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IMAGHyNE French hydrogen valley

Tecno-economic feasibility study for industrial production and transportation of green hydrogen between Auvergne-Rhône-Alpes and Piemonte

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I would like to thank my professor and mentor Massimo Santarelli for the opportunity to work and study a pivotal project for our community and for trusting me in lay down the initial analysis for future studies on this subject.
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Abstract

The development of green and low carbon hydrogen supply chain is becoming crucial and many energy-intensive industries are interested in swapping from Steam Methane Reforming (SMR) to hydrogen electrolysers. These industries vary from the transport sector to the methanol production, glass industry, semiconductors sector and to generate high temperature for steel industries. A techno-economic feasibility study is presented for the industrial production and transportation of hydrogen between the Auvergne-Rhône-Alpes region in France and the Piemonte region in Italy, under the premises of IMAGHyNE, a new hydrogen valley supported by the EU.

The core analysis of the study revolves around the evaluation of the hydrogen production capacity and costs, introducing then some hypotheses regarding the trade of hydrogen between the two countries. Essential is the use of the Levelized Cost of Hydrogen (LCOH) and the Levelized Cost of Hydrogen for Transport (LCOH-T), metrics that are essential in assessing the economic feasibility of hydrogen production and its subsequent transportation. The methodology involves detailed modelling of various scenarios, incorporating parameters such as CAPEX, OPEX, WACC, capacity factors and energy prices. Since the plants involved are 3 in Italy and 5 in France, different electricity spot market prices are considered, along with some PPA green contracts. Some plants are indeed self-sufficient with the aid of on-site PV plants or other RES, relying on the grid to reach the right volume of production. The transportation is studied with some preliminary hypotheses, assuming a standard trip between Lyon and Turin and with the final comparison between three different technologies: Compressed Gas Hydrogen (CGH2), Liquefied Hydrogen (LH2) and Liquid Organic Hydrogen Carriers (LOHC). Preliminarily, the volume of green hydrogen produced by the 8 plants and available for trade is not known, even though each one of them is confirmed that will produce H2 for itself or for associated industries. Therefore, 4 scenarios of hydrogen volume available are implemented and studied alongside the three technologies.

Results indicate that the economic feasibility of hydrogen production and transport varies significantly with technology, energy supply agreement and electrolyser's size. The LCOH analysis reveals low competitive costs, with values ranging between 5€ to 7€ per kg of hydrogen for France and between 7€ and 10€ for Italy. This disparity is due to smaller Italian plants and higher electricity prices in the Italian market. The competitiveness of green hydrogen is currently low for the European market since the average EU price of hydrogen produced via Natural Gas was 2.67€/kg in 2021. Finally, a trade among the two regions between 400 and 2,600 tonnes of hydrogen per year would be possible. The higher initial investments for LH2 are not completely appealing for this study due to the short distance, meanwhile the LOHC and CGH2 show similar results, with a best-case scenario of 30% of hydrogen availability that achieve respectively an average transport cost of 3.2€ and 3.6€ per kg.

Giving the elevate industrialisation of both regions these projects will help decarbonise the industries, with 8,873 tonnes of green and low carbon hydrogen produced yearly between the two regions. The IMAGHyNE project is expected to last until 2029 and this work contributes to lay down the basis for the ongoing analysis on hydrogen infrastructure at a regional level and cooperation between nations.

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Glossary

AEM: Anion Exchange Membrane electrolyser
CAPEX: Capital Expenditure
CF: Capacity Factor
CGH2: Compressed Gas Hydrogen
DCF: Discounted Cash Flow
DSO: Distribution System Operator
ENTSOE: European Network of Transmission System Operators for Electricity
HRS: Hydrogen Refuelling Station
IVA: Imposta sul Valore Aggiunto (equal to VAT)
LH2: Liquefied Hydrogen
LNG: Liquefied Natural Gas
LOHC: Liquid Organic Hydrogen Carriers
LCOH: Levelized Cost Of Hydrogen
LCOH-T: Levelized Cost Of Hydrogen for Transport
NPV: Net Present Value
O&M: Operation and Maintenance
OPEX: Operational Expenditure
PEM: Proton Exchange Membrane electrolyser
PNRR: Piano Nazionale di Ripresa e Resilienza
PPA: Power Purchase Agreement
PUN: Prezzo Unico Nazionale
PV: Photovoltaic
RES: Renewable Energy System
SMR: Steam Methane Reforming
TSO: Transmission System Operator
TVA: Taxe sur la Valeur Ajoutée (equal to VAT)
VAT: Value Added Tax
WACC: Weighted Average Cost of Capital

1. Introduction

1.1 General H2 introduction and benchmark

Hydrogen is the most abundant element in the universe and it has been the focus of intensive research and development. Even though it is a gas that it is already well known in the heavy industry sector, it is essential to study new ways to produce it, in order to decarbonise and lower the CO2 emission and carbon footprint of these industries. Hydrogen is in fact increasingly viewed as a key component in the transition to a low-carbon energy system and to use it as a new green fuel. Hydrogen's energy content is significant since it has nearly three times the energy density per unit mass compared to traditional fossil fuels like gasoline. Despite its abundance, hydrogen does not exist in free form in nature and must be extracted from compounds, primarily water and hydrocarbons.

The process of extracting hydrogen, commonly referred to as hydrogen production, can be achieved through several methods:

The first method is Steam Methane Reforming (SMR) and it is the most common method for producing hydrogen today, accounting for most of the global hydrogen production. This process involves reacting methane (CH_4) with steam at high temperatures to produce hydrogen and carbon dioxide (CO_2). While SMR is cost-effective and widely implemented, it is carbon-intensive, leading to the designation of this hydrogen as "Grey Hydrogen". When Carbon Capture, Utilization, and Storage (CCUS) technologies are integrated into the SMR process to capture and store the CO_2 emissions, the resultant hydrogen is referred to as "Blue Hydrogen" that has a lower environmental impact. Secondly, electrolysis is the process of using electricity to split water into hydrogen and oxygen. This method, when powered by renewable energy sources, produces what is known as "Green Hydrogen" and it is the most sustainable and environmentally friendly form of hydrogen production as it does not produce carbon emissions. The electrolyser technologies primarily used include alkaline electrolysis and proton exchange membrane (PEM) electrolysis. Both technologies have seen significant advancements and cost reductions, although the widespread adoption of electrolysis is still limited by the availability of inexpensive renewable electricity. It is important to mention that electrolysed hydrogen can be also produced by nuclear generated electricity, assigning the label "Pink Hydrogen". Another method can be the production through some by-product of industrial processes, such as chlor-alkali electrolysis in the chemical industry. This hydrogen is often referred to as "by-product Hydrogen" and can be captured and utilized instead of being vented into the atmosphere. It is cost effective, although its availability is dependent on the scale and nature of the primary industrial process. An already developed alternative can be also the production of hydrogen via methane pyrolysis, that splits methane into hydrogen and solid carbon compounds, supplied by electrical energy and therefore it can be combined with renewable energy production. In this case the label is "Turquoise Hydrogen". Lastly, some newer methods are under development. For instance, high-temperature electrolysis using solid oxide electrolyser cells (SOECs) and biomass gasification represent some promising routes.

The different methods of production are present worldwide differently, most of the hydrogen is produced from non-renewable sources and less than 1% of the production derived from green solutions (in 2022). The current situation is well explained by the following graph [1]:

[1] IEA. *Global Hydrogen Review 2023*. Paris: International Energy Agency, 2023.

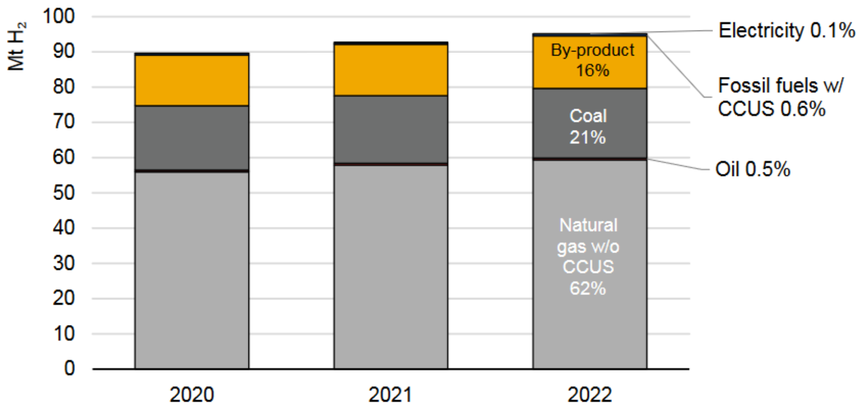

Figure 1.1 – World hydrogen production divided by technology (CCUS = Carbon Capture, Utilisation and Storage).

Finally, it is essential to visualise the comparison between the various hydrogen production methods on the base of price, using the LCOH parameter. The Levelized Cost Of Hydrogen, as it will be explained further in the next paragraphs, is an essential meter that can be used to compare the price in Euro per kilogram of hydrogen (€/kg) [2].

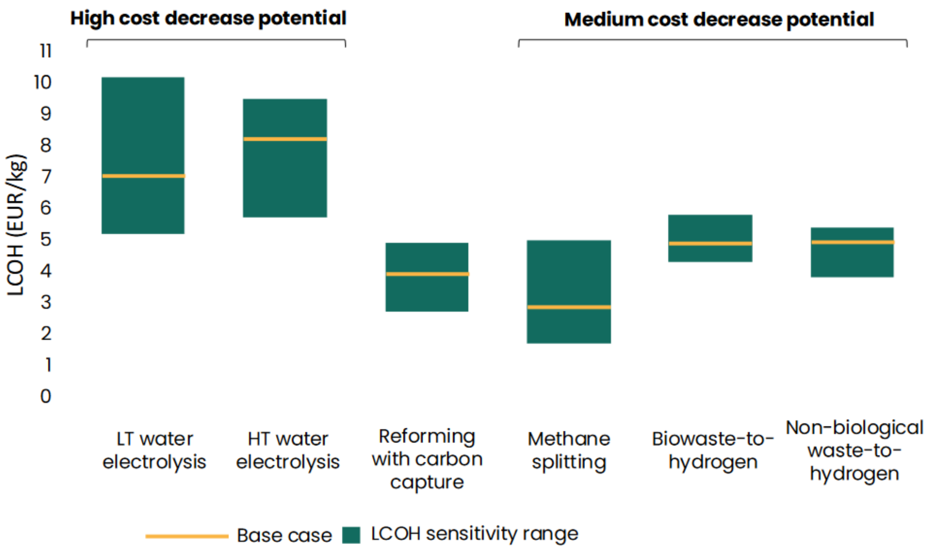

Figure 1.2 – Range of LCOH using sensitivity assumption for 2023.

The low and high temperature electrolysing processes have a high cost decrease potential, even though for now their LCOH is double the price of the SMR processes. This method is not expected to decrease further because it is a well-established technology, meanwhile the others have much more margin of improvement with researches, tests, and experience.

1.2 Hydrogen production and industrial uses

Hydrogen has emerged as a pivotal element in the transition towards sustainable energy, with its production methods and applications being critical to its role in a decarbonized future. However, hydrogen's versatility extends beyond its use in hydrogen fuel cell vehicles to significant applications in heavy industry. The main sectors are the production of directly reduced irons (DRI), ammonia, methanol, flat glass, semiconductors and hydrogen intensive use for high

[2] Hydrogen Europe. Clean Hydrogen Production Pathways Report 2024. June 2024.

temperatures for the steel industry. The traditional industries and refineries are the principal hydrogen users and their decarbonisation highly depends on the grade and origin of the hydrogen involved.

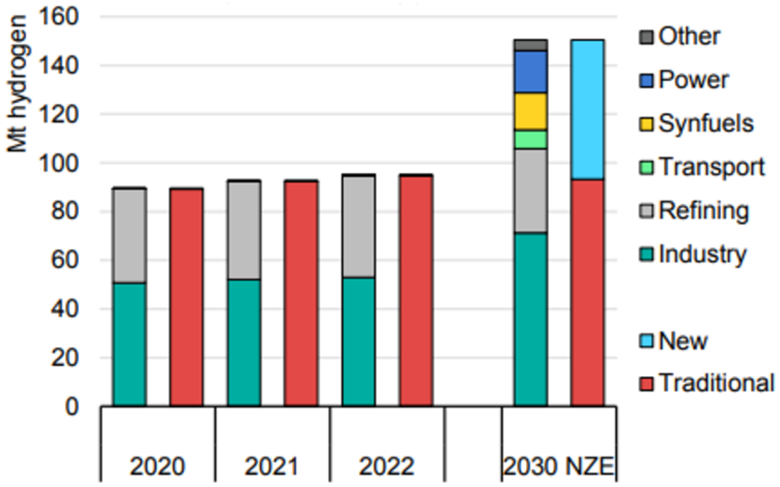

Figure 1.3 – Hydrogen use by sector 2020-2030 globally, with Net Zero Emission scenario.

Globally, the production and consumption of hydrogen have seen a significant increase. As of 2022, global hydrogen demand grew from 92 to 95 million tonnes (Mt), with Europe consuming about 8% of this total (7.6 Mt). As it can be seen from the previous graph, the production, being mainly from steam methane reforming (SMR), is mainly focused for the refining and heavy industry, accounting for 81% of the total demand [1].

