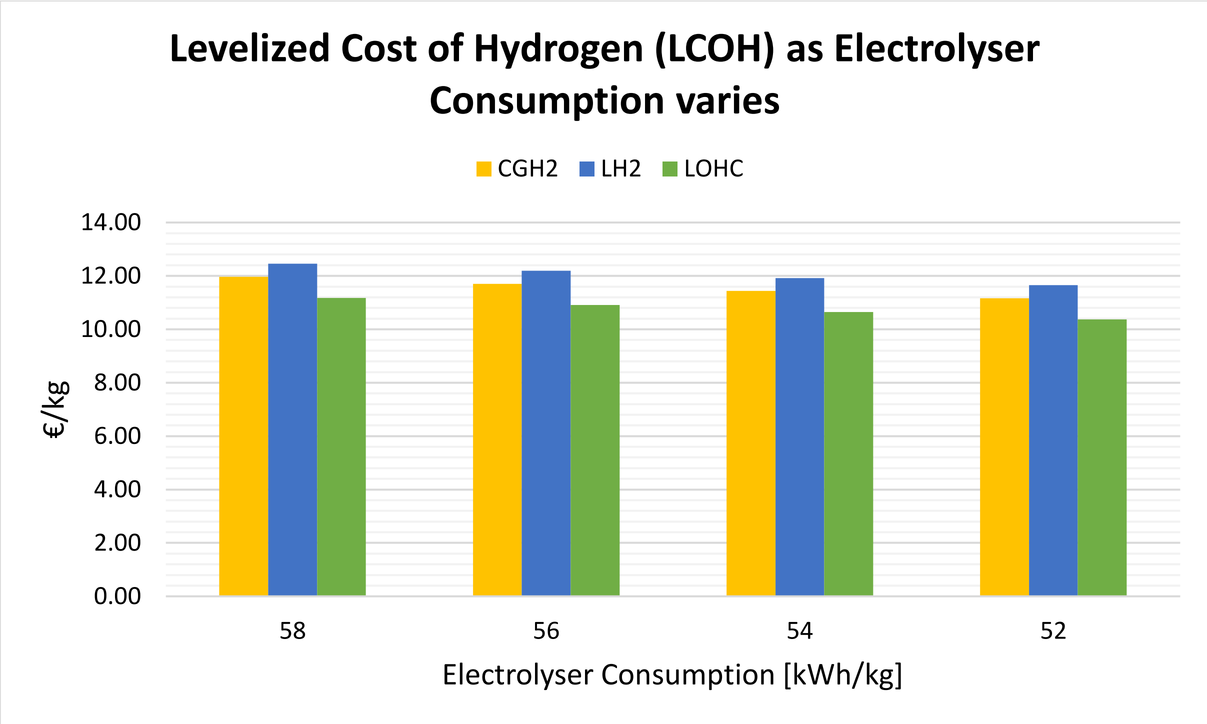


Figure 63: Scenario ITA - Levelized Cost of Hydrogen as Electrolyser Consumption varies

Variable Parameter: *Wind Energy Cost*

PEM Electrolyser Consumption 58 kWh/kgH_2

Capacity Factor 25%

Wind Energy Cost [€/MWh]	CAPEX Stack	CAPEX Auxiliary	OPEX System	Electricity for Production	Water	CAPEX Civil Works & Other Costs	LCOH Production [€/kg]
80	0,83	1,53	0,64	4,64	0,01	0,99	8,64
75	0,83	1,53	0,64	4,35	0,01	0,99	8,35
70	0,83	1,53	0,64	4,06	0,01	0,99	8,06
65	0,83	1,53	0,64	3,77	0,01	0,99	7,77
60	0,83	1,53	0,64	3,48	0,01	0,99	7,48
55	0,83	1,53	0,64	3,19	0,01	0,99	7,19
50	0,83	1,53	0,64	2,90	0,01	0,99	6,90

Table 52: Scenario ITA - Production Cost as Wind Energy Cost varies

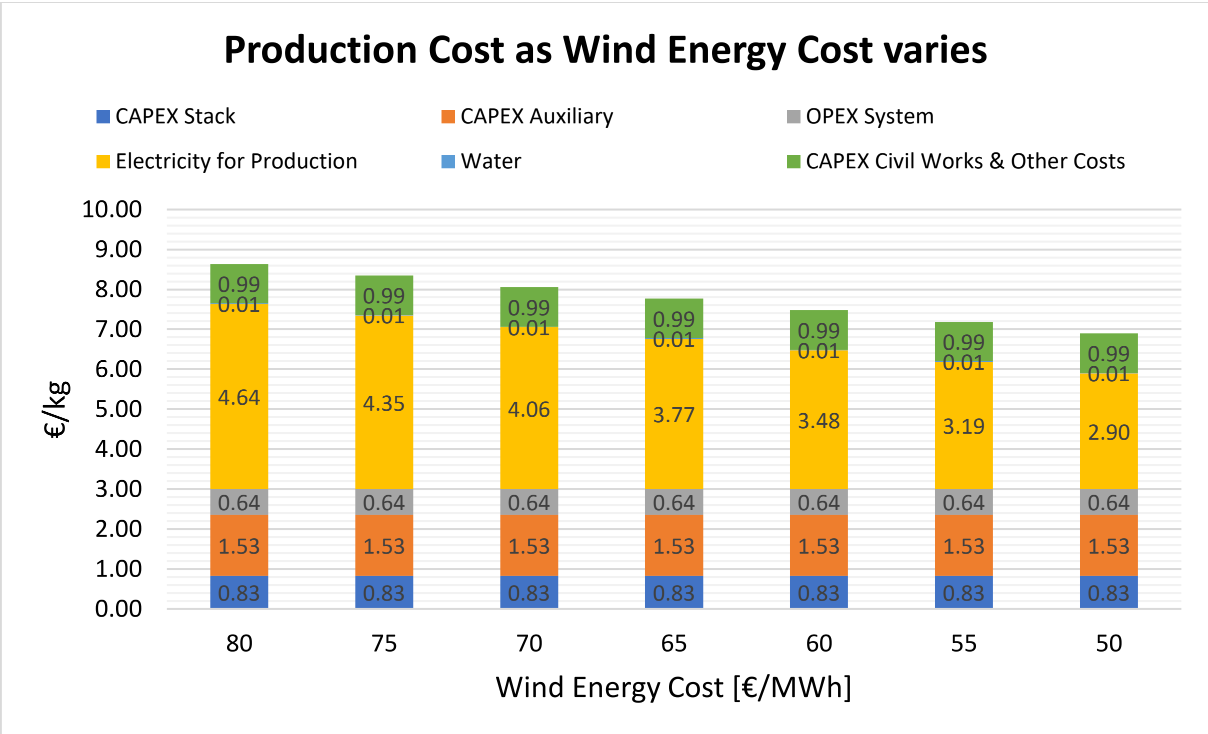


Figure 64: Scenario ITA - Production Cost as Wind Energy Cost varies

Wind Energy Cost [€/MWh]	LCOH Production [€/kg]	Total LCOH - CGH2 [€/kg]	Total LCOH - LH2 [€/kg]	Total LCOH - LOHC [€/kg]
80	8,64	12,84	13,33	12,05
75	8,35	12,55	13,04	11,76
70	8,06	12,26	12,75	11,47
65	7,77	11,97	12,46	11,18
60	7,48	11,68	12,17	10,89
55	7,19	11,39	11,88	10,60
50	6,90	11,10	11,59	10,31

