ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA

SCUOLA DI INGEGNERIA

DEPARTMENT
of
ELECTRICAL, ELECTRONIC, AND INFORMATION ENGINEERING
"Guglielmo Marconi"
DEI

MASTER DEGREE
in
ELECTRIC VEHICLE ENGINEERING

DISSERTATION
in
Advanced Sensors for Electric Vehicles M

Feasibility Analysis of Hydrogen Production and Storage for Hydrogen Powertrain Testing

Candidate:
Mattia Davario

Supervisor:
Prof. Lorenzo Peretto

Co-Supervisor:
Prof. Federico Tramarin

Company Co-Supervisor:
Giulio Marmorato, Ph.D

Session III
Academic Year 2022/2023

Table of Contents

Abstract

This thesis is the result of a six a six-month “internship for preparation for the final examination” in collaboration with AVL Italia (RE). During this internship, I had the opportunity to delve into the dynamics of sustainable energy, focusing on the significative role of hydrogen. The collaboration with AVL Italia provided a practical context to explore challenges and opportunities related to the integration of hydrogen into propulsion systems, enriching theoretical understanding with direct experiences in the field of advanced technologies.

Discovering a new world related to hydrogen and its applications, with a specific focus on storage and production solutions at AVL's technical center, integral components of the feasibility study outlined in this thesis, this experience has provided an in-depth perspective on the challenges and opportunities associated with the use of hydrogen as an energy carrier. Today, I am actively involved as a project manager in the realization of the study, which is gradually taking shape within the mentioned company.

1 Introduction

To effectively address the necessity of mitigating climate change, as emphasized by both the Paris (COP21) and Glasgow (COP26) Climate Agreements, propulsion technologies must rapidly achieve substantial CO_2 reduction. Electric powertrains, powered by batteries charged with renewable energy, adhere to global mandates and are leading in academic and industrial research efforts. However, recognizing that this technology cannot sufficiently meet various needs in personal mobility, sustainability, and feasibility, internal combustion engines (ICE) fuelled by non-fossil hydrocarbons and hydrogen (H_2) play a parallel, significant role. In the current energy landscape, hydrogen is considered a versatile energy carrier with wide applications across all energy sectors.

Renewable energy sources such as solar, wind, geothermal, and tidal energy emerge as the primary solution for transitioning toward a low-impact environmental energy system. However, because these sources naturally produce energy intermittently and in a way that cannot be programmed, it creates difficulties for directly using it in everyday applications. In this situation, hydrogen comes forward as a promising solution to deal with challenges linked to the widespread storage, transportation, and conversion of renewable energy. Hydrogen, a carbon-free molecule characterized by high specific energy density [J/kg], shows flexibility for various uses without creating harmful emissions. Unlike traditional energy storage methods like batteries, capacitors, and hydroelectric pumping, hydrogen allows for the storage of large quantities of energy for extended periods. However, for global adoption of these technologies, competitiveness in terms of costs and performance compared to traditional energy vectors throughout the entire hydrogen supply chain (production, storage, and utilization) is crucial. Despite its potential, industrial and domestic use of hydrogen remains challenging due to technological limitations, notably storage challenges. Hydrogen, under standard conditions, has an extremely low density; therefore, increasing its storage density for compact and efficient storage systems is crucial. Generally stored as compressed gas, cryogenic liquid, or in a solid state through physical or chemical bonding with suitable materials, overcoming these storage hurdles is essential for the widespread adoption of hydrogen-based technologies.

In the context of sustainable energy, hydrogen is making a significant impact, ready to change how we think about global energy. This thesis explores the many aspects of hydrogen in a detailed and organized investigation.

The foundational chapter, "Hydrogen World" (Chapter 2) provides a broad overview of hydrogen. Beginning with a detailed examination of hydrogen's properties, the thesis explores in depth fundamental characteristics that make hydrogen a robust energy carrier. After that, the analysis focuses on the environmental impact of hydrogen, critically assessing its implications for sustainability. Following this, information about the economic landscape, exploring its implications for global economies and industries, is provided. The details of market dynamics are further discussed, including a global and European overview, along with a detailed examination of Italy's National Hydrogen Strategy and Hydrogen Valleys.

Chapter 3 narrows the focus to hydrogen uses in logistics and transportation, exploring fuel cells, their operation and structure, internal combustion engines (H2ICE), hydrogen utilization in these engines, a comparative study between H2ICE and hydrogen fuel cells, and a broader comparison with alternative propulsion systems, including an analysis of alternative fuel scenarios.

Moving into Chapter 4, titled "Hydrogen Cycle," the thesis thoroughly explores the complete lifecycle of hydrogen. Various methods of hydrogen production are detailed, with a specific focus on green hydrogen generated through different electrolysis techniques. Hydrogen storage methods are examined, assessing the feasibility and applicability of various storage technologies. Safety considerations become a key focus, exploring Italian laws and regulations to ensure adherence to safety protocols. A crucial point in this chapter is the examination of production, storage, and safety considerations at AVL Italia, which includes a feasibility analysis of hydrogen technologies. Raising the analysis, hydrogen is integrated into smart grid applications, exploring Second Life Battery Energy Storage Systems (BESS). The application of MATLAB tools for customer support is further presented, highlighting the integration of advanced technologies for comprehensive analysis and support.

Moving into Chapter 5, titled "About AVL," the focus shifts to AVL's significant role in hydrogen testing. The chapter explores the meaning of "Test" and examines how hydrogen is integrated into testing methodologies. AVL's testing solutions are outlined, providing a view into AVL's approach to managing the complexities of hydrogen testing. Additionally, the chapter explores AVL's testing facilities, with a specific focus on the conversion of an engine test cell into a dedicated hydrogen test cell. This highlights AVL's adaptability and innovation in the testing field, emphasizing the practical integration of hydrogen technologies within testing facilities.

In conclusion, this thesis traverses the intricate landscape of hydrogen, integrating together theoretical insights and practical applications to make a significant contribution to the discussion surrounding hydrogen's pivotal role in shaping the trajectory of sustainable energy. Through a careful exploration of hydrogen's properties, environmental implications, economic dimensions, market dynamics, practical applications, and integration into testing methodologies, this thesis seeks to provide a comprehensive understanding of hydrogen's transformative potential across various aspects of the energy landscape.

2 Hydrogen World

Hydrogen, a fundamental element in the universe, is emerging as a pivotal choice in the pursuit of sustainable energy solutions. Its unique properties and versatile applications position it at the forefront of transformative advancements, challenging conventional energy norms. In this exploration, we delve into the intrinsic characteristics of hydrogen, examining its potential to redefine our global energy landscape. As a clean and efficient energy carrier, hydrogen holds promise in addressing critical challenges, making it a compelling choice for a future marked by environmental consciousness and energy sustainability.

2.1 H_2 Overview

Hydrogen, composed of a nucleus housing a proton and an orbiting electron, represents the most basic and lightweight atom. Its significance lies in being the most prevalent element on our planet. Typically found in a demineralized state, hydrogen occurs naturally only as part of a molecule, primarily in hydrocarbons and water. It manifests as a gas at standard temperature and pressure (293.15 K and 1 atm), having an extraordinarily low boiling point of -252.76 °C (20.3 K) under ambient pressure. Additionally, hydrogen, is also, under normal conditions, colourless, odourless, and non-toxic, making it environmentally neutral.

Property	**Hydrogen**
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)
Lower heating value (LHV)	120.1 MJ/kg
Higher heating value (HHV)	141.88 MJ/kg
Specific volume	12.1 m^3/kg
Specific heat Cp	14.310 kJ/kgK
Gas constant R	4.126 kJ/kg°C
Thermal conductivity	0.182 W/m °C
Heat of combustion	144000 kJ/kg

Table 1: Thermodynamic properties of hydrogen (at 25°C and 1 atm) [engineeringtoolbox.com]

Changes in the state of hydrogen occur within a narrow range of temperature and pressure. The process of liquefaction relies primarily on cooling rather than compression. This liquefaction process significantly increases the density of hydrogen, by a factor of 800. To put it in perspective, LPG has a factor of 250 and natural gas has a factor of 600. This makes hydrogen liquefaction an interesting transportation method for long distances. The transportation temperature is extremely low (-253°C), necessitating a highly efficient insulation system to prevent hydrogen from evaporating. Alternatively, hydrogen can be transported in its gaseous form under moderate or high pressures.

2.2 H_2 Environmental Impact

Hydrogen is not exactly an energy source, but rather what is called an energy carrier or energy vector, meaning a medium that allows the storage of energy that can be converted in a second time into other forms, such as electricity or combustion. However, molecular hydrogen (H_2) is quite rare on our planet (present in the atmosphere only in extremely small quantities being 14.4 times lighter than air, it is not retained by it, but disperses into space) and therefore must be produced, either from water using electrolysers (which split the water molecule H_2O through electrolysis) or from gas or even oil. Under certain conditions that depend on how it is produced, hydrogen can represent a sustainable energy solution and can complement or replace energy sources with a greater environmental impact [1]. Let’s see the main advantages of hydrogen:

- Abundance: The most abundant source of hydrogen on Earth is water. Through processes like electrolysis and electrochemical conversion with a fuel cell, the only by-products produced are oxygen and water. Its availability is therefore limitless.

- High Energy Density: Although its low density, hydrogen has exceptional energy density. One kg of hydrogen releases 4.1 times more energy than 1 kg of coal, 2.8 times more than 1 kg of petrol and 2.4 times more than 1 kg of natural gas.

- Renewable Energy Storage: Hydrogen enables the long-term storage of excess renewable energy for future use.

- Lightweight: While hydrogen storage has a lower theoretical efficiency compared to battery storage, it can be up to 10 times lighter. This reduces both volume and mass requirements for energy storage, even taking into account the weight of the tanks used for storage. This is why fuel cells-battery hybridization becomes highly significant when maximizing the autonomy of transportation, both on land and at sea. This makes hydrogen particularly well-suited for "heavy mobility" sectors like trains, buses, trucks, and ships, which require substantial power to cover long distances on a single energy tank.

- Environmental Cleanliness: When produced from renewable sources, hydrogen production is carbon neutral. Its use in a fuel cell doesn't emit CO_2, NOx, or fine particles. It only releases pure water and heat, devoid of any minerals. In fact, the ambient air that enters the cell for the chemical reaction exits much purer after being filtered upstream of the process.

- Quick Recharge: In the realm of mobility, hydrogen refuelling can be done in a matter of minutes, in contrast to several hours for its battery equivalent. This is a major advantage for the future of electric mobility.

Despite these favourable attributes and the significant contributions hydrogen offers in terms of climate protection, it is essential to conduct a more comprehensive assessment of hydrogen production in relation to climate protection. The categorization of hydrogen into various "colours" aims to offer insights into its production methods, the energy sources employed, and the extent of its climate-friendliness.

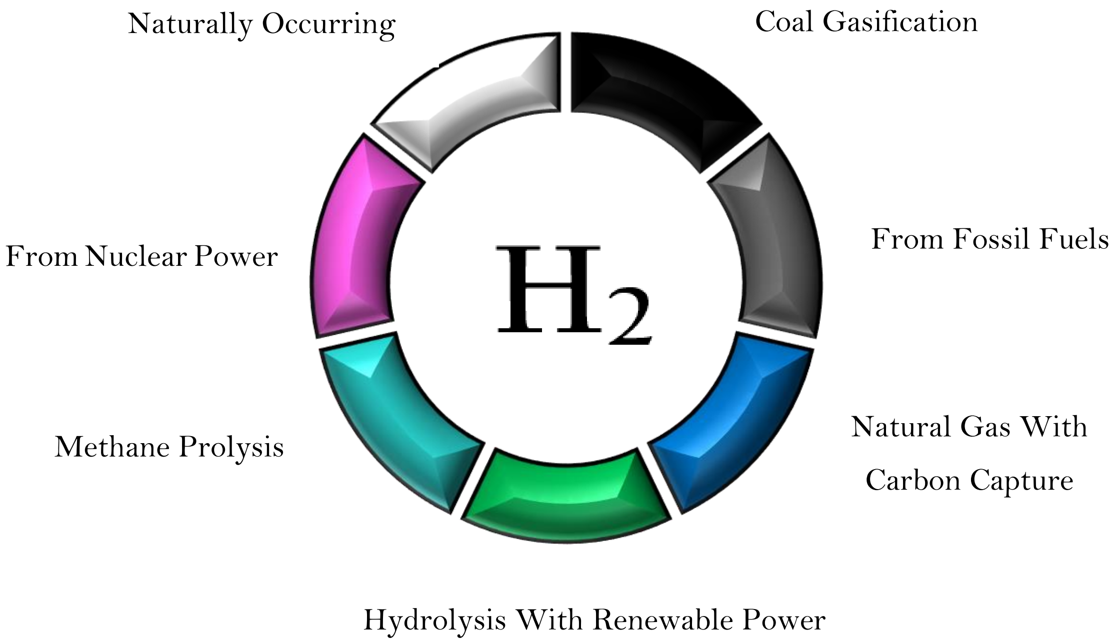


Figure 1 - Color Palette of Hydrogen

Black/Brown: Black or brown hydrogen is produced from coal. The black and brown colours refer to the type bituminous (black) and lignite (brown) coal. The gasification of coal involves conversion of coal from its solid state into gaseous form. It is a method used to produce hydrogen. However, it is a very polluting process, and CO_2 and carbon monoxide are produced as by-products and released to the atmosphere. The cost associated with brown hydrogen production is less when compared to hydrogen production from electrolysis and natural Gas [2].

- **Grey:** Currently, this is the most common form of hydrogen production. Grey hydrogen is derived through the steam reforming of fossil fuels like natural gas or coal. This process results in the direct release of CO_2 into the atmosphere. For every tonne of hydrogen produced, ten tonnes of carbon dioxide are emitted, making grey hydrogen harmful to the climate. Additionally, the term "grey hydrogen" is applicable when non-renewable energy sources are used for the electrolysis of water instead of eco-friendly alternatives.

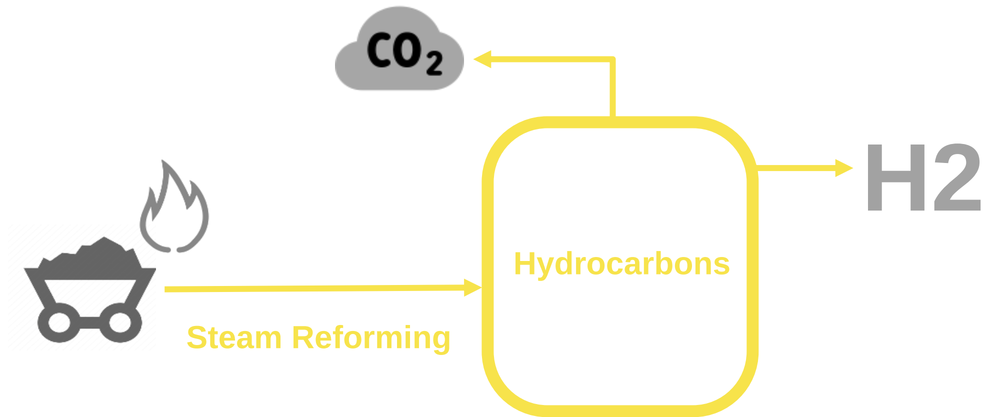


Figure 2 - Grey Hydrogen Production Process

- **Blue:** Similar to grey hydrogen, blue hydrogen is produced mainly from natural Gas using a process called "steam reforming ", in which both natural gas and heated water are carried in the form of steam, but the CO_2 emissions are captured and stored (CCS) underground or utilized (CCU) rather than being released into the atmosphere. This makes blue hydrogen a lower-emission option compared to grey hydrogen but is considered mostly a transitional solution in the shift towards a more sustainable and low-carbon energy system. However, the long-term impacts of storage are uncertain, and leakage can still negatively affect the environment and climate. Indeed, the total greenhouse gas emissions over the lifecycle of blue hydrogen can include both carbon dioxide and unburned fugitive methane emissions.

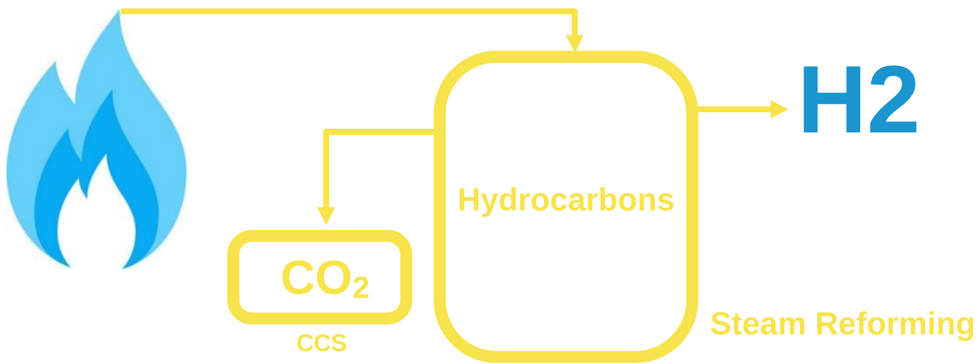


Figure 3 - Blue Hydrogen Production Process

- **Turquoise:** This represents a new entry in the spectrum of hydrogen colours and its large-scale production has not yet been proven [3].
  This kind of hydrogen is generated through a thermal process in which natural gas undergoes methane pyrolysis, resulting in the production of hydrogen and solid carbon. Consequently, turquoise hydrogen is generally not entirely climate-neutral when considering the entire production process and the subsequent treatment of carbon as a byproduct. However, it holds potential to be regarded as a low-emission hydrogen, dependent on the utilization of renewable energy to power the thermal process and the permanent storage or utilization of carbon [3].

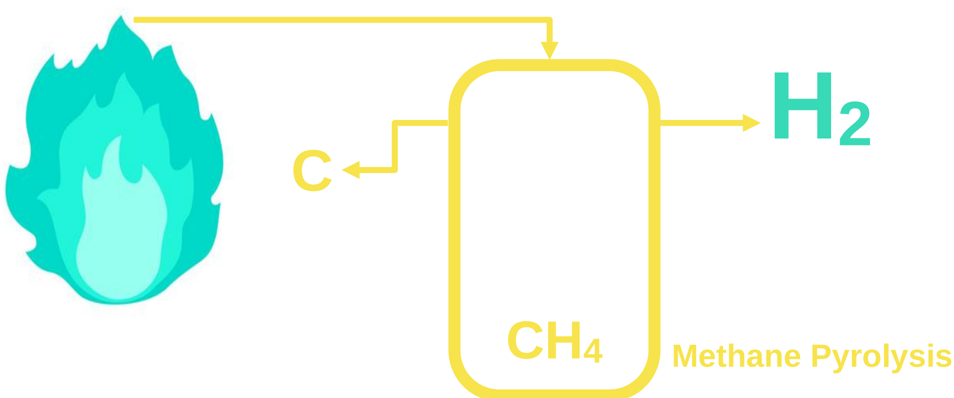


Figure 4: Turquoise Hydrogen Production Process

- **Pink/Purple:** Like green hydrogen is generated through electrolysis but in this process, the electricity is generated by nuclear power that is after used to split water into hydrogen and oxygen. The term "pink" is used to represent the combination of the red colour associated with nuclear energy and the blue colour commonly associated with hydrogen (this is why it is also referred to purple).
  It can be considered a potential low-carbon and emission-free method of hydrogen production, as nuclear power does not produce direct greenhouse gas emissions during electricity generation. However, it is worth noting that the production of nuclear energy comes with its own set of environmental and safety considerations. This method is still in the experimental and developmental phase, and its widespread implementation would require careful consideration of various factors, including safety, regulatory frameworks, and public acceptance.
- **Green:** is generated without emitting greenhouse gases. It is produced by the electrochemical process of electrolysis, in which water (H_2O) is split into its 2 elemental components, hydrogen (H_2) and Oxygen (O_2), using electricity produced by renewable energy sources like solar or wind power or also hydroelectric power. This means that the entire process is carried out without emitting greenhouse gases. As a result, green hydrogen is considered a clean and sustainable energy carrier with the potential to play a significant role in reducing carbon emissions in various industries, including transportation, energy storage, and industrial processes.

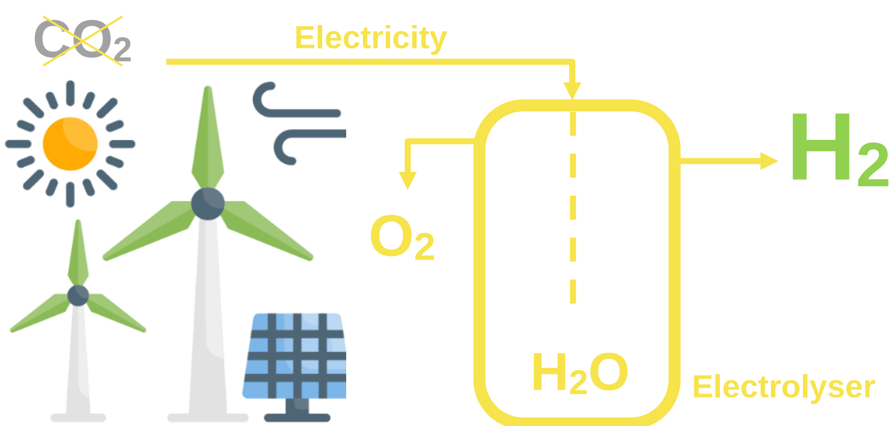


Figure 5 - Green Hydrogen Production Process

The following Table 2 reports a summary of the main hydrogen categories with a focus on the processes and products:

Colour		Fuel	Process	Products
	Black/Brown	*Coal*	*Steam reforming or gasification*	$H_2+CO_{2(released)}$
	White	*N/A*	*Naturally Occurring*	H_2
	Grey	*Natural Gas*	*Steam Reforming*	$H_2+CO_{2(released)}$
	Blue	*Natural Gas*	*Steam Reforming*	$H_2+CO_{2(\%captured\ and\ stored)}$
	Turquoise	*Natural Gas*	*Pyrolysis*	$H_2+C_{(solid)}$
	Pink/Purple	*Nuclear Power*	*Catalytic Splitting*	H_2+O_2
	Green	*Renewable Electricity*	*Electrolysis*	H_2+O_2

Table 2 - Hydrogen Type Summary

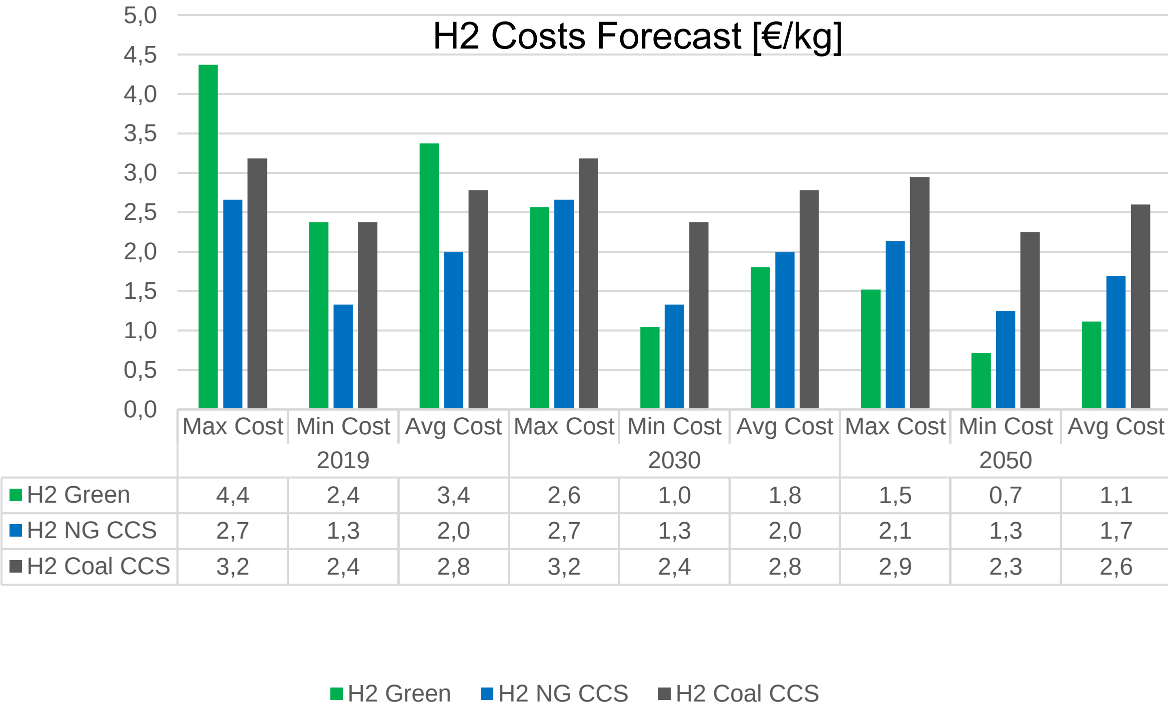
2.3 H_2 Economy

In order to accelerate the global transition to a low-carbon economy, all systems energy sources must be actively decarbonised. For decades now, hydrogen has been a key element in the energy and petrochemical sector and today, in particular, green hydrogen is rapidly growing by importance, both politically and economically, as a vector versatile and sustainable energy in a future energy mix zero emissions. However, to exploit its full potential, a coordinated effort between the private and the public sector will be needed, by focusing on the scalability of technologies, the reduction of costs, the development of enabling infrastructures and the definition of adequate policies and effective market structures. Only in this way will we be able to avoid replicating at a systemic level the inefficiencies of the past that have characterized the regional approaches to the development of new energy infrastructures.

In the coming years, a growth in demand is expected in various applications. Due to the increasing emissions from the transport sector, as well the rapid adoption of renewable energy sources (RES) for electricity generation over the last years, a renewed interest in hydrogen use for mobility is rising again, since green hydrogen can contribute to the decarbonization of the transport sector [4].

In the near future, the large-scale development of green hydrogen may present challenges due to its reliance on a substantial supply of renewable electricity. Consequently, during the transition from fossil fuels to green hydrogen, there will be a transition period involving blue hydrogen (thanks to CCS and CCU) that allows a more gradual introduction of green hydrogen into the market.

Indeed, as depicted in Table 3, whose values have been sourced from [5], there is a noticeable shift in the cost dynamics of the two hydrogen production technologies over time.



	2019			2030			2050		
	Max Cost	Min Cost	Avg Cost	Max Cost	Min Cost	Avg Cost	Max Cost	Min Cost	Avg Cost
H2 Green	4,4	2,4	3,4	2,6	1,0	1,8	1,5	0,7	1,1
H2 NG CCS	2,7	1,3	2,0	2,7	1,3	2,0	2,1	1,3	1,7
H2 Coal CCS	3,2	2,4	2,8	3,2	2,4	2,8	2,9	2,3	2,6

Table 3 - Hydrogen Cost Forecast Comparison: Green VS Natural Gas (CCS) VS Coal (CCS) - Adapted from[5]

In particular, looking at the columns reporting the average costs for the next three decades (forecast) can be noticed the interchangeability between blue hydrogen and green hydrogen, with forecasts indicating the greater cost-effectiveness of green hydrogen in 2050, while a competitive parity is projected for 2030. It is crucial to note that these projections rely on the assumption of substantial investments being made in the near future to enable large-scale production of green hydrogen. This underlines the significance of incentives and funds allocated by governments in driving this transition and making hydrogen more accessible and convenient in the near future.

2.4 Market approach and trends

The International Energy Agency (IEA) draws up every year the “Global Hydrogen Review”, a publication that monitors progress in the hydrogen sector, with a specific focus on the role played by low-emission hydrogen as a crucial driver to the transition to clean energy, and a crucial tool for reducing carbon emissions, especially in industries facing significant challenges in this regard. The recent energy crisis has further emphasized the vital role of low-emission hydrogen in securing our energy future. As a result, governments worldwide have strengthened their commitments to achieving net-zero emissions. Most of the production still relies on fossil fuels, and low-emission hydrogen production has not yet become widespread but according to the forecast, the annual production of low-emission hydrogen could reach 38 Mt in 2030, if all the planned projects are realised, although 17 Mt come from projects at early stages of development. Of the total, 27 Mt are derived from electrolysis and low-emission electricity, while the remaining 10 Mt from fossil fuels with carbon capture, utilization, and storage [6].