In Europe, the hydrogen production landscape is evolving rapidly, driven by ambitious climate targets and substantial investments in clean hydrogen projects. The various demands for each European country are shown in the following plot:

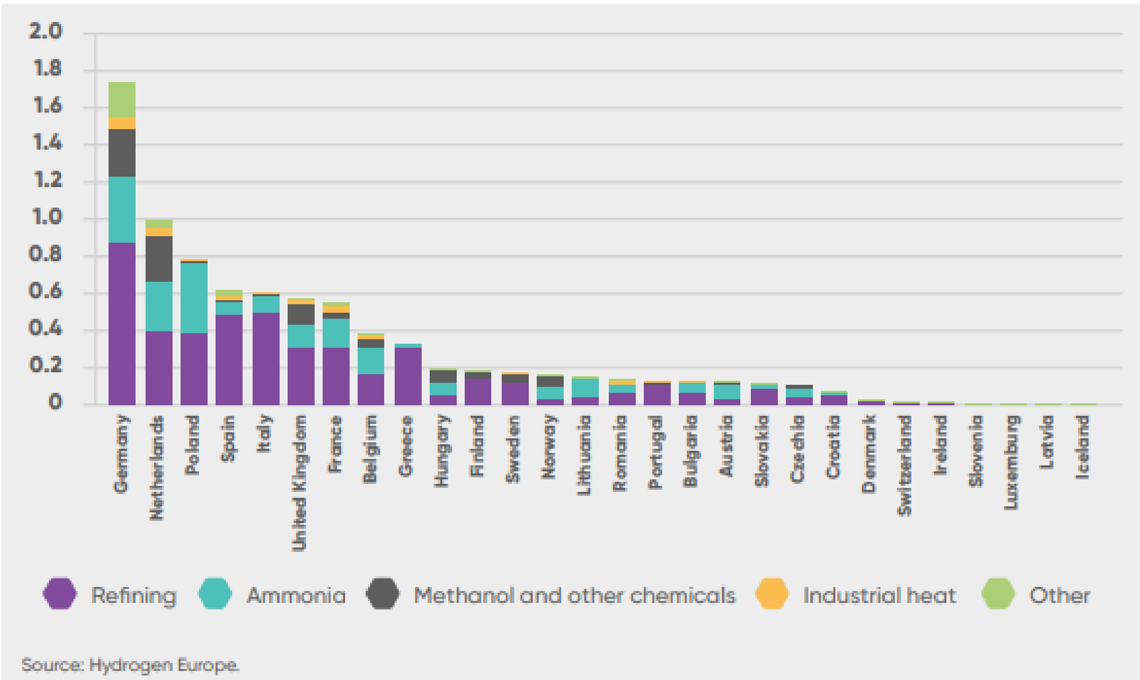

Figure 1.4 – Hydrogen demand in Europe in 2022 by country and end-use (Mt per year).

[1] IEA. *Global Hydrogen Review 2023*. Paris: International Energy Agency, 2023.

France, a notable player in ammonia production, is investing heavily in green hydrogen to meet its industrial demands. Similarly, Italy is focusing on enhancing its hydrogen infrastructure to support industrial applications and reduce its carbon footprint. These countries are integral to the European Union's (EU) goal of achieving 42% renewable hydrogen consumption in industrial applications by 2030 [3].

Lastly, the production of hydrogen in Europe and worldwide can be differentiated in 3 categories and it depends on the related industry:

- Captive dedicated H2 production: In this case the production and consumption of hydrogen are closely related. Companies invest in steam reforming or fuel cell systems for H2 production and on-site use.
- Merchant dedicated H2 production: production is not integrated with end use in this case, but sales agreements are made and the customer industry buys hydrogen from an external manufacturer that uses transport by road or local hydrogen exchange networks.
- By-product H2: in this case, industries that produce hydrogen as a waste product, can sell it or use it in combined cycles to produce thermal or electrical energy.

In this analysis, different industries that decided to supply their own hydrogen demand with the construction of electrolysers, the first category will be analysed with the captive dedicated hydrogen production [4].

1.3 Piemonte and in Auvergne-Rhone-Alpes energy mix

Piemonte, a region in Northern Italy, has a substantial energy production infrastructure with a focus on renewable energy sources. As of 2023, the region boasts nearly 11 GW of gross installed power capacity. This capacity is distributed among various sources, including thermal power plants (approximately 5 GW, with 400 MW fuelled by biomass), hydroelectric plants (35.6% of the total capacity), and photovoltaic (PV) systems (18.3%). The PV capacity is increasing by about 200 MW annually.

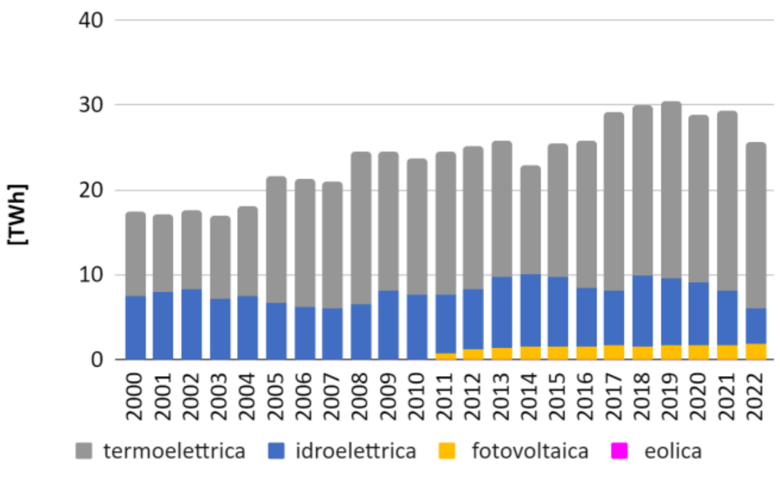

Figure 1.5 - Piemonte energy mix up to 2022. From TERNA

[3] Hydrogen Europe. *Clean Hydrogen Monitor 2023*. October 2023.
[4] IEA. Hydrogen in North-Western Europe. Paris: International Energy Agency, 2023.

In 2022, Piemonte produced 4.1 TWh of net energy from hydroelectric sources, a significant decline from the 2018 production levels. This drop is largely attributed to reduced precipitation and severe summer droughts. Despite these challenges, the region maintains a stable electricity demand of around 25 TWh per year, with renewable energy sources covering 30% of this demand in 2022. The reduced contribution from hydroelectric power due to climatic conditions significantly influenced this percentage. The region's hydroelectric power infrastructure has remained relatively stable over recent years, although it has incorporated numerous small-scale "micro-hydro" plants over the past 15 years. These small-scale installations contribute to the overall hydroelectric capacity, which is already extensively utilized to manage thermal power consumption through calibrated pumping and production actions. This fine-tuned regulation allows hydroelectric plants to produce energy during peak hours, thereby reducing greenhouse gas emissions. However, their potential for green hydrogen production is limited and of marginal utility [5].

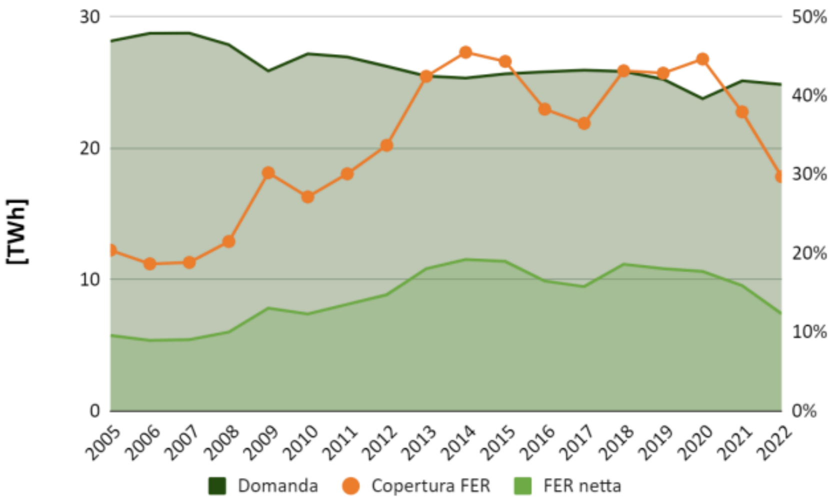

Figure 1.6 - Piemonte energy demand, percentage of RES cover and TWh of renewable energy produced. TERNA

France on the other hand, is well-known for its Nuclear fleet and for the consequently low electricity prices. This carbon neutral thermal power is mainly used as a base load response for the electricity demand of the country, regulated then by renewables, storage systems and conventional thermal power plants. The Auvergne-Rhone-Alpes region is covered by two Nuclear power plants in Saint-Albain and in Bugey, with a combined nominal power of 6.25 GW. Regarding the renewable energy production, the region can rely on a robust dams' infrastructure and is the greatest region for hydroelectric power generation, with an installed capacity of 11.45 GW (2021) [6] and a yearly energy production for 2022 of 18,660 GWh. It is therefore essential to underline the difference in hydroelectric energy generation between the two regions, being that the French region produces almost five times the amount of Piemonte. A rapid growth can also be seen in the other RES, with wind, PV and biogas application throughout the region [7]. In the following figure the different values of energy produced during 2022 from various sources, being mainly the Nuclear and thermal fleet, the hydroelectric plants and the other renewable sources:

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[5] Regione Piemonte. "Rapporto statistico sull'energia." Sviluppo energetico sostenibile. Accessed June 2024.
[6] France Hydro Electricité. "Chiffres clés." Last modified 2023.
[7] Observatoire régional climat air énergie Auvergne-Rhône-Alpes. "La production d'énergie en Auvergne-Rhône-Alpes." Last modified December 2023.

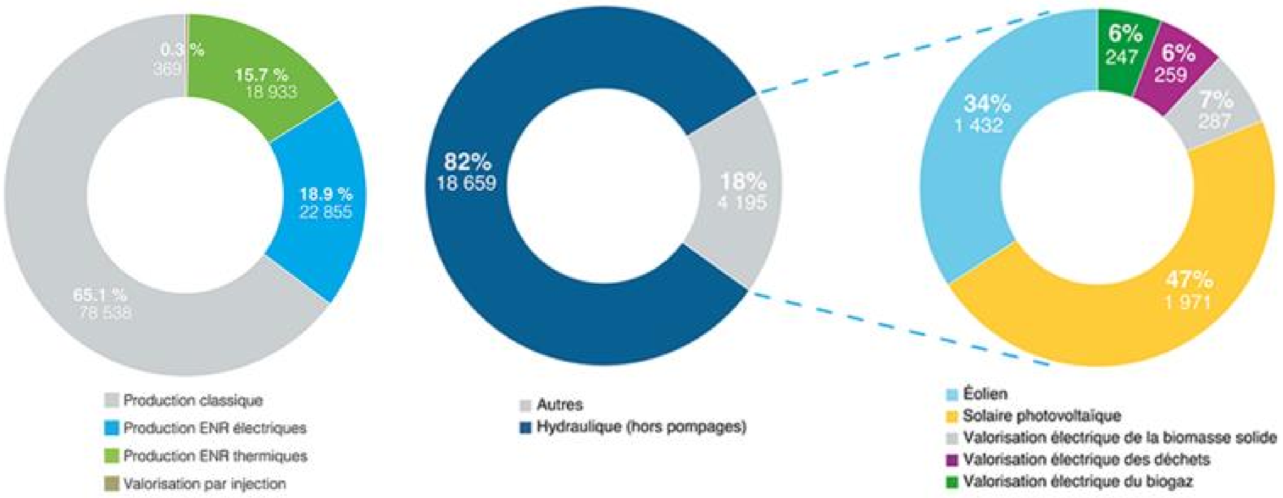

Figure 1.7 – The energy mix for Auvergne-Rhone-Alpes for 2022 with energy produced (GWh) and percentage values

Lastly, a great difference between the two whole countries, is the abundance of electrical energy produced. It can be easily calculated that between 2000 and 2020 the net exchange of energy between France and Italy is almost of 300 TWh. France is therefore exporting on average 14 TWh of electrical energy per year to Italy [8].

1.4 Current hydrogen European network and transport benchmark

One of the significant challenges facing the hydrogen economy is its transport and storage. Different hydrogen transport alternatives are already present and their advantages and disadvantages will be expanded in the following, extracted from the IREA Hydrogen Trade paper [9]. The main different carrier players are:

- Ammonia as a H2 carrier.
- Liquid Hydrogen.
- Liquid Organic Hydrogen Carriers (LOHCs)
- Compressed Gas Hydrogen.

For starter, Ammonia (NH_3) is a well-established chemical commodity produced on a large scale globally. It can be used as a hydrogen carrier and it presents several advantages. Firstly, is already produced and traded extensively worldwide, which means that the infrastructure for its production, storage, and transportation is largely in place, reducing therefore the initial investment and the R&D process. The high energy density and hydrogen content of ammonia make it an efficient carrier, since it can contain about 17.6% hydrogen by weight, which allows for the transportation of large quantities of hydrogen in a relatively small volume. Additionally, it can be easily liquefied under moderate pressure, making its storage and transport more manageable compared to gaseous hydrogen. Despite these advantages, ammonia is toxic and corrosive element, posing significant handling and safety challenges. The synthesis of ammonia is energy-

[8] IEA. "Electricity Net Exports in France, 2000-2020." Paris: International Energy Agency, 2022.
[9] International Renewable Energy Agency. "International Trade and Green Hydrogen: Supporting the Global Transition to a Low-Carbon Economy." December 2023.

intensive, requiring high temperatures and pressures, which can offset some of the environmental benefits. Moreover, converting ammonia back into hydrogen involves high energy consumption, especially if the hydrogen needs to be used in applications that require high purity. This reconversion process typically requires temperatures up to 900°C, further increasing energy demands.

Liquid hydrogen (LH_2) offers another viable option for transporting hydrogen. One of the primary advantages of liquid hydrogen is its limited energy consumption for regasification. When hydrogen is liquefied, it can be stored and transported at a very low temperature (around -253°C), which reduces the volume significantly compared to its gaseous state which make it easier to handle large quantities of hydrogen. It does not require a purification system at the destination, simplifying the logistics of transport and delivery. The process of liquefaction is already a commercial technology and it is well established in the industry. One of the most significant issues is its very low volumetric energy density, which necessitates large storage volumes. The liquefaction process is highly energy-intensive, resulting in high energy losses and low efficiency due to the cryogenic temperatures required to maintain it in a liquid state. These temperatures also lead to high equipment costs, increasing the capital investment cost.