Table 53: Scenario ITA - Levelized Cost of Hydrogen as Wind Energy Cost varies

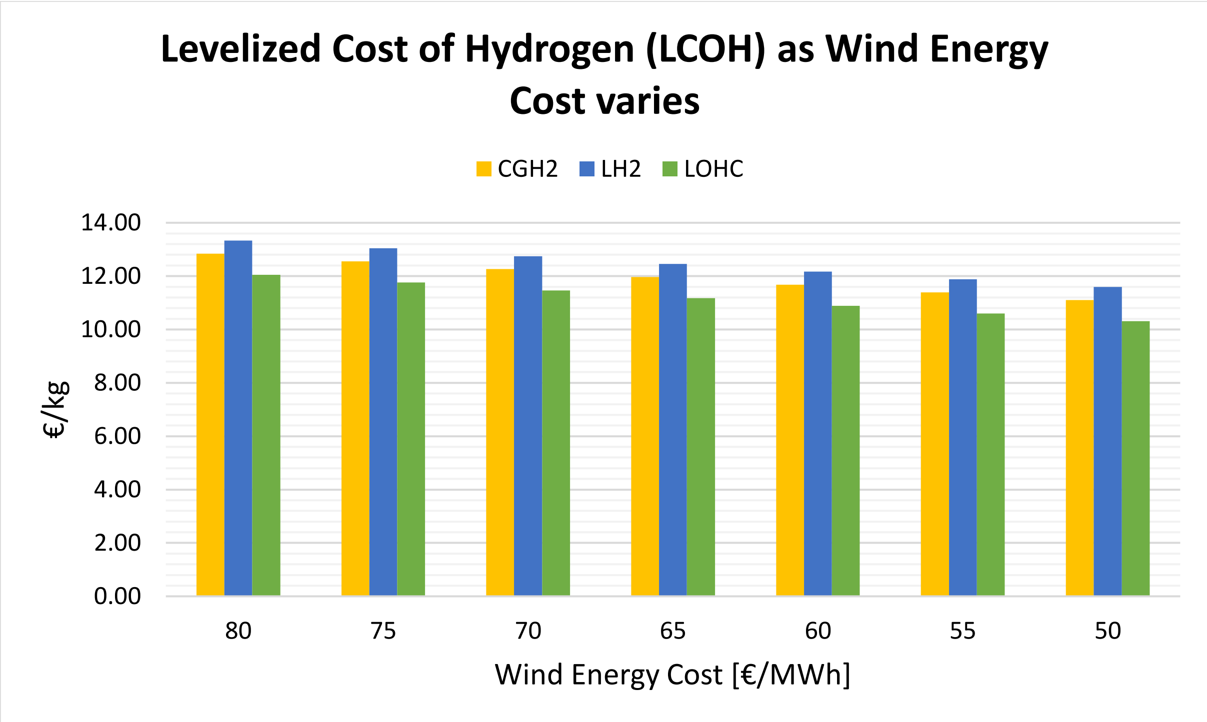


Figure 65: Scenario ITA - Levelized Cost of Hydrogen as Wind Energy Cost varies

A sensitivity analysis parameterizing two variables is carried out:

Variable parameters:

- ***Capacity Factor***
- ***PEM Electrolyser Consumption***

Wind Energy Cost = 0.065 €/kWh = 65 €/MWh

Production Cost

CF [%] / Consum. [kWh/kg]	15%	20%	25%	30%	35%
58	10,42	8,76	7,77	7,37	6,90
56	10,06	8,46	7,50	7,12	6,66
54	9,70	8,16	7,24	6,86	6,42
52	9,34	7,86	6,97	6,61	6,18

Table 54: Scenario ITA - Production Cost as CF varies for different electrolyser consumptions

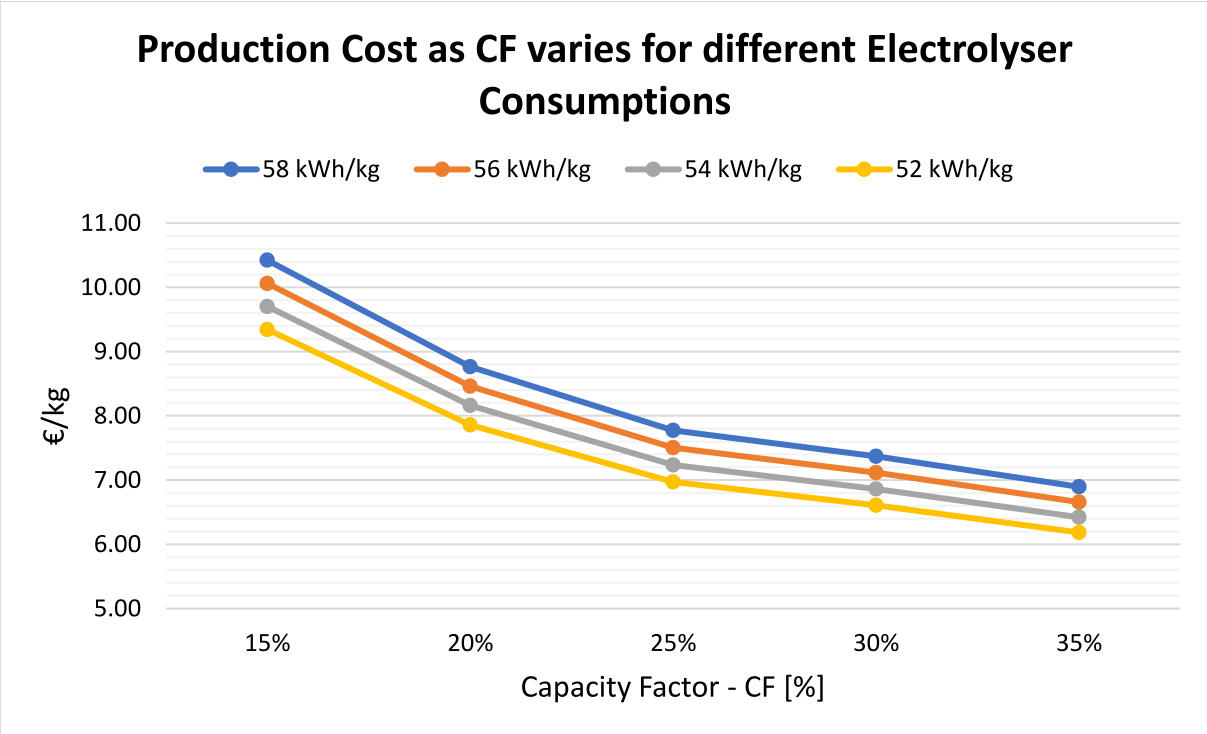


Figure 66: Scenario ITA - Production Cost as CF varies for different electrolyser consumptions

Assuming to exploit wind energy with a CF = 35% together with the lower value of the electrolyser consumption range (52 kWh/kgH_2) would result in a production cost of 6.18 €/kgH_2: 1.59 €/kgH_2 less than the base case.

Levelized Cost of Hydrogen – CGH2 scenario

CF [%] / Consum. [kWh/kg]	15%	20%	25%	30%	35%
58	**14,62**	**12,96**	**11,97**	**11,57**	**11,10**
56	**14,26**	**12,66**	**11,70**	**11,32**	**10,86**
54	**13,90**	**12,36**	**11,44**	**11,06**	**10,62**
52	**13,54**	**12,06**	**11,17**	**10,81**	**10,38**

Table 55: Scenario CGH2 ITA - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