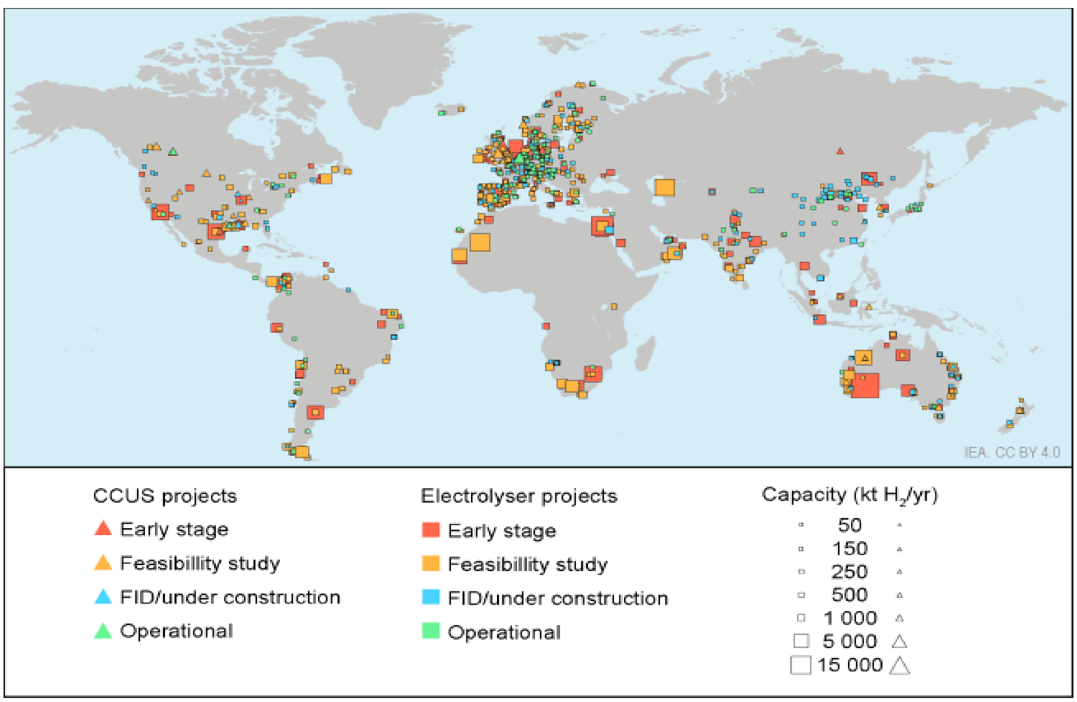


Figure 6 - Map of Announced Low-Emission Hydrogen Production Projects - IEA Hydrogen Project database [6]

2.4.1 Global and Europe Overview

In 2022, global hydrogen consumption reached 95 Mt, sustaining its upward trajectory. This growth trend was temporarily disrupted in 2020 due to the Covid-19 pandemic and subsequent economic slowdown.

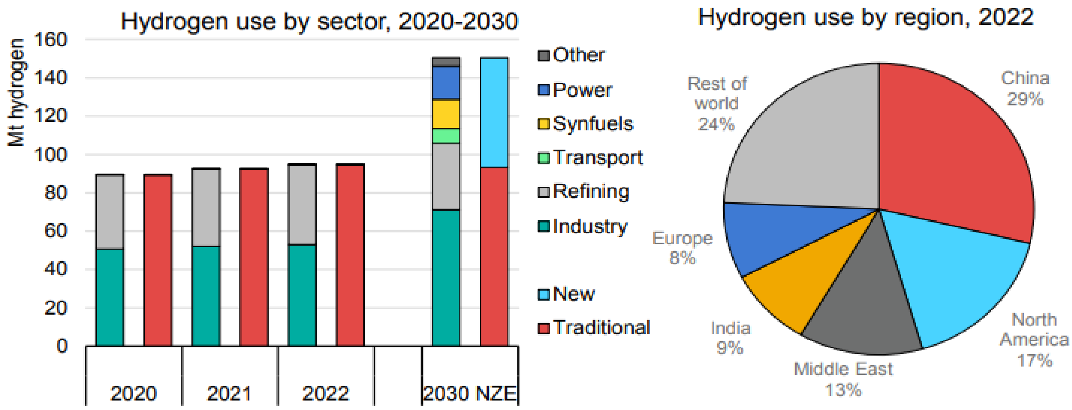


Figure 7 - Hydrogen Use by sector and by region, historical and in the Net Zero Emissions by 2050 Scenario, 2020-2030 - IEA

Hydrogen use has shown robust growth globally, except in Europe, where it declined significantly, a drop of nearly 6% driven by reduced activity, especially in the chemical industry, due to the high increase of the natural gas prices caused by the energy crisis (after Russia's invasion of Ukraine). On the contrary, North America and the Middle East experienced robust growth, compensating the drop in Europe with approximately 7% growth in both regions. China, while showing modest growth at around 0.5%, remains the world's largest consumer of hydrogen with nearly 30% of global use (over than twice that of the United States).

This growth in global hydrogen use is primarily driven by energy trends rather than specific hydrogen policies. Most of this increase occurred in traditional applications, particularly in refining and the chemical sector, and has not contributed significantly to climate change mitigation efforts. The adoption of hydrogen in new applications such as heavy industry, transport, hydrogen-based fuel production, and electricity generation and storage, remains minimal, constituting less than 0.1% of global demand, and it is crucial for the clean energy transition.

Fortunately, according to the updated 2023 report of the IEA's Net Zero Emissions by 2050 Scenario (NZE Scenario), hydrogen use is projected to grow by 6% annually until the end of the decade. This would mean surpassing 150 million tons of hydrogen use by 2030, with nearly 40% originating from new applications. [6]

During the third edition of the "Hydrogen Forum" held by "Il Sole 24 Ore" in march 2023, the Head of Cabinet of Commissioner Kadri Simson, Stefano Grassi, has underlined that in Europe there is a fundamental risk. Almost 600 projects have been mapped at European level, but only 10% of these have reached the mature stage and investment threshold. For most projects, a decision will have to be made within 2-3 years if they will become operational and secure funding. Europe made a promising start in the initial phase, but now other contenders are ramping up and intensifying their efforts. If Europe is not careful, it risks falling behind because there are ambitious programs in India, China, Japan, and the USA. The risk is that the planned investments may not materialize and find better conditions elsewhere.

2.4.2 Italy overview: National Hydrogen Strategy and Hydrogen Valleys

In 2015, the EU made its first formal commitments to fight climate change through agreements like the Paris Agreement (COP 21) and the Sustainable Development Goals (Agenda 2030), aiming to limit global temperature rise. This led to the creation and implementation of initial decarbonization plans. The EU's Clean Energy Package (2016) mandated a 40% reduction in CO2 emissions by 2030 compared to 1990 levels. Subsequently, the European Green Deal (2019) established a target of zero emissions by 2050. Each member country, including Italy, must formulate its own plan in alignment with these EU directives.

In Italy, the Integrated National Plan for Energy and Climate (PNIEC) was established in 2019, outlining the role of hydrogen in achieving EU objectives, particularly in sectors that face challenges in decarbonization and in managing excess renewable energy generation. Additionally, the National Energy Strategy was set in place in 2017 to further support these efforts.[7]

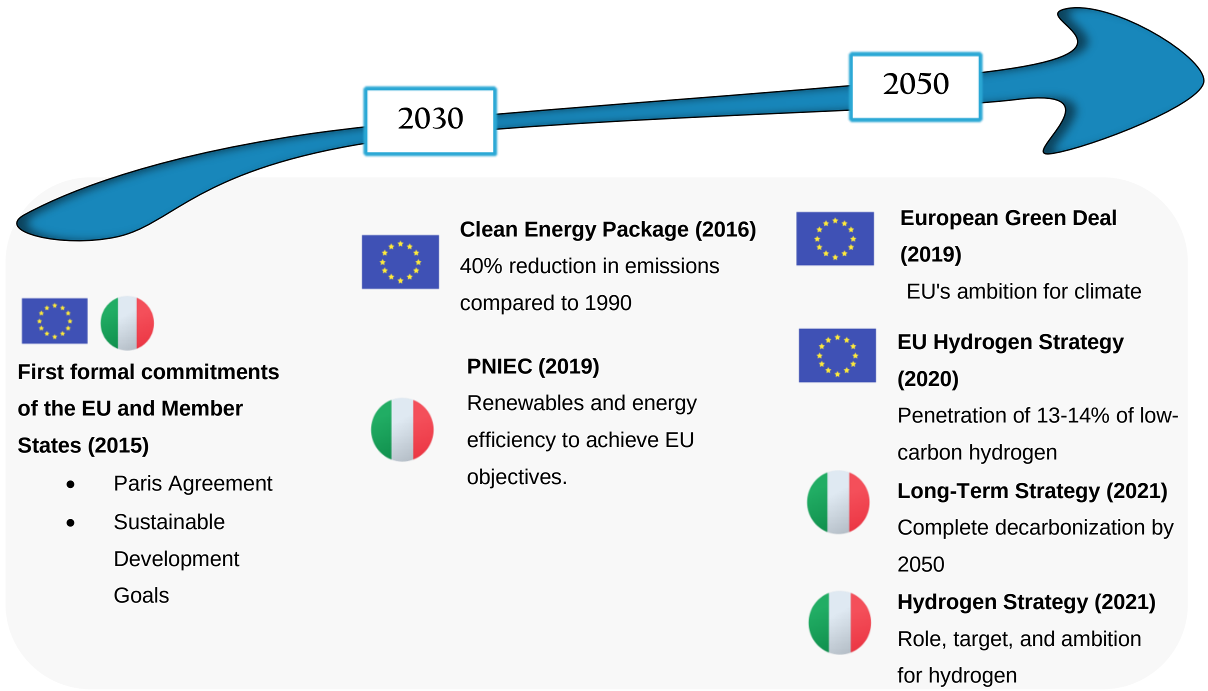


Figure 8 - Key Environmental Milestones for the EU and Italy – Revised from [7]

In 2020, Italy's Ministry of Ecological Transition (MiTE) introduced initial hydrogen guidelines (Strategia Nazionale Idrogeno: Linee Guida Preliminari) for consultation, before the finalization of the national hydrogen strategy. The guidelines indicate that by 2030 the targets are as follows [7]:

- Achieve 2% of the final energy demand through H2.
- Reduce CO2 emissions by 8 Mt.
- Install 5 GW of electrolyser capacity for H2 production.
- Invest 10 billion euros in hydrogen generation, with half of the funding coming from European sources.
- Boost GDP by 27 billion euros.
- Create numerous temporary (200,000) and permanent (10,000) jobs.

For 2050, the objectives include:

- Increase hydrogen's share in the energy mix from less than 2% to 13-14%.
- Install 500 GW of electrolyser capacity for H2 production.
- Achieve hydrogen penetration rate of up to 20% in final energy consumption.

According to the Hydrogen Innovation Report [8], Italy's projected involvement in establishing electrolysis-based hydrogen production facilities over the next 7 years is limited to 24 projects out of a European total of 631. These projects are expected to provide 1.97 GW of electrolysis capacity, significantly lower than Europe's total of 93.55 GW, and falling short of the 5 GW target outlined in the guidelines.

The main fault lies in the lack of a national strategy. Italy is stuck at the guidelines phase, whereas the five most proactive European nations, including Germany, Spain, the Netherlands, Denmark, and the UK (accounting for approximately 75% of production), already have well-defined regulations in place. Each of these countries has declared capacities surpassing 10 GW by 2030, with figures ranging from 11.4 GW in the UK to 17 GW in Germany.

To accelerate the achievement of European targets for total decarbonization, hydrogen is indispensable. It is crucial for the so-called "hard-to-abate" sectors (steel and foundries, chemicals, ceramics, paper, and glass) and for heavy transport, as there are limited viable alternatives due to the challenges in electrification.

In addition, the significance of “hydrogen valleys” advancing hydrogen mobility is confirmed. These are centres for the production and consumption of renewable hydrogen capable of enabling end uses. Through the National Recovery and Resilience Plan (PNRR), a total of 500 million euros have been allocated for these initiatives playing a crucial role in initiating a hydrogen market. The winning projects in the competition amount to 54 in total, with a significant focus on Southern Italy, where 50% of the funds are allocated.

Hydrogen Valleys can be considered local ecosystems focused on both the production and consumption of hydrogen, with a preference for renewable sources. They represent a flexible and evolving concept, designed to address unique local requirements rather than following a rigid, standardized model. These parameters for identifying Hydrogen

Valleys have been established by "The Hydrogen Valley Platform," a collaborative initiative led by "FCH JU" and "Mission Innovation." The key points can be summarized as follow [11]:

1- Development Scale: These hydrogen districts are not just demonstrative projects but aim for the market with multimillion-dollar investments. The dimensions are usually defined by a series of significant byproducts.
2- Clear Geographical Scope: Hydrogen Valleys are always designed around the destination and its characteristics, such as a large port and its hinterland.
3- Complete Value Chain Engagement: Hydrogen Valleys must cover the entire value chain, from H_2 vector production to treatment, storage, and distribution. In most cases, the district also includes renewable power generation facilities to feed the electrolysers.
4- Supply to Different Sectors: Hydrogen hubs ideally cater to various needs, from mobility to industry, and can be considered ecosystems where various final applications share a common infrastructure.

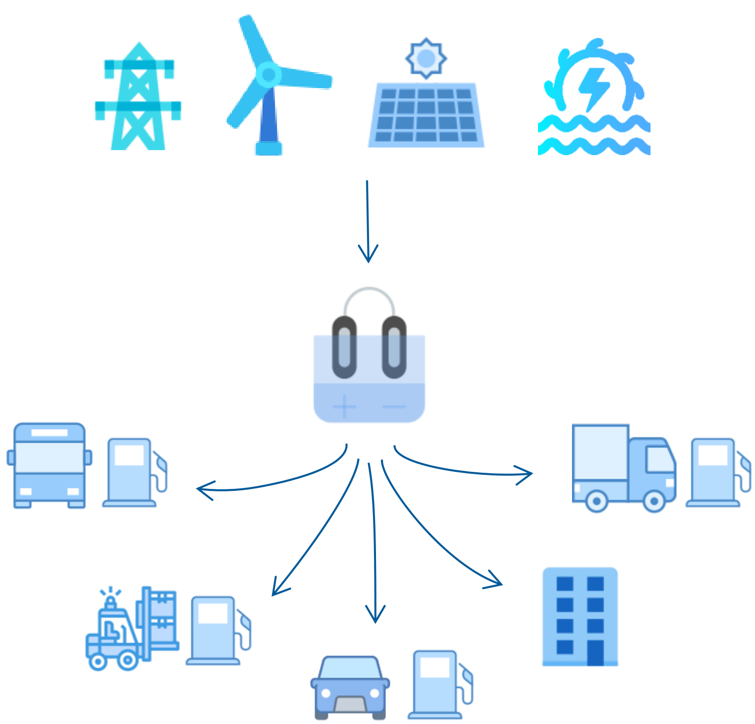


Figure 9 - Hydrogen Valley local, small-scale & mobility-focused

The inherent versatility of hydrogen allows for its integration into various sectors and the establishment of diverse supply chain setups. As a result, hydrogen valleys may exhibit a wide range of diversification in:

- Production methods (e.g., electrolysis, steam methane reforming, gasification).
- Logistics, aligned with the state of the molecule (e.g., gaseous, liquid, or transported via alternative carriers).
- Infrastructure (e.g., conveyed through pipelines, trucks, ships, or rail tanks).
- Ultimate applications (e.g., industrial processes, transportation, residential heating).

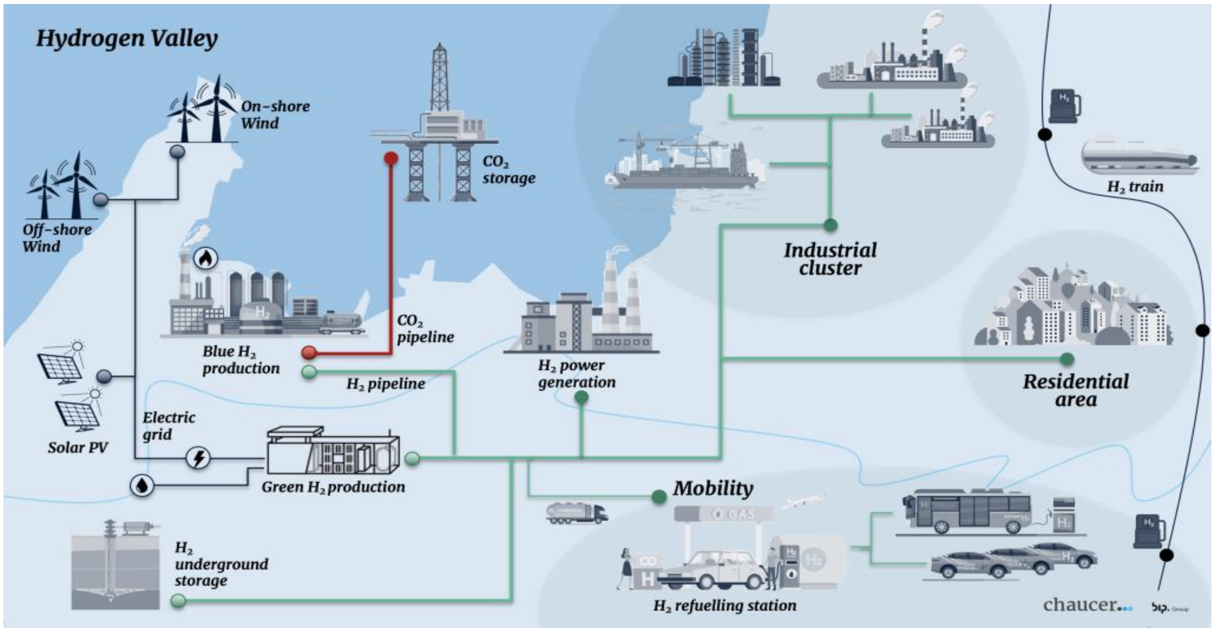


Figure 10 - Hydrogen uses and Hydrogen Valley Ecosystem [9]

In areas where there is a concentration of demand for green hydrogen, it will create favourable conditions for the emergence of initial hydrogen valleys in specific geographical regions. These points of formation must be strategically located, such as in proximity to critical road and rail intersections and industrial hubs. Unfortunately, finding areas that are both suitable for renewable production and align with these criteria can be challenging.

Three potential production and transport models have been identified [8]:

1- On-site total production: This minimizes transport costs by producing hydrogen directly where it is used.
2- On-site production with electricity transport: Renewable electricity is transferred from the production site to the consumption point via the grid, where it is then converted into hydrogen using electrolysis.
3- Centralized production with hydrogen transport: Renewable electricity is utilized on-site to produce hydrogen, which is then transported to users either through the gas network or heavy transport.

While the first option aligns most closely with the concept of a hydrogen valley, it may not always be feasible to have power generation in close proximity to hydrogen production. It serves as a good alternative but may not be universally applicable.

Currently, due to the limited development of a hydrogen distribution network (with less than 2% integration into the natural gas network in the near future), the third option may be the most expensive one. However, when considering the system as a whole in the long-term and on a global scale, it is expected to provide benefits that outweigh the costs.

Currently, 10 regions in Italy along with the province of Trento have published rankings of eligible projects for funding [10].

1- **Abruzzo:** Three projects have been approved for funding, with a total investment of around 20 million euros out of 24 million available.
2- **Basilicata:** Three projects are in the ranking for admission and funding, totalling 18 million euros.
3- **Calabria:** Two proposals have won the regional tender for hydrogen Valleys. This amounts to over 21.5 million euros in eligible contributions.
4- **Emilia Romagna:** Only the IdrogeMO project, led by Hera with SNAM and HERAmbiente, has been considered eligible for funding in the region, receiving 19.5 million euros. This initiative will establish a hydrogen district in Modena capable of producing up to 400 tons of H_2, powered by a 6 MW photovoltaic park.
5- **Liguria:** Enel SpA's project, which involves the development and construction of an electrolysis plant in a partially decommissioned industrial area, has nearly

exhausted the allocated 14 million euros. Estimated production: around 134 tons of hydrogen annually.

6- **Piemonte:** Three projects in Piemonte are eligible for funding with an amount of 19.5 million euros.

7- **Puglia:** Out of 17 proposed projects are eligible for the Hydrogen Valley call, only 5 can be financed based on available resources.

8- **Sardegna:** The evaluation process of the nine received applications deemed only two of them fully eligible for the requested amount, and one partially.

9- **Toscana:** The Rosignano HVG project, presented by Solvay chimica Italia and Sapio, emerged as the winner of the call, receiving 17.5 million euros.

10- **Trento**: Three projects have been deemed eligible for funding for a total amount of 14 milion euros.

11- **Valle D'Aosta**: Two projects eligible for funding, proposed by Cogne Acciai Speciali (7.9 million) and Compagnia valdostana delle Acque (6.1 million), for a total of 14 million euros.

2.4.3 H_2 Current Uses

Hydrogen finds diverse applications through:

1. Hydrogen fuel cells.
2. Combustion in modified engines (H2ICE).
3. Conversion into chemicals.

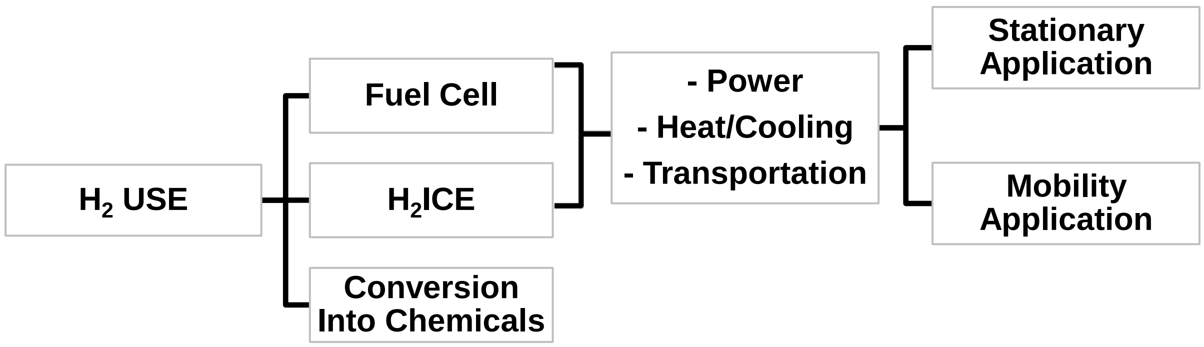


Table 1 - Hydrogen Current Uses

Fuel cells essentially perform electrolysis in reverse, converting stored hydrogen's chemical energy into electricity and heat through an electrochemical reaction with oxygen. On the other hand, Hydrogen combustion involves a high-temperature exothermic redox chemical reaction with oxygen in an engine.

- Both processes release only water as a byproduct.
- Both technologies meet the needs for power generation and heat production supplying the demand of the three main sectors: power, heat/cooling, and transportation.

These sectors can be further categorized into stationary and mobile applications. For stationary energy purposes, hydrogen is employed for storage and subsequent conversion into electricity. Hydrogen proves highly advantageous in applications that require large quantities and prolonged storage periods. Among the technologies there are compression, liquefaction, cryogenics.

Fuel cells are gaining popularity as a secondary power source, offering an alternative to engine or turbine-driven generators and rechargeable batteries. Given that both fuel cells and hydrogen engines produce both electricity and heat, their integration into combined heat and power (CHP) systems holds significant promise for enhancing energy efficiency in residential and commercial buildings. Regarding mobility applications, hydrogen is employed as an energy source in the transport sector. In both stationary and mobile scenarios, transport technologies utilize fuel cells and combustion engines, with different modes of transportation.

Currently, a substantial number of forklift trucks in the industrial sector are powered by hydrogen fuel cells. This underscores the potential for developing a market for small vehicles dedicated to transportation and services.

Finally, hydrogen can also be used to produce chemicals, materials, and fuels. Today, it plays a crucial role as a primary raw material in the petrochemical sector. A notable share of hydrogen is dedicated to the production of ammonia, which serves various functions including fertilizer, fermenter, cleaner, and refrigerant [13].

3 H_2 Uses: Logistic and Transportation Focus

In order to achieve a sustainable, secure, and universally accessible energy system necessitates, the transition needs a significant transformation of the entire mobility ecosystem including industrial, road, and off-road vehicles, as well as maritime and aviation transportation sectors.

Figure 11 - Future Mobility System [29]

To successfully address the trend of mitigating climate change as delineated in the Paris (COP21) and Glasgow (COP26) Climate Agreements, propulsion technologies need to rapidly achieve CO_2 reduction in the very short term.

In recent years, the significance of electric propulsion systems powered by renewable energy-charged batteries has become evident. It is not only a widely supported public initiative but also the primary focus of research for both academic and industrial communities. However, it is important to recognize that this technology may not entirely fulfil the different demands related to personal mobility, sustainability, and feasibility.

In the near future, it is widely recognized that there is not one energy source able to completely control the global energy market. Instead, a widely accepted approach is to use a mix of energy sources based on what is available in different countries or regions, or the option to import energy resources.

Therefore, in the transportation sector, which has few options for nearly zero-emission energy carriers (such as electricity and advanced biofuels), internal combustion engines (ICE) fuelled by non-fossil hydrocarbons and hydrogen (H2ICE), and fuel cell (FC) powertrains will play a crucial role, in parallel with electric powertrains,

Hydrogen, when integrated with Internal Combustion Engine (ICE) technologies, holds potential to address emission reduction challenges. The Hydrogen-fuelled ICE (H2ICE) represents the only alternative allowing the ICE powerplant to operate without CO_2 emissions from tank-to-wheel, at the exhaust system. Despite its combustion advantages, hydrogen engines require precise design to avoid irregular combustion, and for this reason, H2 engines are subjected to a series of tests to ensure their durability, reliability, safety, as well as performance.

In addition, hydrogen offers several advantages over batteries, such as significant weight reduction and the ability to achieve high range with short refuelling times, which is crucial. This makes hydrogen a viable option for various applications, including heavy-duty trailers, buses, trucks, and small airplanes. However, it comes with a drawback: reduced efficiency. This is particularly noticeable in Fuel Cell technology, which involves two energy conversions, resulting in lower overall efficiency. Present technologies have not yet reached the required level of high efficiency. As a result, substantial investment in fuel cell depends on progress in the cost, performance, reliability, durability, and safety of its components in automobiles. However, should be underlined that lot of research is being done on both technologies as shown in the following Figure 12, in which companies like AVL are developing specific solutions for different applications, both ICE and FC.

Figure 12 - AVL Hydrogen Engine and PEM Fuel Cell - https://www.dieselprogress.com/news/avl-moves-ahead-with-hydrogen-engine/8010310.article

3.1 H_2 Fuel Cell

The development we have seen recently in hybrid car technology has shown that the time required between consecutive refuelling procedures can be reduced, presenting a potential solution to address the mentioned drawbacks. By incorporating a second energy storage system into the vehicle, enabling the battery to charge while driving, the duration between refuelling stops is extended, leading to an improvement in range autonomy. A notable example of a hybrid device is the combination of hydrogen and proton-exchange membrane (PEM) fuel cell [14]. In comparison to the electric vehicle, it shows advantages which can attract many consumers.

The hydrogen fuel cell demonstrated its capability to directly convert chemical energy into electricity, among other advantages. Such technology has become a priority for the world's largest car manufacturers. In any case, a deeper study is needed for the development and application of hydrogen-based fuel cells, both for electric cars and pure hydrogen vehicles.

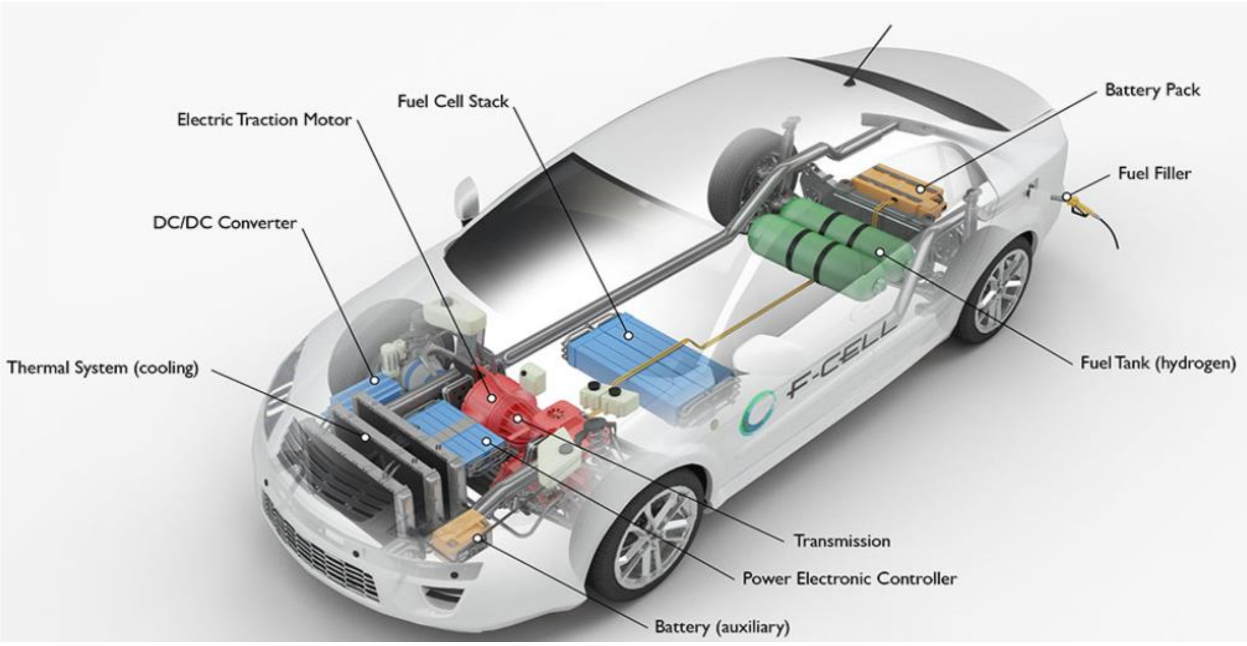


Figure 13 - Fuel Cell Powertrain [https://afdc.energy.gov/]

A hydrogen fuel cell (FC) is an electrochemical device that converts the chemical energy of a fuel (hydrogen in this case) directly into electricity, with water as the only byproduct. It operates on the principle of combining hydrogen (H_2) and oxygen (O_2) from the air to produce electricity, heat, and water. Unlike a battery, which stores electrical energy, a fuel cell can generate electricity as long as it is supplied with hydrogen. H_2 fuel cell technology provides a high-density source of energy with good energy efficiency compared to conventional combustion engines, achieving an electrical energy conversion efficiency of 60% or higher, resulting in reduced emissions. Indeed, the power generation process do not generate greenhouse gas emissions, eliminating carbon dioxide and air pollutants responsible for smog and health issues. Additionally, fuel cells generate minimal noise during operation due to their fewer moving parts and show great versatility in applications, both in transportation and stationary, also ideal for remote areas.