Liquid Organic Hydrogen Carriers (LOHCs) represent a relatively new and innovative method for hydrogen transport. LOHCs can be transported using existing infrastructure, which makes them suitable for multi-modal transport, including road, rail, and maritime. This advantage is particularly significant in Europe, where diverse transport networks are already in place. LOHCs have a low capital cost for all steps involved in the transport process, and they can be easily stored under ambient conditions without the need for high pressures or cryogenic temperatures. However, the dehydrogenation process requires high amount of energy, that can negate some of the energy savings from the ease of transport. It requires also further purification of the hydrogen produced, which adds complexity and cost to the process. Only a small percentage (between 4% and 7%) of the weight of the carrier is hydrogen, which means that large quantities of the carrier liquid are required to transport significant amounts of hydrogen.

Transporting hydrogen by compressing it and using gas pipelines is another method that leverages existing infrastructure. This approach is already proven at a commercial scale, and many existing natural gas pipelines can potentially be repurposed to carry hydrogen, which significantly reduces the need for new infrastructure investments. Pipelines also provide a carbon-free method of transporting hydrogen over long distances, contributing to the reduction of greenhouse gas emissions. However, storage in specific types of reservoirs (such as natural caves) can lead to losses and contamination. The materials suitable for hydrogen are not already present in NG pipelines and for this reason many pipelines need to be refurbished and retrofitted. This technology implementation merely depends on the presence of an already built infrastructure or an easy geomorphology of the transition area, which will vary considerably the capital investment needed.

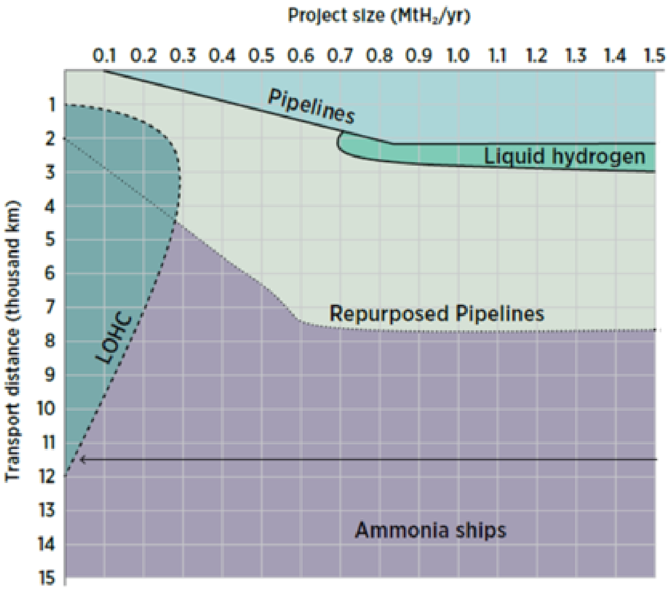

Figure 1.8 – Transport technologies comparison based on distance and H2 volume traded.

As it can be evaluated from the previous figure, a separation between the different transportation technologies based on the transport distance (Y Axis) and the volume of hydrogen traded (X Axis) can be carried out. The Liquid Hydrogen has a marginal role, in contrast to the ammonia shipping that seems the most attractive combination for high distance trades. On the other hand, for short distances, the best solution might be the combination of pipelines, both new and repurposed. The feasibility of the pipeline increase with the volume of hydrogen traded per year and it is limited to a moderate distance. Lastly, the LOHC carriers, even if they are new to the industry, they can be competitive for low volume traded but they can cover longer distances [10].

In Europe gas pipelines represent the most widely used method for hydrogen transport in Europe, particularly in regions with established natural gas infrastructure. Countries like Germany and the Netherlands are actively exploring the repurposing of their natural gas pipelines for hydrogen transport as part of their broader hydrogen strategies.

Looking to the future, the European Union's commitment to achieving net-zero emissions by 2050 is driving significant investment in hydrogen infrastructure, most likely being a diversified approach, using different methods based on regional strengths and infrastructure. Ammonia may play a more significant role in maritime transport and industrial applications, while LOHCs could become more prevalent for flexible, multi-modal transport. The expansion and retrofitting of gas pipelines will be crucial for large-scale hydrogen distribution, particularly in countries with extensive existing networks.

The IMAGHyNE project will create the conditions for accelerating the implementation of a first ambitious regional pipeline network to connect to the European backbone under development. The detailed feasibility study that will be conducted to implement a pipeline between Saint-Fons, Lyon-Saint-Exupéry airport and the HY-FEN pipeline route will pave the way for the construction and development of a regional distribution network. This will allow the transport of up to 80,000 tons of hydrogen per year, equivalent to the production of 400 MW of electrolysis.

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[10] International Renewable Energy Agency. "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review and Cost Analysis." International Renewable Energy Agency, accessed June, 2024.

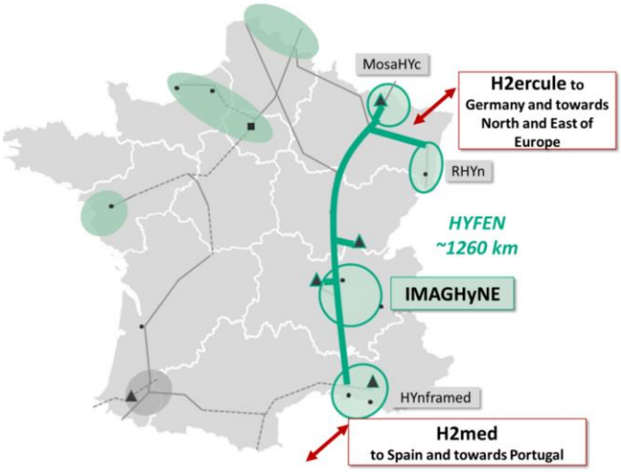

Figure 1.9 -Hydrogen connection infrastructure with the implementation of the IMAGHyNE project.

It is therefore clear that the intention of the project is to enable Europe to develop a dense H2 exchange network, using existing natural gas pipelines [1].

1.5 IMAGHyNE project

The IMAGHyNE project, presented the 12th of February 2024 in Lyon [11], aims to significantly accelerate the deployment of hydrogen technologies within the Auvergne-Rhône-Alpes region. The project focuses on creating a comprehensive and integrated hydrogen ecosystem, which will connect various hydrogen hubs across the region and beyond. The main goals include [12]:

- Establishing 57 MW of electrolysis capacity to produce 8,000 tons per year of low-carbon and renewable hydrogen.
- Implementing a flexible hydrogen supply chain, which includes 20 high-capacity tube-trailers and a multi-tonne hydrogen storage system in an underground salt cavern.
- Setting up 13 multi-modal hydrogen refuelling stations to support the trans-European transport network and decarbonize public transport fleets.
- Deploying 203 on-road fuel cell vehicles and 63 off-road fuel cell vehicles and stationary equipment to decarbonize various sectors, including agriculture, mountainous regions, and airports.
- Enhancing the overall robustness of the energy and hydrogen supply chain by integrating flexible industrial players.
- Designing an efficient multi-user hydrogen system and preparing for large-scale deployment.
- Actively promoting and sharing the project results with technical and institutional stakeholders, as well as the general public, to foster the adoption of hydrogen technologies across Europe. For these reasons many research entities are included in this project such as Politecnico di Torino.

[11] Conseil régional Auvergne-Rhône-Alpes. "La Région Présente IMAGHyNE: Le Projet de Grande Vallée Hydrogène." Last modified February 14, 2024.

[12] IMAGHYNE. *Proposal Template Part B: Technical Description*. Investment to Maximise the Ambition for Green Hydrogen in Europe, 2023.

By achieving these objectives, IMAGHyNE aims to lay the foundation for a sustainable hydrogen economy that integrates seamlessly into the broader energy system, thereby addressing the needs of high-emission sectors and enhancing regional, national, and European hydrogen initiatives. Furthermore, the project will facilitate the replication and expansion of hydrogen valleys across Europe, such as HEAVENN, Green Hysland, TH2ICINO, and the North Adriatic H2 Valley, by leveraging the Auvergne-Rhône-Alpes region's strategic position. This will help connect different European regions with hydrogen infrastructure, thereby fostering a pan-European hydrogen network that supports the REPowerEU objective of doubling the number of hydrogen valleys by 2025.

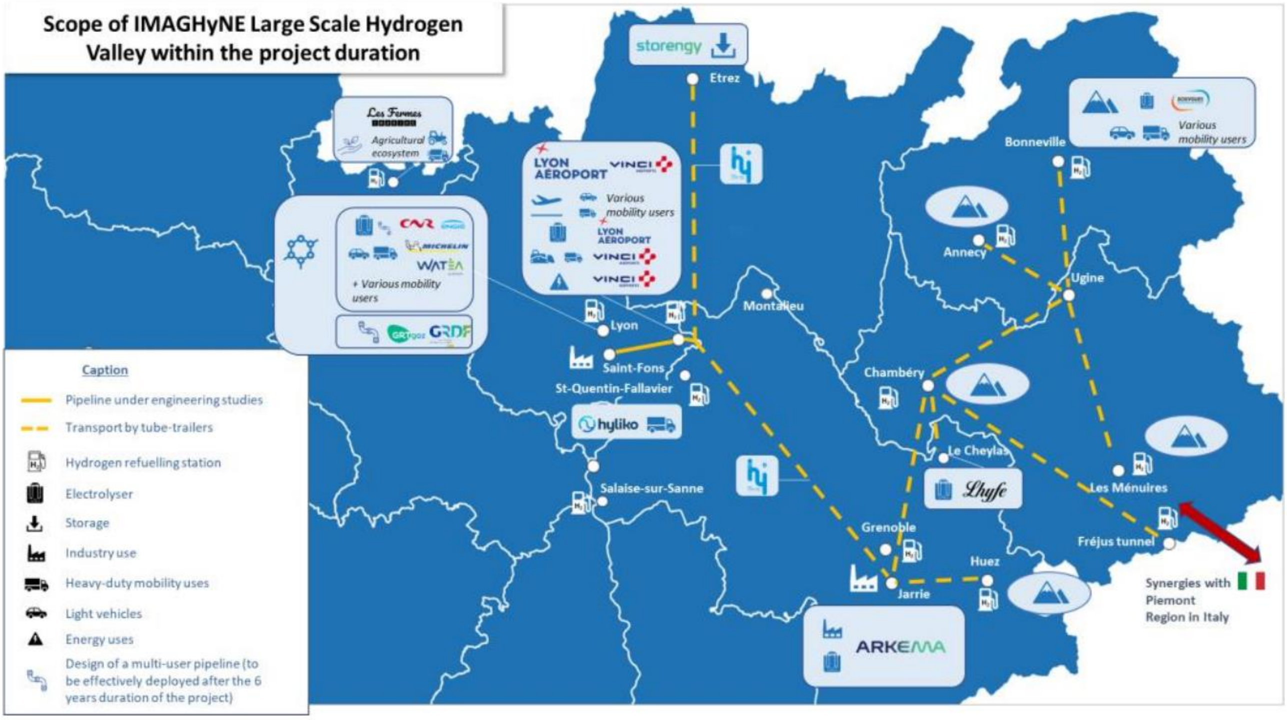

Figure 1.10 - IMAGHyNE strategic map with electrolysers, storage facilities, HRS, pipelines and trailers network to link different industries.

A smaller preliminary project is in development in Piemonte called HyPIE (Hydrogen Valley in Piemonte) [13]. This project aims to bolster the EU's decarbonization strategy by promoting hydrogen production, storage, and usage across various sectors [14]. The project's objectives include:

- Establishing hydrogen refueling stations and electrolyzers (about 5MW) to support green hydrogen production and distribution.
- Enhancing hydrogen applications in transportation, industrial processes, and energy production to replace fossil fuels.
- Leveraging the region's robust research ecosystem involving universities and technological hubs to advance hydrogen technologies.
- Connecting with other hydrogen valleys across Europe, enhancing collaboration, and ensuring the replicability of the model in other regions.
- Conducting awareness campaigns to increase public understanding and acceptance of hydrogen technologies.

[13] HYPIE. *Hydrogen Valley in Piemonte*. 2023.
[14] Il Sole 24 Ore "Idrogeno Verde: Gattinara Ospiterà l'Impianto Finanziato con Fondi PNRR." May 6, 2024.

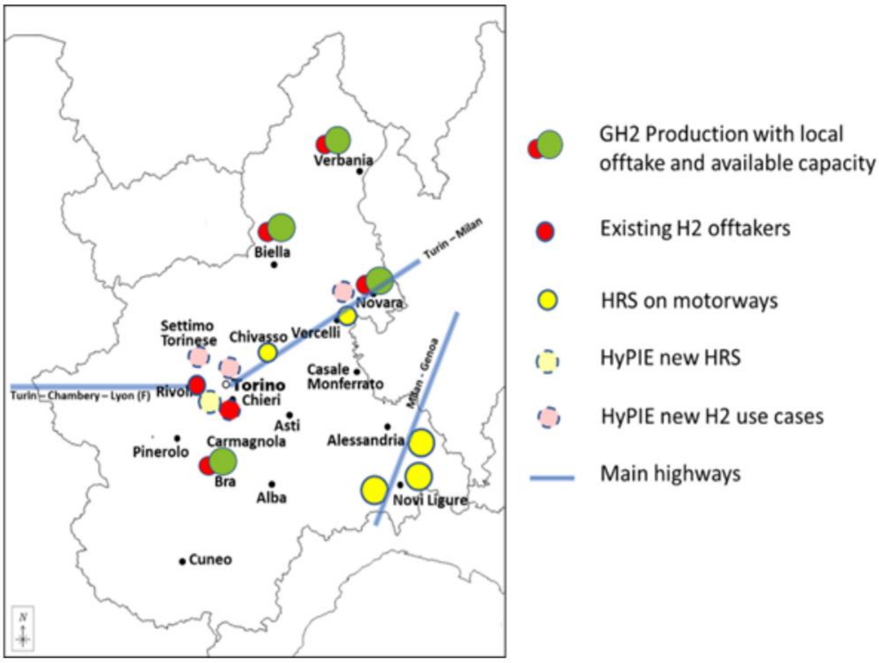

Figure 1.11 - HyPIE strategic map with electrolysers, offtakers, HRS and main mobility paths.