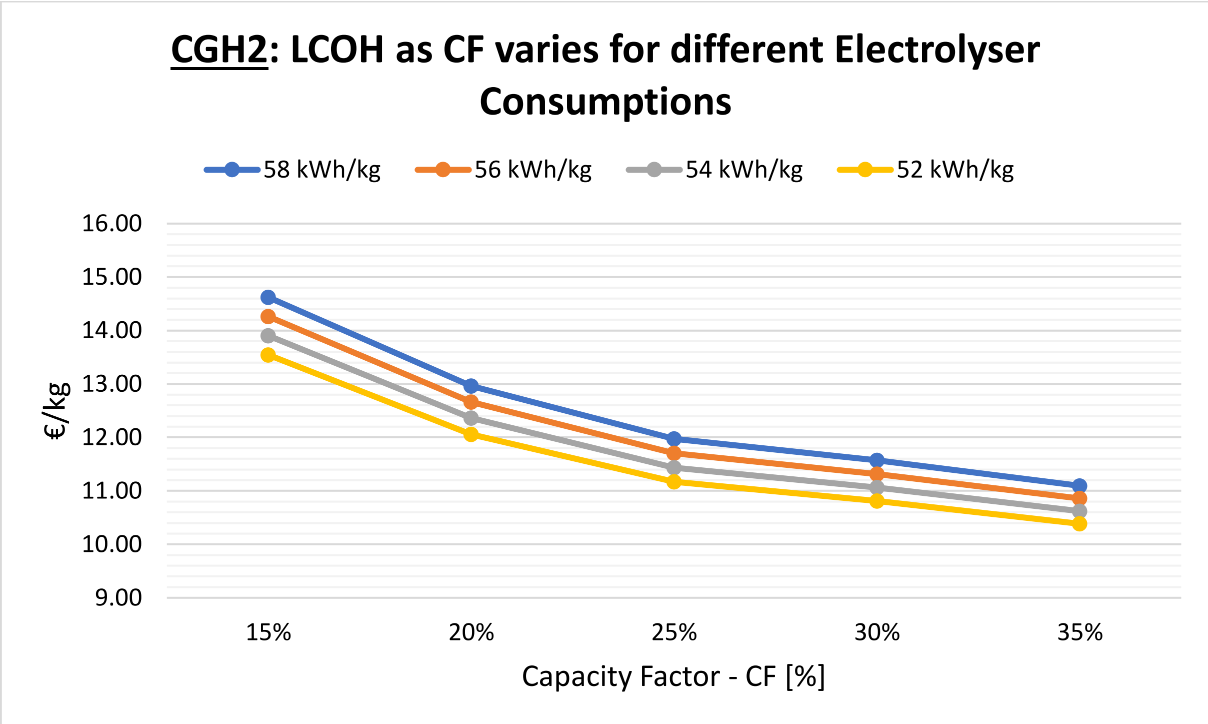


Figure 67: Scenario CGH2 ITA - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

The final cost of hydrogen in the best combination of CGH2 scenario would fall to 10.38 €/kgH_2.

Levelized Cost of Hydrogen – LH2 scenario

Consum. [kWh/kg] \ CF [%]	15%	20%	25%	30%	35%
58	15,11	13,45	12,46	12,06	11,58
56	14,75	13,15	12,19	11,80	11,35
54	14,39	12,85	11,92	11,55	11,11
52	14,03	12,55	11,66	11,30	10,87

Table 56: Scenario LH2 ITA - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

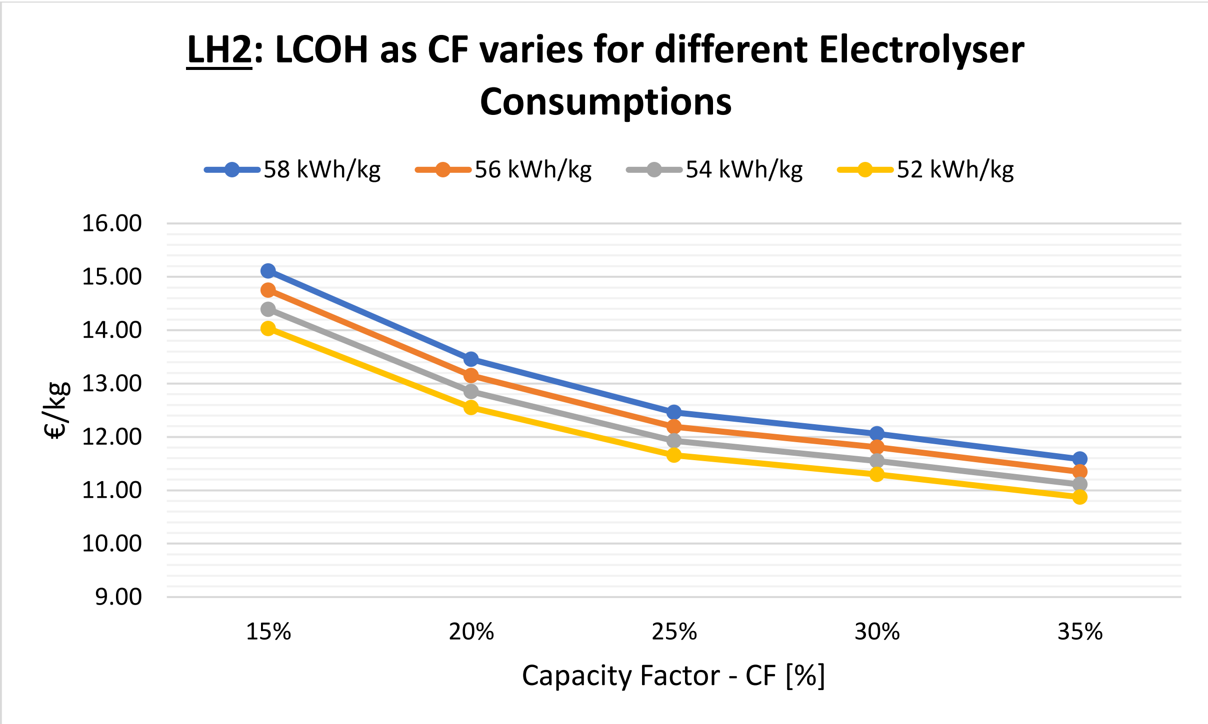


Figure 68: Scenario LH2 ITA - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

The final hydrogen cost in the LH2 scenario would at best reach 10.87 €/kgH_2.

Levelized Cost of Hydrogen – LOHC scenario

Consum. [kWh/kg] \ CF [%]	15%	20%	25%	30%	35%
58	13,83	12,17	11,18	10,78	10,30
56	13,47	11,87	10,91	10,52	10,07
54	13,11	11,57	10,64	10,27	9,83
52	12,75	11,27	10,38	10,02	9,59

Table 57: Scenario LOHC ITA - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

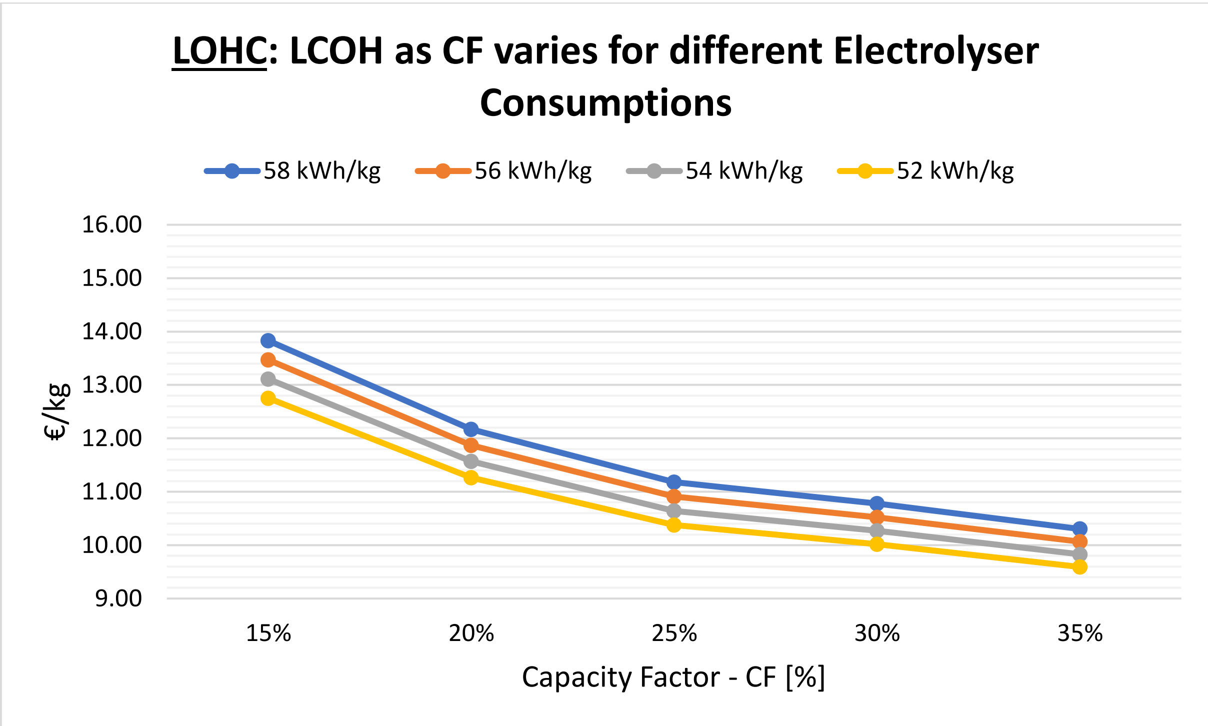


Figure 69: Scenario LOHC ITA - Levelized Cost of Hydrogen as CF varies for different electrolyser consumptions

In the Italian LOHC scenario, the final cost could fall below the 10 €/kgH_2 barrier with an electrolyser consumption of 52 kWh/kgH_2 and an excellent capacity factor of 35%: 9.59 €/kgH_2.