The challenges are mainly related to the H_2 molecule and FC materials:

1) **Hydrogen production, safe storage, and transportation:** Depending on production methods, hydrogen may still have a carbon footprint if derived from non-renewable sources.

2) **Infrastructure investment:** building a complete hydrogen infrastructure is costly and demands significant investment.
3) **Cost:** Hydrogen fuel cell technology is presently more expensive than some alternatives, employing raw and precious materials such as platinum and iridium, limiting widespread adoption.
4) **Efficiency Losses:** if the entire power generation process is considered, from hydrogen production to electricity production, the multi-stage process of converting leads to efficiency losses. Indeed, the various efficiencies of the energy chain must be considered:

   energy production plant → hydrogen manufacturing plant → fuel cell

   A significant portion of the input energy is inevitably lost (this loss can exceed 70% depending on the methods employed for initial electrical energy production for hydrogen generation and the techniques used for hydrogen production).

3.1.1 Fuel Cell Operation and Structure

The operation of a hydrogen fuel cell can be broken down into three main reactions:

1) **Anode Reaction:** Hydrogen molecules undergo a process of electrolysis, separating into protons (H^+) and electrons (e^-) at the anode. This reaction is represented as:

$$\boldsymbol{H_2 \rightarrow 2H^+ + 2e^-} \qquad (3.1)$$

Cathode Reaction: Oxygen molecules are reduced at the cathode, combining with protons and electrons to form water. The reaction is:

$$\boldsymbol{O_2 + 4H^+ + 4e^- \rightarrow 2H_2O} \qquad (3.2)$$

Overall Reaction: The overall process in a hydrogen fuel cell involves the combination of the anode and cathode reactions, resulting in:

$$\boldsymbol{2H_2 + O_2 \rightarrow 2H_2O + energy} \qquad (3.3)$$

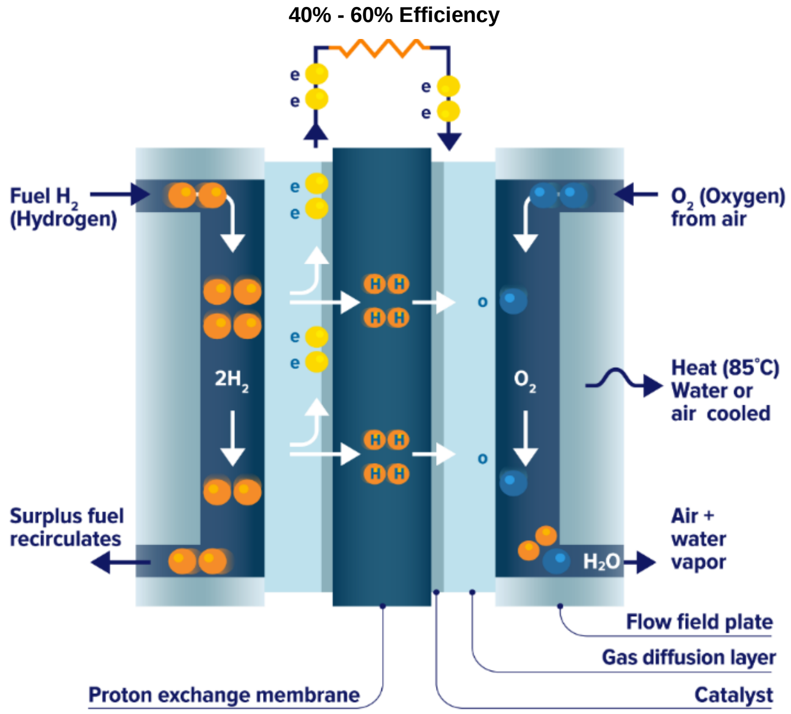


Figure 14 - Fuel Cell Basic Structure
[https://www.chfca.ca/fuel-cells-hydrogen/about-fuel-cells/]

In this reaction, hydrogen (H_2) is oxidized at the anode to produce protons (H^+) and electrons (e^-). The electrons travel through an external circuit, generating electric current that can be used to power the load. Meanwhile, the protons migrate through the electrolyte to the cathode. At the cathode, electrons, protons, and oxygen (O_2) react to form water molecules (H_2O).

The reaction produces electrical energy, heat, and water as byproducts, making fuel cells an intriguing option for clean and sustainable energy production.

A single hydrogen fuel cell is capable to provide only a theoretical voltage of approximately 1.2V, which is lower when real application is considered. A stack is a multitude of cells connected in series in order to obtain a higher chemical voltage. A Fuel cell typically consists of these main layers:

1) Anode Layer: This is where hydrogen is split into positively charged ions (protons) and negatively charged electrons at the beginning of the energy generation process.

2) Electrolyte: is an ionically conductive layer that allows protons to move from the anode side to the cathode side, while blocking the movement of electrons. It can be made of various materials, such as a proton exchange membrane.
3) Cathode Layer: the reaction between oxygen and the protons from the electrolyte occurs, producing water as a byproduct.
4) Catalyst: The catalyst, usually made of platinum, accelerates the electrochemical reactions occurring at the anode and cathode [16].
5) Bipolar Plates: Bipolar plates are used to distribute the reactant gases, collect the generated electricity, and provide structural support for the fuel cell stack [16].

In particular, anode catalyst layer (ACL) and cathode catalyst layer (CCL), together with the proton-exchange membrane and the gas diffusion layer (GDL), form what is known as MEA (membrane electrode assembly).

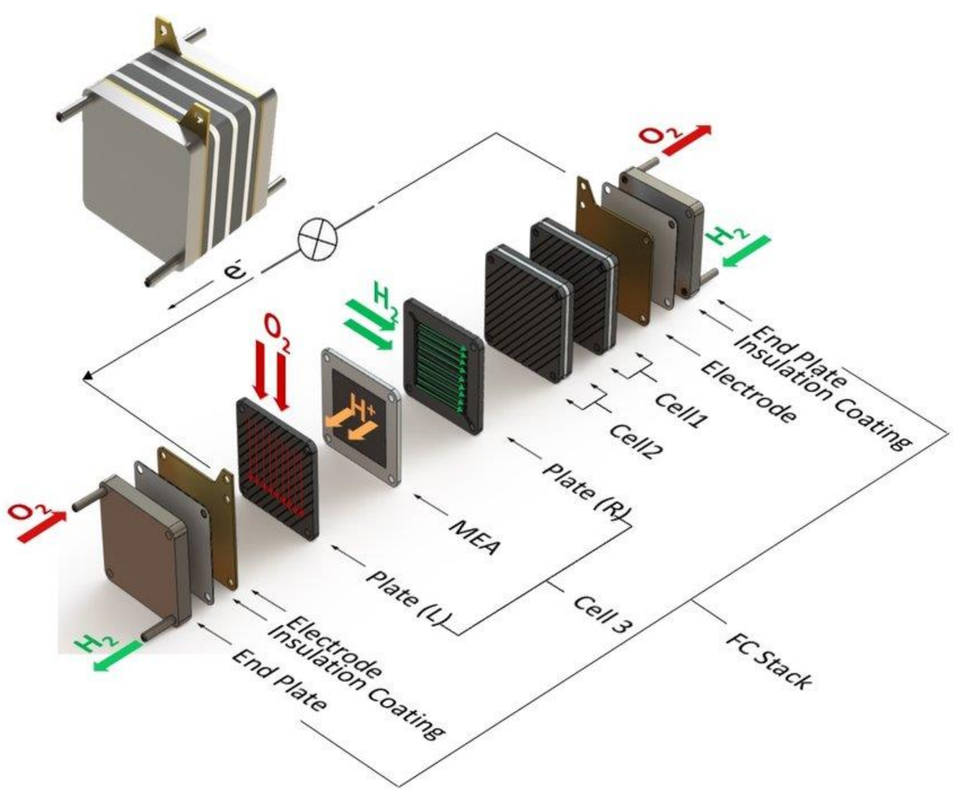


Figure 15 - Schematic of a Fuel Cell Stack Operation and Components [A review on prognostics and health monitoring of proton exchange membrane fuel cell (researchgate.net)]

Fuel cells are classified primarily on the type of electrolyte they utilize. This classification determines the kind of the electrochemical reactions, catalysts, operating temperature range, required fuel, and other key factors within the cell. The main are [17]:

- Proton Exchange Membrane Fuel Cells (PEMFC): They employ a polymer electrolyte membrane and operate at relatively low temperatures, making them well-suited for transportation and portable power applications.
  - Normal operating temperature: 60°C ÷ 120°C.
  - Typical Efficiency: 40% ÷ 60%.

- Alkaline Fuel Cells (AFCs): They employ an alkaline electrolyte solution. They have been utilized in space missions (Apollo and Space Shuttle) and submarines thanks to their high efficiency and power density.
  - Normal operating temperature: 60°C ÷ 100°C.
  - 250 °C in space missions.
  - High efficiency, also over 70% even at full power operation.

- Phosphoric Acid Fuel Cells (PAFC): They use a liquid phosphoric acid electrolyte and are commonly used in mid-size stationary power generation for commercial buildings and utilities.
  - Operating temperature: 150°C ÷ 220°C.
  - Typical Efficiency: 40%.
  - Considered a "mature" technology with no further expected advancements.

- Solid Oxide Fuel Cells (SOFC): Solid Oxide Fuel Cells (SOFCs) employ a solid ceramic electrolyte and operate at high temperatures, which makes them well-suited for large-scale stationary power generation and combined heat and power systems.
  - Operating temperature: 500°C ÷ 1000°C.
  - Typical Efficiency: 50% ÷ 60%.
  - Their residual gases can be used to power a gas turbine, increasing the energy efficiency of the plant. In these hybrid systems, known as Combined Heat and

Power (CHP) devices or cogeneration plants, efficiency can even reach peaks of 90%.

- Molten Carbonate Fuel Cells (MCFC): They employ a molten carbonate salt electrolyte and are engineered for large-scale stationary power generation. Additionally, they have the flexibility to utilize diverse fuel sources such as natural gas and biogas.
  - Operating temperature: 600°C ÷ 650°C.
  - Typical Efficiency: 60%.
  - Challenges in managing a corrosive liquid at high temperature.

	ALKALINE (AFC)	PROTON EXCHANGE (PEM & HTPEM)	PHOSPHORIC ACID (PAFC)	MOLTEN CARBONATE (MCFC)	SOLID OXIDE (SOFC)
Anode	Platinum or Carbon (GenCell)	Platinum	Platinum	Steel/nickel	Ceramic
Electrolyte	Potassium Hydroxide (KOH)	Polymer Membrane	Phosphoric Acid (H3PO4)	Molten Carbonate	Yttria-Stabilized Zirconia (YSZ)
Type	Liquid	Solid	Liquid	Solid	Solid
Fuel	• Hydrogen • Ammonia (GenCell)	• Hydrogen	• Hydrogen • Methanol	•Natural gas •Methanol •Ethanol •Biogas • Coal gas	•Natural gas •Methanol •Ethanol •Biogas •Coal gas
Temperature	• 60-70 ºC	• 80-100 ºC • 200 ºC	• 150-200 ºC	• 650 ºC	• 500-1000 ºC
Efficiency	60-70% (80% CHP)	30-40%	40-50% (80% CHP)	50% (80% CHP)	60%
Power	0.5–200kW	0.12-5kW	100 - 400kW	1kW - 2MW	0.01 -2000kW
Startup Time	< 1 min	< 1 min	n/a	10 min	60 min
Pros	• Quick startup • Temperature resistant	• Quick startup • Small and Light weight	• Stable • Maturity	• Fuel variety • Efficient	• Fuel variety
Cons	• Liquid catalyst adds weight • Relatively large	• Sensitivity to humidity or dryness, salinity and low temperatures	• Phosphoric acid vapor • Less powerful	• Slow to respond • Highly corrosive	• Long startup time • Intense heat

Table 2 - Different Type of Fuel Cell - adapted from [16]

Currently, the Proton Exchange Membrane fuel cell (PEMFC) stands out as the most suitable technology for a wide range of transport applications, both light and heavy. In contrast to other fuel cell technologies, PEM fuel cells offer advantages, including rapid start-up, effective cold starts in low-temperature environments, high power density, versatile operating capacity, and a lightweight, compact system. They also operate within a practical temperature range.

3.2 Internal Combustion Engine (H2ICE)

Given the global efforts to address climate change, the widespread adoption of a reliable and cost-effective propulsion technology like the internal combustion engine (ICE) can make a substantial difference. This is particularly true when renewable fuels replace conventional fossil fuels. Hydrogen fuels can play a crucial role in this transition by enabling IC engines to produce zero CO_2 emissions and minimizing the release of harmful pollutants.

The H2ICE is appealing because the ICE is currently a mature technology. These include attributes like reliability, durability, an established supply chain, existing manufacturing, and recycling infrastructure, as well as affordability. These attributes make the H2ICE a solution in the near-term to integrate hydrogen into the transportation market and for its long-term adoption.

The H_2-fueled internal combustion engine offers a practical option for powertrain applications, producing zero tank-to-wheel CO_2 emissions. Additionally, it can run on less refined hydrogen, reducing fuel production costs. By implementing technologies like high boost pressures, direct injection, advanced combustion techniques, laser ignition, and specialized SCR systems, a highly efficient and competitive propulsion system can be achieved [18].

Regarding the pollutant emissions, combustion leads to the production of some NOx (nitrogen oxides) with trace of particulates due to the combustion of a minimal amount of lubricating oil. However, employing a lean mixture, a proper after-treatment system, and specific lubricating oil can eliminate their impact. Advanced hydrogen SCR (Selective Catalytic Reduction) catalysts and particulate filters are effective in reducing these emissions to zero.

H2ICE technology might be more cost-effective than the current state of EV powertrain technology because it relies less on scarce and costly materials like rare earth metals.

Anyway, the cost-effectiveness of a hydrogen combustion engine compared to electric vehicle technology depends on various factors, including production scale, availability of resources, and technological advancements. As of now, electric vehicle technology has seen significant advancements and is becoming more cost competitive. However, the cost of hydrogen production, storage, and distribution infrastructure can impact the overall affordability of hydrogen combustion engines. It is essential to consider both technologies' complete lifecycle costs, including manufacturing, operation, and maintenance, to make a comprehensive comparison. What we can say is that if this technology undergoes developments in the same way as EV technology, then it could be more convenient.

3.2.1 Hydrogen Use in Internal Combustion Engines

Engines are broadly classified into two main groups based on the fuel injection method [18]. Figure 16 provides a general classification of hydrogen ICE technology:

- Port Fuel Injection (PFI): Hydrogen PFI engines typically use spark discharge for ignition. They can also operate in dual-fuel mode with pilot diesel or utilize auto-ignition in the homogeneous charge compression ignition (HCCI) mode.

- Direct Injection (DI): In hydrogen direct injection (DI) studies, ignition is typically achieved through spark assistance or hot-surface methods, such as using a glow plug. This injection mode also holds the potential for dual-fuel operation, where hydrogen is ignited by the high-temperature environment generated by pilot diesel-fuel combustion, known as the H2DDI mode.

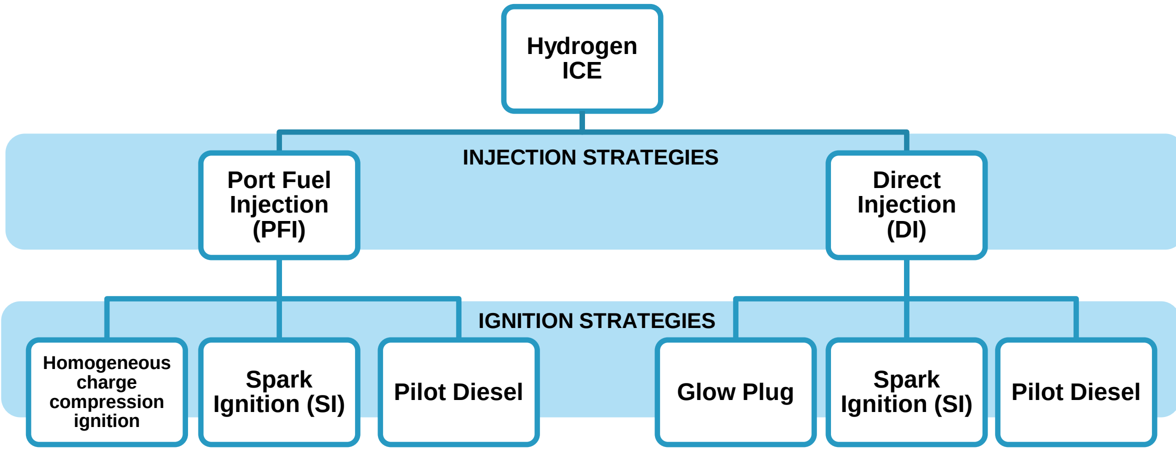


Figure 16 - Hydrogen Engine Combustion Types

Most prototypes of hydrogen internal combustion engines (H2ICE) utilize a Port Fuel Injection (PFI) system. Converting conventional gasoline engines to run on hydrogen is a relatively straightforward process. However, hydrogen PFI systems come with well-known drawbacks, including issues like pre-ignition, knocking, backfiring, low volumetric efficiency, and compression loss. These factors limit the engine's potential load and efficiency.

These limitations can be addressed by transitioning to a Direct Injection (DI) system. Achieving proper injection, ignition, and mixture formation are crucial elements in preventing abnormal combustion. Implementing DI alongside specialized injection strategies that prevent hydrogen from flowing back towards the intake manifold serves as an effective measure to prevent backfire. An additional approach to manage abnormal combustion involves increasing air dilution. Due to hydrogen's high flammability range, it is feasible to operate the engine at an extremely low Fuel-Air Equivalence Ratio. This lean hydrogen combustion further offers the significant advantage of greatly reducing NOx emissions. [20].

It is highly likely that the future of spark ignition (SI) engines will rely on direct injection. Therefore, mid to high pressure DI, probably could be the way to implement hydrogen combustion.

Although it is a promising strategy, the low engine compression ratio in conventional SI engines limits the thermodynamic efficiency. Therefore, dual-fuel hydrogen-diesel direct

injection in compression-ignition (CI) engines shows promise in overcoming power and compression ratio limitations associated with hydrogen use in spark-ignition engines. This approach involves substituting spark ignition with pilot fuel ignition, enabling rapid combustion of gaseous fuel [20]. In CI hydrogen engines, a high-pressure injection system is crucial, requiring almost double the pressure levels of SI engines, reaching up to 600 bars. However, the limited availability of injection systems is challenging for the expansion of hydrogen CI engines. Big companies are doing research to create hydrogen Direct Injection (DI) systems, primarily for large Heavy Duty (HD) CI engines such as in maritime transport. The successful development and widespread implementation of these systems are essential for establishing hydrogen as the primary fuel for CI engines.
The figure 17 shows the developments of H2ICE in the short and mid-term:

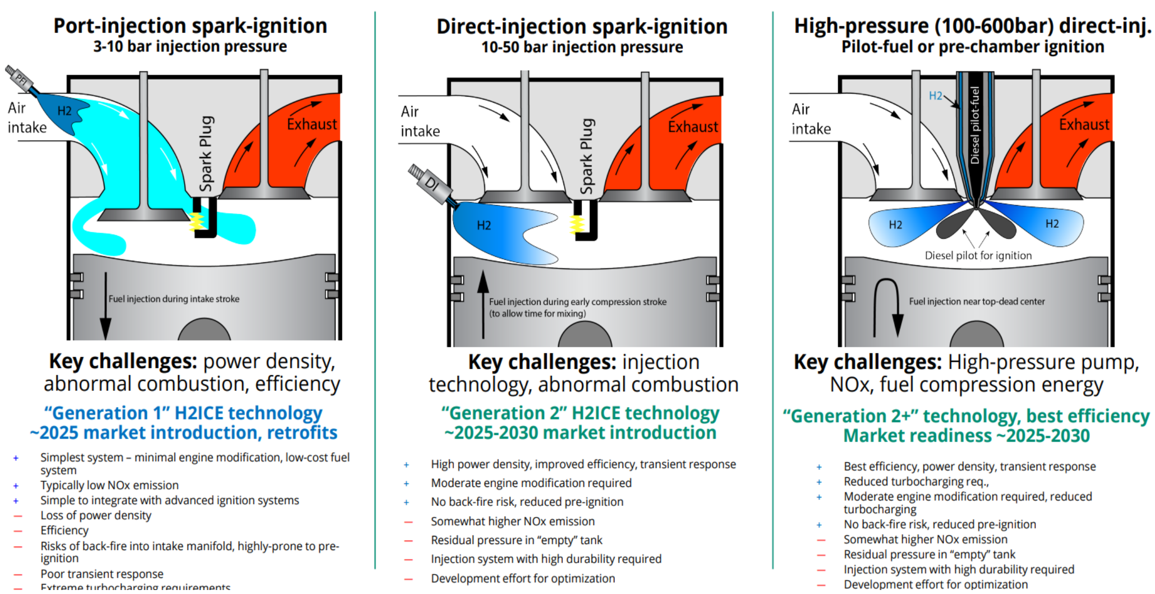


Figure 17 - H2ICE Technical Concepts Differentiated By Fuel Injection [34]

During a workshop held at the AVL headquarters in Graz has been showed the H2ICE market approach regarding the most interesting and important paths for the mobility sector. As we can see from the following table is that at the moment the developments are focused in the heavy and medium duty sectors, for road and urban vehicles, but also in shipping sector, that is very important and currently the fuel strategy is more oriented in mixed fuel, with ammonia, diesel, in order to reduce the high amount of emissions produced in this area.

For what concerns the recent approaches, research and development have been made on non-road mobile machinery and light duty (LD) vehicles. An important thing to notice is the difference between the combustion engine concepts and which are the current best solutions for each sector. In addition, it is reported the Air/Fuel ratio, which is crucial topic for hydrogen internal combustion engine, indeed, compared to stoichiometric gasoline ICEs, the air consumption level of a lean H_2 engine is expected to be about 50% higher. To supply such a high mass flow, it is expected that high boost pressure is necessary in the H2ICE application. Due to the wide range flammability of hydrogen, the H2ICE can operate with a wide range of fuel-air mixtures. An important benefit is its ability to operate on a lean mixture, where the amount of fuel is less than the chemically ideal amount for combustion with a given quantity of air. This makes starting an engine on hydrogen relatively straightforward. In the ultra-lean and lean area can be found mostly the heavy-duty applications.

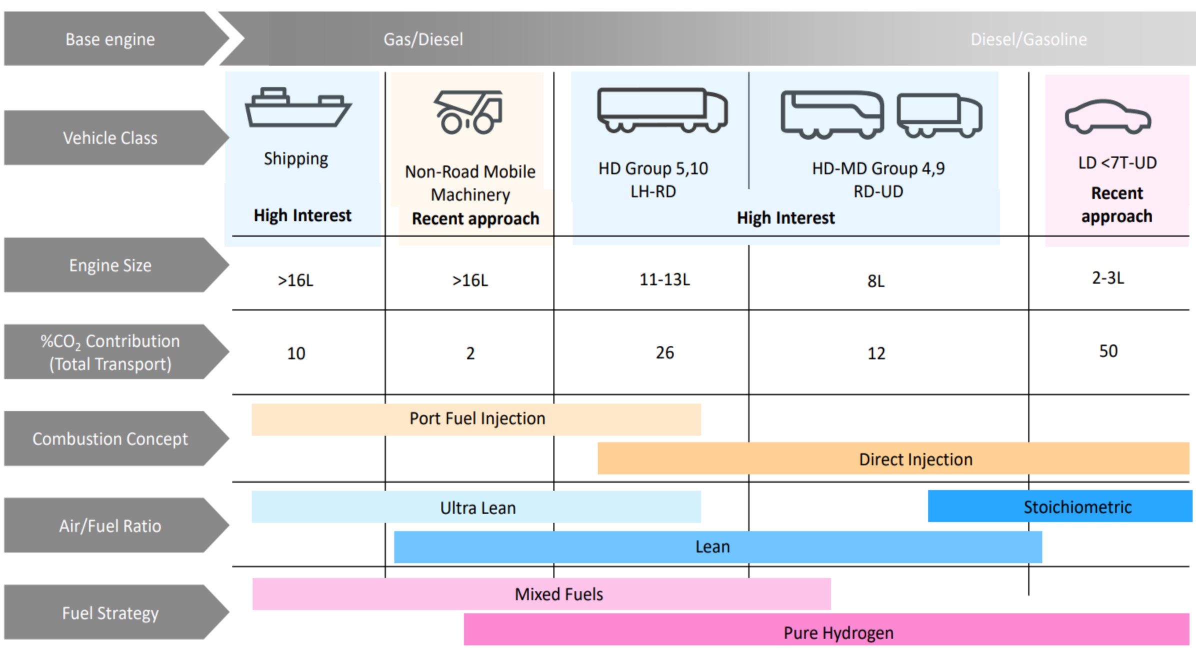


Table 3 - H2 Market Approach [29]

It is recent news (October 2023) that AVL Racetech celebrated a new success: its two-liter hydrogen racing engine prototype achieved the same high results obtained in the simulations on the test bench. The new turbo H2ICE aims to debunk the reputation of the

H2ICE, mostly characterized by low performance and lean combustion (high air/fuel ratio).

The high-performance engine, tested in Graz, Austria, has impressive specifications. It can deliver 410hp at 6,500rpm and a maximum torque of 500Nm between 3,000 and 4,000rpm [21]. With a specific power density around 205hp per liter (150 kW per liter), the engine achieves a highly competitive level in the world of motorsport. Already reaching 205hp per liter would be a notable achievement, but doubling the values would overshadow even a car like the Bugatti Chiron, which reaches 188hp. The closest rival in terms of standard performance is the SSC Ultimate Aero TT, capable of generating 205hp per liter.

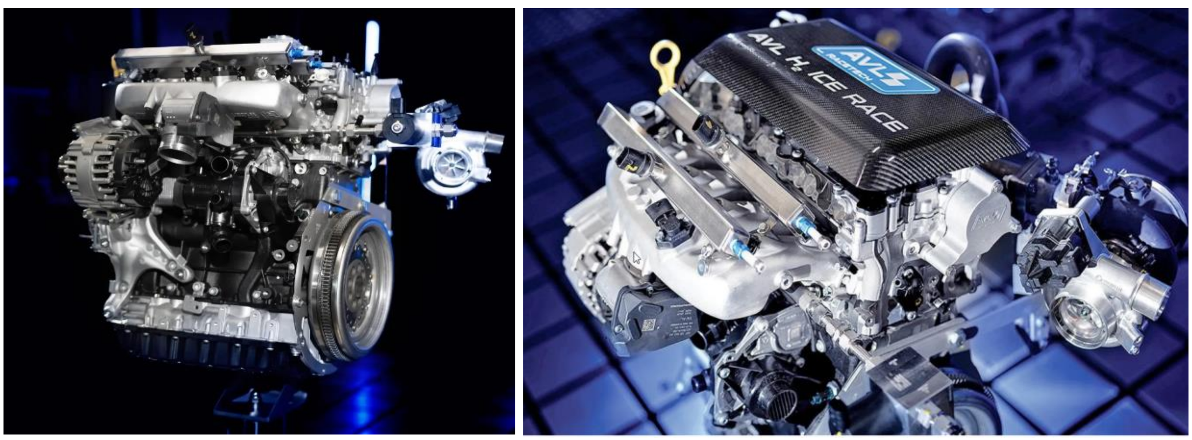


Figure 18 - 410 hp from 2- Liter Turbo Engine - H2ICE Race Engine from AVL RACETECH [21]

To overcome the historical challenges of H2ICE, AVL has made several design enhancements, including an intelligent Premixed Fuel Injection (PFI) water injection system. This system increases the water content in the engine's aspirated air to prevent premature ignition. The air-fuel ratio is set at 1 (stoichiometric combustion), placing the engine outside the lean range. The reduced air requirement is addressed by using a specially designed turbocharger [21].