It is clear how the IMAGHyNE and the HyPIE projects can benefit from each other by sharing knowledge, experience and ultimately trading H2 for industrial purposes. As the following map can easily describe, the implementation of these two Hydrogen Valleys can be of essential importance for the trade and exchange of hydrogen between Mediterranean regions, creating a corridor of H2 production sites and supplying many high energy intensive industries.

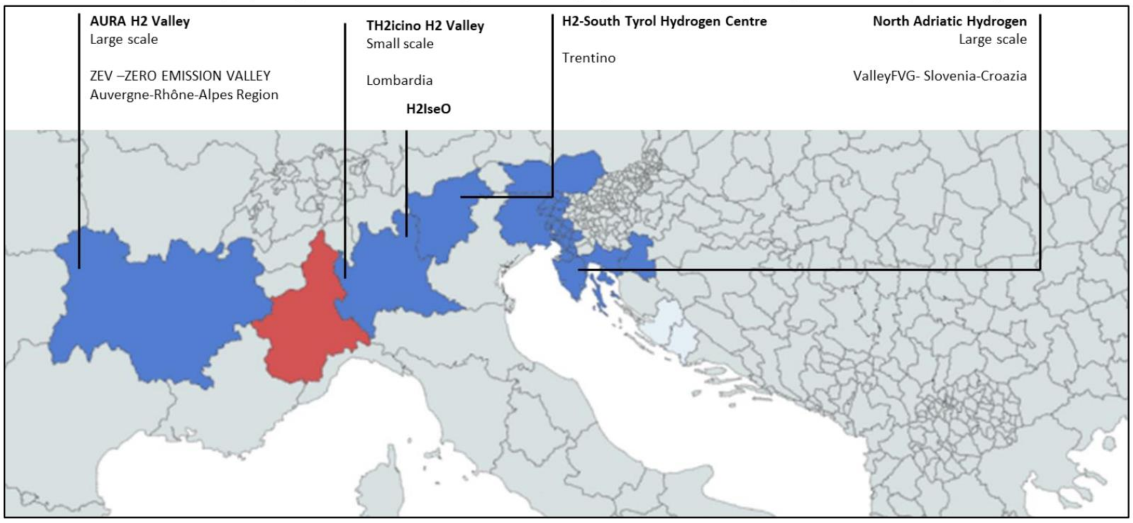

Figure 1.12 - France, Italy, Slovenia and Croatia hydrogen corridor.

2. Analyses

In this second section the different analyses will be explained with the different mathematical methods and various hypotheses used. After presenting the general framework of the H2 production and usage through Europe it is essential to dive deep into the understanding of the hydrogen production in the Auvergne-Rhone-Alpes and Piemonte region and how this hydrogen can be shared and traded between France and Italy. Both production and trade will be analysed alongside with economical parameters, to measure the economic feasibility and the desirability of purchasing H2 from these producers.

2.1 Single electrolysers analysis

ELECTROLYSERS

Between the French and the Italian projects eight electrolysers are in deployment. They vary in technology, size, source of electricity and usage of H2.

The electrolysers inside France are the following:

- **Lyon electrolyser by ENGIE and CNR**: with a capacity of 15 MW is strategically located near the city center of Lyon, close to the Rhône River. It utilises renewable energy sourced directly from a hydroelectric dam operated by CNR, ensuring a consistent supply of green hydrogen. The primary purpose of this electrolyser is to support the local chemical park industries in Lyon and act as a distribution hub for hydrogen trailers dedicated to the mobility sector. It is estimated that it will produce approximately 2,200 tonnes of renewable hydrogen per year starting from the end of 2025.
- **Vinci Airport and Aéroports de Lyon**: they will deploy a 5 MW electrolyser on the Lyon-Saint Exupéry Airport site, located 30 km away from Lyon city-centre with a traffic of 11 million passengers a year. It utilises at first Power Purchase Agreement (PPA) with green certificates and a co-developed onsite solar PV plant of 3 MWp. By 2030 the solar park will reach the size of 110 MWp. The green H2 production will be dedicated to fuel H2 fuel-cells vehicles operating in the airport, ground service equipment and hydrogen backup generators. This plant will produce up to 730 tonnes of renewable hydrogen per year from the end of 2025.
- **Arkema electrolyser**: inside the Grenoble industrial hub this company will deploy a 30 MW electrolyser in Jarrie to serve on-site industrial uses to produce hydrogen peroxide and supply existing and future usages in industries and mobility in the Alpes area. As Arkema is an electro-intensive site, it already benefits from high power connection to the electricity grid, the advantages of which are described in the Impact Section. The electrolyser will therefore be supplied by low carbon electricity from the grid with an increasing share of renewable electricity from PPA contracts with green certificates. This will amount to approximatively 4,000 tonnes of low-carbon hydrogen per year from the end of 2025.
- **Lhyfe electrolyser**: alongside the Arkema project, inside the Grenoble industrial area, Lhyfe will deploy a 5 MW PEM electrolyser in Le Cheylas to decarbonise local industries and supply mobility ecosystems in the South-East of the territory, identifying several industries within 200 km that will use renewable hydrogen as a substitute for grey hydrogen and/or natural gas in their processes. The electrolyser will be supplied by renewable electricity from PPA contracts with green certificates and up to 730 tonnes of renewable hydrogen will be produced by the electrolyser from the end of 2025.

- **Bouygues Energies & Services**: inside the mountain hub a 2 MW electrolyser will be deployed in order to decarbonise on-road and off-road mountain vehicles. It will be supplied by renewable energy from PPA contracts to supply mountain partners in the North-East of the region. Several hydrogen supply paths are explored in the Alpine region. Some stakeholders will be supplied with hydrogen produced in the Grenoble and Lyon industrial and urban hubs, while others will require on-site production to promote the development of the local economy and benefit from lower hydrogen prices. This electrolyser will produce up to 290 tonnes of green H2 per year from 2025.
-

The Italian electrolysers are listed below:

- **Sarpom S.P.A.**: this oil refinery will deploy a 4 MW electrolyser in Trecate (Novara) in order to decarbonise its own industrial processes. The generation of hydrogen will be supplied by solar PV plant of 6.7 MWp that will generate sufficient energy to produce up to 600 tonnes of H2 per year from the second half of 2026.
- **FILMS S.P.A.**: with a 1 MW AEM electrolyser and a solar PV field of 1 MWp this plant in Premosello-Chiovenda (Verbania) will produce green and low carbon hydrogen for its own metallurgic processes.
- **RF Idra**: this company will produce green hydrogen for the manufacture of bricks with a 1 MW electrolyser along with a solar PV plant of 1 MWp in Gattinara (Novara).

A fourth electrolyser is programmed to be implemented in the next years in Cuneo by Alstom with a nominal power of 300 kW. However, this plant will mainly produce for internal porpoises and it will not receive national fundings, therefore it will not be included in the present study.

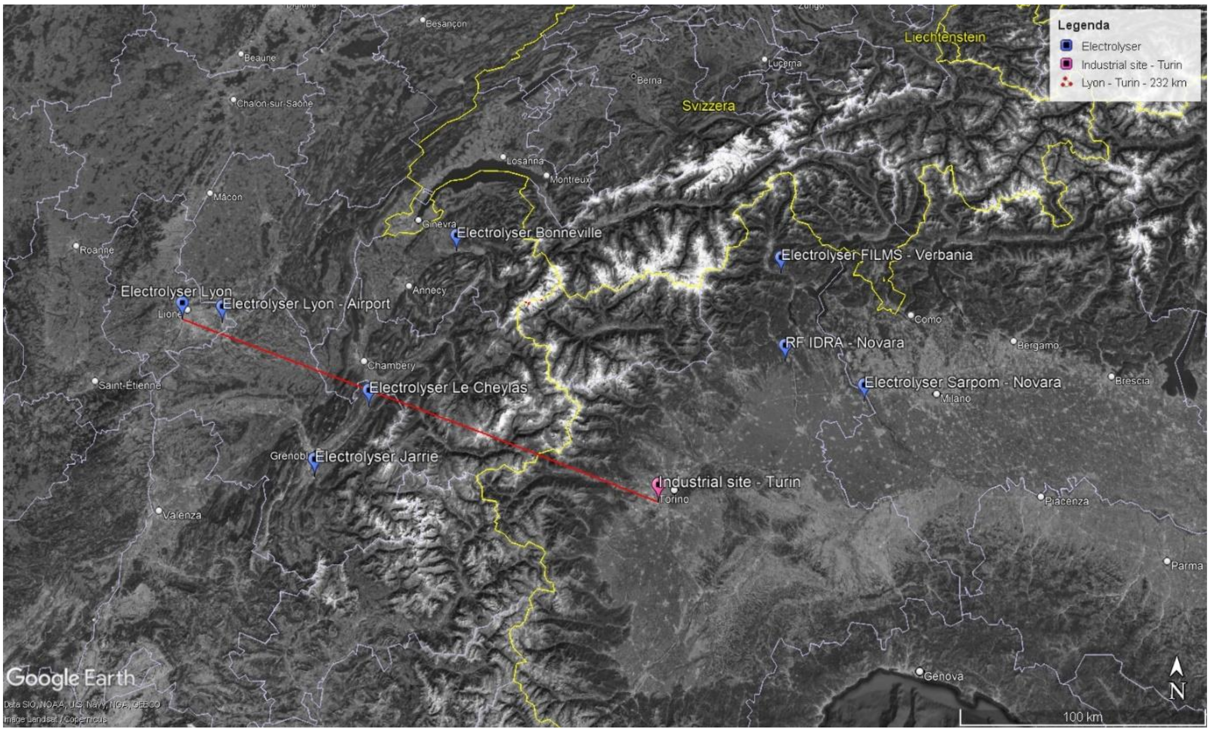

Figure 2.1 – French and Italian electrolyser mapped out geographically and aerial distance between Lyon and Turin.

SUBSIDIES AND FUNDS

French and Italian projects will receive different types of incentives. It is essential to understand how to approach the subsequent cost analysis, considering the presence or absence of funding. For a fair comparison, the same style of analysis should be adopted for both European regions.

Since all the projects in question are subsidised by European or National funds, in order to achieve more accurate results, it has been decided to include the different funding.
Regarding the IMAGHyNE project in France the total budget is estimated to be **192.164.346,25 €** and with a sum of EU funds of **20.004.308,44 €**. The single subsidies from the European Union can be gathered from the EU Funding & Tenders Portal [15]. Currently, a call for funds has been issued also by the *ADEME* (French Environment and Energy Management Agency) and the Ministry of Environment, Energy and Sea to fund projects related to hydrogen. Even though it is evident that some funds are going to be directed towards this project, the results of this call are not yet published and therefore they will not be considered in this analysis. Only the LHYFE project has received co-funding from European funds managed by the Auvergne-Rhône-Alpes region. This funding comes from the FTJ (Fond de Transition Juste), a grant available to SMEs in a small part of the Rhône and Isère territories and it amounts to approximately **€5.5 million**. Regarding the Bouygues project it is delayed and no info are yet available.
On the other hand, no direct EU funds have been set for Italy and Piemonte's hydrogen project. The only public funds available derive from the PNRR (Piano Nazionale Ripresa Resilienza) which gathers capital from the EU recovery plan and redistributes it towards various projects. The total PNRR funding for the Piedmont region for the H2 development call for proposals in decommissioned industrial areas is **€19.5 million**, divided between the three main projects in this region [16, 17, 18, 14].
In the following table it is summarised the CAPEX, public funds and electrolyser power capacity.

		MW	*Total project cost*	*Electrolyser cost*	*EU fund*	*National fund*
FRANCE	Lyon - Engie&CNR	15	26,605,610.00 €	11,928,800.00 €	2,750,000.00 €	?
	Lyon Airport	5	26,695,600.00 €	7,300,000.00 €	750,000.00 €	?
	Arkema	30	34,000,000.00 €	34,000,000.00 €	3,600,000.00 €	?
	Lhyfe	5	7,827,095.00 €	5,057,000.00 €	72,000.00 €	3,553,489.51 €*
	Bouygues	2	4,825,000.00 €	3,600,000.00 €	300,000.00 €	?
ITALY	Sarpom spa	4	16,800,000.00 €	16,800,000.00 €	- €	16,800,000.00 €
	Films spa	1	3,354,781.00 €	3,354,781.00 €	- €	1,502,000.00 €
	RF Idra srl	1	3,000,000.00 €	3,000,000.00 €	- €	1,198,000.00 €

Table 2.1 - Summarised values of electrolysing power, project Capex and EU/National funds

**The national fund for the Lhyfe electrolyser is brought from 5,5 mln € to 3,5 mln € based on the ratio of electrolyser/total project cost of 64,6%.*

2.2 LCOH Methodology and assumptions

LCOH METHOD

To introduce the methodology used for this analysis is essential to start from the definition of the LCOH method. The Levelized Cost of Hydrogen is a crucial metric used to assess the economic feasibility of hydrogen, from various production technologies. It represents the unit cost (€/kg) of

[15] European Commission. "IMAGHYNE - Horizon Europe Project." EU Funding & Tenders Portal. Accessed June, 2024.
[16] Italian Government, programmazione economica. "SARPOM." OpenCUP. Accessed June, 2024.
[17] Italian Government, programmazione economica. "FILMS." OpenCUP. Accessed June, 2024.
[18] Italian Government, programmazione economica. "RF Idra." OpenCUP. Accessed June, 2024.
[14] Il Sole 24 Ore "Idrogeno Verde: Gattinara Ospiterà l'Impianto Finanziato con Fondi PNRR." May 6, 2024.

producing H_2 over the lifespan of a production facility and it includes all CAPEX, OPEX such as maintenance and replacements and the cost of energy inputs required to produce hydrogen, that will be a crucial aspect in the next paragraphs. This metric allows stakeholders to compare the costs of different hydrogen production methods on a common basis, facilitating informed decision-making regarding investment and policy. Therefore, the LCOH provides a transparent and standardized measure to evaluate whether hydrogen production can be cost-competitive with other energy sources, including fossil fuels and renewable electricity.
It uses a DCF model, that takes into account all relevant costs and revenues over the project's lifetime. The general formula for LCOH is as follows [3]:

$$LCOH\left[\frac{€}{kg}\right]=\frac{\left(CAPEX_0+\sum_{y=1}^{n}\frac{OPEX_y+EC_y}{(1+r)^y}\right)}{\sum_{y=1}^{n}\frac{H_{2,y}}{(1+r)^y}} \tag{2.1}$$

Where:

- $CAPEX_0$ Investment expenditures in year zero.
- EC_y Energy costs in year *y*.
- $OPEX_y$ Other operational and maintenance costs in year *y*.
- $H_{2,y}$ Amount of hydrogen produced in year *y*.
- r Discount rate or WACC.
- n Lifetime of the hydrogen production system in years.