Variable parameters:

- ***Capacity Factor***
- ***Wind Energy Cost***

PEM Electrolyser Consumption = 58 kWh/kgH_2

Production Cost

CF [%] / Electricity [€/MWh]	15%	20%	25%	30%	35%
80	11,29	9,63	8,64	8,24	7,77
75	11,00	9,34	8,35	7,95	7,48
70	10,71	9,05	8,06	7,66	7,19
65	10,42	8,76	7,77	7,37	6,90
60	10,13	8,47	7,48	7,08	6,61
55	9,84	8,18	7,19	6,79	6,32
50	9,55	7,89	6,90	6,50	6,03

Table 58: Scenario ITA - Production Cost as CF varies for different wind energy costs

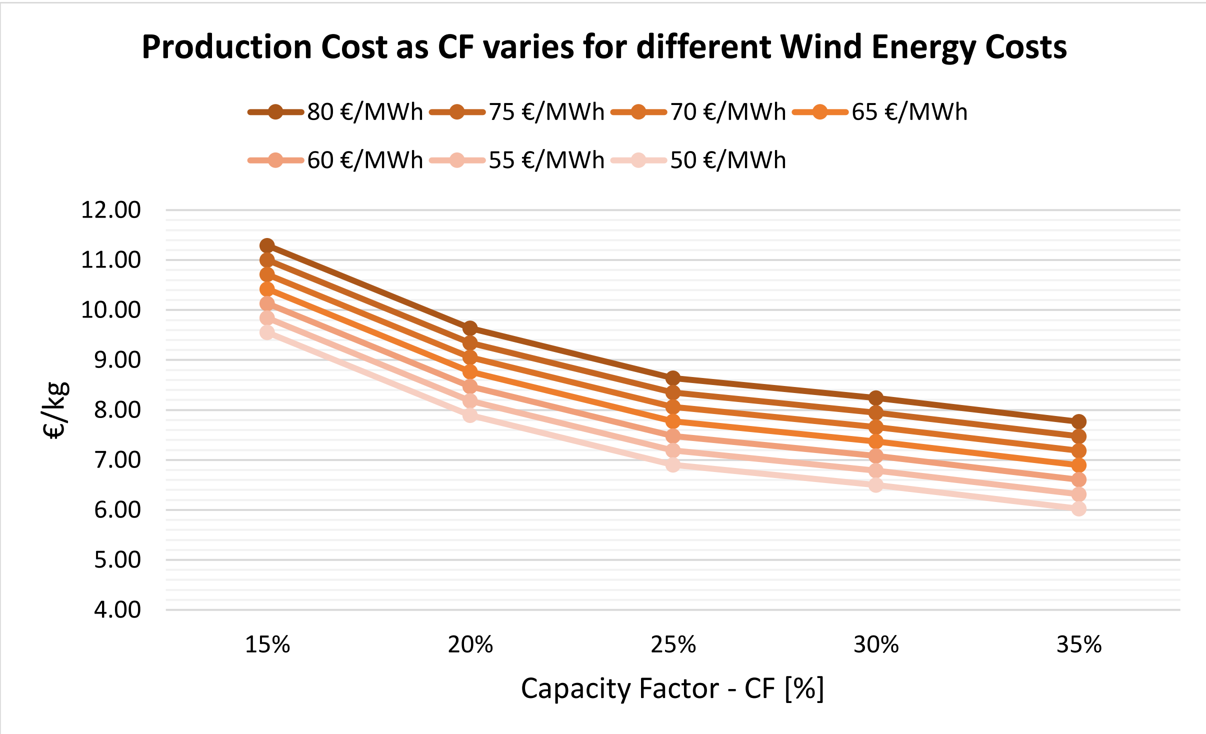


Figure 70: Scenario ITA - Production Cost as CF varies for different wind energy costs

High plant uptime (CF = 35 %) combined with the lower value of the wind energy cost (50 €/MWh) would result in a hydrogen production cost of 6.03 €/kgH_2: 1.74 €/kgH_2 less with respect to base case.

Levelized Cost of Hydrogen – CGH2 scenario

Electricity [€/MWh] \ CF [%]	15%	20%	25%	30%	35%
80	15,49	13,83	12,84	12,44	11,97
75	15,20	13,54	12,55	12,15	11,68
70	14,91	13,25	12,26	11,86	11,39
65	14,62	12,96	11,97	11,57	11,10
60	14,33	12,67	11,68	11,28	10,81
55	14,04	12,38	11,39	10,99	10,52
50	13,75	12,09	11,10	10,70	10,23

Table 59: Scenario CGH2 ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs

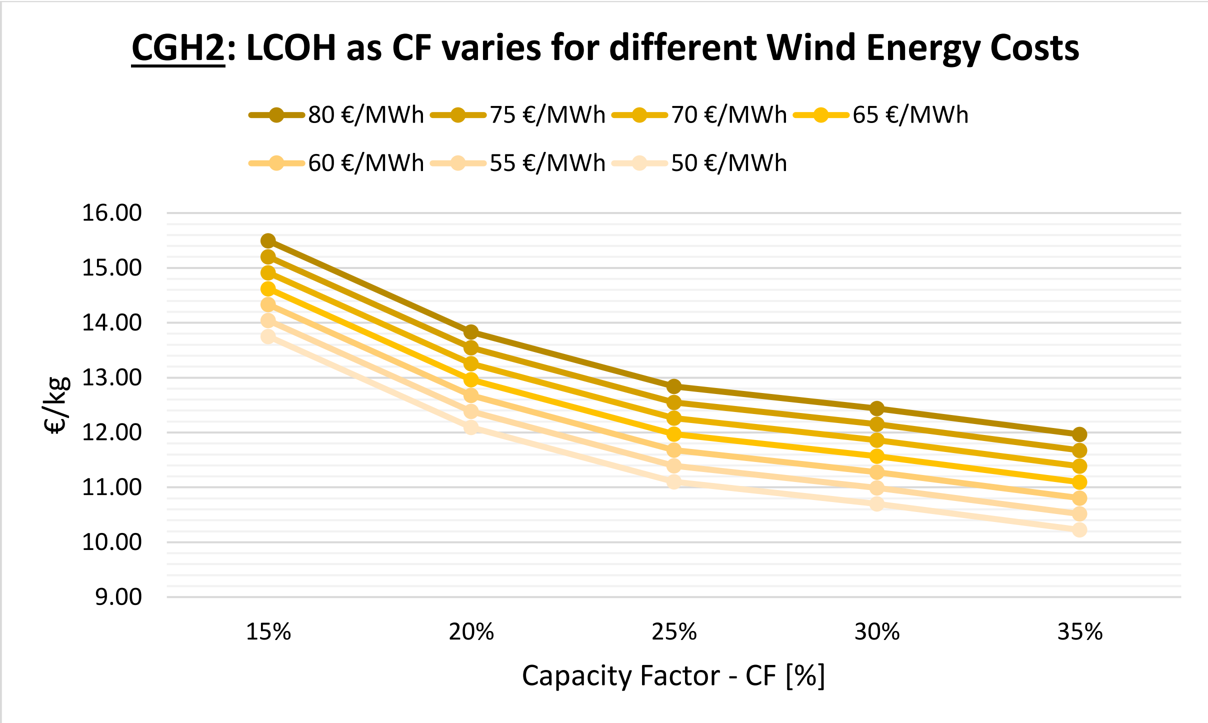


Figure 71: Scenario CGH2 ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs

The final cost of hydrogen in the best combination of CGH2 scenario would fall to 10.23 €/kgH_2.