3.3 H2 ICE and H2FC comparison

The advantages of hydrogen ICE compared to the FC technology include a higher tolerance to fuel impurities, flexibility to switch between fuels, reduction of rare materials usage and a more straightforward transition from conventional vehicles. In addition, hydrogen ICE technology benefits from the reduced cost of using the existing mature manufacturing facilities and processes for conventional ICEs. The development of advanced hydrogen ICEs (DI and dual-fuel methods) is still in the conceptual stage. Most hydrogen-fuelled ICE prototypes use port fuel injection (PFI) system, benefiting from a straightforward conversion from existing gasoline engines. Contrarily to FC powertrain systems, H2 ICEs can be fuelled with non-purified hydrogen, resulting in significantly lower production cost of hydrogen fuel.

Considering the possible developments of the next generation of H2ICE, the resulting thermodynamic efficiency could be similar to that of a modern Fuel Cell powertrain.

The difference between the technologies is summarized in the following Table:

Characteristic	H2ICE	H2FC
Efficiency	Good: mid - high load	**Excellent: low - mid load**
Cooling needs	**Intermediate**	High, critical for stationary and slow-moving applications
Emissions	NOx (and minor CO_2) Low with after-treatment	**None**
Durability	**High**	Improving with new R&D
Robustness	**High**	Sensitive to vibration
Noble metal consumption	**Low – intermediate** (After-treatment)	High
Fuel purity	**Tolerant to contaminants**	High-purity H2 required
Fuel flexibility	**Diesel/NG backup**	Can be flexible, efficiency penalty
Upfront cost	**Low**	High
Cold start	No issues	Temperature conditioning
Resale value	Depending on infrastructure	Unclear

Table 4 - H2ICE and FC Comparison

FCEVs and hydrogen ICEs are not in competition; rather, their development complements each other. The progress in one area supports the other, as both contribute to the advancement of a shared infrastructure for hydrogen production, transportation, and distribution. Additionally, both technologies utilize the same vehicle storage tanks. Together, they play a crucial role in achieving the goal of reducing emissions in the vehicle and transportation sector towards a sustainable future.

3.4 Comparison between Hydrogen and other propulsion system

In 2023, hydrogen-powered cars are still in their early stages of development, with limited models available on the market. Notable manufacturers like BMW and Honda are actively exploring Fuel Cell technology, contributing to the emergence of hydrogen-powered vehicles. At the moment, the Toyota Mirai and Hyundai Nexo are the only two hydrogen cars officially available for purchase.

- The Toyota Mirai features an electric motor producing 182hp and 300 Nm of torque, with a range of 709 km with a full tank.
- The Hyundai Nexo (163hp and 400Nm of torque), requiring 6.33 kg of hydrogen to fill its 152-liter tank (This means that, at an average price of around 13.7 euros

Figure 19 - Toyota Mirai vs 2023 Hyundai Nexo

per kg, it requires 70/80 euros for a full tank of hydrogen), provides a range of 666 km.

The refuelling cost is not reduced compared to current public charging station rates for electric cars but is instead aligned with them. However, the range is often superior, and the refuelling speed from empty takes only 4 minutes [33].

The prices of the mentioned hydrogen cars are in line with those of competing Battery Electric Vehicles (BEVs). The primary obstacle to the extensive adoption of hydrogen cars in 2023 is not the cost but rather the challenges associated with refuelling. In Italy, for example, only two refuelling stations are available, both situated in the Northeast region of the country.

Let's examine (thanks to H2IT, the Italian Association for Hydrogen and Fuel Cells) the comparison between a medium-sized car powered by batteries and one powered by hydrogen (produced through electrolysis). It is estimated that about 50 kWh are required to produce 1 kg of hydrogen through electrolysis. Assuming a production of approximately 20 kWh in fuel cells (with an efficiency of about 60%), the medium-sized vehicle will cover about 100 km with 1 kg of H2, given a consumption of approximately 5 km/kWh. In the electric case, a battery charging efficiency of 90% is considered. It is evident that the direct use of electrical energy, avoiding double transformation, allows for a more efficient utilization of energy.

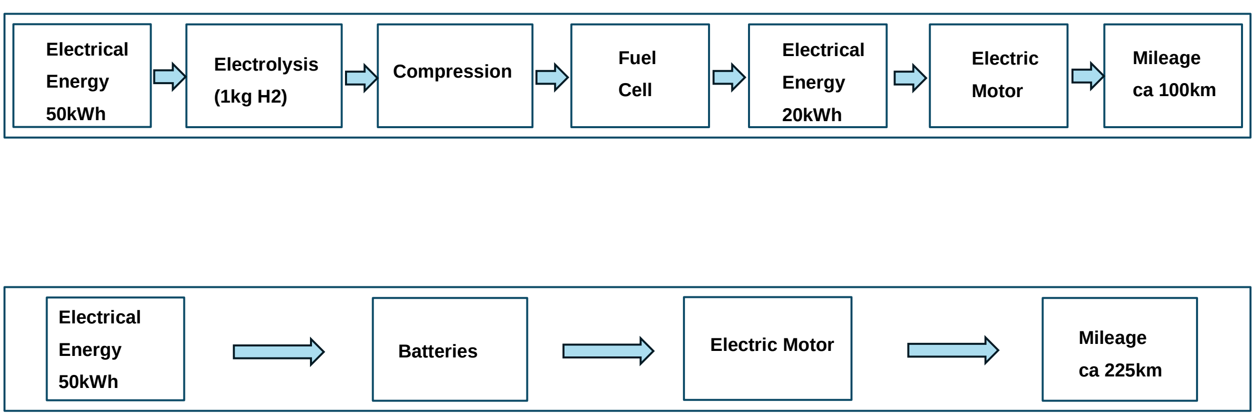


Figure 20 - Efficiency Comparison for Hydrogen and BEV

In conclusion:

- Whenever possible, it is more cost-effective to use energy in the form it is produced from renewable sources, avoiding transformations that lead to inefficiency.
- For light vehicles, it seems more suitable to develop the use of electric cars compared to hydrogen-powered ones. However, this requires ongoing research and development efforts to further improve batteries in terms of cost and charging times, as well as to develop metal recovery technologies for effective and sustainable long-term battery disposal, reducing the need for extracting new quantities of metals.
- It is believed to be more effective to reserve the use of hydrogen for cases where batteries reasonably cannot reach, especially in the Heavy-Duty sector (buses, trucks, lorries, trains, ships), or in commercial vehicles where low autonomy and long battery charging times make the application technologically unfeasible and inefficient.

The well-to-wheel (WtW) efficiency represents the overall efficiency of an energy process, encompassing the entire cycle from resource extraction to production, distribution, and final use. To compare efficiency between hydrogen and diesel in the well-to-wheel context, it is essential to consider all the steps involved in their respective fuel life cycles. In terms of percentage efficiency:

1. **Hydrogen Well-to-Wheel Efficiency:**

Hydrogen Production: The efficiency of hydrogen production depends on the method used (e.g., electrolysis, methane reforming). Green hydrogen produced through renewable-powered electrolysis is considered more sustainable. Efficiency varies, but let's assume an approximate value of 70%.

Transport and Distribution: Hydrogen needs to be compressed or liquefied for transport. Efficiency can vary, but let's assume an approximate value of 90%.

Usage in Fuel Cell: The efficiency of hydrogen fuel cells is typically in the range of 40-60%, depending on the technology. Let's assume an average value of 50%.

Diesel Well-to-Wheel Efficiency:

Diesel Production: The efficiency of the oil refining process to obtain diesel is generally below 90%. Let's assume an approximate value of 85%.

Transport and Distribution: Diesel needs to be transported and distributed, and efficiency can vary. Let's assume an approximate value of 95%.

Usage in Internal Combustion Engine: The typical efficiency of a diesel engine varies, but let's assume an approximate value of 30%.

Process	***Efficiency***
Hydrogen Production	~70%
Transport and Distribution	~90%
Usage in Fuel Cell	~50%
Diesel Production	~85%
Transport and Distribution	~95%
Usage in Diesel Engine	~30%

Table 5 - Efficiency of the various processes for hydrogen and diesel

Calculation of Well-to-Wheel Efficiency:

Hydrogen: 70% (production) * 90% (transport) * 50% (fuel cell) = **~32%**

Diesel: 85% (production) * 95% (transport) * 30% (diesel engine) = **~24%**

For an immediate comparison between Battery Electric Vehicles (BEV) and Fuel Cell vehicles, the following diagram, created by Volkswagen, highlights how, for passenger cars, the BEV option is superior.

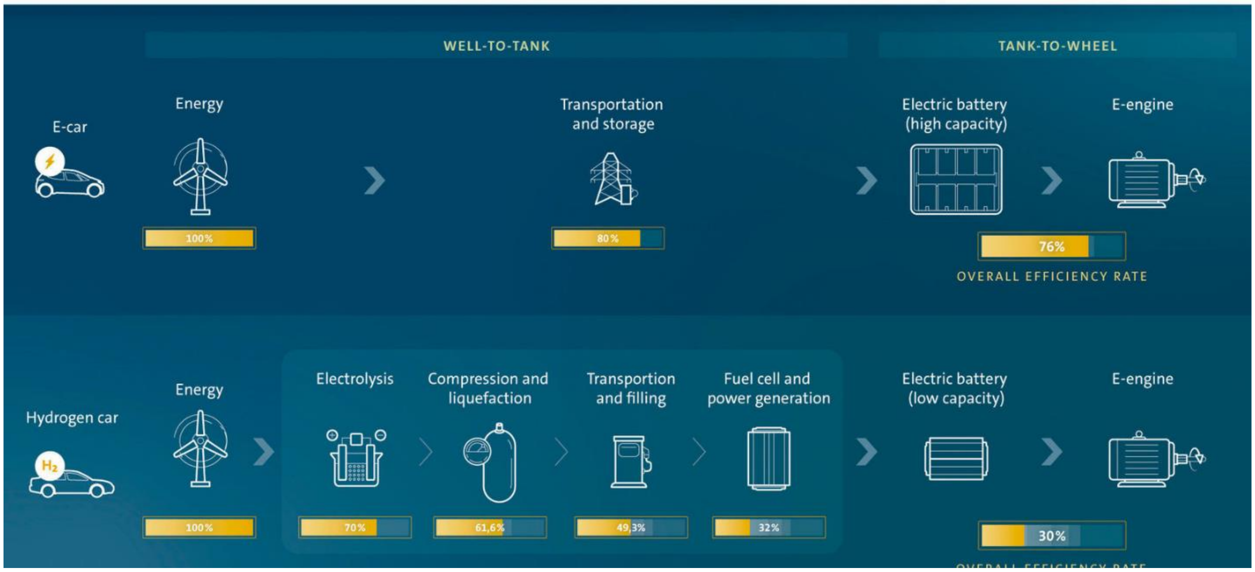


Figure 21 - Hydrogen and Electric Drive Efficiency Rates in Comparison [www.volkswagen.com]

3.4.1. Alternative Fuel Scenario

When considering hydrogen as an energy carrier in the alternative fuel scenario, especially for commercial applications, the prospect of large-scale hydrogen availability appears promising, with estimates pointing towards realization around 2035.

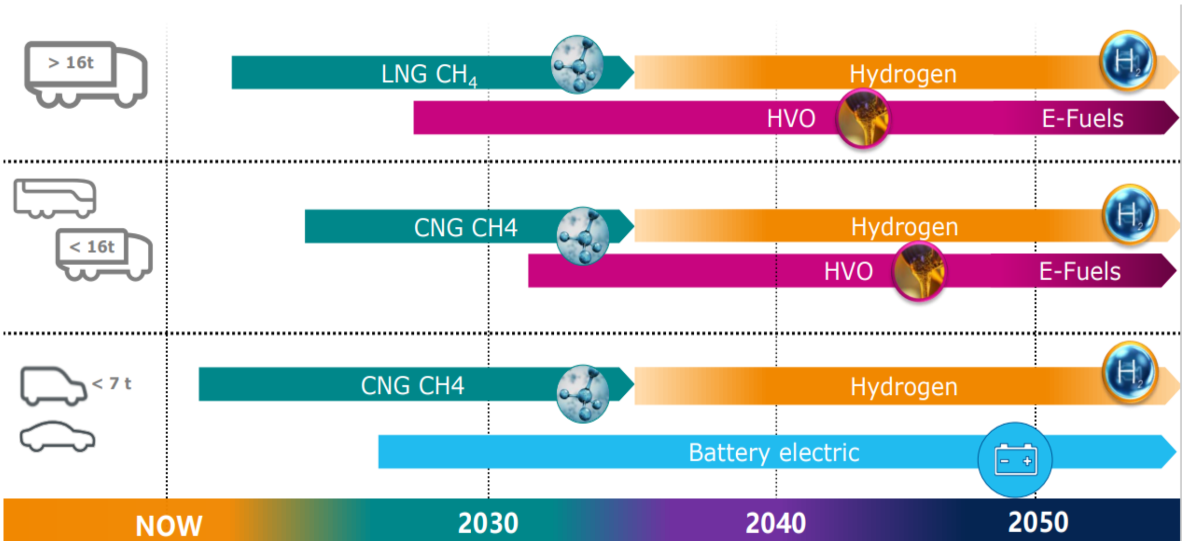


Figure 22 - Alternative Fuel Scenario - AVL Showcase Webinar [31]

Initially, hydrogen will find application and demand primarily in the heavy-duty industry. Later, as hydrogen production scales up, it is likely to become accessible for broader transportation use. There is a potential shift on the horizon, especially in the heavy-duty sector where hydrogen could replace LNG for loads exceeding 16 tons and CNG for loads below this threshold. However, this transition is contingent upon the successful scaling up of hydrogen production to meet the demands of these applications.

Currently, hydrotreated vegetable oil (HVO) is actively employed in heavy-duty applications >16 tons. Looking ahead, the potential rise of E-fuels production could potentially lead to the displacement of HVO post-2050, but all of this depends on the production scalability and resource availability. Battery electric vehicles (BEVs) have already made inroads in the passenger car segment, establishing their significance for the future. It's evident that the future will involve a variety of alternative fuels, with no singular fuel emerging as dominant over the others. Hydrogen in this context is expected to play a significant role in this transition phase.

Regarding the prospects and current situation of hydrogen availability for mobility in Italy, the Ministry of Infrastructure and Transport (MIT) has unveiled the list of 36 projects qualifying for public funding to establish hydrogen refuelling stations. A State contribution of around 103.5 million euros, funded through the National Recovery and Resilience Plan (PNRR), will support the initiatives. This initiative is set to increase the number of hydrogen refuelling stations to 38 nationwide by 2026. Alongside the creation of 36 new stations, the existing 2 stations in the provinces of Bolzano and Mestre will play a pivotal role in enhancing the hydrogen infrastructure across the country [32].

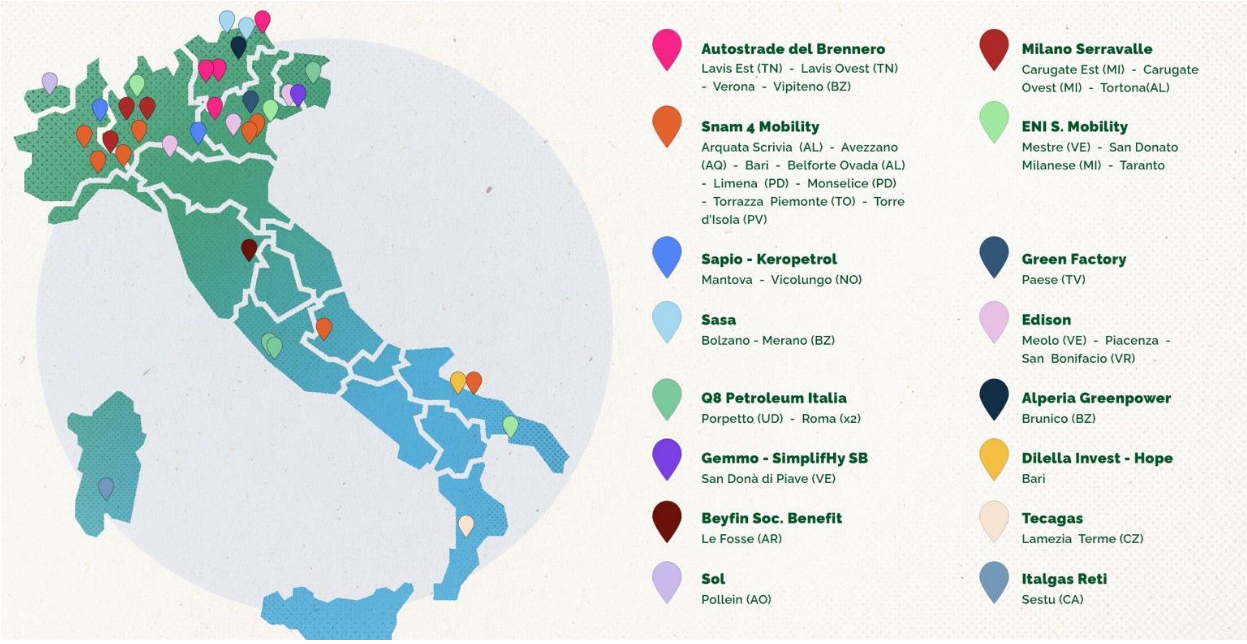


Figure 23 - Approved Hydrogen Refueling Stations

4 Hydrogen Cycle

Hydrogen Cycle represents a conceptual model and comprehensive approach that outlines the various stages of hydrogen's journey within an energy ecosystem. This includes its production, distribution and storage, safe application, and the utilization across various sectors. Since the topic of its utilization has already been discussed, in the following paragraphs, we will focus on production, storage, and safety issues, particularly in the Italian context, with the subsequent feasibility study conducted in collaboration with AVL Italy.

The hydrogen cycle is the conversion of water to hydrogen and oxygen, followed by its transformation to fuel and electricity and finally its ‘recycling’ back to water. Hydrogen is obtained through electrolysis, separating it from oxygen. Additionally, it can be derived from natural sources like wood and organic materials.

The primary challenge in hydrogen production is sourcing clean energy (e.g. wind, solar, nuclear, hydro) for electrolysis. Using coal and oil-based power stations leads to pollution. Moreover, hydrogen storage is expensive.

The extracted hydrogen can be used in traditional engines or, more efficiently, in fuel cells to generate electricity. The only byproduct is pure water, making it an environmentally friendly energy source.

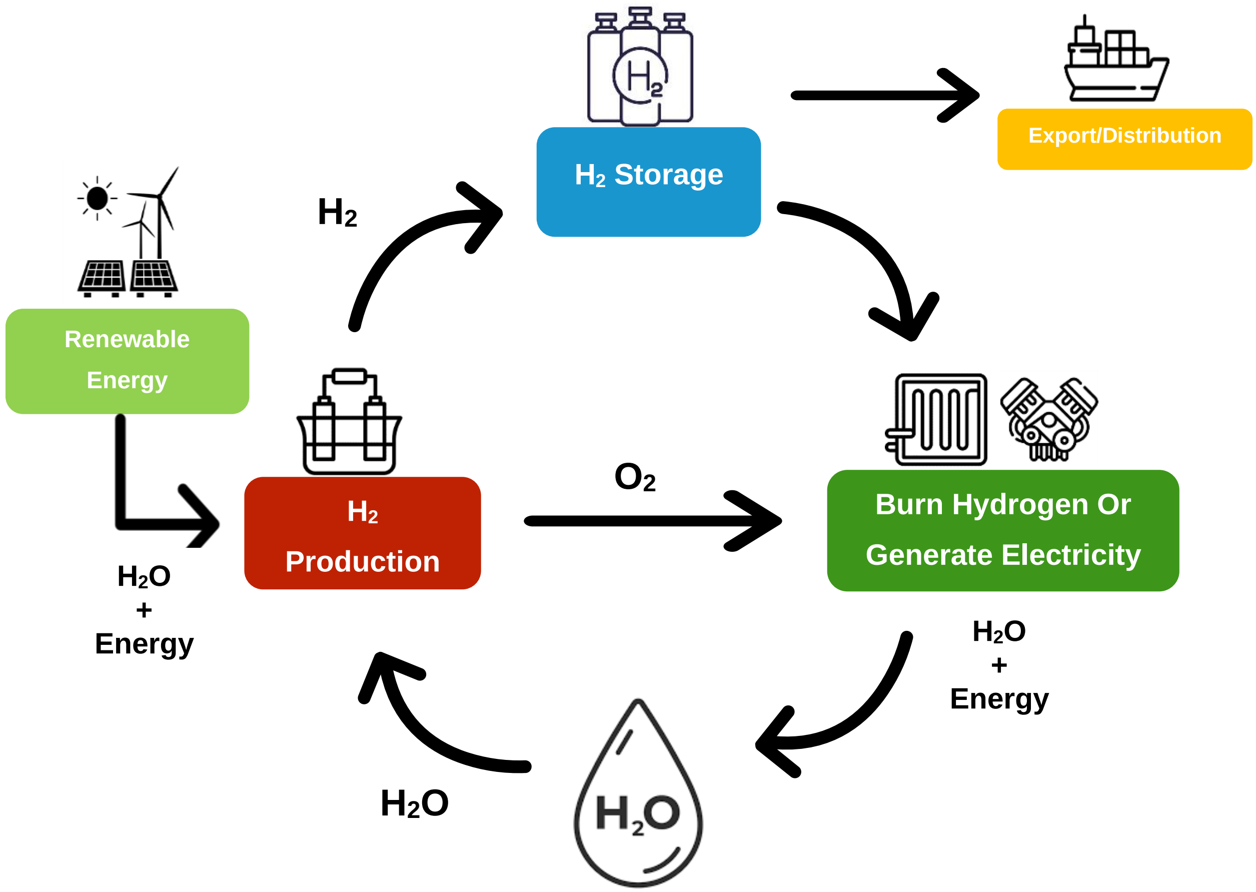


Figure 24 - Hydrogen Cycle

4.1 Production

Today, about 95% of the hydrogen used on Earth, mostly for industrial purposes, is obtained from methane reforming or coal gasification processes. These methods generate significant amounts of carbon dioxide emissions but are currently the most cost-effective options available. We have already discussed the hydrogen colour palette in the section regarding the environmental impact of each production type. Let's provide a summary with the following outline.

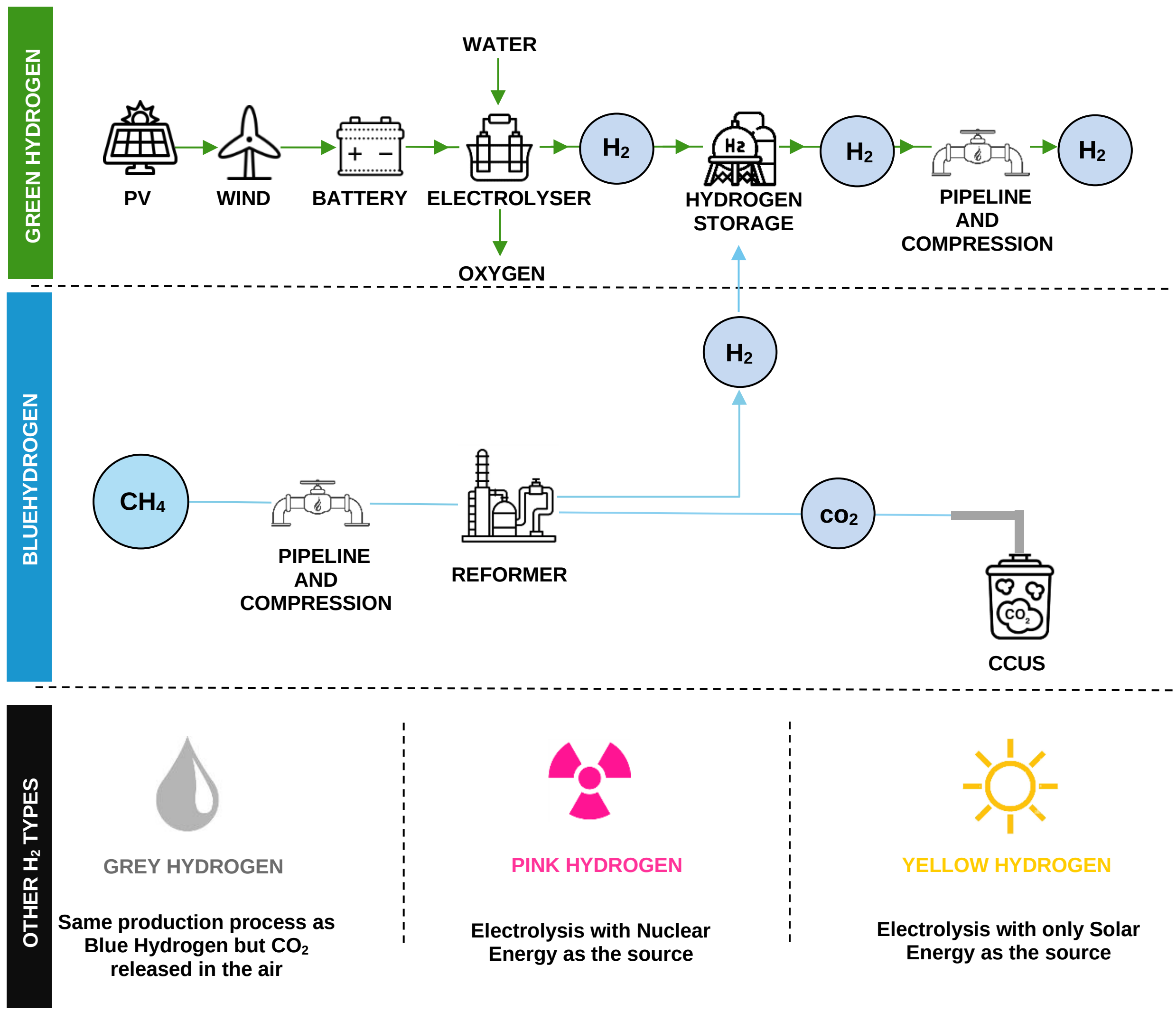


Figure 25 - Main Hydrogen Colours

Hydrogen Types Summary:

1) Blue Hydrogen:
   - Production: Natural gas split into hydrogen and CO2 (Steam Methane Reforming or Auto Thermal Reforming).
   - CO2 Capture: greenhouse gasses are captured through CCUS.
   - Environmental Impact: Mitigated.

2) Green Hydrogen:
   - Production: Water split by electrolysis.
   - By-products: Hydrogen and Oxygen. Hydrogen can be used, and oxygen can be vented to the atmosphere with no negative impact or used for Fuel Cell as in Figure 24.
   - Power Source: Renewable energy (wind or solar).
   - Environmental Impact: Cleanest option, no CO_2 by-product.

3) Grey Hydrogen:
   - Production: Like blue hydrogen (Steam Methane Reforming or Auto Thermal Reforming).
   - CO_2 Capture: No CCUS, CO_2 released into atmosphere.

4) Pink Hydrogen:
   - Production: Electrolysis, powered by nuclear energy.

5) Yellow Hydrogen:
   - Production: Electrolysis, powered by solar energy.

The future will see a transition from grey, through blue, to green hydrogen. Currently, large-scale green hydrogen production facilities are not cost-competitive with traditional methods. However, the expected reduction in electrolyser costs and significant advancements in renewable energy technologies are quickly reshaping the landscape. This suggests a promising future for green hydrogen production. In the next section, the current state of electrolyser technology and green hydrogen production will be outlined.

4.1.1 Green Hydrogen: Electrolyser Different Types

The fundamental concept of electrolysis remains consistent across various technologies. However, these technologies differ depending on physical, chemical, and electrochemical aspects. Currently, there are four primary types of electrolysis technologies [23].