This formula ensures that all costs are appropriately accounted for over time, discounted to their present value, and then averaged over the total hydrogen production.

ENERGY COST AND ENERGY SUPPLY ANALYSIS

A critical point inside the LCOH calculation is the energy cost, which is often the most substantial ongoing expense in hydrogen production. For electrolytic hydrogen, the cost of electricity is critical. Different energy sources can vastly impact the LCOH. Variations in electricity prices, influenced by factors such as market dynamics, renewable energy penetration, and grid stability, hugely impact the result. As seen in the previous paragraphs the different plants, both in Italy and France, have chosen various types of energy feed, such as from direct solar PV plants, with PPA green contracts, from local dams and from the national grid.

For starters, to conduct a comprehensive analysis of electricity market prices for France and Italy, it is imperative to gather energy spot price for both country, which in simple terms is the grid electricity price for every hour. In order to have the most accurate results, the data from 2023 have been chosen from the ENTSOE website [20]. These Day-Ahead prices data are expressed hourly have been inserted into an Excel spreadsheet to further calculate the final prices.

Another source of renewable energy found in the project listed for this analysis is from PPA green contracts, which are agreements designed to facilitate the procurement of renewable energy directly from producers, ensuring a steady and reliable supply of green energy for the project,

[3] Hydrogen Europe. "Clean Hydrogen Monitor 2023." November, 2023.
[19] ENTSO-E. "Day-Ahead Prices." Accessed January, 2024.

usually at a fixed cost. An average price from the literature [20] [21] can be determined as **65 €/MWh** before taxes and charges. This value is merely an assumption because it depends on the single contract stipulated between the electrolysing company and the energy producer. This value will be used as a fixed electricity price for the French companies that have selected the PPA agreements and for the one electrolyser in LYON (ENGIE and CNR) that produce its own energy with the local dam on the river Rhone.

The final electricity price can be then calculated adding the service charges and taxes, both for France and Italy as follows:

- For **Italy** the charges for energy-intensive industries are around 20% of the PUN, with excise duties of approximately €4,820.00 per month. Additionally, a 22% VAT (IVA) is applied [22] [23].
- For **France** there are excise duties of €2.05/MWh for companies requiring more than 36 kVA of power, charges of 10.11% if the plant is directly connected to the TSO, and a VAT (TVA) of 20% [24].

And summarised in the following table:

	Excise	***Charge***	***Tax (IVA/TVA)***
Mean FR price	2,05 €	10,11 %	20 %
Mean IT price	4.820€/month	20 %	22 %

Table 2.2 - French and Italian service charges and taxes over grid electricity prices.

Since industries usually work with taxable capitals, it is therefore possible to neglect the VAT percentage in the following analysis.

To have a better understanding of the energy productivity of the plants that have on-site PV generation, it is essential to understand the irradiance and the amount of renewable energy produced, along with the compensation from the grid needed to guarantee a constant level of H2 production. To calculate the average daylight hours and solar irradiance for the regions of Lyon and Novara, it is possible to employ the European PVGIS tool [25]. By simulating a PV plant of 1 MW peak of power with the irradiance data of 2023 it is possible to obtain a final and reliable estimate of how much power a scalable 1 MW plant can produce. Since there are different plants in this analysis, with various PV peak powers, the final hourly energy production can be easily brought from the one of the 1 MW plant to the desired plant by simply multiplying for the right peak power. To guarantee a constant electrolysing production during the whole year and during the day, to satisfy the industry's demand, part of the energy during the day will be pulled from the grid. A hypothesis of a Capacity Factor (CF) of 0,7 has been chosen for the night production,

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[20] Martinez Alonso, A., Naval, N., Matute, G., Coosemans, T., & Yusta, J. (2023). Phasing out steam methane reformers with water electrolysis in producing renewable hydrogen and ammonia: A case study based on the Spanish energy markets. *International Journal of Hydrogen Energy*.
[21] Matute, G., Yusta, J.M., Naval, N. (2023). Techno-economic model and feasibility assessment of green hydrogen projects based on electrolysis supplied by photovoltaic PPAs. *International Journal of Hydrogen Energy*, 48(13), 5053-5068. ISSN 0360-3199.
[22] ARERA. "Oneri generali di sistema e ulteriori componenti." Accessed June, 2024.
[23] Sorgenia. "Le Accise Energia Elettrica." Accessed June, 2024.
[24] EDF. « Quelles sont les taxes applicables sur l'électricité? » Accessed June, 2024.
[25] "Photovoltaic Geographical Information System (PVGIS)." European Commission, Joint Research Centre. Accessed June, 2024.

meaning that without sun generation energy, the electrolysers will produce ad reduced capacity, in order to use fewer energy from the grid on an annual basis and exploiting at 100% the daytime. The following equations can be used to calculate the total electricity cost per year, being two summatory for every hour in one year, one for daytime and one for nighttime:

$$EC_{yearly}\ [€] = \sum_{h=1}^{n=8760} \left(\left(MW_{H2} - MW_{p-PV} \right) \cdot 1\ hour \cdot SP \right)_{h-day} + \left(MW_{H2} \cdot 1\ hour \cdot SP \cdot CF \right)_{h-night} \qquad (2.2)$$

With:

- EC_{yearly} Total energy cost per year in €.
- MW_{H2} Design power of the electrolyser in MW.
- MW_{p-PV} Design peak power of PV plant in MW.
- SP Spot price after tax and charges in €/MW.
- CF Capacity factor of 0,7.

The yearly production of hydrogen can be instead easily estimated as follows:

$$H_{2,yearly}\ [kg] = \sum_{h=1}^{n=8760} \left(MW_{H2} \cdot 1\ hour \right)_{h-day} + \left(MW_{H2} \cdot 1\ hour \cdot CF \right)_{h-night} \qquad (2.3)$$

PARAMETERS AND CALCULATIONS

To assess and evaluate the true LCOH for every plant it is essential to make various hypotheses, where information about the design, technology and use of these electrolyser are missing. The following parameters from the 2023 Clean Hydrogen Monitor [3] have been a good preliminary base for the calculation of the levelized cost of hydrogen:

Useful parameters	
WACC	6%
Maintenance	2%
CF	85%
Hour yearly	8760
Stack replacement [hours]	80,000
Stack replacement cost [%CAPEX]	35%
Stack degradation every 1000 h	0.12%
Energy consumption [kWh/kg]	52.4
H2 production [kg/MWh$_e$]	19.084

Table 2.3 - Parameters for LCOH calculation

Regarding the production of hydrogen and the CF it is essential to underline two different approaches. For the plants of Airport Lyon, RF-IDRA, FILMS and SARPOM that have onsite PV production, the H2 production and energy cost per year have to be conducted following the equations (2.2) and (2.3). For all the other plants, that have PPA agreements with local energy producers, the procedures to calculate the hydrogen production and electricity cost per year are the following:

$$EC_{yearly} = MW_{H2} \cdot CF \cdot h_{year} \cdot PPA_{price} \qquad (2.4)$$

$$H_{2,yearly} = MW_{H2} \cdot CF \cdot h_{year} \cdot H_{prod\ rate} \qquad (2.5)$$

[3] Hydrogen Europe. "Clean Hydrogen Monitor 2023." November, 2023.

With:

- h_{year} Hours in one year.
- PPA_{price} Power Purchase Agreement price [€/MWh].
- $H_{prod\ rate}$ Hydrogen production rate per MWh of electricity [kg/MWh].

The rest of the calculation can be applied to every project inside this analysis, from the baseline that the price for electricity and the production of hydrogen per year are consolidated for each electrolyser. With the assumption that the facilities are operational for 20 years the following equation can be applied to finalise the LCOH evaluation:

$$LCOH = \frac{CAPEX_0 - SUBS_0 + \sum_{y=1}^{n=20}\left(\frac{\left(OPEX_{maint} + EC_{yearly} + OPEX_{repl}\right)_y}{(1+r)^y}\right)}{\sum_{y=1}^{n=20}\left(\frac{\left(H_{2,yearly} - \frac{h_{cum,stack}}{1000h}\cdot 0{,}12\%\right)_y}{(1+r)^y}\right)} \tag{2.6}$$

With:

- $SUBS_0$ European and/or National subsidies and funds
- $OPEX_{maint}$ and $OPEX_{repl}$ are respectively the maintenance cost and the electrolyser stack replacement cost that happens only after 80,000 hours of operation at full capacity.
- $h_{cum,stack}$ are the equivalent cumulative hours of operation of the stack, multiplied by the degradation factor of 0,12% every 1000 hours. This parameter will be set to zero every time the stack is replaced.

This last formula is the final step towards the calculation of an objective parameter that can be used as a baseline for further confrontation between the different electrolysers.

2.3 LCOHT for transportation

TRANSPORT BASELINE

The transport of hydrogen involves various possibilities as introduced in section 1.4, both regarding the type of material transported and its state, as well as the means of transportation. As discussed previously, one promising system would be the use of new or refurbished pipelines dedicated to hydrogen service. This can be implemented when old natural gas pipelines can be refurbished or new pipelines can be easily built. Unfortunately, as shown by the layout of natural gas infrastructure, there are no pipelines that directly connect the two regions [26].

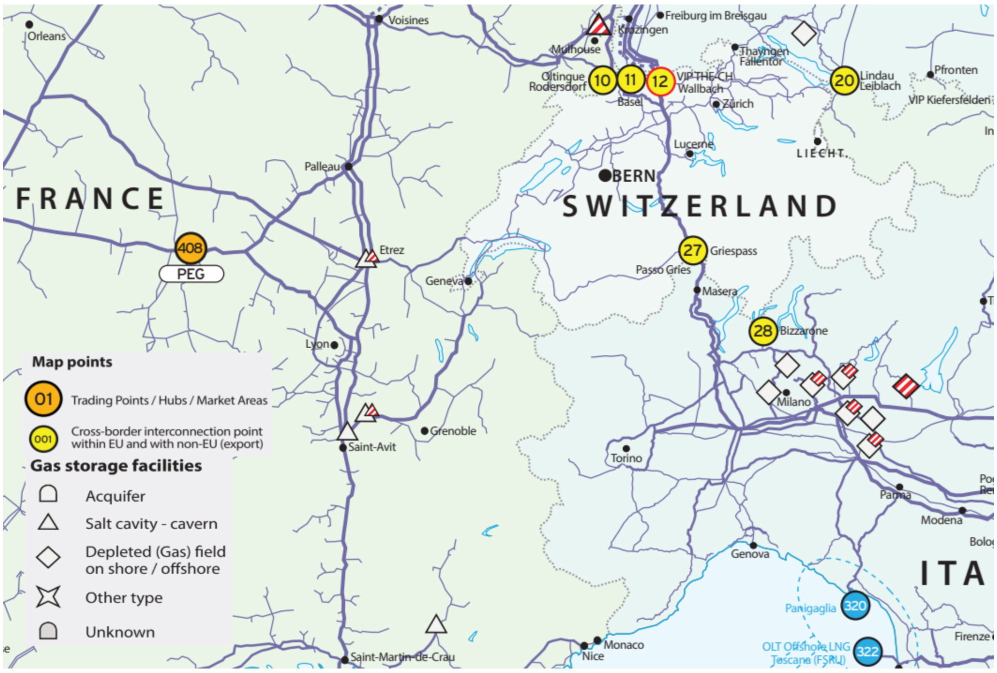

Figure 2.2 – Natural Gas pipelines' infrastructure focused onFrance-Switzerland-italy.

The construction of new ones does not appear initially feasible due to the complexity of the project, the Alps in between and most relevant the low volumes of hydrogen currently available for trade.

Given the volumes that are expected, road or rail transport emerges as a viable alternative. Various transport methodologies can be considered and this analysis will focus on the comparison between three different methods:

- Compressed gas hydrogen
- Liquid hydrogen
- Liquid Organic Hydrogen Carriers (LOHCs)

These three transportation technologies can be easily compared to each other via the use of the same system employed before, the LCOH calculation method.