Levelized Cost of Hydrogen – LH2 scenario

Electricity [€/MWh] \ CF [%]	15%	20%	25%	30%	35%
80	15,98	14,32	13,33	12,93	12,45
75	15,69	14,03	13,04	12,64	12,16
70	15,40	13,74	12,75	12,35	11,87
65	15,11	13,45	12,46	12,06	11,58
60	14,82	13,16	12,17	11,77	11,29
55	14,53	12,87	11,88	11,48	11,00
50	14,24	12,58	11,59	11,19	10,71

Table 60: Scenario LH2 ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs

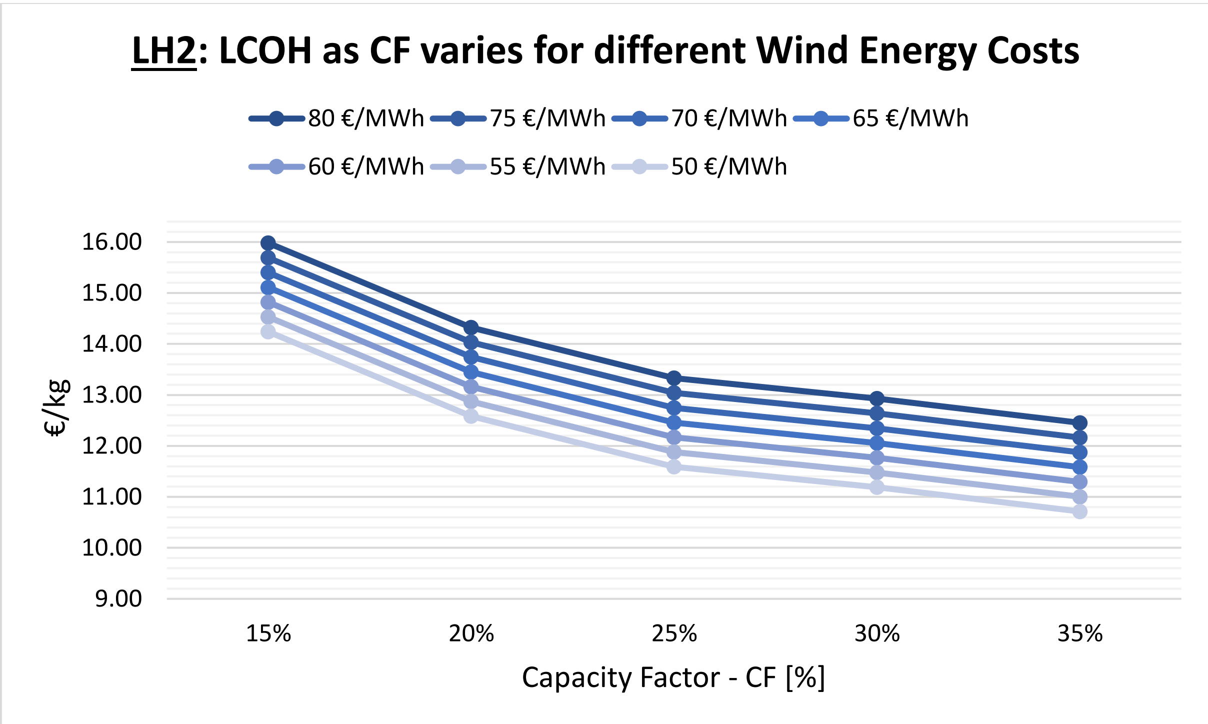


Figure 72: Scenario LH2 ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs

The total LCOH for liquefied hydrogen that can be achieved in the Italian scenario according to the best configuration is 10.71 €/kgH_2.

Levelized Cost of Hydrogen – LOHC scenario

CF [%] / Electricity [€/MWh]	15%	20%	25%	30%	35%
80	14,70	13,04	12,05	11,65	11,17
75	14,41	12,75	11,76	11,36	10,88
70	14,12	12,46	11,47	11,07	10,59
65	13,83	12,17	11,18	10,78	10,30
60	13,54	11,88	10,89	10,49	10,01
55	13,25	11,59	10,60	10,20	9,72
50	12,96	11,30	10,31	9,91	9,43

Table 61: Scenario LOHC ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs

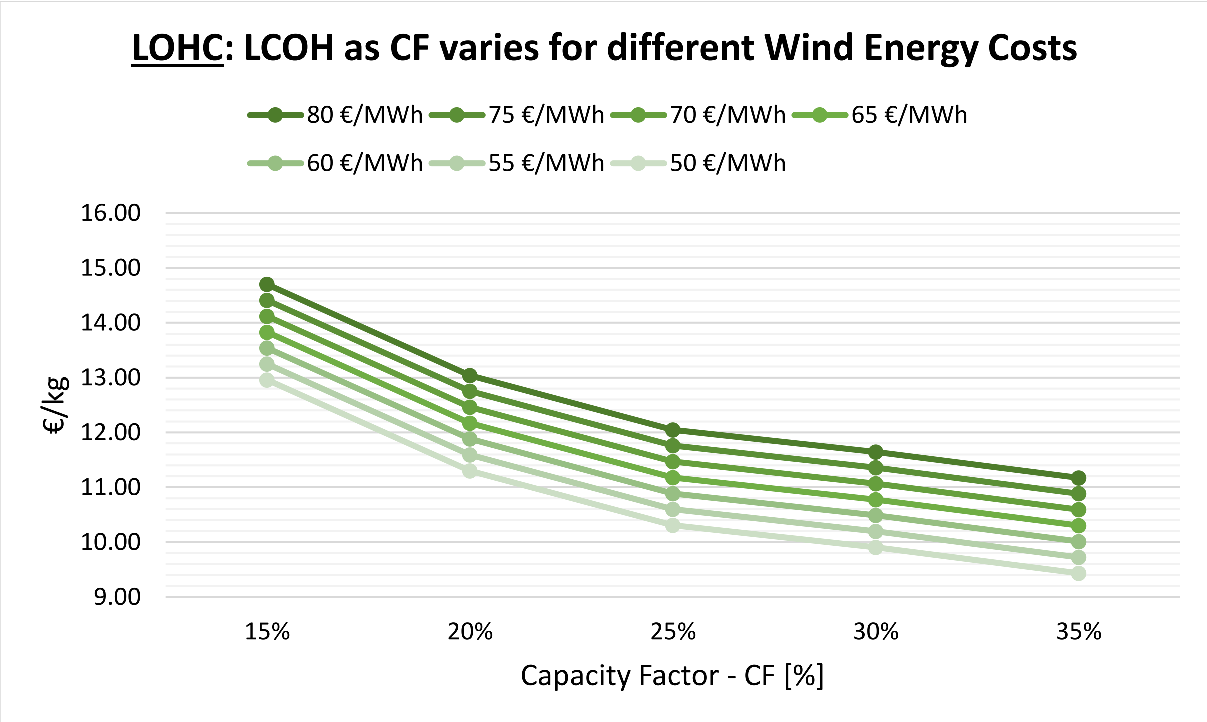


Figure 73: Scenario LOHC ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs

With the most cost-effective methodology (LOHC scenario), it could be reached a cost of 9.43 €/kgH_2 in the most optimistic configuration.