1) AEL (Alkaline Electrolyser), with alkaline electrolysers

2) PEM (Proton Exchange Membrane) with proton exchange membrane
3) AEM (Anion Exchange Membrane) with anion exchange membrane
4) SOEL (Solid Oxide Electrolyser), with solid oxide electrolysers

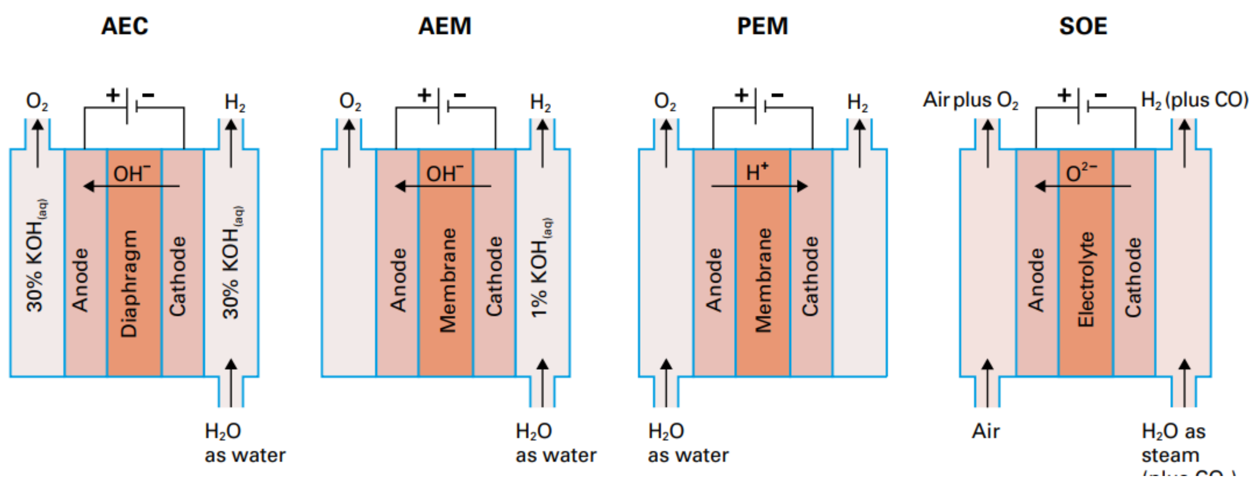


Figure 26 - AEC, AEM, PEM and SOE for hydrogen production.
[http://www.sbh4.de/assets/electrolyser-aec-aem-pem-soe.pdf]

1. Alkaline Electrolyser (AEL): This type uses an alkaline electrolyte, typically potassium hydroxide and operates at relatively low temperatures. It has been in use for several decades (is a mature and commercial technology. It has been used since the 1920s) and is known for its efficiency.

This technology offers the following advantages:

- Good efficiency, 55-65% (on LHV)
- No use of noble metals (resulting in lower production costs and a lower electrolyser selling price)
- Economical materials
- High lifespan
- Established and reliable technology

However, the alkaline technology also comes with some disadvantages:

- Low current density, resulting in larger plant sizes for the same amount of produced hydrogen compared to other technologies.
- Electrodes degradation (operating temperature dependent)
- Reduced gas purity
- Low working pressure

2. Proton Exchange Membrane Electrolyser (PEMEL): PEM electrolysers are the most common commercially. They employ a solid polymer electrolyte membrane and operate at higher temperatures compared to AELs. They are known for their high efficiency and capability to function effectively under varying loads.

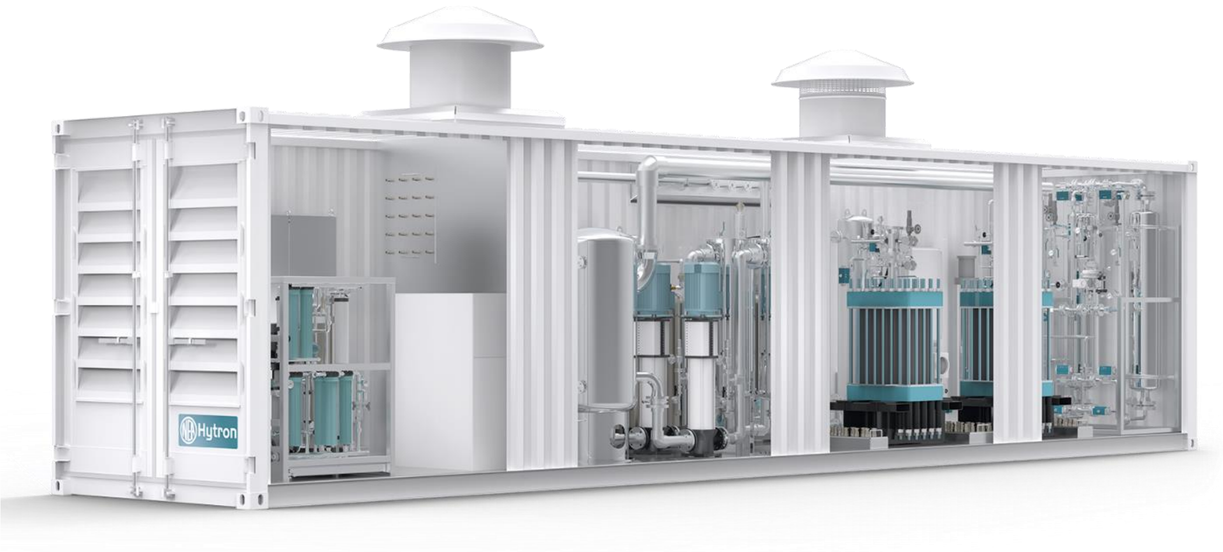


Figure 27 - Example of a PEM Electrolyser [22]

Advantages:

- High efficiency: 60 – 70% (on LHV).
- Efficient mass transport, particularly due to the solid electrolyte.
- Elevated current density, resulting in greater hydrogen production per unit area.
- Superior hydrogen purity.
- Capability to operate at partial loads (20%-100%) with high reactivity, making integration with renewable sources easier.
- Suitable for high-pressure operation, making the system more efficient without using necessarily external compressors.

Drawbacks:

- Possible membrane degradation.
- Initial investment costs are high.
- Reliance on rare metals like platinum and iridium, which still have a significant environmental impact during extraction.
- Components have low recyclability.

3- Solid Oxide Electrolyser Cell (SOEC): They employ a solid ceramic electrolyte and operate at high temperatures. They are known for the high efficiency and can be integrated with high-temperature processes (they use heat to make hydrogen from steam). The technology is still at demonstration level.

Advantages:

- Very high efficiencies (80%-90% on LHV).
- Capability to operate in reverse mode, acting as a fuel cell.
- Do not use noble metals.

Drawbacks:

- Operations at high temperatures (500-850 °C)
- Limited flexibility in load variations
- Short lifespan
- Primarily used at an academic level, although the first commercial installations are beginning to appear.
- Still very high costs, but with prospects of significant reduction in the coming years.

3. Anion Exchange Membrane (AEM): is a type of electrolyser that uses a solid polymer electrolyte membrane with anion exchange properties. They are somewhere between alkaline electrolysers and PEMELs. It is the latest technology, presently deployed at the large prototype level.

Advantages:

- Good efficiency: 50%-70% (on LHV)
- Less corrosive electrolyte compared to alkaline technology.
- No use of noble metals, leading to lower production costs, more affordability, and reduced environmental impact.
- Ability to operate at high pressures with good purity.

Drawbacks:

- Low current density, resulting in larger sizes and higher costs for the same hydrogen production compared to other technologies.
- Very innovative but less developed technology, with few large-scale applications
- High cell degradation coefficient.

	AEC	PEM	SOEC	AEM
Operating temperature (°C)	**70-90**	**50-80**	**500-850**	**40-60**
Gas outlet pressure (Bar)	**1-30**	**<70**	**Close to atmospheric**	**<35**
Stack lifetime (h)	**60-100k**	**50-80k**	**<20k**	**>5k**
Technology readiness	**Matured**	**Commercialised**	**Demonstration**	**Prototype**

Table 6 - Main electrolyser parameters [https://www.irena.org/]

Each type has its own advantages and is suited for different applications based on factors like efficiency, operating temperature, and cost.

4.2 Storage

Hydrogen storage is a critical element for the development of a sustainable energy system. Due to its extremely low density (1kg of H2 occupies about 12 m^3 at room temperature and atmospheric pressure), storing hydrogen in an effective, safe, and reliable manner is the most significant challenge. Currently, there are three different methods for hydrogen storage:

- Compressed gas storage.
- Cryogenic liquid storage
- Material-based storage (also referred to as "solid-state").

Among these, the first two are by far the most common, while the last method is currently less mature.

Hydrogen has the highest energy content per unit mass, containing three times the energy of diesel with the same weight (~140 MJ/kg compared to ~45 MJ/kg). However, in terms of volume, hydrogen exhibits a low energy density (0.01 MJ/L), as indicated in the table 7. Compared to conventional hydrocarbons, storing hydrogen with equivalent energy content will require larger tanks or an increase in density. This highlights a crucial aspect in the practical application and storage of hydrogen for energy purposes.

FUEL	*SPECIFIC ENERGY DENSITY (MJ/kg)*	*VOLUMETRIC ENERGY DENSITY (MJ/L)*
HYDROGEN	120-142	0,01
PETROL/GASOLINE	44-46	34,2
DIESEL	42-46	38,6
METHANOL	22,7	15,6
BIODIESEL	42	33
NATURAL GAS	50-55	0,03

Table 7 - Energy Densities for Different Fuels

Depending on the application, the required characteristics for hydrogen storage may significantly change. For instance, in the transportation sector, it's crucial to store hydrogen with a high energy density since the occupied space and the weight of the tank are crucial aspects to consider on the vehicles.

4.2.1 Hydrogen Storage Methods

As mentioned earlier, hydrogen storage must take place in a way that significantly increases its energy density. It is known that to increase the density of a gas, either the pressure must be increased, or the temperature must be reduced:

$$PV = nRT \tag{4.1}$$

Where:

- *P=Pressure (Pa)*
- *V=Volume (m^3)*
- *n=number of moles*
- *R=Gas constant = 8.314 J $mol^{-1}K^{-1}$*
- *T= Temperature (K)*

❖ **Gaseous state storage:** In the gaseous state, possible methods include:

- Salt caves
- Exhausted gas fields
- Pressurized containers
- Rock caverns

Natural depleted deposits or salt caves offer large underground storage volumes with low costs, as nature has already created suitable structures. Storage period can also be extended (up to months or even seasons). However, in the absence of these natural formations, pressurized containers are necessary, which have larger surface areas and hold smaller volumes.

Figure 28 - Hydrogen Cylinders and Tube Trailer

This storage technology is the simplest, requiring only a pressurized tank and a compressor to reach the desired pressure. For small-scale applications, this is the most straightforward method as it allows for storage at room temperature.

There are four types of high-pressure cylinders for tank storage [26]:

- Type I: they are constructed from metal, are employed to store industrial gas at pressures ranging from 150 to 300 bar. While they are widely utilized and cost-effective, their weight makes them unsuitable for vehicle applications.
- Type II: they are equipped with a durable metal ring liner surrounded by carbon or glass fiber material. The operating pressure for this tank is typically 100 to 500 bars, and it is mainly used in industrial applications.
- Type III: they are equipped with an internal metal liner to prevent hydrogen leakage through diffusion. They are encased in composite materials to withstand mechanical stress. This design, involving thinner metal and increased use of composites, results in lighter tanks compared to Types I and II. it is often found in vehicles and can store hydrogen at pressures up to 350 bar,
- Type IV. They employ a high-density polymer liner for gas diffusion prevention, enclosed by a carbon fiber compound. They come with metal valves for hydrogen refuelling and can handle pressures of up to 700 bar. They are commonly used in the passenger car and heavy-duty commercial vehicle sectors.

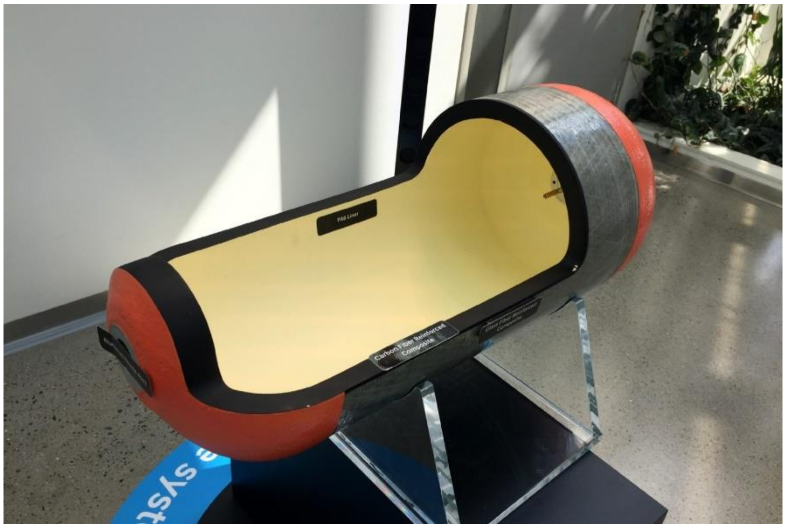


Figure 29 - Hyundai NEXO Hydrogen Tank. Three high-pressure fuel tanks are cleverly packaged in the rear of NEXO, with the ability to hold up to 6.33kg of hydrogen at a pressure of 700 bar.

Type III and IV vessels are ideal for portable applications that demand weight reduction and operate at pressures between 350 and 700 bar. Their higher cost is attributed to the use of carbon fiber.

❖ **Liquid state storage:** In the liquid state, possible methods include:

- Liquid hydrogen.
- Ammonia: Ammonia stands out as a promising hydrogen carrier due to its high hydrogen content and ease of transport. It is generated by combining hydrogen and nitrogen, providing a means for subsequent hydrogen release through a process called "ammonia cracking." Continued research and development are crucial for widespread implementation.
- LOHCs: Liquid Organic Hydrogen Carrier Systems involves liquid organic compounds to store hydrogen. These compounds can absorb and release hydrogen, making them a potential solution for safe and efficient hydrogen storage.

The next diagram in Figure 30 shows that hydrogen is naturally in a gaseous state at ambient conditions. Converting it to a liquid form requires both compression and cooling, which is a costly process. As a result, this type of storage is typically employed for small quantities and short durations. For larger volumes and extended periods, an alternative approach involves chemically binding the hydrogen molecule, such as by forming ammonia or utilizing organic liquids that achieve a liquid state at ambient conditions or through compression [24].

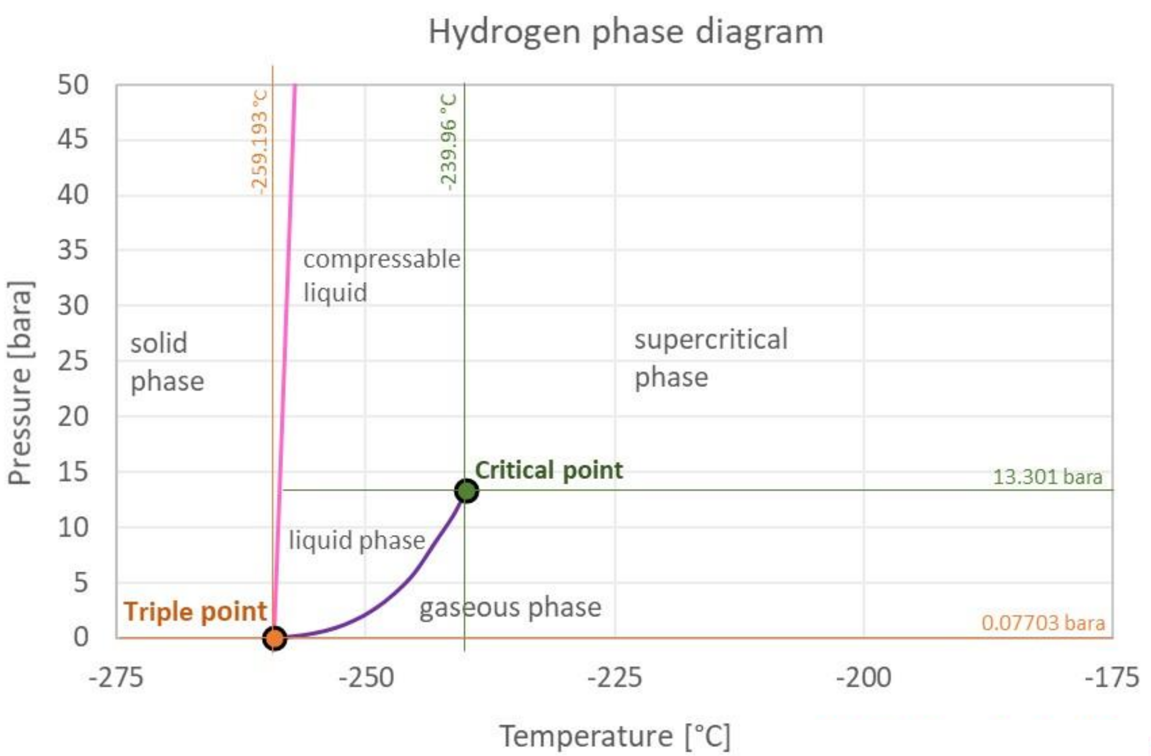


Figure 30 - Hydrogen Phase Diagram [https://www.engineeringtoolbox.com]

Storing hydrogen in liquid form through liquefaction allows for high storage densities even at atmospheric pressure. However, it requires a significant amount of energy due to hydrogen's extremely low boiling point (-253°C at 1 bar). Another factor to consider is the boil-off rate, which is the rate of evaporation of liquid hydrogen. Due to the extremely low boiling temperature, effectively insulating the tank and maintaining cryogenic temperatures for extended periods is challenging. This results in notable losses, as the evaporation of liquid hydrogen increases pressure, leading to the release of gas through safety valves. The heat transference from the surroundings to the stored liquid hydrogen and thus the boil-off rate is reduced by minimising the surface-to-volume ratio of the vessels by making them spherical, as shown in Figure 31:

Figure 31 - Liquid Hydrogen Tank [www.nasa.gov]

These factors, along with the high energy consumption, limit the applicability of this solution to cases where cost is not a decisive factor and hydrogen consumption occurs in short periods. Over long distances, trucking liquid hydrogen is more economical than trucking gaseous hydrogen because a liquid tanker truck can hold a much larger mass of hydrogen than a gaseous tube trailer can.

- **Storage using materials (or "solid-state")**

  The solid-state storage techniques have captured the attention of researchers worldwide and are being studied and developed as technology for the future energy system. They are in the testing phase.

- Metal hydrides: exploit the crystalline chemical structures of metal hydrides, creating interstitial sites where dissociated hydrogen molecules can bind. This allows for a significant amount of hydrogen to be stored in compact volumes.

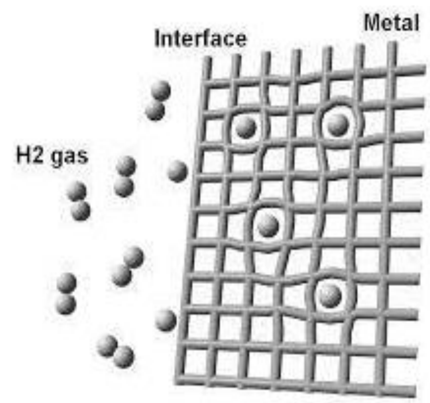


Figure 32 - Schematic of Formation [https://indico.ictp.it]

Additionally, due to the relatively weak bonds, the process of creating and breaking them requires less energy [25]. In metal hydride tanks, hydrogen is stored through reversible chemical reactions that occur between a metal alloy and gaseous hydrogen. The solid metal hydride acts like a sponge capable of absorbing and releasing hydrogen.

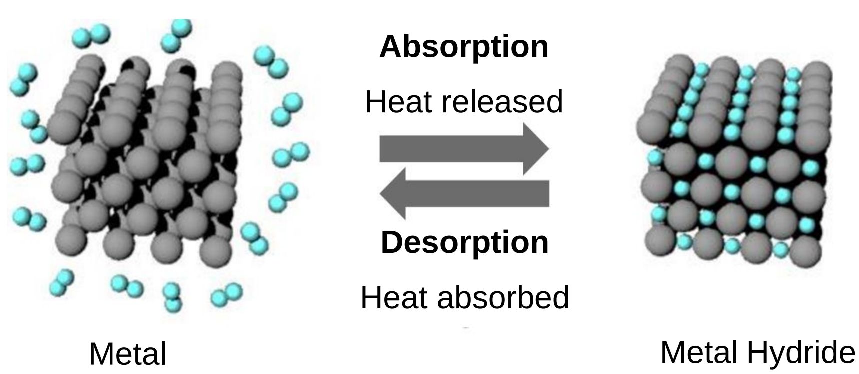


Figure 33 - Metal Hydride Storage Processes

4.3 H_2 Safety

All fuels carry inherent determined by three crucial factors: ignition source, oxidant, and the presence of the fuel itself. Implementing precise engineering controls can effectively reduce these risks for different fuel types, including hydrogen.

Hydrogen presents several safety benefits compared to commonly used fuels. It is non-toxic and, being lighter than air, disperses rapidly into the atmosphere upon release. This property is crucial as it ensures that in case of an accident, the fuel dissipates rather than remaining in place, potentially leading to a fire hazard, as seen with batteries or petroleum.

However, remain risks associated with hydrogen that demand extra engineering precautions for its safe application, given its lower ignition energy and a broader range of flammable concentrations in the air when compared to petrol or natural gas, ensuring proper ventilation, and implementing effective leak detection are crucial for hydrogen systems. Moreover, the use of specialized flame detectors is essential, as hydrogen combustion produces a nearly invisible flame. These measures are crucial in guaranteeing the secure handling of hydrogen [27].

4.3.1 Italian laws and regulations

In the context of safety in industrial plants, it is crucial to carefully consider factors related to the proper implementation of hydrogen. From a regulatory perspective, in the past it has been followed an old decree that was designed for methane, a gas that may seem similar but is actually very different. The accurate management of parameters such as employed pressures and distance limits, for instance, plays a critical role, especially in environments with limited space or the presence of components close to potentially hazardous areas within the plant. It is therefore crucial to note how regulatory evolution has played a significant role in this context. This regulatory progress has represented a significant step forward during the feasibility study phase at AVL Italy industrial plants.

Italy with the Ministerial Decree of July 7th has established the rules for the design, construction, and management of plants to produce so-called green hydrogen. This is what is widely discussed for sustainable mobility, used as a fuel, but not only, and it is

obtained from renewable sources. The decree outlines fire safety requirements for hydrogen production and storage activities, specifying location criteria, prevention measures, and protection directives. Its objective is to assess risks to people's safety, health, and the environment, and to set construction regulations for these facilities.
The published decree is the first step, regulatory-wise, and a committee continues to work on safety, in collaboration with the fire department. Risks must be assessed, rules updated, and any necessary interventions in case of emergency must be defined.
Therefore, the new regulation opens the door to green hydrogen by specifying materials, distances, pressures, and various technical details of the plants.
The Ministerial Decree regulates hydrogen production plants through electrolysis:
These concerns (Article 4):

- Electrolysis-based hydrogen production plants (commonly known as electrolysers).
- The respective systems for gaseous hydrogen storage:
  - Newly constructed.
  - Existing as of the effective date of the decree, in case of significant modifications related to fire safety resulting in changes to pre-existing fire safety conditions, limited to the parts affected by the intervention.

According to the technical rule (Article 3), hydrogen production plants must be designed to ensure fire safety requirements by:

1. Minimizing the potential for accidental gas release, as well as fire and explosion hazards.
2. Limiting, in case of an incidental event, harm to individuals.
3. Limiting, in case of an incidental event, damage to buildings or adjacent areas.
4. Ensuring that rescue teams can operate under safe conditions.

The technical rule in Article 5 outlines the construction requirements for pressure equipment and assemblies comprising the plant, emphasizing compliance with community standards and protection against overpressure, minimizing the possibility of

accidental hydrogen releases, and adhering to instructions in the installation, use, and maintenance manual provided by the manufacturer or as specified by the designer or industry best practices.
The following Table 8 provides the safety distances to be observed for the hazardous elements listed in the decree:

a) electrolyser;
b) buffer tank;
c) compression system;
d) hydrogen storage;
e) pressure reduction and stabilization unit;
f) loading station (loading bays);

HYDROGEN PRESSURE (barg)	**SAFETY DISTANCES** (m)		
	EXTERNAL	**PROTECTION**	**INTERNAL**
700<P≤1000	30	15	15
500<P≤700	25	15	15
300<P≤500	20	15	15
100<P≤300	17	12	12
50<P≤100	12	8	8
30<P≤50	8	6	6
10<P≤30	7	5	5
P≤10	5	3	3

Table 8 - Safety Distances for dangerous element of the plant [DM 7 Luglio 2023]

For all the information, is it possible to visit the decree at the following link: https://www.gazzettaufficiale.it/atto/stampa/serie_generale/originario
This topic will be revisited during the feasibility study phase.

4.4 Production, Storage, Safety at AVL Italia

AVL Italia is a division of the international company AVL List GmbH, specializing in engineering and services for the development of engines and vehicles. AVL is one of the world's leading mobility technology companies for development, simulation, and testing in the automotive industry, and in other sectors.

The Italian branch of AVL focuses on consulting and development services for the automotive industry and related sectors. These services may include testing and analysis of engines and vehicles, design and development of components, development of propulsion systems, and integration of innovative technologies to optimize engine efficiency and performance. The internship took place at AVL Technical Centre Italy (TCI) in Cavriago (RE).

Figure 34 - AVL TCI, Technical Center Italia [www.avl.com]

The primary focus of the activity has been focused on hydrogen production and storage, with a wide array of topics and goals. The work has been structured into three main phases:

- Initially, a precise literature analysis and benchmarking activity, specifically addressing hydrogen requirements within the automotive sector, including both Hydrogen Internal Combustion Engines (H2ICE) and fuel cell technologies, which we talked about before. A general scouting was conducted both overall and among AVL's customers to understand who was transitioning towards hydrogen, which technology they were employing, the power levels involved, and future scenarios.

- The second phase was dedicated to benchmarking potential technical solutions for supply and storage, with a particular focus on safety considerations, which we will discuss now.

- In conclusion, the third phase focused on applying the insights obtained from the earlier stages. This involved defining storage size criteria and conducting a "Make or Buy" analysis for implementing test beds and test fields. The primary objective was to evaluate whether it was more advantageous to use externally sourced hydrogen or produce it on-site within customer test fields.

The underlying idea of the project was to start from our company to acquire knowledge and know-how, so that we could later offer solutions to our clients. We developed various tools to assist clients in their decision-making and in the design and evaluation phase.

4.4.1 Feasibility Analysis

The AVL facility is situated in a building that was previously owned by Landi Renzo S.p.A. and later sold to AVL. The current Landi structure is now adjacent to ours.

Project Goals: Hydrogen Supply at AVL / Landi Renzo Settlement, Cavriago (RE)

Figure 35 - AVL and Landi Renzo Facilities

1. Feasibility Assessment:
   a) Identify possible configurations for H_2 supply.

2. Requirements for H2ICE Testbed usage:

Average H_2 Flowrate	20-25 Kg/h [225 - 275 Nm^3/h]	
Peak H_2 Flowrate	35 Kg/h [390 Nm^3/h]	
Operating pressure:	60 bar	
Usage Time	Maximum daily running time	**16h/d**
	Maximum usage days per week:	**5d/w**
	weeks of use per month	**4w/m**
Estimated annual consumption:	96000 Kg (1.150.000 m^3)	

Table 9 - H2ICE AVL Testbed Requirements

3. Analysis:
   a) Plant Analysis:
      - Detailed examination of the facility's infrastructure.
   b) Areas Analysis:
      - Assess the suitability of different areas for H2 supply configurations.

4. Safety and Prevention:
    a) Identify Fire Prevention Process.
    b) Consider safety aspects for the proposed configurations.

In the Figure 36, AVL’s areas are highlighted in blue, while Landi's property is marked in yellow. From the outset, AVL's constrained outdoor spaces, the areas adjacent to the other company, AVL's central location in the industrial area of Cavriago with roads and houses nearby, have represented the primary challenges for the analysis of potential hydrogen storage or self-production.

Figure 36 - AVL and Landi Renzo Areas

Essentially, three areas have been identified and marked on the map. Among these, Landi's area has been taken into consideration due to its proximity. This assessment was conducted to address challenges related to space constraints, with the potential to expand and possibly discuss property exchanges. It also opens up the possibility of collaborative projects with Landi Renzo, potentially involving shared investments if Landi Renzo wishes to collaborate with AVL.

1) AVL AREA
2) AVL AREA + LANDI NORTH (Adjacent to AVL area)
3) AVL AREA + LANDI EAST

Figure 37 - Identified Area Top View: AVL, Landi East, Landi North

Figure 38 Identified Area Rear View: AVL, Landi East, Landi North

Regarding safety aspects, the focus is on issues related to the placement and security of storage units and electrolysers due to the AVL's central position within the industrial area and distances restriction. It's important to note that last year's studies were carried out in accordance with the regulations outlined in DM October 23, 2018, which was less structured compared to the new DM of July 7, 2023, discussed in our analysis. The following table details the safety distances that have been observed:

ITEM	PROTECTION DIST. (m)	INTERNAL SAFETY DIST (m)	EXTERNAL SAFETY DIST (m)
Compressors	15	-	30*
Storage	15	15	30
BOX Trailer	15	15	30

*can be reduced at 15m by appropriate shielding

Table 10 – Distances for the "Hazardous Elements Of The System"

As can be seen, the distances are not based on different pressure levels as in the new decree (Table 11).

This lack of distinction would lead to maximum distances (30m) if the new one was considered, valid for pressures 700<P≤1000 [bar], even if the study is focused on P≤300bar.

Figure 39 and Figure 40 illustrates the minimum safety distances (for the three areas under consideration) to be respected, both in the case of storage alone and in the case of hydrogen production, indeed, the electrolyser by decree [30] is considered a 'hazardous element of the plant' since it can be made up of:

a)	Hydrogen production units;
b)	Pressure reduction and hydrocarbon gas measurement cabin (applicable only in the case of production units incorporating hydrocarbon reformers);
c)	Hydrogen gas measurement device (only in the case of pipeline supply);
d)	Compressors;
e)	Storage units;
f)	Dispensing units for refueling vehicles;
g)	Cylinder transport vehicles (reserve supply system);
h)	Cabin for electrical energy transformation;
i)	Rooms designated for ancillary services (operator's office, sales room, warehouse, restroom, washing facility, flame-free workshop, rest area, operator's residence, etc.).