LCOH-T

To calculate a truthful parameter that can be used as a comparison value between scenarios and production plants a similar method to LCOH is deployed. In this way, it is possible to evaluate the most affordable and most suitable scenario. The scenarios are identified by the various hydrogen production site, the availability of hydrogen in the market and the type of transportation. It is expected that a larger production facility will have a lower levelized cost of

[26] NTSOG. "Transmission Capacity Map 2021." Accessed June, 2024.

hydrogen thanks to the scalability and the higher production rate. Since there is no current evidence on how much hydrogen each industry will require locally from the associated electrolyser it is not possible to estimate with precision the quantity of H2 available for trade and transportation between Italy and France, that will depend also on the demand not yet clear. Therefore, as will be shown later, different scenarios will be hypothesized, in order to have a general view of how different volumes will impact the cost for transportation. It is expected that the price for transportation will decrease with the increase of hydrogen volume available for trade. Finally, the different transportation will be characterised by different CAPEX and OPEX, since the various technologies and the multiple parameters involved.
The general equation is:

$$LCOHT\ \left[\frac{€}{kg}\right] = \frac{\left(CAPEX_0 + \sum_{y=1}^{n} \frac{OPEX_y + EC_y}{(1+r)^y}\right)}{\sum_{y=1}^{n} \frac{H_{2,t,y}}{(1+r)^y}} \quad (2.7)$$

With every term similarly explained as in equation (2.1) with the exception of $H_{2,t,y}$ which is referring to the volume of hydrogen in kilograms available for trade in a single year. Different parameters and formulas are present inside each term, differently from the previous case. It is of relevance to calculate firstly the number of trucks and number of trips in a year that are needed to fulfil the exchange and trade of the hydrogen available. These parameters can be evaluated as follows, using a ceiling formula $\lceil x \rceil$ [27]:

$$N_{trips,y} = \left\lceil \frac{H_{2,t,y}}{CL} \right\rceil \quad (2.8)$$

And

$$N_{trucks} = \left\lceil \frac{H_{2,t,y}}{CL \cdot W_{days} \cdot T_d} \right\rceil \quad (2.9)$$

With:

- $N_{trips,y}$ is the number of trips necessary to trade and transport the right volume of H2 per year.
- N_{trucks} is the number of trucks that a production plant needs to be prepared for trading and move such quantities of hydrogen yearly.
- CL is the capacity load of every trailer, this parameter depends on the different type of technology implemented.
- W_{days} working days in one solar year.
- T_y trips per day. Every lorry can make a maximum number of trips per day if necessary.

These parameters are of essential importance to continue with the analysis and they are the baseline for the different calculations and scenarios. The equation (2.7) can be divided further into:

$$CAPEX_0 = N_{trucks} \cdot (P_{truck} + P_{trailer})_{tec} + I_{tec} \cdot H_{2,t,y} \quad (2.10)$$

$$\begin{aligned} OPEX_y &= (O\&M + Fuel + Tolls + Wages + Replacements)_{year} = \\ &= P_{O\&M} \cdot CAPEX_0 + N_{trips,y} \cdot \big(0{,}02 \cdot D_{L,T} \cdot C_{fuel} \cdot P_{fuel} + 2 \cdot D_{L,T} \cdot P_{toll} + \\ &+ P_{Frejus} + 2 \cdot h_{L,T} \cdot P_{wages}\big) + P_{replacements} \end{aligned} \quad (2.11)$$

$$EC_y = H_{2,t,y} \cdot E_{cons,tech} \cdot E_{price} \quad (2.12)$$

[27] Wikipedia contributors. "Floor and Ceiling Functions." *Wikipedia, The Free Encyclopedia*. Last modified June 13, 2024.

With:

- P_{truck} and $P_{trailer}$ respectively are the price for a truck and for a trailer, the last depends on the technology implemented for the transportation.
- I_{tec} is the infrastructure cost for the different technologies in €/kg$_{H2}$.
- $P_{O\&M}$ is the price of Operation and Maintenance yearly, being a percentage of the CAPEX.
- $D_{L,T}$ and $h_{L,T}$ are respectively the distance in km and the driving hours between Lyon and Turin.
- C_{fuel} and P_{fuel} are respectively the consumption rate of fuel in litre/100km and the price of fuel in €/litre.
- P_{toll} price for highways' tolls, in €/km.
- P_{Frejus} is the price for Frejus' tunnel toll, going back and forth per every single trade.
- P_{wages} hourly wage for drivers, in €/h.
- $P_{replacements}$ is the price for replacement, usually a fixed value for purchasing new trucks and trailers.
- $E_{cons,tech}$ electricity consumption for the transformation from hydrogen to transportable hydrogen, in kWh/kgH2.
- E_{price} electricity price in €/kWhe.

From the formulation (2.12) it is possible to note out that every trip is calculated back and forth, with the addition of a constant that multiply the factors two times.

TRANSPORT PARAMETERS

To introduce the different parameters that can ease the calculations a German case study needs to be cited. A 2021 study analysed hydrogen transport in Germany with a view towards 2050 [28]. Germany is heavily investing in hydrogen for mobility, planning to establish a comprehensive network of refuelling stations across the country. The primary hydrogen production hubs are located in the northern regions, meaning that some efficient transport methods to supply refuelling stations nationwide are needed. The study projects that 15 electrolysers will supply hydrogen to 9,683 refuelling stations. This ambitious plan underscores the importance of developing reliable and cost-effective hydrogen transport methods. It analyses three different transportation methods (Compressed Gas H2, LOCH and Liquefied H2) and gathers many information about prices and formulations that can be used to express, as previously explained, an objective economical parameter like the Levelized Cost Of Hydrogen.

Most of the parameters listed are gathered from the German case study such as the O&M percentage, the fuel consumption and cost, the driver wages, the highway tolls, the initial investment capitals for trucks and trailers (only for LH2 and LOHC). Another document has been reviewed for the capital cost and capacity load of Compressed Gas Hydrogen trailers [29]. This technology is the most used and well known, they are cheaper and have lower capacity (at 350 bar of pressure). The data of capacity load of Liquefied Hydrogen and for LOHC have been selected from the portal Hydrogen Europe [30].

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[28] Reuß, M., Dimos, P., Léon, A., Grube, T., Robinius, M., and Stolten, D. "Hydrogen Road Transport Analysis in the Energy System: A Case Study for Germany through 2050." *Energies* 14, no. 11 (2021): 3166.

[29] Solomon, Mithran Daniel, Wolfram Heineken, Marcel Scheffler, and Torsten Birth-Reichert. "Cost Optimization of Compressed Hydrogen Gas Transport via Trucks and Pipelines." *Energy Technology* 12, no. 1 (2024): 2300785.

[30] Hydrogen Europe. "Tech Overview: Hydrogen Transport & Distribution." Last modified November 2021.

Useful parameters	
O&M [%Capex]	12%
Fuel [l/100km]	34.5
Fuel p [€/l]	1.2
Driver p [€/h]	35
Toll tax [€/km]	0.13
Investment truck	120,000.00 €
Investment trailer CGH2	600,000.00 €
Investment trailer LH2	860,000.00 €
Investment trailer LOHC	150,000.00 €
CGH2 infrastructure [€/kg]	0.24
CGH2 electr consumption [kWh/kg]	3
LH2 Infrastructure [€/kg]	12.47
LH2 electr consumption [kWh/kg]	15
LOHC Infrastructure [€/kg]	7
LOHC electr consumption [kWh/kg]	0.35
Average electr. Price [€/kWh]	0.1
WACC	6%
Frejus toll (2 way)	630
Capacity load CGH2 [kg/cad]	900
Capacity load LH2 [kg/cad]	3500
Capacity load LOHC [kg/cad]	1800
working days	250
Lyon-Turin [km]	315
Lyon-Turin [hours]	4
Trips per day	2

Table 2.4 - Parameters necessary for transport LCOHT calculation

Regarding the infrastructure needed to transform low pressurised hydrogen into compressed H2, in liquefied H2 or to mix it with organic carriers, other documentation can be found, extracting and arranging data that can be used per unit of kilogram of hydrogen produced/traded. The parameters that regulate the CGH2 can be extrapolated from the IMAGHyNE costs display, on which various prices of compressor and infrastructure are presented [imaghyne paper X]. For the LH2 and LOHC parameters instead, it is possible to rely on two papers redacted respectively by the Department of Energy of the USA [31] and from the European project named HySTOC [32].
Additional considerations include the toll costs for the Fréjus Tunnel that crosses the Alps that separate the two countries, classified under vehicle class 4, amounting to **€630** for a round trip [33]. Furthermore, assumptions were made about the replacement of the truck tractor and tank trailer after 10 years of operation to ensure the reliability and efficiency of the transport system. Finally, as for the electrolysers' parameters explained in section 2.2, the overall process and LCOH calculations will be held over 20 years of operation.

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[31] James, Brian, and Amgad Elgowainy. "Liquid Hydrogen Storage and Delivery: Cost Estimates and Outlook." *Hydrogen and Fuel Cell Technologies Office, U.S. Department of Energy*. Last modified January 2020.
[32] European Commission. "Guidance on Gender Equality Plans." *Horizon Europe Programme, European Commission*. Last modified October 2021.
[33] Mont Blanc Tunnel. "Vehicles Classification and Tolls." Accessed June, 2024.

SCENARIOS

After grasping the mathematical formulations and the parameters involved it is essential to continue by explaining the different scenarios that can be studied. As stated previously, there are not current or available data about the volume of hydrogen that each industry will use internally, exchange locally or put in the market. Therefore, it is necessary to implement various hydrogen market availability scenarios, starting from the yearly volume of hydrogen produced in each electrolyser analysed. This yearly volume $H_{2,y}$ is the amount of green or low carbon hydrogen that can be produced in an electrolyser annually and the following scenarios assume that a percentage of that can be transformed, transported and traded between the two countries, taking Lyon – Turin as the reference trip:

Scenario	***S1***	***S2***	***S3***	***S4***
% available for trade	5%	10%	20%	30%

Table 2.5 – Transport scenarios, percentage of hydrogen volume over yearly production

3. Results

In the following sections the calculation introduced in the previous paragraph will be computed in order to achieve objective results regarding the cost of production of hydrogen for each single plant and about the cost for transportation, with the different scenarios hypothesized. To easily understand the difference between results graphs and table will be used.

3.1 Results LCOH

CALCULATIONS

As explained in section 2.2 it essential to start from the calculation of the irradiance through the software PVGIS [23] and the production of energy hour by hour. To do so it is possible to use the year 2023 as a reference for the calculations. For Novara (Italy) an estimated value of energy produced in one year from a solar PV plant of 1 MW peak is 1.42 GWh, meanwhile for Lyon (France) a value of 1.36 GWh is assessed. For the plants of Lyon-Airport, Films, RF-Idra and Sarpom the equations (2.2) and (2.3) are to be employed. For every hour in the reference year, it is therefore necessary to calculate the electrical energy consumption (both from the grid and the local PV plant) and the hydrogen production. The summation of these two arrays of values will converge into the annual energy consumption EC_{yearly} and annual hydrogen production$H_{2,yearly}$. For the plants mentioned above, the following results are calculated:

[23] "Photovoltaic Geographical Information System (PVGIS)." European Commission, Joint Research Centre. Accessed June, 2024.

	Electricity Cost [€/year]	H2 production [t/year]
IT - FILMS	923,263.90 €	141
IT - SARPOM	3,146,820.64 €	564
IT - RF IDRA	923,263.90 €	141
FR - Lyon Airport	3,586,695.05 €	704

Table 3.1 – Electricity OPEX and H2 produced yearly for PV-integrated electrolysers.

To calculate the electricity cost, as explained in the previous paragraph, it is necessary to use the ENTSOE data for hourly spot market price, that differs from Italy and France. In the following figure it is possible to visualise the difference in energy prices between the two countries in a weekday in spring:

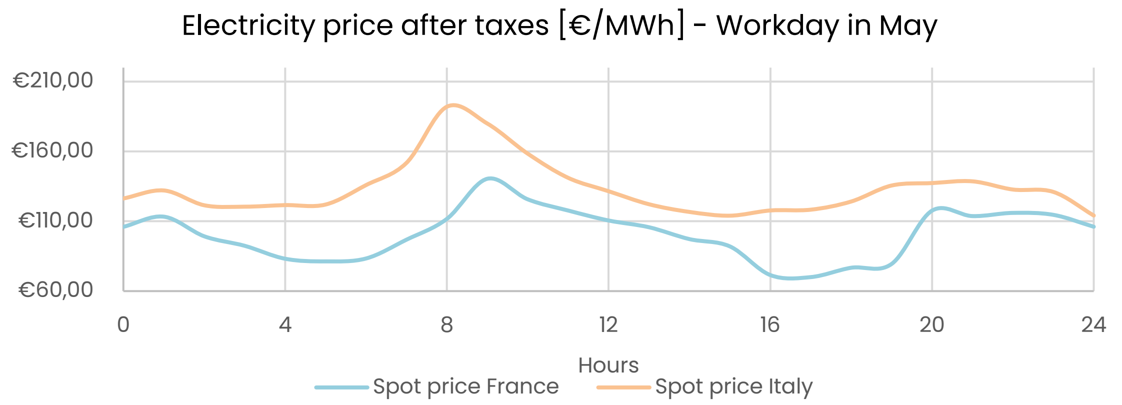

Figure 3.1 - Hourly spot price (after excise and charges) for France and Italy in a working day in May

The remaining plants' electricity cost and hydrogen volume production can be obtained from equations (2.4) and (2.5), using the parameters in Table 2.3 with the average PPA's contract price of 65 €/MWh. The results can be summarised as follows:

	Electricity Cost [€/year]	H2 production [t/year]
FR - Lyon ENGIE & CNR	8,222,785.34 €	2112
FR - Arkema	16,445,570.67 €	4225
FR - Lhyfe	2,740,928.45 €	704
FR - Bouygues Energies	1,096,371.38 €	282

Table 3.2 - Electricity OPEX and H2 produced yearly for PPA's electrolysers.

From these two preliminary tables it is already possible to estimate the yearly production, without considering the degradation of the stacks, for the two regions, being **846 tonnes** for Piemonte and **8,027 tonnes** for Auvergne-Rhone-Alpes.