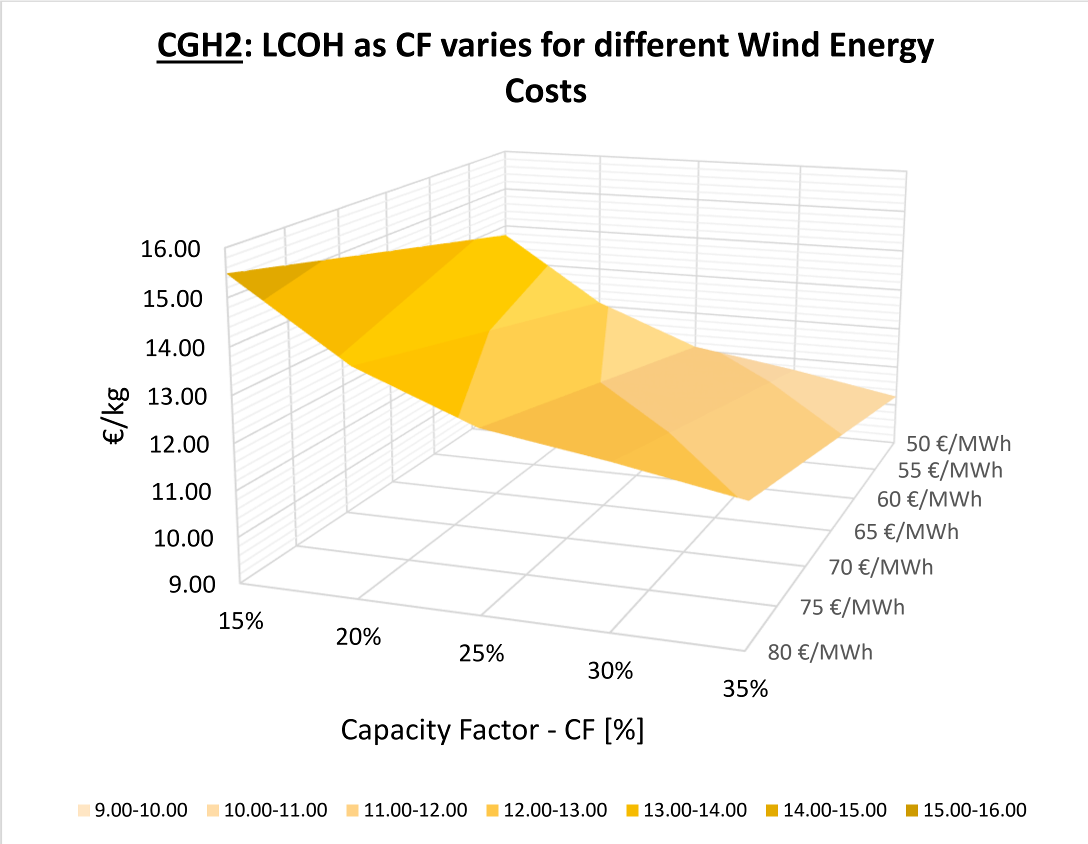


Figure 74: Scenario CGH2 ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs (3D)

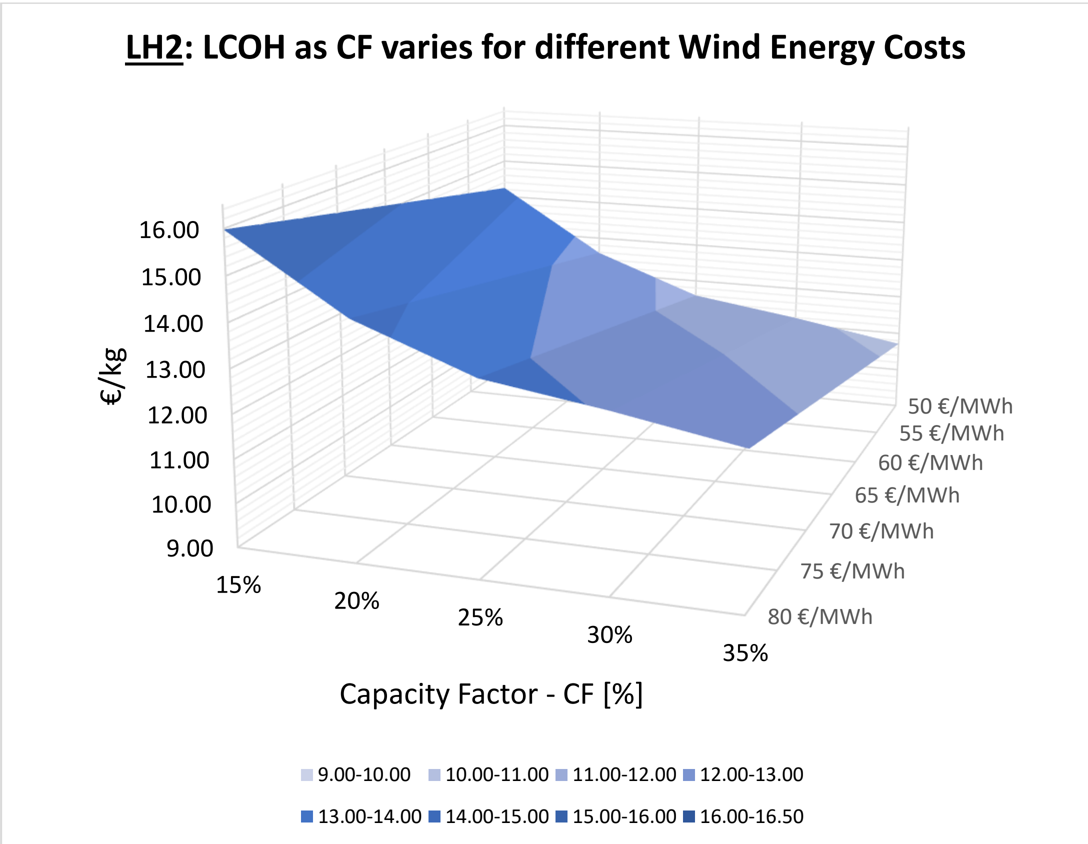


Figure 75: Scenario LH2 ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs (3D)

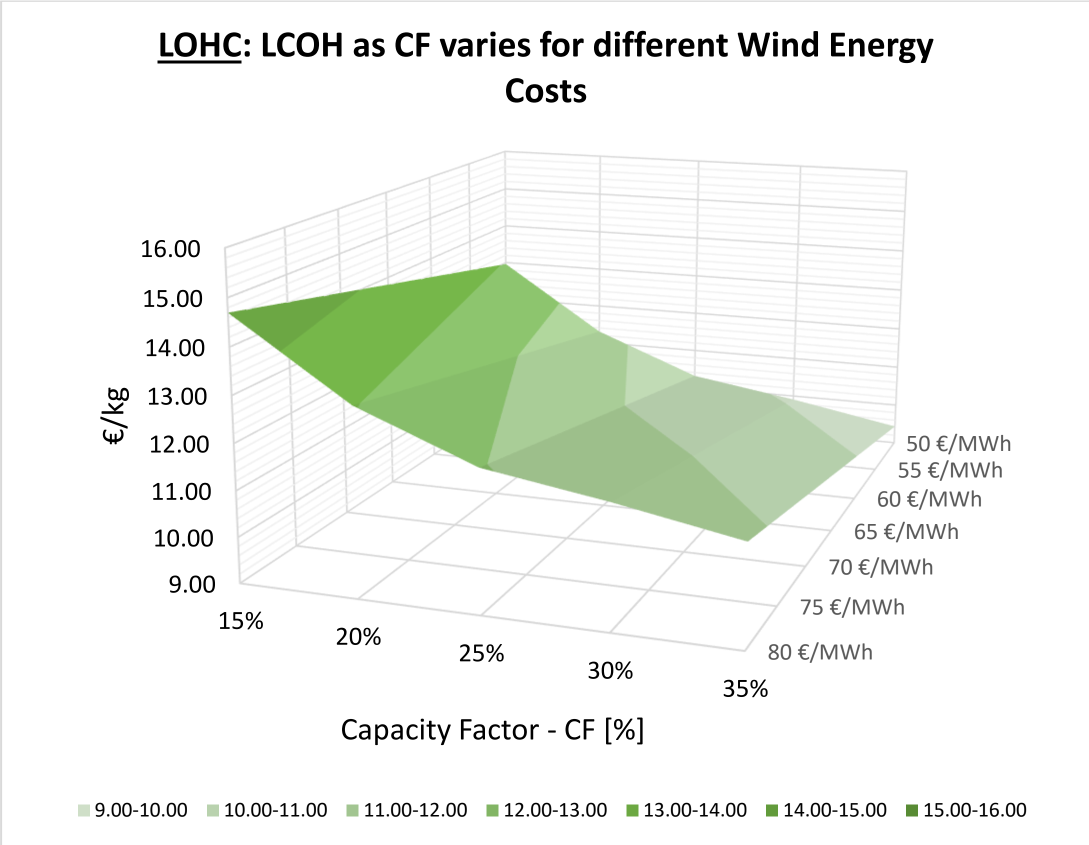


Figure 76: Scenario LOHC ITA - Levelized Cost of Hydrogen as CF varies for different wind energy costs (3D)

Chapter 4

CONCLUSIONS

4.1 Scenarios comparison

At the end of this techno-economic study on the final cost of green hydrogen produced by electrolysis through wind energy for Italian FCEVs mobility assumed to 1% market penetration, a graphical comparison is shown between all the scenarios analysed, which are indicated by the following abbreviations:

- **LH2 ARG**
  Production in Argentina, liquefaction, liquid state storage, ocean transport in Italy and road distribution to Italian LH2 HRS.

- **LOHC ARG**
  Production in Argentina, storage via Liquid Organic Hydrogen Carrier (Dibenzyltoluene), ocean transport in Italy and road distribution to Italian LOHC HRS.