Table 11 - On-site Production Unit Components

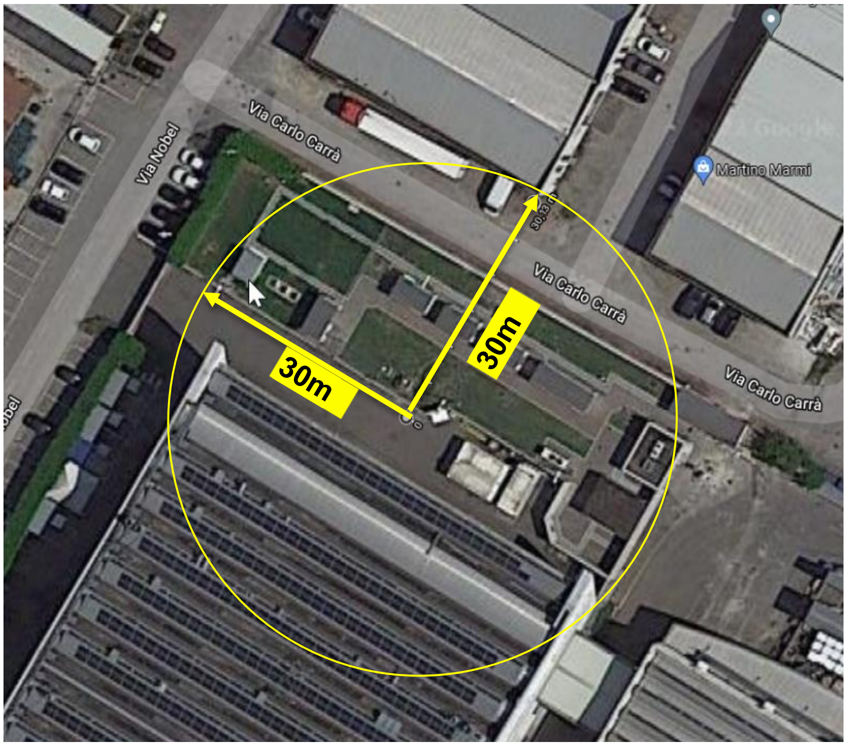


Figure 39 – Area Limits of AVL & AVL+ Landi North (Areas 1&2)

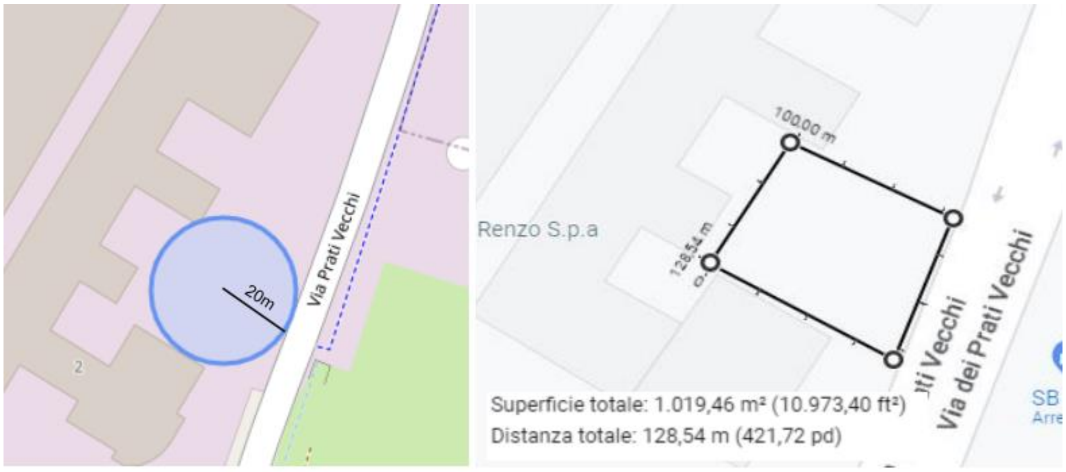


Figure 40 - Area Landi East n°3

From these considerations, safety limits have emerged, and based on this, various hydrogen supply methods have been identified. With the support of an expert in the field, the feasibility, advantages, and disadvantages of the scenarios have been highlighted.

Hydrogen Trailer:

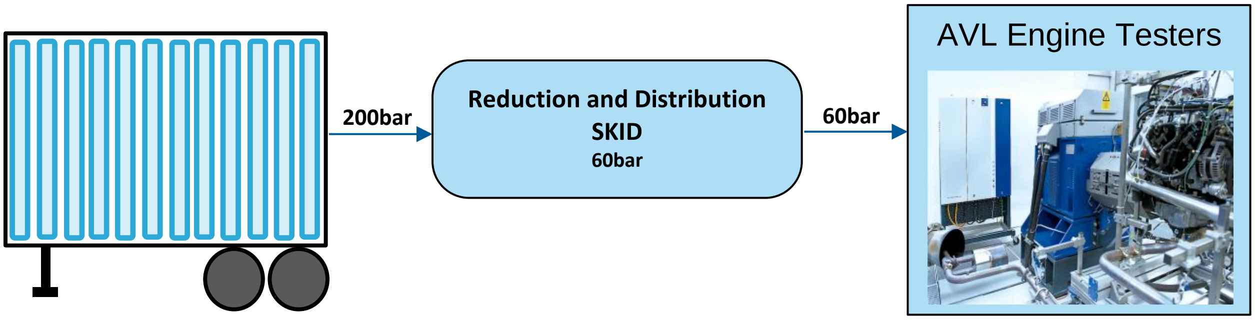


Figure 41 - Hydrogen Supply via Trailer Diagram

1. Quick Installation and Lower Investment:
    - Advantageous in terms of both time and cost compared to other solutions.
2. High Safety Distances Imposed:
    - Requires extensive space due to the imposed safety distances.
3. Regulatory Configuration Limited to AREA 3:
    - From a regulatory perspective, this configuration is feasible only in AREA 3, east of the Landi Renzo building.
    - However, this location is far from the point of use due to the length of the pipeline.
4. Traffic-related Limitations:
    - A medium-sized cylinder transport vehicle can cover only one day of work and having two available (with already limited space) could lead to high traffic frequency and potential congestion.

It is important to note that the study was conducted with the aim of maximizing flow rates and consumption to understand the maximum limits. Subsequent steps, up to the current state, have revealed that the average hydrogen consumption is significantly lower. However, it is crucial to ensure peak consumption in tests where high-power engines are at full load.

Figure 42 - Hydrogen Trailers [AirLiquide]

On-Site Production:

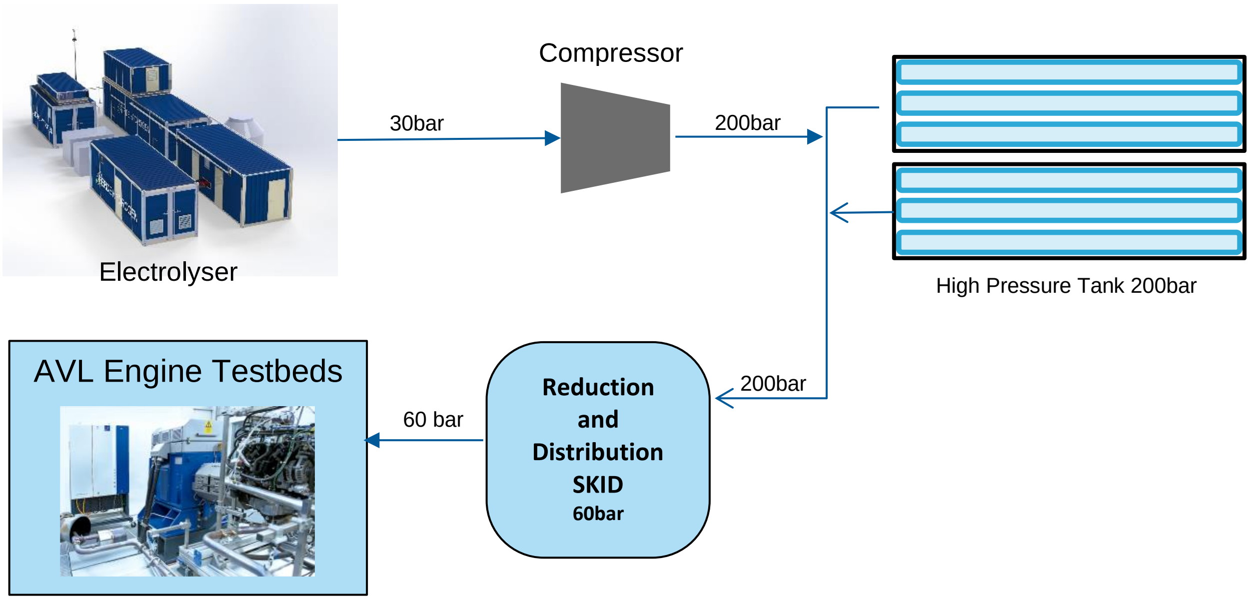


Figure 43 – On-Site Hydrogen Production Diagram

For the self H_2 production, several considerations have been made regarding its sizing. However, it does not represent an alternative to storage but could be part of a subsequent step, for example a phase n°2, where storage acts as a buffer for the surplus hydrogen produced. Here, we highlight the main advantages and disadvantages of a production plant, along with the economic calculations that have been conducted. An Excel tool has been created to estimate production and consumption, keeping into account the existence or not of a storage unit, based on the actual operational situation inside an engine test cell, considering shifts, hours, and days of the week.

ADVANTAGES	1. Lean and Modular System	Enables flexibility and scalability.
	2. Instant Production	Reduces reliance on extensive storage.
	3. Lower Risks and Distances (Only for Compressor Units)	-Minimizes transportation distances. -Mitigates long-term storage risks.
	4. On/Off Capability	Facilitates quick and efficient operation
	5. Possible Integration in Smart Grid	Enhances efficiency and offers a faster ROI
DISADVANTAGES	1. Dependence on Suitable Storage	Production may halt without a proper storage unit
	2. High Initial Investment:	Presents a barrier to entry for some businesses

Figure 44 - On Site H_2 Production - Advantages Vs Disadvantages

After receiving proposals from various electrolyser suppliers, the optimal solution for the scope has been selected, and the proposed sizes are ~500 kW per electrolyser (AEL):

Mercury System G-128/D:

Power Supply	3x 400Vac+N - 50-60 Hz
Power Consumption at the maximum power	456 kW
Hydrogen Production	85,3 Nm^3/h
Oxygen Production	42,6 Nm^3/h
Hydrogen Purity	99,5%
Demineralized water consumption at the maximum power	72 l/h
Hydrogen and Oxygen Pressure	30 barg
Weight	7600 kg

Table 12 - Mercury System G-128/D Datasheet

With this capacity, the estimated hydrogen production at full capacity is little bit higher than 7 kg/h.
It is crucial to highlight that there is already an authorized bunker in the Landi Area for storing up to about 50 kg. Therefore, we consider this value as an indicative starting storage capacity.
By entering the data into the Excel tool, we can derive information and generate charts to assist us in evaluating if the quantities of stored, produced, and consumed hydrogen are sufficient to meet the objectives.
Three distinct scenarios have been analysed, since the electrolysers are modular, and they can be interconnected, even in later stages:

1. First Scenario: 3X 500 kW: 21kg/h H2 production
2. Second Scenario: 2X 500 kW:14 kg/h H2 production
3. Third Scenario: 500 kW: 7kg/h H2 production

- Starting storage: 50kg
- H_2 Avg. Consumption: 24kg/h

H_2 Estimation - Excel Tool		
Avg Consumption	*24 kg/h*	3X500kW 24 kg/h Avg
Production	*21 kg/h*	
Storage	*50*	
Avg Consumption	*24 kg/h*	2X500kW 14 kg/h Avg
Production	*14 kg/h*	
Storage	*50 kg*	
Avg Consumption	*24 kg/h*	500kW 7 kg/h Avg
Production	*7 kg/h*	
Storage	*50 kg*	

Table 13 - Data Input for the three scenarios

From the analysis of the chart below, it emerges that, starting with an initial storage of 50 kg, the most effective system is represented by 3 electrolysers, with a production of 21 kg/h. In this scenario, with a consumption of 24 kg/h over two shifts of 8 hours, for 5 days per week, the system operates optimally without the risk of hydrogen supply exhaustion. In this case, the electrolyser will continue to produce until the storage limit of 50 kg is reached, which will occur approximately within 2.5 hours. Subsequently, the electrolyser will be turned off (also in the weekend) and restarted on Monday morning. However, this scenario involves the highest initial investment. In the other two scenarios we observe a prevalence of negative values, and the production fails to meet the requirements, so it would be an ineffective and counterproductive investment.

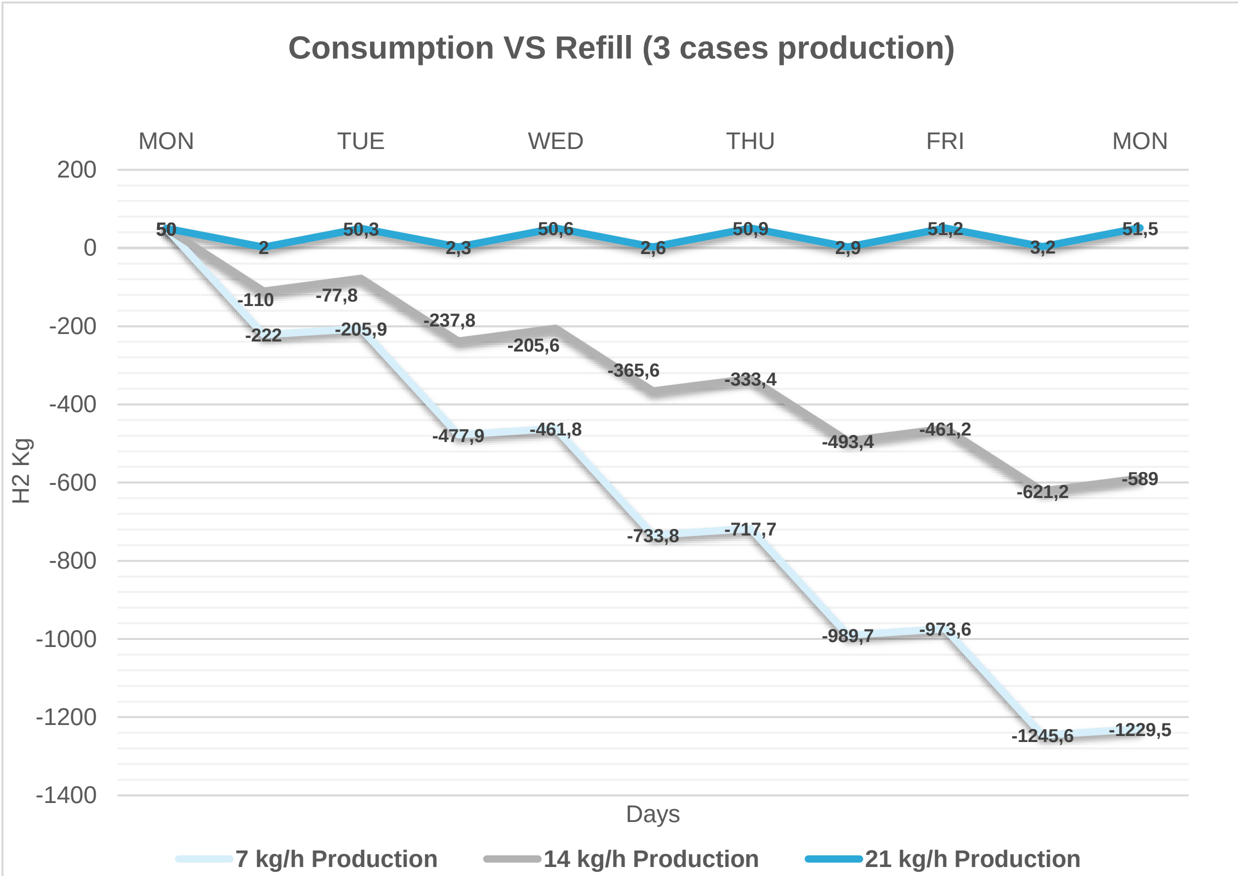


Figure 45 - Production in Three Scenarios vs. 50kg Maximum Storage Refill

The chart below shows the focus on the best-case scenario where there will be no hydrogen depletion, ensuring continuity in operations.

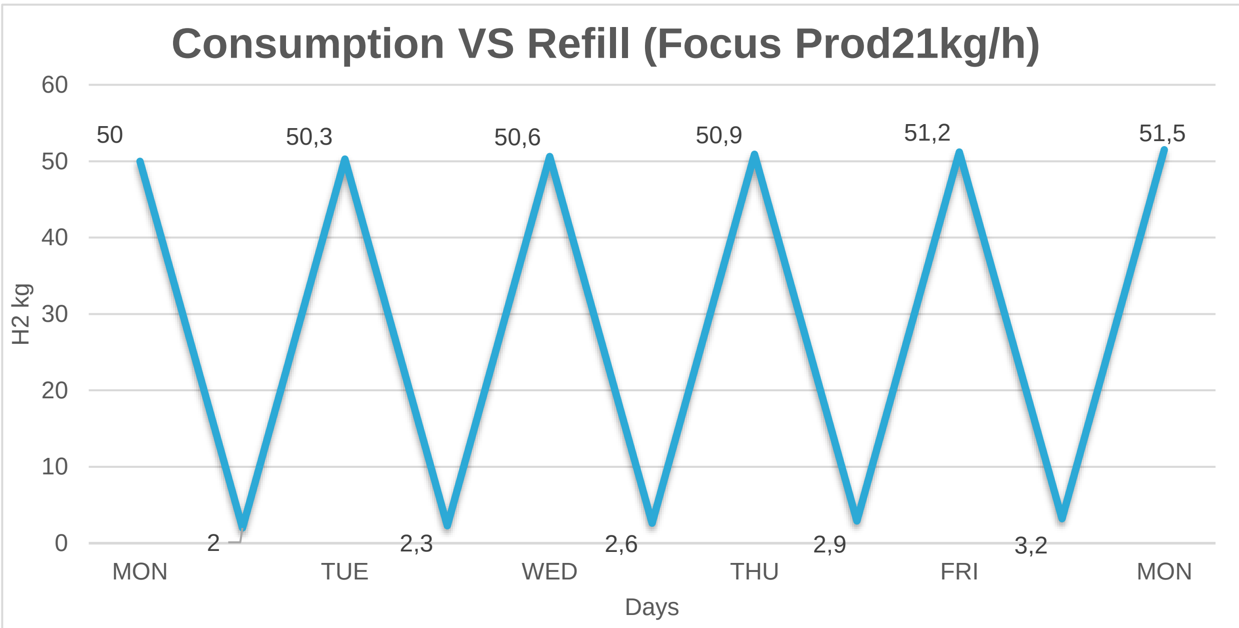


Figure 46 - First Case Scenario Focus

Certainly, it should be said that given the high investment in the electrolyser, a quicker return on investment (ROI) would be achieved if it were kept running continuously without frequent ON/OFF cycles. Therefore, the storage limit can pose an economic obstacle if it is limited. Having a very large tank available, and running the system 24/7, significantly improves the scenario as we can see in the next chart.

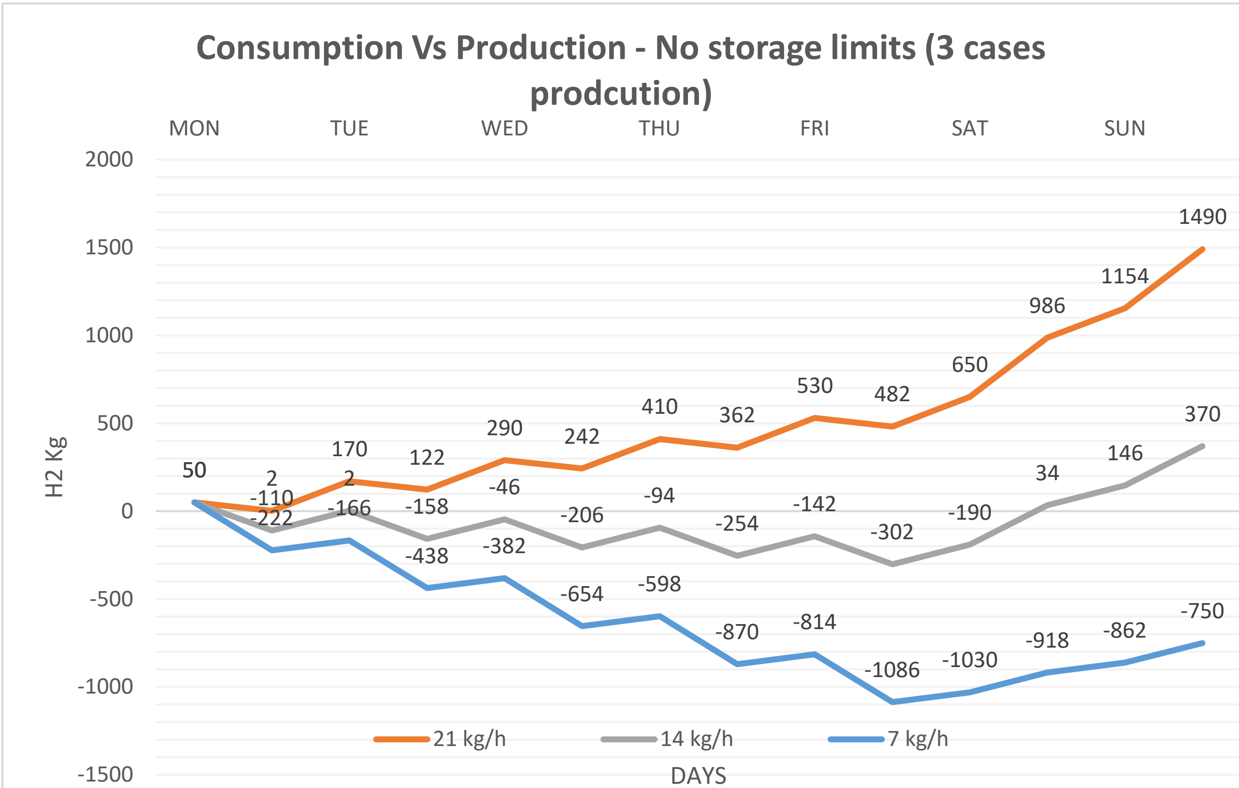


Figure 47 - Optimal Case Scenarios without Storage Constraints

The following Figure 48 shows the general Excel Tool:

Figure 48 - Excel Tool for Electrolyser Scenarios Selection

The table below provides a comprehensive overview of the outcomes derived from the exhaustive feasibility study, covering the relevant areas:

Scenarios	*Production (electrolyser)*	*Compressor 60Bar (booster)*	*Compressor 200Bar*	*Cylinders Bundle (15kG) or X2*	*Trailer Tank (or backup)*	*Trailer tanks (max2)*	*Skid Reduction and distribution*	*AREA AVL (1)*	*AREA AVL+ LANDI NORTH (2)*	*AREA AVL + LANDI EAST (3)*
1	✓	✓						✓	✗	✗
2	✓	✓		✓				✗	✓	✗
3	✓		✓		✓			✓	✗	✗
4	✓	✓	✓		✓			✗	✓	✗
5	✓	✓	✓		✓		✓	✓	✗	✗
6	✓	✓	✓		✓			✗	✗	✓
7						✓	✓	✗	✗	✓

Table 14 - Feasibility Analysis Results

The conclusion is that plant safety can be managed through two distinct approaches: the traditional method, based on rigid regulations and simple calculations, and the engineering-performance approach (Fire Safety Engineering), using computational models. The use of Fire Safety Engineering allows for a reduction in operational constraints through works and adjustments that can minimize passive protection measures and optimize plant systems. In short, what can be done is:

1. AVL Site and AVL/LANDI N+E for Cylinder Trailer Storage:

- Not suitable without significant and costly interventions due to space limitations.

2. AVL Site for On-Site Production (Electrolytic) and Direct Use:

- Suitable for on-site production without the need for backup storage.
- Constraint on compressor positioning.

3. AVL/LANDI N Site (Adjacent Space) for Production and Minimal Storage:

- Suitable for on-site production and minimal storage (cylinders).
- Challenges: Distances and active protection systems for cylinder trailers.

Actually, following the release of the new decree, the situation has been completely revolutionized. The new rules on distance limits have significantly improved the situation, and today at AVL, we are working on the project, which consists of 2 steps: a first step involving the storage in hydrogen cylinders and a second step where the electrolyser will be involved, having the storage as a buffer tank. It has been financed and initiated and will be ready in the near future.

4.5 H_2 Smart Grid Based Analysis

In a future perspective, a sort of smart grid has been planned where the use of renewable energy (AVL already owns a photovoltaic system on the roof of the plant) and storage systems from second-life batteries in containers (BESS) can coexist to create green hydrogen that can be used also in a refuelling station for secondary users.

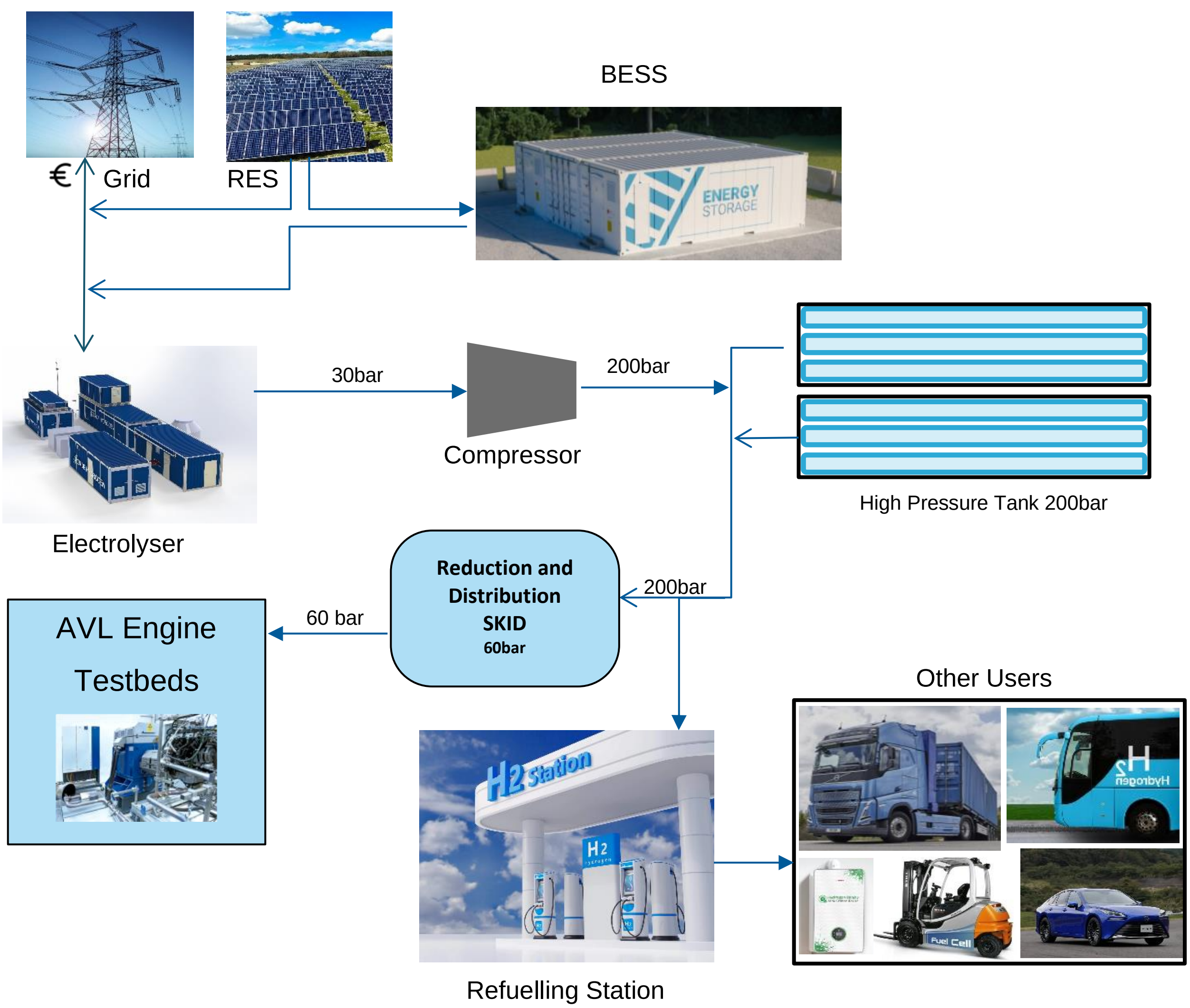


Figure 49 - H_2 Smart Grid based,Components and Functions

A new PV system has been considered. Based on the electricity demand, a suitable solution for a 1.5MW load could be:

- 6000kWp PV system
- 450W modules ~13300 units
- 22000mq field = 2.2 hectars

Advantages:

- Fast return on investment

Low operating and maintenance

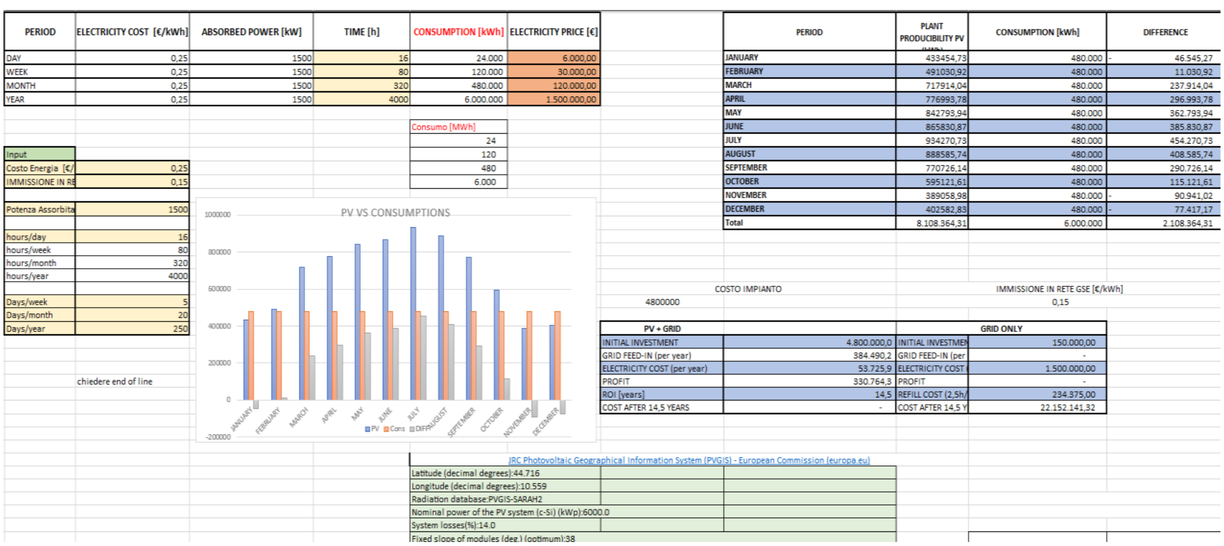
Disadvantages:

- High initial investment
- Land required for the installation

Figure 50 - Possible Solar Plant Area

A second Excel tool has been created to provide an economic estimate of the investment and ROI, considering a system with an electrolyser powered by a PV system or solely by the electrical grid. However, possible European and national funding for industries and the cost of electricity (studied during a specific global period due to Covid-19 and the Russia-Ukraine war) are not considered here. The cost of electricity and its reintegration into the grid is indicative, and a more comprehensive study with additional data is necessary.