The final LCOH for every electrolyser facility can be finally implemented with the equation (2.6), since each internal term now is defined. Considering then the CAPEX and the subsidies both from National and European funds (stated in Table 2.1) the following price for production of hydrogen are calculated:

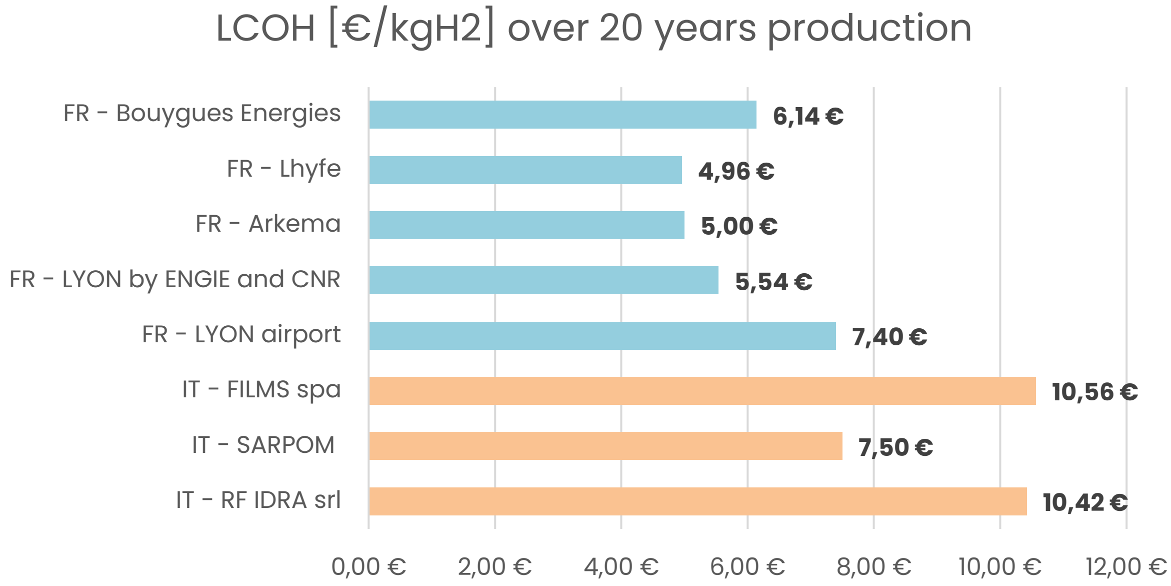

Figure 3.2 – LCOH results for French and Italian electrolysers.

With a substantial difference between France and Italy, respectively with an average LCOH of **5.81 €/kg** and **9.50 €/kg**.

RESULTS' ANALYSIS

A first comparison between the two regions would suggest a big difference both in hydrogen levelized cost and in hydrogen volume production. French electrolysers are scaled up, with larger infrastructure and higher capital investments in the beginning. This higher scale of production is eventually cheaper in price per single unit of production and therefore the price for 1 kg of hydrogen is lower respect to Piemonte. In that case instead, the electrolysers, even though having higher subsidies compared to the French counterpart, are characterised by lower electrolysing power and therefore lower total production. This factor and the difference in spot price defined in Figure 3.1, that show a substantial difference in electricity price between the two nations, are the main driving variables that lead to a higher hydrogen levelized cost.

The Lyon airport facility will deploy in the future years more capacity of electricity production, with the increase of the internal PV plant fleet. The LCOH of this plant is the highest in the French region but it will not be the case in a few years.

On the other hand, looking at the lowest options, similar values are obtained for Arkema and Lhyfe. Although the LCOH are similar the reason is quite different. For the Arkema electrolyser the main factor that brings down price is the scale, this plant has indeed an electrolysing power of 30 MW, while Lhyfe only 5 MW. On the other side the Lhyfe production plant has rallied up proportionally more subsidies than the rest of the other plants. It is necessary to remind however that the assignment of national funds is not yet completed in France and further incentives will be included in the future.

A final consideration can be carried out on the difference between the Italian electrolysers. The Sarpom plant has a hydrogen price per kilogram more similar to the French counterpart. This is because this plant is larger (4 MW compared to the 1 MW of FILMS and RF-Idra) and because it has rallied 100% of the PNRR national funds, having in this way a total initial CAPEX of 0 €.

3.2 Results LCOH-T

CALCULATIONS

The process for calculating the transport's relative LCOH (or LCOHT) is quite similar to the previous, since the basic formulation (2.7) is the same and only some new parameters are inserted, alongside with few assumptions and new equations.

For starter it is essential to identify the various scenarios introduced in Table 2.5. In this section the degradation of the stacks is to be neglected, since we are working on a one-year basis for production volumes. In the following table the total H2 production volumes and the various scenarios are summarised:

		Available H2 [t]			
	Production yearly [t]	**5%**	**10%**	**20%**	**30%**
IT - RF IDRA	140.9	7.0	14.1	28.2	42.3
IT - SARPOM	563.7	28.2	56.4	112.7	169.1
IT - FILMS	140.9	7.0	14.1	28.2	42.3
FR - Lyon Airport	704.0	35.2	70.4	140.8	211.2
FR - Lyon ENGIE & CNR	2,112.4	105.6	211.2	422.5	633.7
FR - Arkema	4,224.9	211.2	422.5	845.0	1267.5
FR - Lhyfe	704.1	35.2	70.4	140.8	211.2
FR - Bouygues Energies	281.7	14.1	28.2	56.3	84.5

Table 3.3 – Yearly hydrogen production and H2 volumes for every scenario for each electrolyser

As discussed in section 2.3 the transport methods and technologies that will be analysed are going to be the Compressed Gas Hydrogen (CGH2), the Liquefied Hydrogen (LH2) and the Liquid Organic Hydrogen Carriers (LOHC). Each of these technologies has various initial parameters and variables summarised in Table 2.4. Thanks to equation (2.8) and (2.9) it is possible to calculate the number of trucks/trailers needed for the trade of the available hydrogen for each scenario and the amount of trips needed in one year to satisfy the requirements and moving the right amount of hydrogen volumes. In the following tables these values are summarised, for each technology, each plant and each scenario, making a set of matrices:

	Number of CGH2 trucks				Number of LH2 trucks				Number of LOHC trucks			
Scenario (%H_2)	**S5%**	**S10%**	**S20%**	**S30%**	**S5%**	**S10%**	**S20%**	**S30%**	**S5%**	**S10%**	**S20%**	**S30%**
IT - RF IDRA	1	1	1	1	1	1	1	1	1	1	1	1
IT - SARPOM	1	1	1	1	1	1	1	1	1	1	1	1
IT - FILMS	1	1	1	1	1	1	1	1	1	1	1	1
FR - Lyon Airport	1	1	1	1	1	1	1	1	1	1	1	1
FR - Lyon ENGIE & CNR	1	1	1	2	1	1	1	1	1	1	1	1
FR - Arkema	1	1	2	3	1	1	1	1	1	1	1	2
FR - Lhyfe	1	1	1	1	1	1	1	1	1	1	1	1
FR - Bouygues En	1	1	1	1	1	1	1	1	1	1	1	1

Table 3.4 - Number of trucks needed for each plant in the different scenarios to deliver the right amount of H2.

	Number of trips CGH2				Number of trips LH2				Number of trips LOHC			
Scenario (%H_2)	**S5%**	**S10%**	**S20%**	**S30%**	**S5%**	**S10%**	**S20%**	**S30%**	**S5%**	**S10%**	**S20%**	**S30%**
IT - RF IDRA	8	16	32	47	3	5	9	13	4	8	16	24
IT - SARPOM	32	63	126	188	9	17	33	49	16	32	63	94
IT - FILMS	8	16	32	47	3	5	9	13	4	8	16	24
FR - Lyon Airport	40	79	157	235	11	21	41	61	20	40	79	118
FR - Lyon ENGIE & CNR	118	235	470	705	31	61	121	182	59	118	235	353
FR - Arkema	235	470	939	1409	61	121	242	363	118	235	470	705
FR - Lhyfe	40	79	157	235	11	21	41	61	20	40	79	118
FR - Bouygues En	16	32	63	94	5	9	17	25	8	16	32	47

Table 3.5 - Number of trips needed for each plant in the different scenarios to deliver the right amount of H2.

Different volumes of production mean different amounts of trucks and trailers and a different number of trips to trade the available hydrogen in the market, with the assumption that the reference trip is considered to be Lyon – Turin.

To continue, in order to understand the right value of LCOHT it is essential to employ the equations (2.10), (2.11) and (2.12). The CAPEX and the annual expenditures (OPEX and electricity cost) for each plant and for each infrastructure that will help the distribution of hydrogen. As seen in Table 2.4 the three different technologies have different CAPEX and OPEX parameters. For starter, the CGH2 method is largely known and already employed so the price is quite lower. LH2 instead is already employed globally but it has higher costs due to cryogenic processes and insulation of the tanks. On the other hand, the LOHC method is quite new and not well established in the market, for that reason few data are available and the implementation could be interesting but problematic.
Ultimately, using equation (2.7) it is possible now to calculate the LCOHT for every plant and every scenario. Results can be summarised in the following table:

	LCOHT [€/kg] CGH2				LCOHT [€/kg] LH2				LCOHT [€/kg] LOHC			
Scenario (%H_2)	**S5%**	**S10%**	**S20%**	**S30%**	**S5%**	**S10%**	**S20%**	**S30%**	**S5%**	**S10%**	**S20%**	**S30%**
IT - RF IDRA	27.9 €	14.9 €	8.3 €	6.1 €	40.8 €	22.9 €	14.0 €	11.0 €	12.3 €	7.4 €	5.0 €	4.2 €
IT - SARPOM	8.3 €	5.0 €	3.4 €	2.8 €	14.0 €	9.5 €	7.3 €	6.5 €	5.0 €	3.8 €	3.1 €	2.9 €
IT - FILMS	27.9 €	14.9 €	8.3 €	6.1 €	40.8 €	22.9 €	14.0 €	11.0 €	12.3 €	7.4 €	5.0 €	4.2 €
FR - Lyon Airport	7.0 €	4.4 €	3.1 €	2.6 €	12.2 €	8.6 €	6.8 €	6.2 €	4.5 €	3.5 €	3.0 €	2.9 €
FR - Lyon ENGIE&CNR	3.5 €	2.6 €	2.2 €	2.3 €	7.4 €	6.2 €	5.6 €	5.4 €	3.2 €	2.9 €	2.7 €	2.6 €
FR - Arkema	2.6 €	2.2 €	2.2 €	2.2 €	6.2 €	5.6 €	5.3 €	5.2 €	2.9 €	2.7 €	2.6 €	2.6 €
FR - Lhyfe	7.0 €	4.4 €	3.1 €	2.6 €	12.2 €	8.6 €	6.8 €	6.2 €	4.5 €	3.5 €	3.0 €	2.9 €
FR - Bouygues En	14.9 €	8.3 €	5.0 €	3.9 €	22.9 €	14.0 €	9.5 €	8.0 €	7.4 €	5.0 €	3.8 €	3.3 €

Table 3.6 - LCOHT results for each electrolyser and every scenario proposed.

Additionally, the results can be visualised with three different graphs, each one for the single technology implemented:

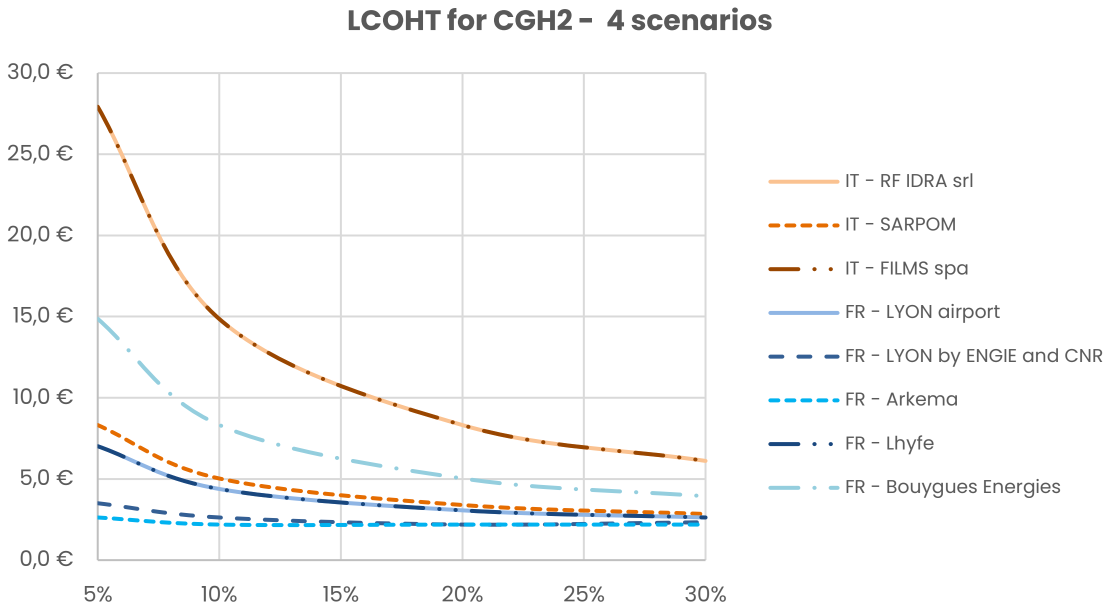

Figure 3.3 - LCOHT plot for Compressed Gas Hydrogen CGH2 over H2 market availability in %.