- **CGH2 ITA**
  Production in Italy, compressed gas phase storage, road distribution to Italian CGH2 HRS.

- **LH2 ITA**
  Production in Italy, liquefaction, liquid state storage, road distribution to Italian LH2 HRS.

- **LOHC ITA**
  Production in Italy, storage via Liquid Organic Hydrogen Carrier (Dibenzyltoluene), road distribution to Italian LOHC HRS.

To have congruence in comparing the data, default Capacity Factors were considered i.e. 50% for Argentine production scenarios and 25% for Italian production scenarios. Also as regard PEM electrolyser consumption, the default value of 58 kWh/kgH_2 was took into account.

The ranges of the cost of electricity produced by wind energy are those taken into account in this study, namely 30-55€/MWh for Argentine scenario (with a default value of 40 €/MWh) and 50-80 €/MWh for Italian scenario (with a default value of 65 €/MWh). Similarly, the ranges of the Capacity Factor are: 20-70% for the Argentine scenario and 15-35% for the Italian one.

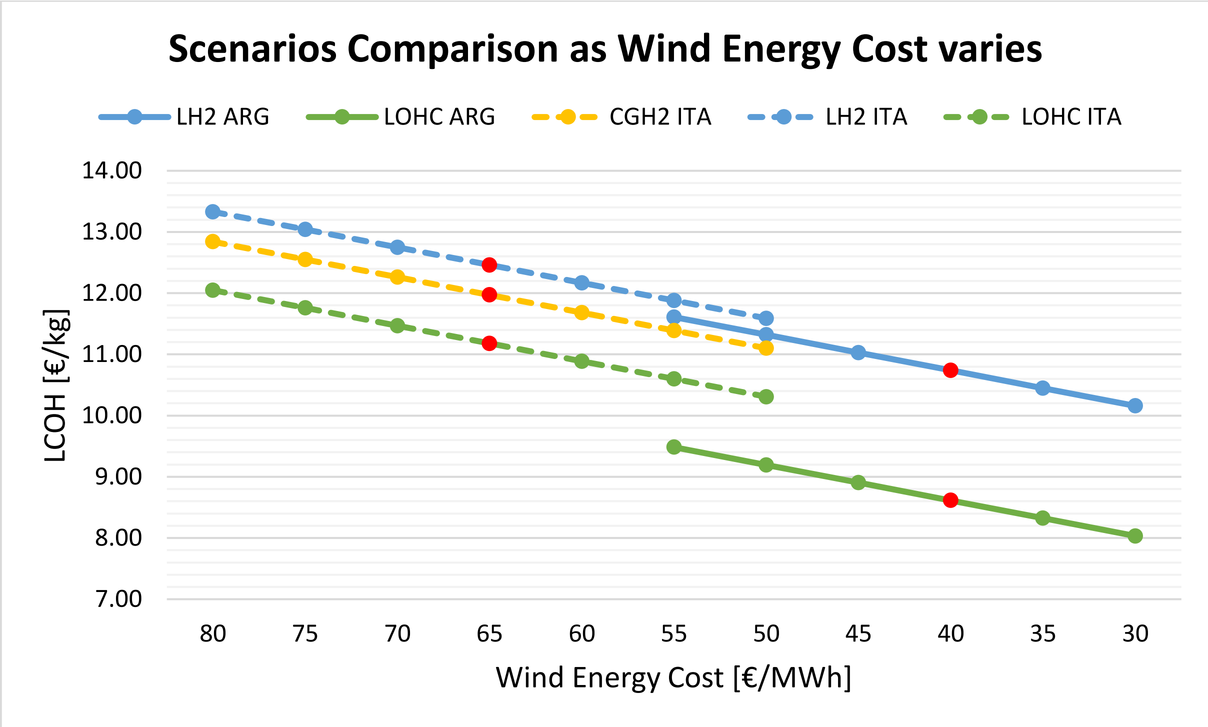


Figure 77: Comparison of the different scenarios as wind energy cost varies

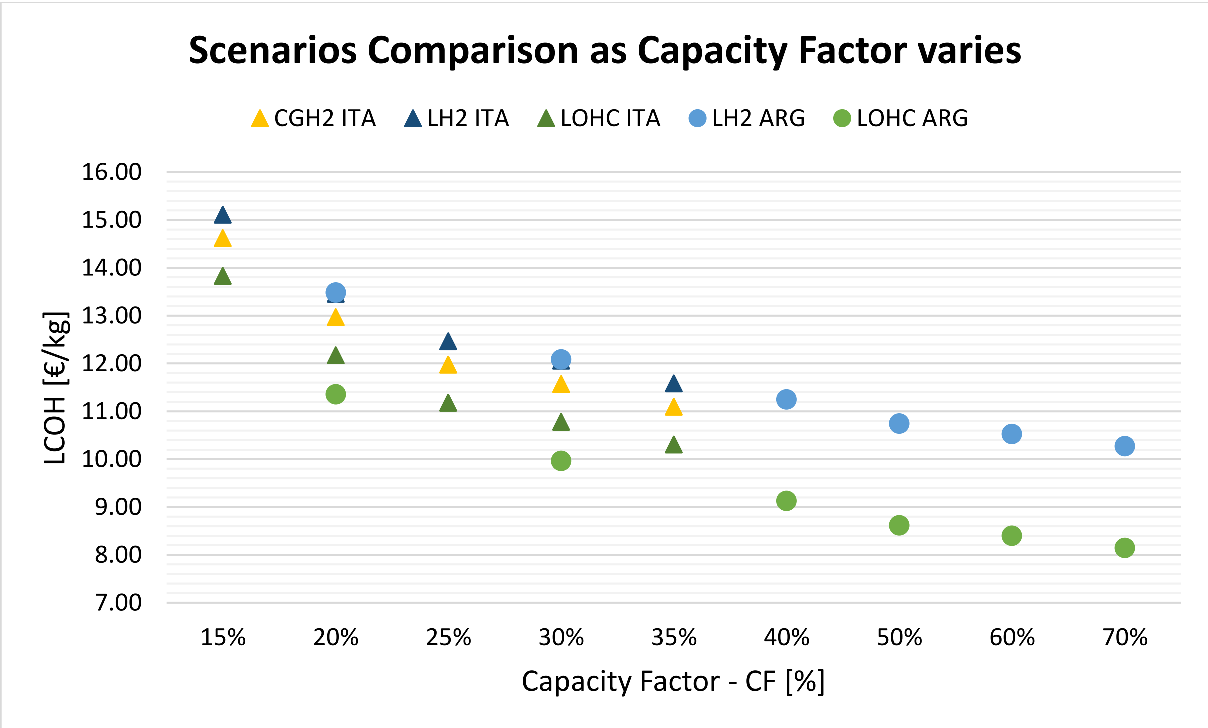


Figure 78: Comparison of the different scenarios as CF varies

Looking at Figures 77-78 it can be said that the overall costs in the scenarios of hydrogen production from wind power in Argentina are more competitive. In fact, the enormous wind potential of Patagonia involves high capacity factors and lower wind electricity costs that make green hydrogen production really attractive. The minimum overall Levelized Cost of Hydrogen is achieved with the storage and transport of hydrogen bound to LOHC, a key technology in the future because it makes hydrogen easier to manage, treating it as a conventional fuel at room temperature and pressure, thus saving on storage and ocean transport.

As can be seen from Figure 77, in which the CF for the Argentine scenario is 50%, the cost for **LOHC ARG** scenario (8.61 €/kgH_2 in the base case), is always below 10 €/kgH_2, even close to 8 €/kgH_2 if the cost of electricity could be further reduced to 30 €/MWh.

Argentine scenario is competitive also in the liquified phase (**LH2 ARG**) because the minor cost of production succeeds to compensate a greater cost faced from downstream of the production to the arrival to the HRS caused by the oceanic transport of LH2, more expensive than LOHC ocean shipping. With the excellent CF and Argentine wind energy costs, the LH2 ARG scenario remains below 12 €/kgH_2 (base case 10.74 €/kgH_2).