Thanks to the "Photovoltaic Geographical Information System (PVGIS)," information on solar radiation and photovoltaic system performance was provided for the specific location, in particular monthly average data for solar radiation, daily irradiance and so on. The following Figure 51 shows an extract of the Excel tool.



PERIOD	ELECTRICITY COST [€/kWh]	ABSORBED POWER [kW]	TIME [h]	CONSUMPTION [kWh]	ELECTRICITY PRICE [€]
DAY	0,25	1500	16	24.000	6.000,00
WEEK	0,25	1500	80	120.000	30.000,00
MONTH	0,25	1500	320	480.000	120.000,00
YEAR	0,25	1500	4000	6.000.000	1.500.000,00

Consumo [MWh]
24
120
480
6.000

Input	
Costo Energia [€/	0,25
IMMISSIONE IN RE	0,15
Potenza Assorbita	1500
hours/day	16
hours/week	80
hours/month	320
hours/year	4000
Days/week	5
Days/month	20
Days/year	250

chiedere end of line

PERIOD	PLANT PRODUCIBILITY PV	CONSUMPTION [kWh]	DIFFERENCE
JANUARY	433454,73	480.000	- 46.545,27
FEBRUARY	491030,92	480.000	11.030,92
MARCH	717914,04	480.000	237.914,04
APRIL	776993,78	480.000	296.993,78
MAY	842793,94	480.000	362.793,94
JUNE	865830,87	480.000	385.830,87
JULY	934270,73	480.000	454.270,73
AUGUST	888585,74	480.000	408.585,74
SEPTEMBER	770726,14	480.000	290.726,14
OCTOBER	595121,61	480.000	115.121,61
NOVEMBER	389058,98	480.000	- 90.941,02
DECEMBER	402582,83	480.000	- 77.417,17
Total	8.108.364,31	6.000.000	2.108.364,31

COSTO IMPIANTO	IMMISSIONE IN RETE GSE [€/kWh]
4800000	0,15

PV + GRID		GRID ONLY	
INITIAL INVESTMENT	4.800.000,0	INITIAL INVESTMEN	150.000,00
GRID FEED-IN (per year)	384.490,2	GRID FEED-IN (per	-
ELECTRICITY COST (per year)	53.725,9	ELECTRICITY COST	1.500.000,00
PROFIT	330.764,3	PROFIT	-
ROI [years]	14,5	REFILL COST (2,5h/	234.375,00
COST AFTER 14,5 YEARS	-	COST AFTER 14,5 Y	22.152.141,32

JRC Photovoltaic Geographical Information System (PVGIS) - European Commission (europa.eu)

Latitude (decimal degrees):44.716
Longitude (decimal degrees):10.559
Radiation database:PVGIS-SARAH2
Nominal power of the PV system (c-Si) (kWp):6000.0
System losses(%):14.0
Fixed slope of modules (deg.) (optimum):38

Figure 51 - Excel Tool for PV system Vs Grid Analysis

From the tool, it is possible to extract a representative graph illustrating the monthly consumption of the electrolyser, monthly production, and the difference that is the profit and could be either electricity returned to the grid or stored within the Energy Storage System (BESS) that can be used during the night.

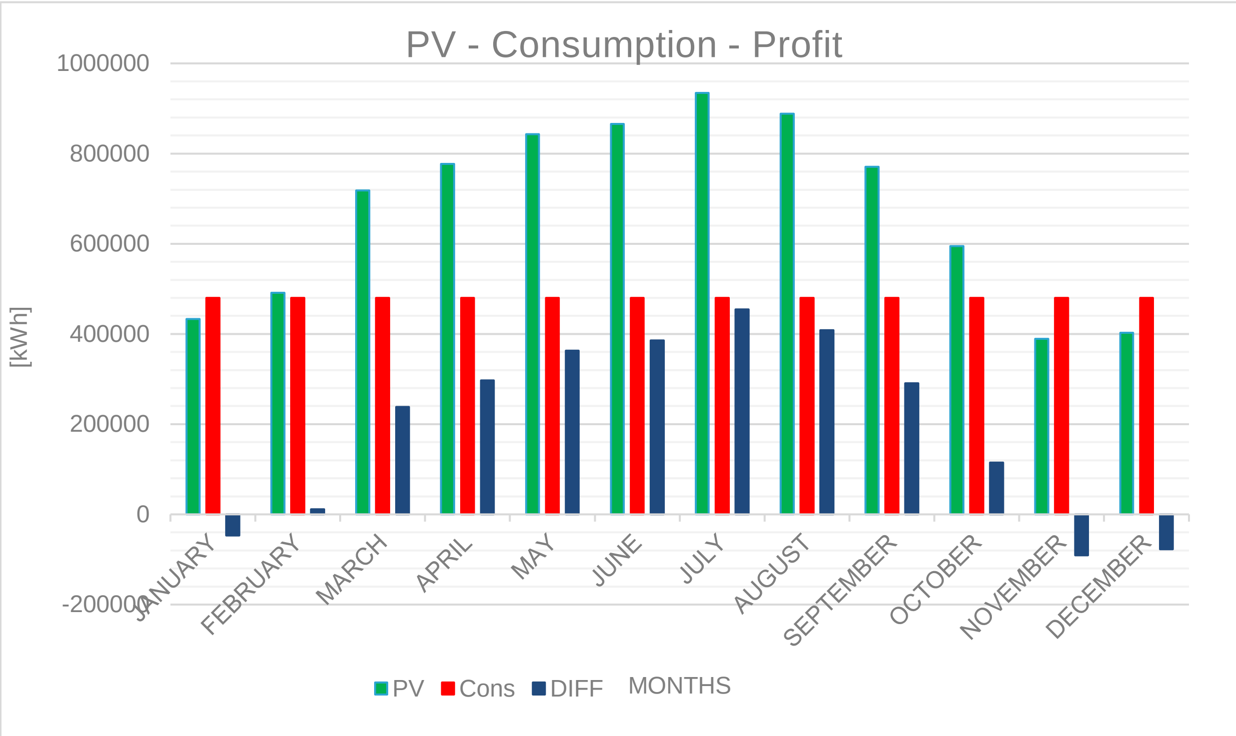


Figure 52 - Production, Consumption, Profit of a PV System

Examining this data, it was possible to conduct a technical-economic study, summarized in the following table. Please note that the ROI could be lower considering the possibility of accessing European and national funding, as well as considering an appropriate cost for electricity.

PV + GRID		GRID ONLY	
INITIAL INVESTMENT	4.800.000,0	INITIAL INVESTMENT (UPGRADE)	150.000,00
GRID FEED-IN (per year)	384.490,2	GRID FEED-IN (per year)	-
ELECTRICITY COST (per year)	53.725,9	ELECTRICITY COST (per year)	1.500.000,00
PROFIT	330.764,3	PROFIT	-
ROI [years]	14,5	REFILL COST (2,5h/day)	234.375,00
COST AFTER 14,5 YEARS	-	COST AFTER 14,5 YEARS	22.152.141,32

Table 15 - Economical Aspects

Considering the initial investments, the use of electricity (high demand), and the profit that could be derived from the combined use, it can be observed that the graphs intersect after approximately 3.5 years. The final costs are zero (ROI) for PV+Grid, and €22 million for Grid only, after about 14 years.

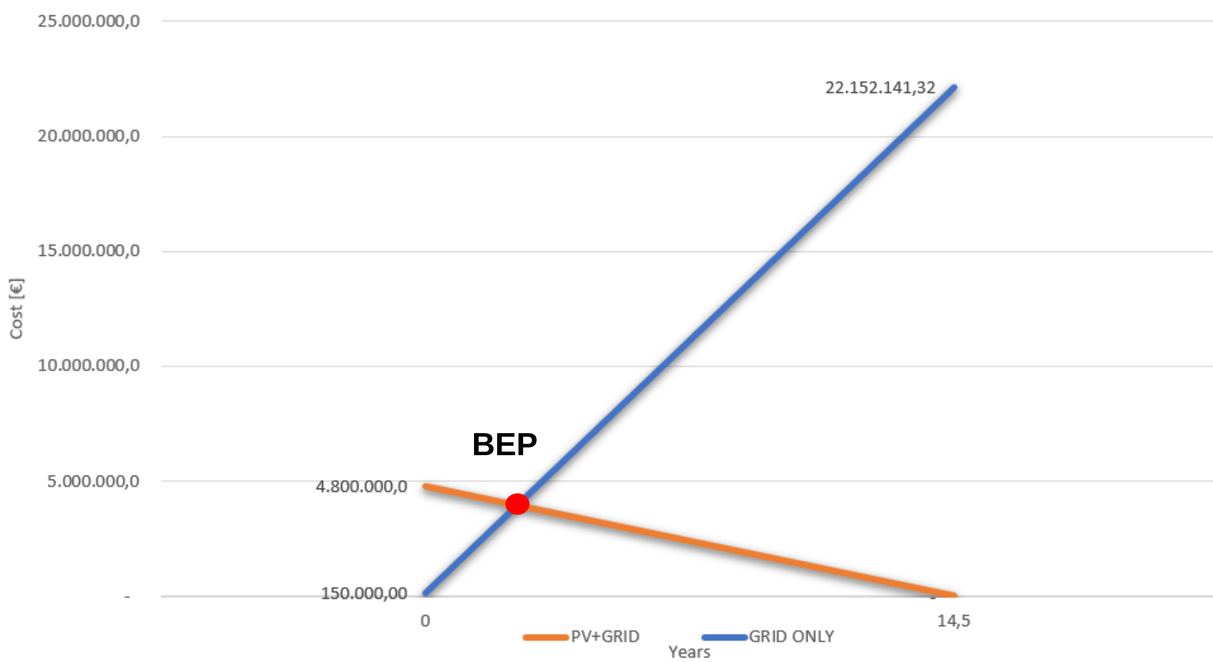


Figure 53 - Investment Scenarios

4.5.1 Second Life Battery Energy Storage System (BESS)

Second Life BESS reuse electric vehicle (EV) batteries with reduced capacity for use in Battery Energy Storage Systems (BESS).

Even after being retired from vehicles, these batteries retain significant life and can be collected in containers and repurposed for stationary energy storage applications, including storing renewable energy, providing grid support, and offering backup power.

This approach not only extends the batteries' usability but also contributes to sustainable energy storage solutions. The advantages of BESS in this study are:

- Possibility of storing energy when PV production exceeds load consumptions.
- Stored energy is used when PV is not producing (night) → H_2 storage refilling (2h)
- Increased self-consumption.
- Modularity
- Second Life EV batteries (not new batteries) → Reduction of the initial investment

Two solutions have been evaluated, 2nd life batteries in containers and in single modules (increase of the modularity).

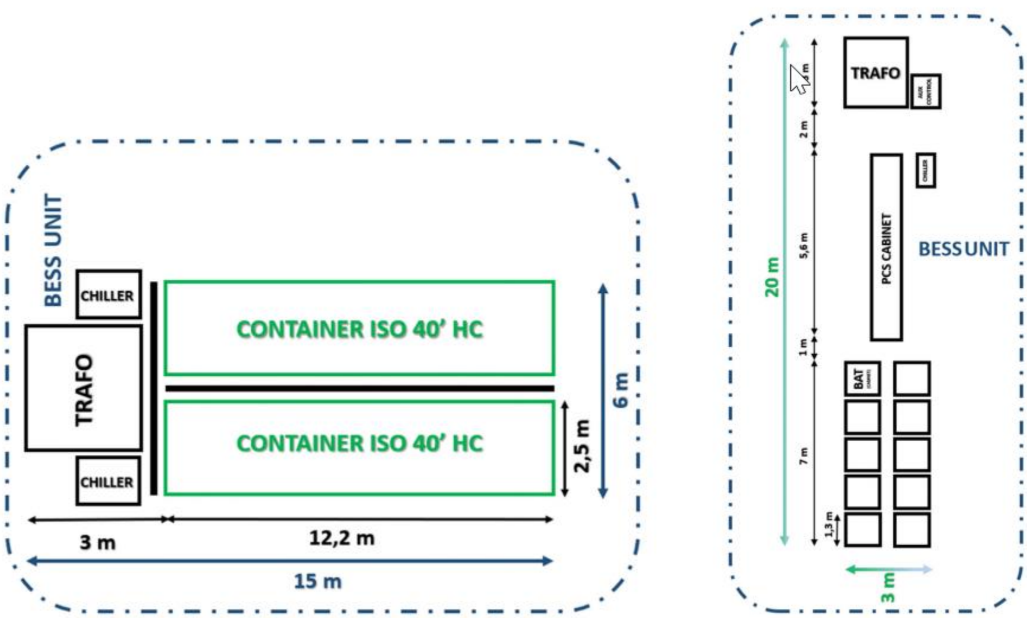
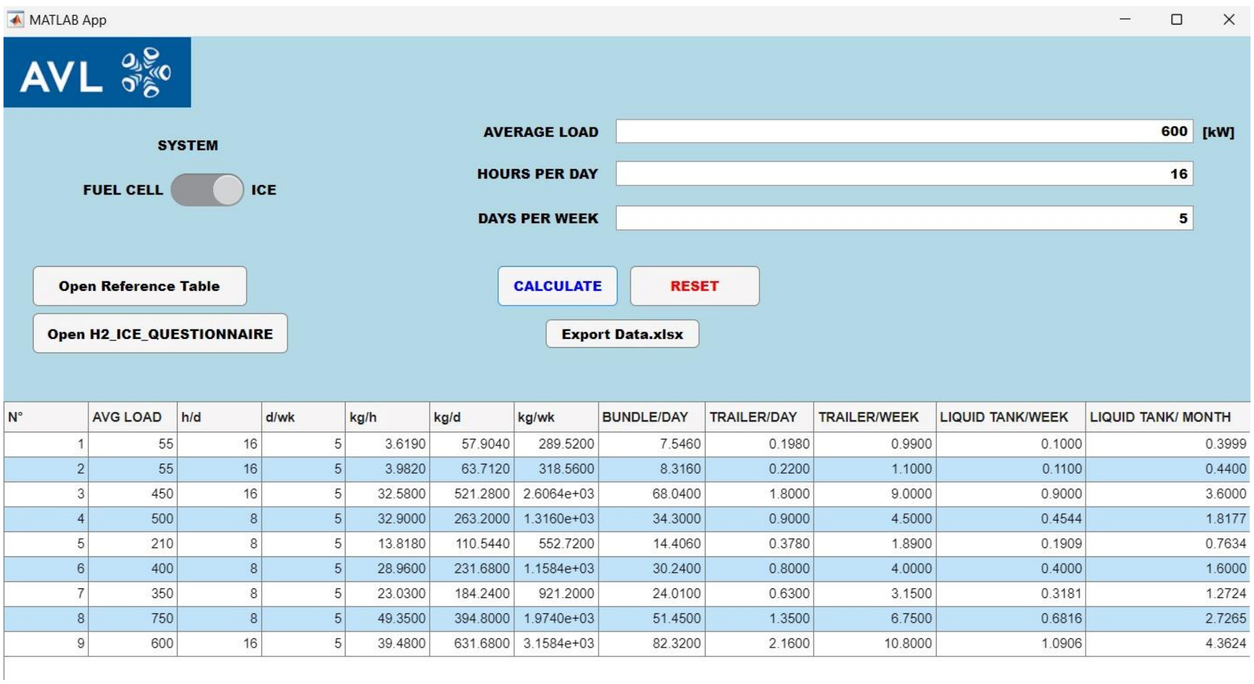


Figure 54 - BESS Solutions

4.6 MATLAB tool for customer support

The first Excel tool shown is also used when developing solutions outside of AVL for customers, for which our intent in AVL is to provide a package of solutions for what concerns the creation of an H_2 infrastructure. In this regard, a second tool created using MATLAB has been developed to address customer requests regarding the sizing of storage and supply systems. It is a standalone MATLAB app that can be installed even without having the MATLAB software itself. The main screen is the following in Figure 55:



N°	AVG LOAD	h/d	d/wk	kg/h	kg/d	kg/wk	BUNDLE/DAY	TRAILER/DAY	TRAILER/WEEK	LIQUID TANK/WEEK	LIQUID TANK/ MONTH
1	55	16	5	3.6190	57.9040	289.5200	7.5460	0.1980	0.9900	0.1000	0.3999
2	55	16	5	3.9820	63.7120	318.5600	8.3160	0.2200	1.1000	0.1100	0.4400
3	450	16	5	32.5800	521.2800	2.6064e+03	68.0400	1.8000	9.0000	0.9000	3.6000
4	500	8	5	32.9000	263.2000	1.3160e+03	34.3000	0.9000	4.5000	0.4544	1.8177
5	210	8	5	13.8180	110.5440	552.7200	14.4060	0.3780	1.8900	0.1909	0.7634
6	400	8	5	28.9600	231.6800	1.1584e+03	30.2400	0.8000	4.0000	0.4000	1.6000
7	350	8	5	23.0300	184.2400	921.2000	24.0100	0.6300	3.1500	0.3181	1.2724
8	750	8	5	49.3500	394.8000	1.9740e+03	51.4500	1.3500	6.7500	0.6816	2.7265
9	600	16	5	39.4800	631.6800	3.1584e+03	82.3200	2.1600	10.8000	1.0906	4.3624

Figure 55 - MATLAB App for Customer Support in Selecting the Best Solutions

Selecting with a switch the technology (H2ICE or Fuel Cell) and entering data related to the engine power [kW] to be tested, hours per day, and days per week, it is possible, thanks to the hydrogen consumption data provided by AVL Graz, to display on the screen the required quantity of hydrogen. Based on this information, is it possible to determine the optimal storage solution and its quantity, in terms of units (Bundle, Trailer, Liquid Tanks) and predict how often they will be depleted (in terms of day/week/) based on the input test hours.

Every time a new request is calculated, a line is added. It is also possible to extract the data in Excel format. Two buttons have been added that will display the reference database tables for consumption and a questionnaire useful during client meetings for various assessments. The MATLAB code implemented is shown below:

```
clc
close all

hydro_cons = importdata('hydro_cons.mat');
cons_solution = importdata('consumption_solutions.mat');
storage_solutions_FC = importdata('storage_solutions_FC.mat');
storage_solutions_ICE = importdata('storage_solutions_ICE.mat');
Motor_Power = 1; % inizializzo primo valore di motor power (da sistemare)



%ICE
engine_power=table2array(hydro_cons(:,1));
engine_consumption=table2array(hydro_cons(:,2));


storage_solution_cons_day_ICE=table2array(storage_solutions_ICE(:,2));
storage_solution_bundle_day_ICE=table2array(storage_solutions_ICE(:,4));
storage_solution_trailer_day_ICE=table2array(storage_solutions_ICE(:,5));
storage_solution_liquid_week_ICE=table2array(storage_solutions_ICE(:,7));
storage_solution_liquid_month_ICE=table2array(storage_solutions_ICE(:,8));

%FUEL CELL
fuel_cell_power=table2array(hydro_cons(:,3));
fuel_cell_consumption=table2array(hydro_cons(:,4));


storage_solution_cons_day_FC=table2array(storage_solutions_FC(:,2));
storage_solution_bundle_day_FC=table2array(storage_solutions_FC(:,4));
storage_solution_trailer_day_FC=table2array(storage_solutions_FC(:,5));
storage_solution_liquid_week_FC=table2array(storage_solutions_FC(:,7));
storage_solution_liquid_month_FC=table2array(storage_solutions_FC(:,8));
%ciclo
while Motor_Power > 0

    Motor_Power = input('Enter a Motor Power Value [kW] or 0 to ESC: ');
     Hour_Day = input('HOURS PER DAY: ');
     Day_week = input('DAYS PER WEEK: ');

 answer = questdlg('Would you like to use ICE or FUEL CELL?','H2 TYPE','ICE','FUEL CELL','Cancel','Cancel');
   switch answer

  %FIRST CASE ICE
 case 'ICE'
        disp([answer ' OUTPUT PARAMETER'])
        p=polyfit(engine_power,engine_consumption,1); %interpolazione, polinomio grado 1

        disp('CONSUMPTION: ')
       %Consumption per hour
        disp('(ICE) kg/h: ')
        disp(polyval(p,Motor_Power)); %valore se non esatto


        %Consumption per day
        disp('(ICE) kg/d: ')
        g =(polyval(p,Motor_Power)*Hour_Day); %valore se non esatto
        disp(g)
        %Consumption per week
        disp('(ICE) kg/w: ')
        disp(polyval(p,Motor_Power)*Day_week*Hour_Day); %valore se non esatto


       %Storage Solutions table
       disp('STORAGE SOLUTIONS: ')
       %disp('STORAGE SOLUTIONS units/time: ')
```

Figure 56 - MATLAB Code #1

```matlab
        %disp('STORAGE SOLUTIONS units/time: ')
        %disp(storage_solutions_ICE);

        %Storage solutions bundle per day

         u = polyfit(storage_solution_cons_day_ICE,storage_solution_bundle_day_ICE,2); %interpolazione, polinomio
         disp('BUNDLE UNITS PER DAY ')
         disp(polyval(u,g));


            %Storage solutions TRAILER_DAY & PER WEEK

         f = polyfit(storage_solution_cons_day_ICE,storage_solution_trailer_day_ICE,1); %interpolazione, polinomio
         disp('TRAILER UNITS PER DAY ')
         disp(polyval(f,g));
        disp('TRAILER UNITS PER WEEK ')
         disp(polyval(f,g)*Day_week);

          %Storage solutions liquid tank week month
        z = polyfit(storage_solution_cons_day_FC,storage_solution_liquid_week_FC,1);
        disp('LIQUID TANK UNITS PER WEEK ')
         disp(polyval(z,g));
        disp('LIQUID TANK PER MONTH ')
         disp(polyval(z,g)*4);

    %SECOND CASE FUEL CELL
  case 'FUEL CELL'
        disp([answer ' OUTOUT PARAMETER'])
        p=polyfit(fuel_cell_power,fuel_cell_consumption,1); %interpolazione, polinomio grado 1

        disp('CONSUMPTION: ')
        %Consumption per hour
        disp('(FC) kg/h: ')
        disp(polyval(p,Motor_Power)); %valore se non esatto

        %Consumption per day
        disp('(FC) kg/d: ')
        s =(polyval(p,Motor_Power)*Hour_Day); %valore se non esatto
        disp(s);
        %Consumption per week
        disp('(FC) kg/w: ')
        disp(polyval(p,Motor_Power)*Day_week*Hour_Day); %valore se non esatto

        %Storage Solutions table
        disp('STORAGE SOLUTIONS: ')
        %disp(storage_solutions_FC);


         %Storage solutions bundle per day

         r = polyfit(storage_solution_cons_day_FC,storage_solution_bundle_day_FC,2); %interpolazione, polinomio
         disp('BUNDLE UNITS PER DAY ')
         disp(polyval(r,s));


         %Storage solutions TRAILER_DAY & PER WEEK

         t = polyfit(storage_solution_cons_day_FC,storage_solution_trailer_day_FC,1); %interpolazione, polinomio
         disp('TRAILER UNITS PER DAY ')
         disp(polyval(t,s));
        disp('TRAILER UNITS PER WEEK ')
         disp(polyval(t,s)*Day_week);

          %Storage solutions liquid tank week month
        c = polyfit(storage_solution_cons_day_FC,storage_solution_liquid_week_FC,1);
        disp('LIQUID TANK UNITS PER WEEK ')
         disp(polyval(c,s));
        disp('LIQUID TANK PER MONTH ')
         disp(polyval(c,s)*4);
   end
```

Figure 57 - MATLAB Code #2

5 About AVL

AVL is an Austrian company specializing in providing engineering, testing, and development solutions for the automotive and energy sectors. Below are some of AVL's key activities in these areas:

1. **Engine and Transmission Development**: AVL is involved in the development and optimization of internal combustion engines, transmissions, and alternative propulsion systems, including hybrid and electric systems.

2. **Engine Testing:** AVL provides advanced testing services to assess the performance, reliability, and emissions of engines. This includes emission testing, fuel consumption measurement, vibration analysis, durability testing, and more.

3. **Electronic Control Systems:** The company works on electronic control systems to ensure efficient and safe operation of vehicles, including those with hybrid and electric propulsion.

4. **Computer Simulations:** AVL uses advanced models and computer simulations to conduct virtual tests, reducing the need for physical prototypes and speeding up development cycles.

5. **Electric Vehicles and Alternative Propulsion Systems:** AVL is involved in the development of technologies related to electric vehicles, including propulsion systems and batteries.

For what concerns the energy sector:

1. **Development of Energy Solutions**: AVL is involved in developing energy solutions, including technologies for sustainable mobility and energy efficiency.

2. **Testing of Energy Components**: AVL conducts tests to assess the efficiency and safety of energy components, including engines and energy storage systems.

3. **Alternative Propulsion Systems**: The company is committed to developing technologies for alternative vehicles and propulsion systems, including those using hydrogen and fuel cells.

In summary, AVL plays a key role in innovation and technological development in both the automotive and energy sectors, contributing to shaping the future of sustainable mobility and energy efficiency.

5.1 What does "Test" mean and H_2 in testing

In the automotive and AVL context, the term "Test" refers to a wide range of activities and analysis conducted to assess the performance and efficiency, quality and safety, compliance, of automotive technologies with industry standards and regulations.
From testing solutions for E-Mobility, Fuel Cell, Automated and Connected Mobility, to ICE/Hybrid propulsion systems, along with standalone measurement equipment and software, AVL has the expertise to support the optimization of companies' testing and validation programs, offering comprehensive solutions from start to the conclusion of the testing process.

5.1.1. Testing Solutions for AVL

AVL provides a comprehensive range of testing solutions that cover various aspects of automotive engineering. This includes testing for E-Mobility (electric mobility), Fuel Cell technologies, Automated and Connected Mobility, as well as Internal Combustion Engine (ICE) and Hybrid propulsion systems [29].

1- **Powertrain Testing:** This involves testing engines and transmissions to ensure they meet performance, efficiency, and emissions standards. AVL Powertrain TS™ is designed to manage the complex validation of ICE-driven vehicles and electric vehicles (EVs) – hybrid EVs, plug-in hybrid EVs, battery EVs, and fuel cell EVs – throughout the development process.