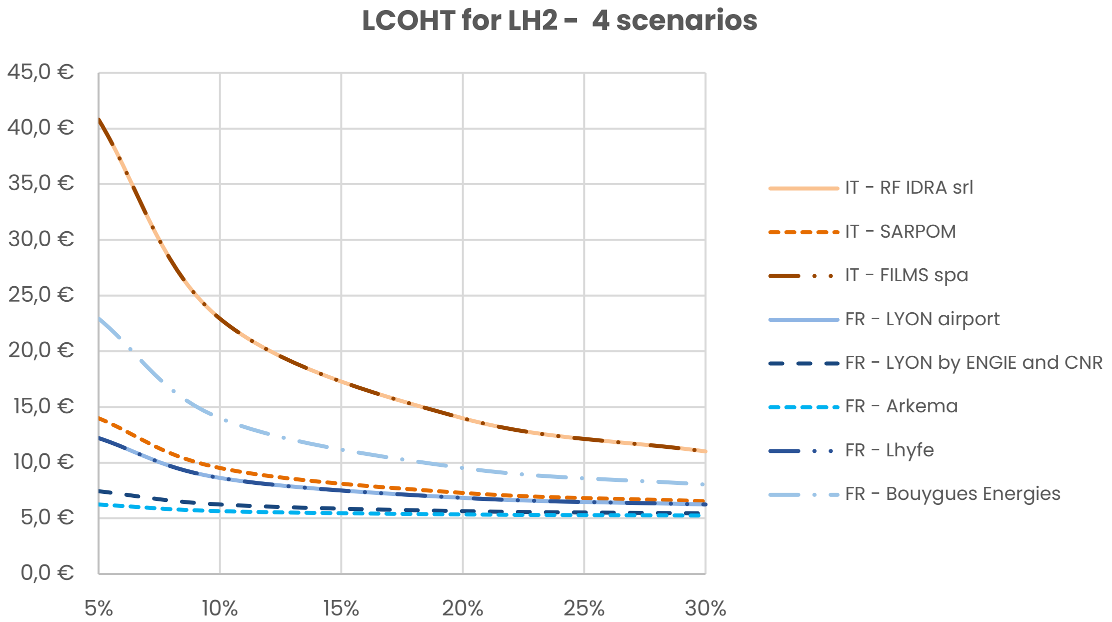

Figure 3.4 - LCOHT plot for Liquefied Hydrogen LH2 over H2 market availability in %.

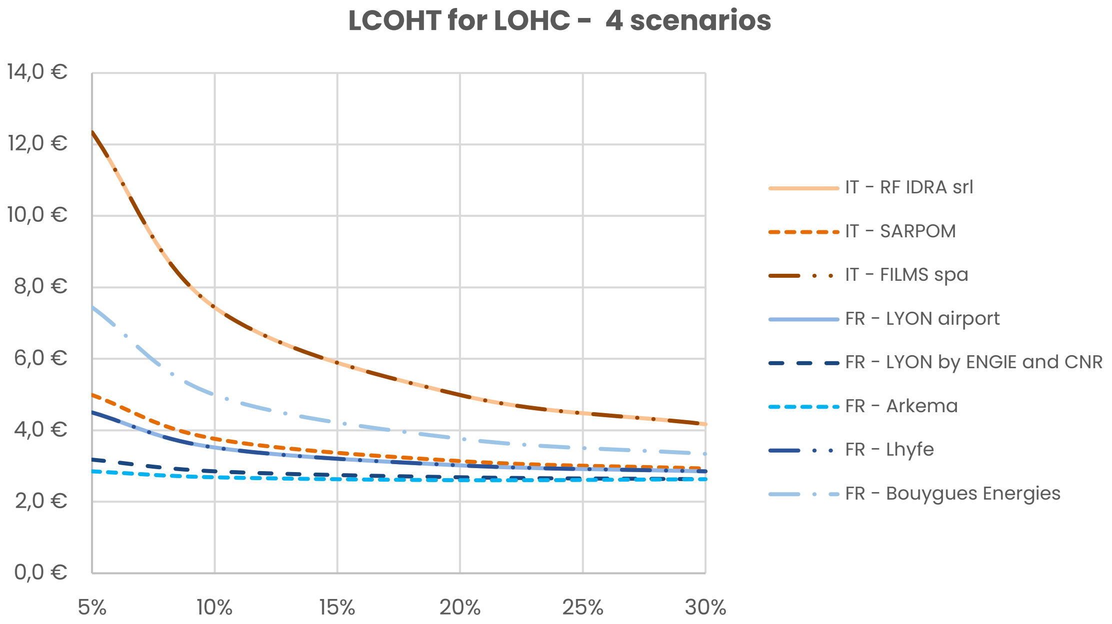

Figure 3.5 - LCOHT plot for Liquid Organic Hydrogen Carriers LOHC over H2 market availability in %.

With the aid of these plots and the trends explained for each plant it is now possible to assess the difference between the various kinds of plants and electrolysers. Each plant indeed will produce different volumes of hydrogen and the more an industry is scaled up the less will be the price for trading and transporting a single unit (kg) of green hydrogen.

To be able to identify and view in clearer way the difference between the three technologies proposed it is practical to group the overall values into mean ones, displaying in this way an average LCOHT per scenario and not for single plant:

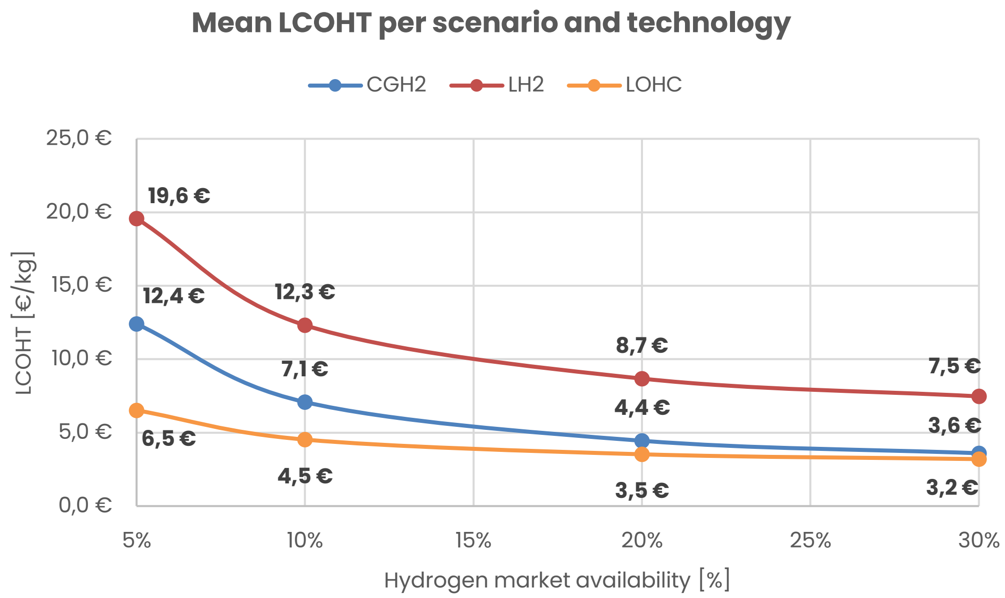

Figure 3.6 - Average LCOHT trend per technology involved over H2 market availability in %.

Results' analysis

It is currently possible to assess and state the main differences between plants, technologies and hydrogen volume scenarios. Starting with the analysis on the plants themselves, it is clear, as introduced previously, that the scale of production is going to be the main factor in diluting and spreading the CAPEX and OPEXs among all the hydrogen volume, decreasing therefore the price per unit (per kg). That is the main reason for the lower prices in the French electrolysers, since their overall production is based on higher electrolysing power and larger volumes of hydrogen are available for trade. Only the Italian plant of Sarpom can guarantee low transportation prices in the 30% availability scenario, being therefore competitive with the French counterparts.

Regarding the different scenario based on the volume tradable, the explanation for the trends obtained is of the same nature as the previous one. A larger volume permits the industries to spread the investment and operational costs on a larger volume of hydrogen. In Table 3.4 the number of trucks/tanks needed for the transportation are quite low for every plant and scenario, being at maximum 3 for Arkema only. Since the variation of trucks needed is quite low it is clear that one truck can move in a year between 400 and 800 tonnes, depending on the technology.

Finally, Figure 3.6 is essential to quickly understand the difference in price between the three technologies proposed. As discussed in section 2.3 and in the introduction, the infrastructure and operating costs for liquefying hydrogen and maintaining it at cryogenic temperatures is elevate. It can be, as demonstrated by the market for LNG, a suitable and economically feasible alternative for long distance trips. However, as seen previously, the distances that are considered in this study are in the order of 200-300 km and the LH2 LCOH is not competitive. On the other hand, the difference between CGH2 and LOHC is quite lower, especially the more it goes near high volumes of hydrogen traded. As explained in the introduction, the infrastructure costs for LOHC are higher and not totally clear at the moment, since is still an in-development technology. The data available are few and the knowledge is limited compared to the simply compressed or liquefied hydrogen.

4. Conclusions

4.1 Conclusions about both studies

The analysis presented in this show the various difficulties that green hydrogen production needs to overcome. The technical and economic feasibility of industrial production and transport of hydrogen between the Auvergne-Rhône-Alpes and Piemonte is critical for the development of a sustainable hydrogen supply chain.
In order to calculate both LCOH and LCOHT a levelized cost mathematical method has been implemented, that included the analysis of CAPEX, OPEX, maintenances, electricity prices, taxes, replacements and interest rates, over a 20 years' timeframe.
The analysis of hydrogen production showed that costs vary significantly between France and Italy, mainly due to the size of the plants and the prices of electricity. In France, hydrogen production costs (LCOH) vary between 5€ and 7€ per kg, while in Italy the costs are higher, fluctuating between 7€ and 10€ per kg. This difference is attributable to the higher electricity prices in Italy, that has a more expensive energy mix compared to France, and the smaller size of the Italian plants compared to the French ones. The Auvergne-Rhône-Alpes is highly expanding its hydrogen production capability, with the use of the European Project IMAGHyNE, therefore larger plants are being designed.
Hydrogen transport has been evaluated by considering a standard journey between Lyon and Turin and comparing three main transportation technologies: Compressed Gas Hydrogen (CGH), Liquefied Hydrogen (LH) and Liquid Organic Hydrogen Carriers (LOHC). Four scenarios of available hydrogen volumes were considered, ranging from 400 to 2600 tonnes per year. The results indicate that the cost of transport varies greatly depending on the technology used and the volume of hydrogen available. In the case of CGH2 and LOHC, for the larger volume scenario, the average transport costs are 3.2€ and 3.6€ per kg respectively. Meanwhile for LH2, the highest initial cost is not justified for the short distance considered in this study, reaching in the same scenario an average cost of 7.5€ per kg.
To better understand the economic feasibility of the best-case scenario, held by the Arkema 30MW electrolyser and the 30% hydrogen volume tradable scenario, the following graph is presented. In this case a final price, including production and transport, is calculated to be around 7.2€ per kg.

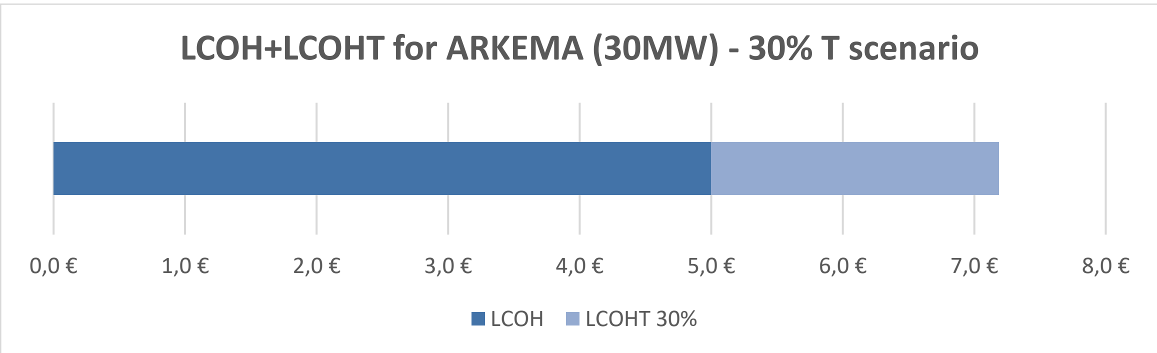

Figure 4.1 – LCOH and LCOHT of the best-case scenario.

Finally, the economic competitiveness of green hydrogen is currently low compared to the European market, where the average price of hydrogen produced by natural gas (SMR) was 2.67€/kg in 2021, before the Russo-Ukrainian war that completely disrupted the Natural Gas market for almost 2 years. However, the IMAGHyNE project and the Piemonte electrolysers aim to produce 8873 tonnes of green and low-carbon hydrogen per year, significantly contributing to the decarbonisation of industries in the two regions.

In conclusion, the study showed that the production and transport of green hydrogen between Auvergne-Rhône-Alpes and Piemonte are technically feasible, but present significant economic challenges. This is mainly due to their production of hydrogen for internal porpoises and/or for local industries. It is clear that plants that are dedicated only for production and trade will present slightly better results.

4.2 Next steps

This work has laid the basis of the analysis of the production and trading system that Auvergne-Rhône-Alpes and Piemonte could sustain in the future years. The IMAGHyNE project, presented in February 2024, will be heavily supported by the contribute of Politecnico di Torino. The university's studies will range from the interconnection with border regions (partner with NOMADS) and the study in depth of corridors for the transportation of hydrogen or derivatives. It will be studied also the use of transportation and pipelines, studying the infrastructure, the safety aspects, the economic feasibility and the strategic value of said interconnections. Specific qualitative risk assessment for deployment of hydrogen in tunnels with also experimental test carried into the "hydrogen tunnel" in POLITO will contribute to these studies.

Generally, further reduction of green hydrogen production and transport costs will be essential. This can be achieved through the adoption of more advanced technologies, the implementation by governments and institutions of subsidies and incentives for green hydrogen and the construction of higher capacity plants, able to exploit economies of scale.

The success of the IMAGHyNE project depends on the collaboration between France and Italy and the partner involved, such as POLITO. It will be crucial to strengthen partnerships between governments, industries and research institutions to facilitate the exchange of knowledge and resources.

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