Using a LOHC to store hydrogen proves to be the most advantageous choice even among Italian scenarios: from a base case of 11.18 €/kgH_2 if the average wind CF in Italy could improve up to 30% and/or if the cost of electricity was reduced to below 60 €/MWh, the **LOHC ITA** scenario would have the same competitiveness as the LH2 ARG scenario with a final cost of less than 11 €/kgH_2. This is due to the very low cost faced from end of production to arrival at the HRS, although the latter is the most expensive due mainly to dehydrogenation and higher electricity consumption. Remember that a LOHC HRS faces a cost of 2.79 €/kgH_2.

The high liquefaction costs make the **LH2 ITA** scenario the least competitive of all. With CF=25% and wind power cost at 65 €/MWh, the final cost is 12.46 €/kgH_2. With an improvement of these parameters it could fall below the threshold of 12 €/kgH_2, in the most optimistic cases.

The scenario **CGH2 ITA** is slightly better than LH2 ITA, in fact there is no liquefaction, however there are still greater impacts due to the GH2 Terminal and road distribution, therefore the competitiveness is placed between LH2 ITA and LOHC ITA with base case equal to 11.97€/kgH_2.

4.2 Fuel Economy comparison

Hydrogen-gasoline equivalence in mobility can be defined as follows:

GASOLINE		
Lower Heating Value	43.6	MJ/kg
Lower Heating Value	12.11	kWh/kg
Density (15 °C, $p=p_{amb}$)	0.7475	kg/l
Energy Density	9.05	kWh/l

Table 62: Chemical-physical characteristics of gasoline

HYDROGEN H_2		
Lower Heating Value	120	MJ/kg
Lower Heating Value	33.33	kWh/kg
Density (STP)	0.0899	kg/Nm^3
Density (GH2, 15 °C, 700 bar)	40	kg/m^3
Density (GH2, 15 °C, 700 bar)	0.04	kg/l
Density (LH2)	70.79	kg/m^3
Density (LH2)	0.0708	kg/l
Energy Density (STP)	3.00	kWh/Nm^3
Energy Density (GH2, 15°C, 700 bar)	1.33	kWh/l
Energy Density (LH2)	2.36	kWh/l

Table 63: Chemical-physical characteristics of H_2

The values of heating value and density of gasoline and hydrogen, from which energy densities were obtained, were consulted and compared by these sources: [32,69–71]

In terms of the energy content ***1 kg of H_2 is equivalent to 3.68 litres of gasoline***, which corresponds to 2.75 kg.

In order to assess the final price of hydrogen for FCEV cars to be competitive in terms of consumption versus gasoline and hybrid cars, fuel economy values of a hydrogen car, a gasoline car and hybrid gasoline/electric car were compared. To make the comparison fair, three models were chosen from the same car manufacturer, the Hyundai, belonging to the same segment.

	Hyundai ix35 Fuel Cell 136 CV [a]	**Hyundai Kona Hybrid 1.6 140 CV [b]**	**Hyundai Tucson 1.6 GDI 132 CV [b]**
Model image			
Power Supply	Hydrogen	Hybrid (Gasoline/Electric)	Gasoline
Dimensions [cm]	442L 182W 167H	417L 180W 157H	448 H 185W 165L
Power	100 KW (136 CV)	104 KW (141 CV)	97 kW (132 CV)
Maximum Torque	300 Nm (immediately)	147 Nm/4000 rpm	160,8 Nm/4850 rpm
Maximum Speed	160 km/h	160 km/h	182 km/h
0 – 100 km/h [sec]	12.5 sec	11.2 sec	11.5 sec
CO_2 emissions[c]	absent	114-123 g/km	179-189 g/km
Fuel Economy[c]	0.95 kg/100 km	5.0 – 5.4 l/100 km	7.9 – 8.3 l/100 km
Fuel Tank Capacity	5.64 kg	38 l	62 l
Range	600 km	700-760 km	745-785 km
List Price	58,000 €	28,150 €[d]	28,600 €[d]

Table 64: Comparison between cars of the same automotive segment (a)

(a): sources [72,73]

(b): source [74]

(c): fuel economy and CO_2 emissions are calculated using the Worldwide harmonized Light-Duty vehicles Test Procedure (WLTP) and the combined average cycle is considered. The WLTP takes into account a driving profile closer to everyday reality than the previous NEDC standard, which was more a simulated laboratory test and served mainly to compare different vehicles. The WLTP claims to simulate a truer driving style and thus achieve more realistic results. [75]

(d): intermediate equipment is considered, XLINE [74]

Starting from the fuel economy, through the mass energy density for hydrogen (33.33 kWh/kg) and volumetric energy density for gasoline (9.05 kWh/l), the energy consumption (i.e. kWh consumed for 100 km travelled) is obtained.

	Hyundai ix35 Fuel Cell 136 CV [a]	Hyundai Kona Hybrid 1.6 140 CV [b]	Hyundai Tucson 1.6 GDI 132 CV [b]
Energy Consumption [kWh/100 km]	31.7	45.3 – 48.9	71.5 – 75.1
Fuel Economy Ratio [$l_{gasoline}/kgH_2$]	-	5.3 – 5.7	8.3 – 8.7

Table 65: Comparison between cars of the same automotive segment (b)

As for compact SUVs, the gasoline/electric hybrid vehicle consumes about 50% more energy than the FCEV. The gasoline vehicle consumes more than twice as much energy as the FCEV.

A very interesting calculation is that of the ratio of the Fuel Economy carried out for the gasoline and for the hybrid towards hydrogen: this value indicates the liters of gasoline consumed by the hybrid vehicle (or by the gasoline vehicle) for each kilogram of hydrogen consumed by the FCEV at the same distance travelled.

The following results are obtained:

- ✓ the kilogram of hydrogen needed for the FCEV car, to be competitive from the point of view of consumption towards the gasoline vehicle, could cost up to 8.3-8.7 times the cost of the litre of gasoline;

- ✓ the kilogram of hydrogen needed for the FCEV car, to be competitive against the hybrid vehicle gasoline/electric, could cost at most 5.3-5.7 the cost of the litre of gasoline.

The average price of gasoline in Italy in this period (January 2021) is 1.45 €/l[76], so the price of hydrogen at the refuelling station, to be competitive against hybrid compact SUV should not exceed **7.7-8.3 €/kgH_2**, while to be competitive against gasoline compact SUV should not exceed **12.0-12.6 €/kgH_2**.

It is curious and interesting to check which scenarios addressed in this work make the price of hydrogen competitive for FCEV mobility. It must be kept in mind that the values obtained from the various scenarios are final costs, while the price to the HRS is comprised of the margin of gain, therefore cautiously it is considered the lower extreme of the range, therefore:

Target Competitive H_2 Price vs…	
Gasoline compact SUV	**12.0 €/kgH_2**
Hybrid compact SUV	**7.7 €/kgH_2**

Table 66: Target for competitiveness of hydrogen prices

Scenarios Analysed	Competitiveness vs GASOLINE	Competitiveness vs HYBRID
LOHC ARG		
LH2 ARG		
LOHC ITA		
CGH2 ITA		
LH2 ITA		

Table 67: Hydrogen prices competitiveness for the different scenarios analysed

The scenario meets the target cost limit both in its base case and in all, or almost all, other sensitivity analysis cases.

The scenario remains within the target cost limits for the base case and for many other sensitivity analysis cases.

The base case scenario provides a final cost that exceeds the target, however in several optimistic cases the sensitivity analysis remains below it.

In general, the scenario does not meet the target that would make hydrogen competitive, except for some sporadic very optimistic case of sensitivity analysis.

The scenario is still far from being able to offer a competitive price, both in its basic case but also in the most optimistic cases of sensitivity analysis.

In terms of consumption, on the market segment of compact SUVs, a FCEV is competitive on gasoline models, in virtually all scenarios studied, especially for the LOHC ARG scenario.

By contrast, to be competitive on hybrid gasoline/electric model there is still a way to go: lower production, storage and transport costs are needed.

Hydrogen is at the beginning of technology's development: it is estimated that an increase in economies of scale and the exploitation of renewable resources will lead to the creation of a virtuous circle which would in turn lead to a progressive increase in production, distribution and demand and consequently to a further significant cost reduction, also with regard to the market price of FCEVs, still very high nowadays.

It should always be stressed that a support should also be provided by a general mentality aimed at clean energy, which translates into government incentives. The path of hydrogen green is traced, now it must be followed.

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