Figure 58 - AVL Powertrain TS™ Testbed [29]

2- **Alternative Fuel Engine Testing**

Beyond hybridization, promising alternatives for emission reduction and greenhouse gas mitigation include fuels like hydrogen, e-fuels, natural gas, biofuels, and alcohol fuels. However, this various range of fuel options for engine-based propulsion systems presents challenges in establishing complex development and testing facilities.

Figure 59 - AVL Fuel Cell System TS™ [29]

3- **Emission Testing:**

Assessing and measuring the emissions of harmful gases produced by internal combustion engines during operation is a critical aspect of testing in the automotive industry. AVL is involved in emission testing to ensure compliance with environmental standards. this includes measuring levels of pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter.

4- **Efficiency and Performance Testing light duty (LD) and Heavy duty (HD)**

Testing the energy efficiency and overall performance of engines and propulsion systems is crucial for evaluating the effectiveness of automotive technologies. AVL conducts these tests to optimize efficiency and meet industry standards.

- Durability and Endurance Testing**:** AVL conducts tests to verify the ability of automotive components and systems to withstand prolonged exposure to various stressors, including load, vibration, and environmental conditions.
- Energy consumption and driving range optimization.
- Failure diagnosis.
- Advanced calibration for drivability.

5- **Testing Equipment and Tools:** AVL develops and provide testing equipment and tools used by automotive manufacturers and research institutions. With safety standards.

6- **NVH and EMC Testing**

Typical applications for NVH involve:

- Transmission NVH
- Propulsion system NVH

NVH (Noise, Vibration, and Harshness) testing in the automotive industry is crucial for ensuring a pleasant and comfortable driving experience. This type of testing involves the evaluation and measurement of noises, vibrations, and harshness generated by vehicles. The following figures show an overview of how NVH testing is typically conducted inside AVL testbeds:

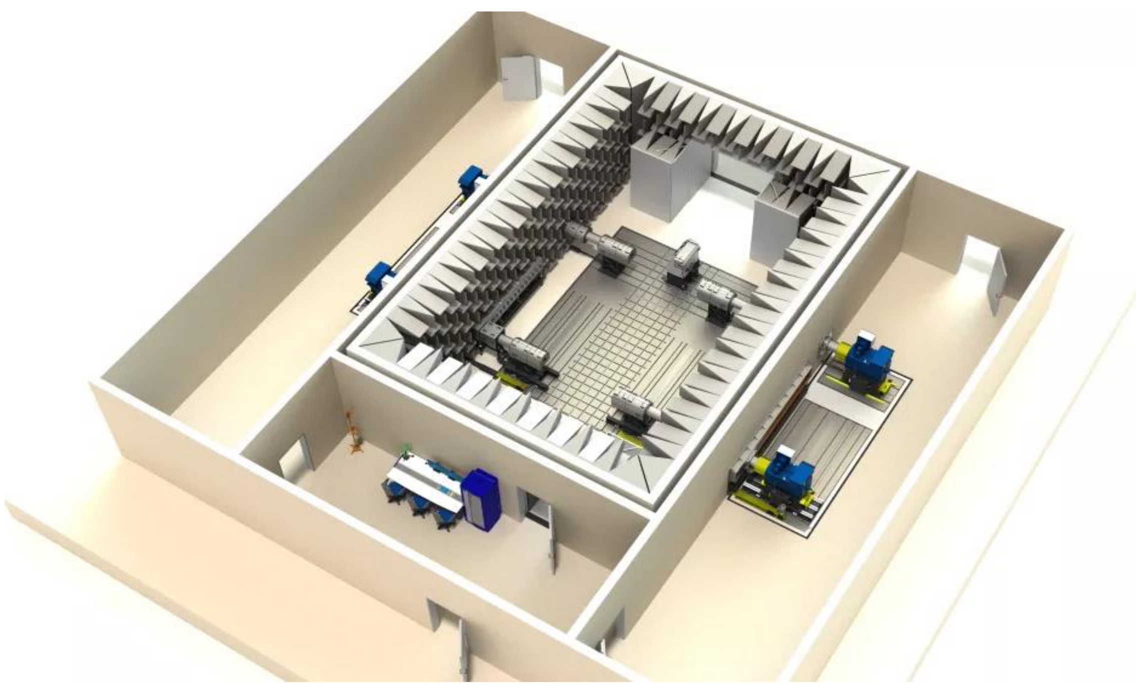


Figure 60 - NVH Testing for E-Mobility [29]

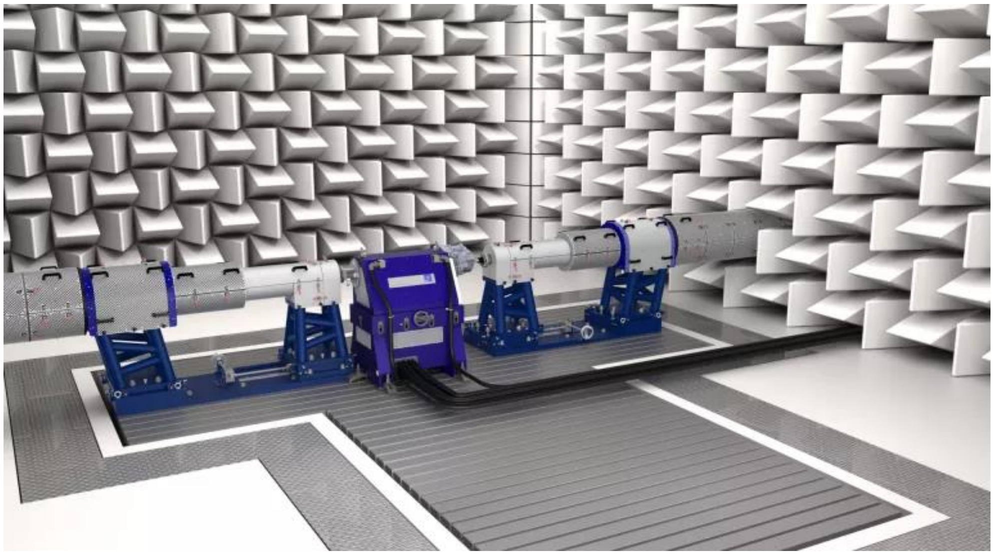


Figure 61 - NVH Testing Chamber [29]

In general, NVH testing take place in controlled environments like acoustic chambers and chassis dynamometers to precisely measure and analyse vehicle noises and vibrations. Through methods like Road Load Data Acquisition and Powertrain NVH Testing, real-world driving conditions are simulated. Advanced analysis techniques, including FFT for example, assist in converting and interpreting the collected data. Additionally, simulations using Finite Element Analysis and computational aeroacoustics predict NVH characteristics.

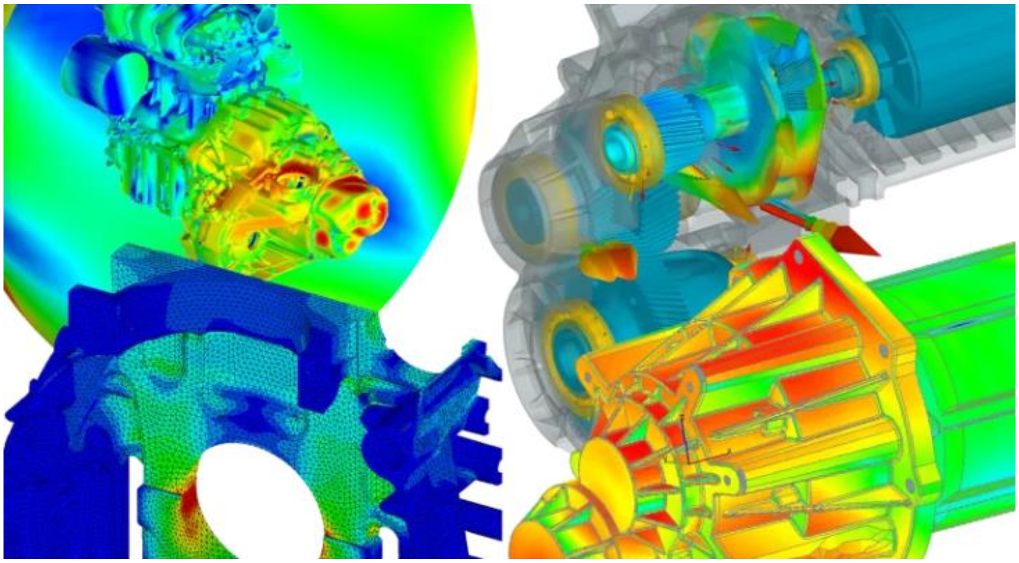


Figure 62 - AVL EXCITE™Multibody Dynamics Software

For what concerns EMC testing, in recent years the automotive industry faces the task of integrating a rising number of electrical and electronic subsystems. Challenges involve escalating complexity, interoperability issues, and the evolution of safety and communication interfaces. To minimize interference among various electrical systems, automotive electromagnetic compatibility (EMC) standards are frequently revised. For E-Mobility sector, AVL offers EMC solutions both for E-Motor and E-Axle.

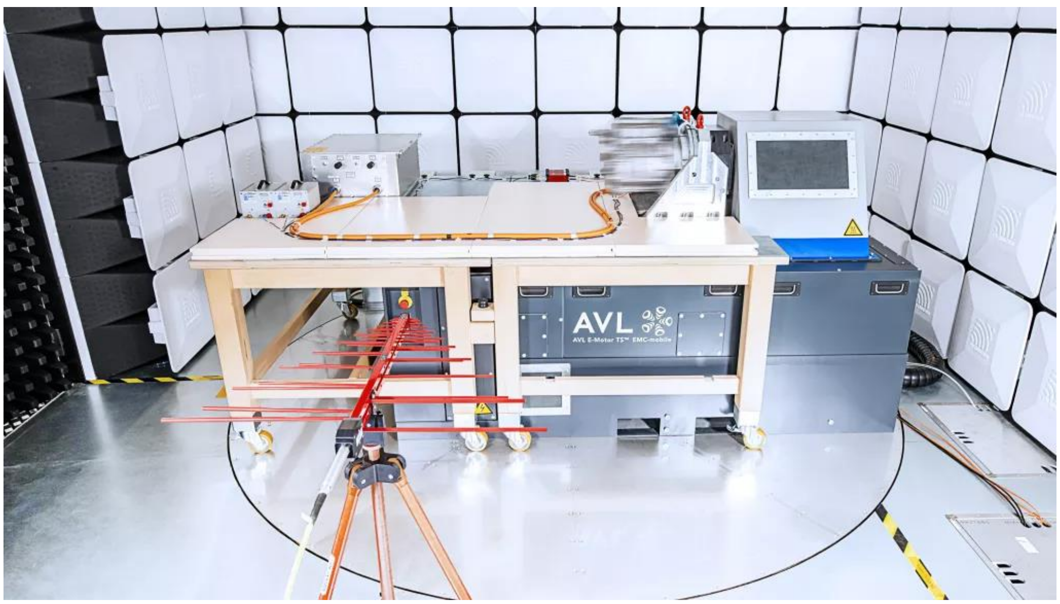


Figure 63 - AVL E-Motor TS™ EMC

7- **Electronic Control Systems Testing:**

Given the increasing integration of electronic control systems in vehicles, AVL is involved in verifying and validating these systems to ensure their correct and safe operation.

8- **Battery and Electric Propulsion System Testing:**

With the rise of electric vehicles, AVL is engaged in testing the performance, efficiency, and safety of electric propulsion systems and batteries.

A battery cell test system comprises a temperature chamber for testing lithium-ion batteries, a cell cycler within the required current and voltage range, and an automation system.

Figure 64 - AVL Battery Cell Test Chamber [29]

The AVL E-STORAGE BTE™ for example is a versatile device serving as both a battery tester and emulator of the E-STORAGE family. It validates batteries, e-motors, inverters, and fuel cells in early development, ensuring excellent dynamic performance and precise measurement control. The main features are:

9- **Simulations and Computer-Aided Testing:**

AVL employs advanced computer simulations and modeling techniques for virtual testing, to predict and optimize the behavior of automotive systems, capable of replacing in-vehicle or testbed setups. reducing the need for physical prototypes and accelerating the development process.

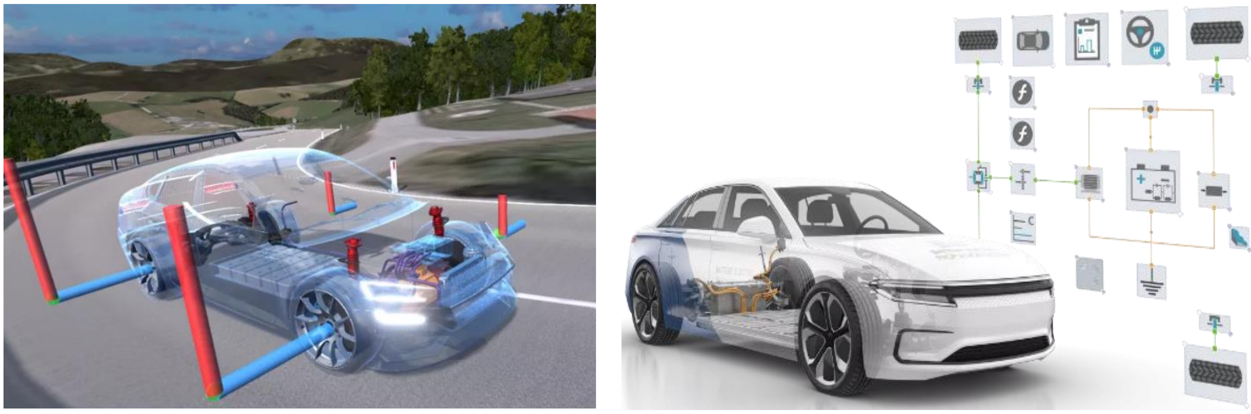


Figure 65 - Examples of Virtual Simulations

5.2 Testing facilities (AVL)

An engine testbed is a specialized facility or system designed to assess the performance, efficiency, and various features of a car engine in a controlled environment. Using these testbeds, automotive engineers can refine engine designs, troubleshoot performance concerns, and ensure that engines comply with regulations and customer requirements. This proactive approach helps in refining and optimizing engines before they are incorporated into vehicles for real-world usage, ensuring that they perform reliably and meet the expected standards.

5.2.1 Conversion of an Engine Test Cell into a Hydrogen Test Cell

Running engines with new alternative fuels on the testbed requires careful consideration of a multitude of modifications and extensions.

Examples include adaptations for fuel consumption measurement, emission measurement instrumentation, combustion air, and additional safety measures in the test cell. Addressing potential hazards associated with handling hydrogen, as discussed in previous sections, involves a comprehensive consideration of the following factors:

1. **High Pressure:** Hydrogen, due to its low density, necessitates storage under high pressure conditions.

2. **Fire and Explosion Risks:** Hydrogen, possessing a high energy content, presents inherent risks of fire and explosion, requiring stringent safety protocols to mitigate these potential hazards, especially given its ease of ignition.

3. **Embrittlement:** Working with hydrogen demands a thorough understanding of materials to ensure a safe, leakage-free environment, as embrittlement is a significant concern.

4. **Temperature Challenges:** Managing temperature is crucial when dealing with hydrogen, highlighting the importance of effective temperature control measures to ensure safety.

Let's see in the following Figure 66 how the hydrogen properties impact on a test cell system:

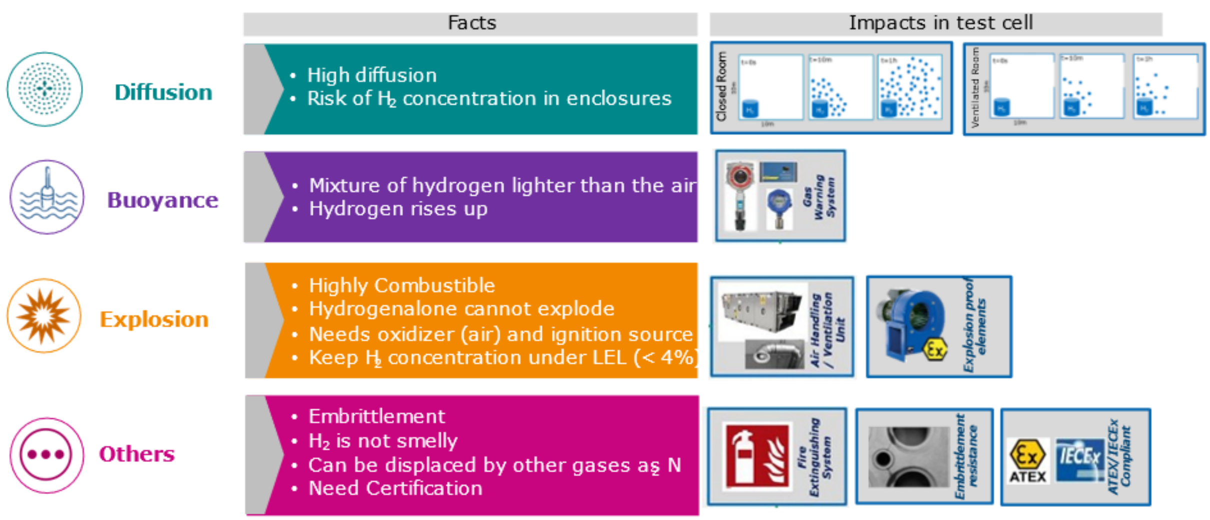


Figure 66 - Hydrogen Properties and Impact on the Test Cell [31]

In the context of hydrogen utilization, it's imperative to acknowledge its unique properties as the lightest and smallest element in the periodic system. Given its lower density than air and high diffusion tendencies, a critical consideration arises regarding potential leakage scenarios. Hydrogen, being lighter than air, has the tendency to ascend rapidly, necessitating a comprehensive understanding of leakage sources and the implementation of effective safety measures. Proper ventilation, gas detection systems, and facility upgrades are mandatory to mitigate hydrogen diffusion. Furthermore, its highly combustible nature, requiring oxygen for ignition within a wide concentration range (between <4% and 70% volumetric percents), underscores the importance of careful safety protocols.

Certifications play a pivotal role in ensuring the safety and compliance of hydrogen facilities, requiring stringent adherence to established standards. The AVL headquarters in Graz exemplifies a comprehensive approach to hydrogen storage, employing various methods such as trailers, buffer tanks, and liquid tanks. This infrastructure supports the operation of both H2ICE engine testbeds and Fuel Cell Testbeds. The placement of these storage facilities within AVL's city-center location presented a notable challenge, but the more permissive regulations in Graz, as opposed to Italy, facilitated the integration of these storage solutions within AVL's operations.

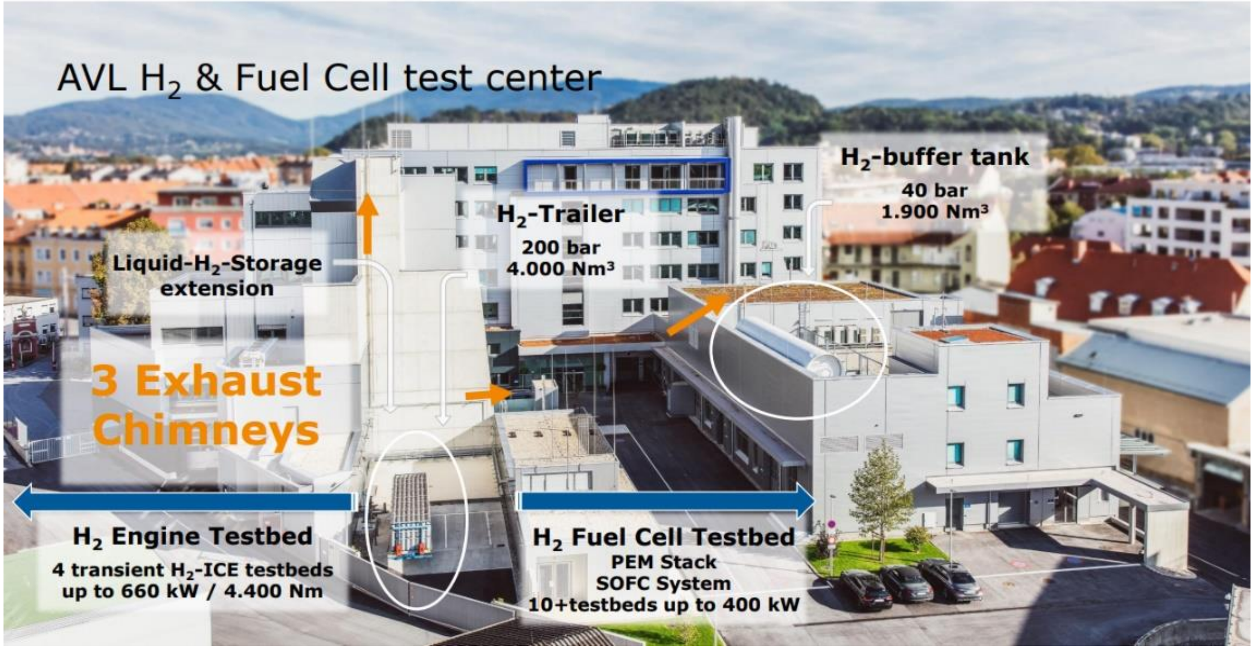


Figure 67 - AVL Headquarter in Graz

Regarding test cells and the associated safety considerations, the following illustration depicts the H2ICE application on the left and Fuel Cell Testing on the right. This delineates the distinct setups and safety factors influencing these critical testing environments.

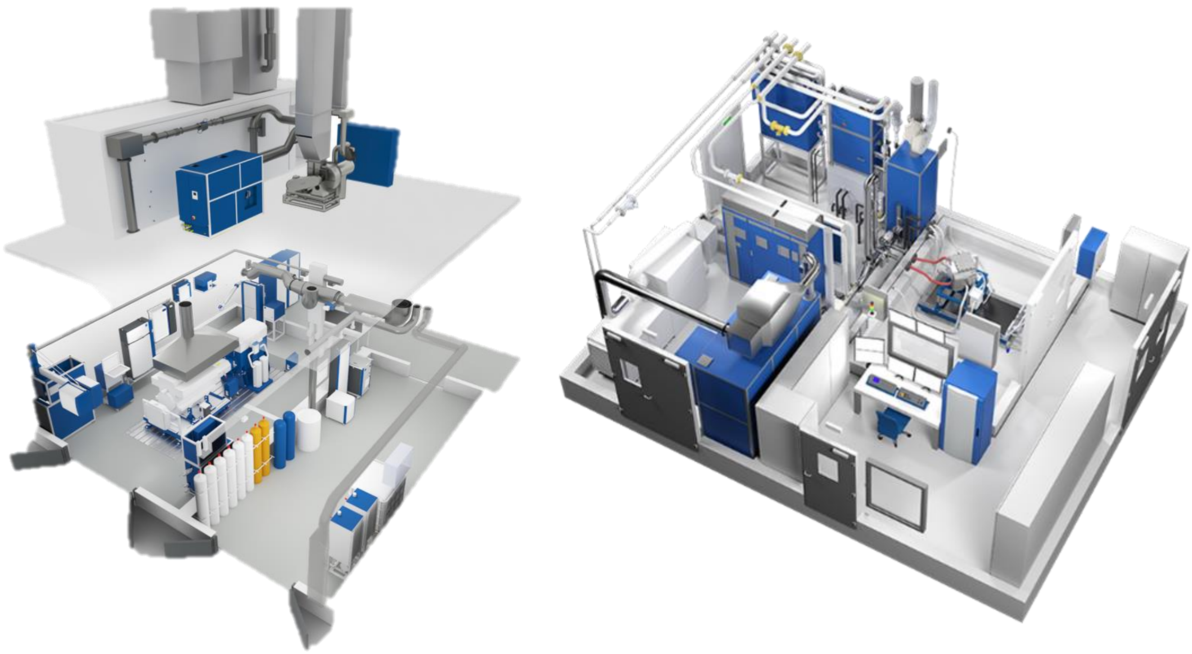


Figure 68 - Fuel Cell and H2ICE Applications [29]

In the process of upgrading an Internal Combustion Engine (ICE) test bed for hydrogen utilization, a comprehensive focus is essential across five critical pillars:

1. **H2 supply:** The hydrogen infrastructure demands meticulous attention, addressing aspects such as the transportation of hydrogen from the tank to the test cell. Ensuring specific conditions including pressure, purity, and mass flow is imperative. Continuous and secure supply, accompanied by stringent safety measures, forms the foundation of this pillar.
2. **H2 Consumption measurement:** Stability and accuracy are paramount considerations in measuring hydrogen consumption, encompassing both low and

high concentrations, as well as low and high pressures. The reliability and precision of measurements significantly influence the efficacy of the testing process.

3. **Air handling unit, Exhaust & ATEX Ventilation**: The ventilation system holds pivotal importance in the context of safety aspects. Adequate air handling, exhaust mechanisms, and adherence to ATEX ventilation standards are crucial elements in establishing a secure testing environment.
4. **Adaptation of Instrumentation:** The transformation of an existing test cell for hydrogen utilization involves upgrading or replacing equipment to align with the unique properties of hydrogen. This adaptive approach allows for the efficient reuse and modification of existing equipment to meet the specific requirements of hydrogen testing.
5. **Test Cell & Facility Safety:** Safety considerations extend beyond individual components to encompass the overall working environment. Certifications from the authorities are indispensable, ensuring that the test cell and the facility adhere to the highest safety standards. This pillar underscores the paramount importance of a secure and certified working environment in hydrogen-related testing activities.

In the context of H2 ICE applications, there are several challenges within the test cell environment. Explosions and diffusion, arising from the unique properties of hydrogen, have already been discussed.

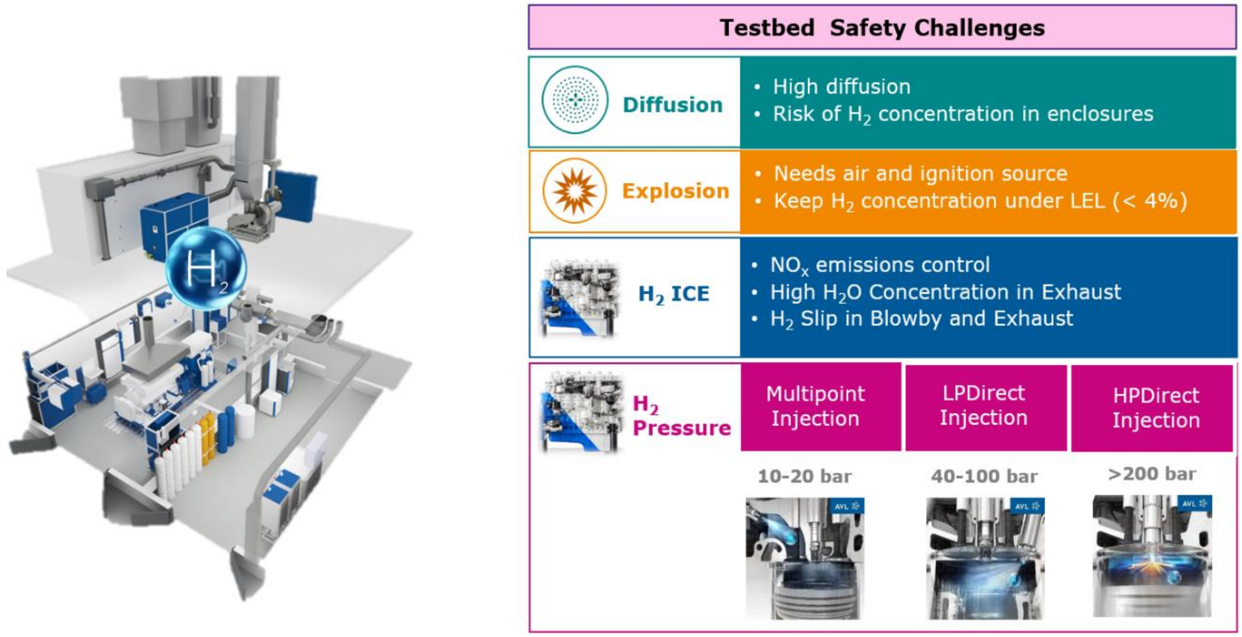


Figure 69 - H2ICE Application Challenges [31]

An additional crucial aspect concerns the challenges in optimizing engine performance. As reported earlier, the generation of NOx emissions in H2ICE demands a deep assessment. Under extremely low lambda conditions, NOx emissions exhibit a substantial increase, necessitating a strategic shift toward lean combustion.

Equally significant is the consideration of water concentration in the exhaust, a factor that requires careful attention due to its elevated levels, nearly double that observed in a conventional diesel testbed.

The hydrogen pressure within the test cell is one of the main important parameters, primarily regulated by the injection system. The well-established multipoint injection (MPI) operates within a pressure range of 10-20 bars (similarly to the pressure encountered in Fuel Cell applications). However, the challenge extends to include Direct Injection (DI), encompassing both Low-Pressure Direct Injection (LPDI) and High-Pressure Direct Injection (HPDI). Pressure thresholds span from 40 to 100 bars for LPDI and exceed 200 bars for HPDI applications.

Pressure is particularly crucial as it defines the quality of releases within the test cell, influences maximum concentrations, and contributes to the overall complexity of the safety system.

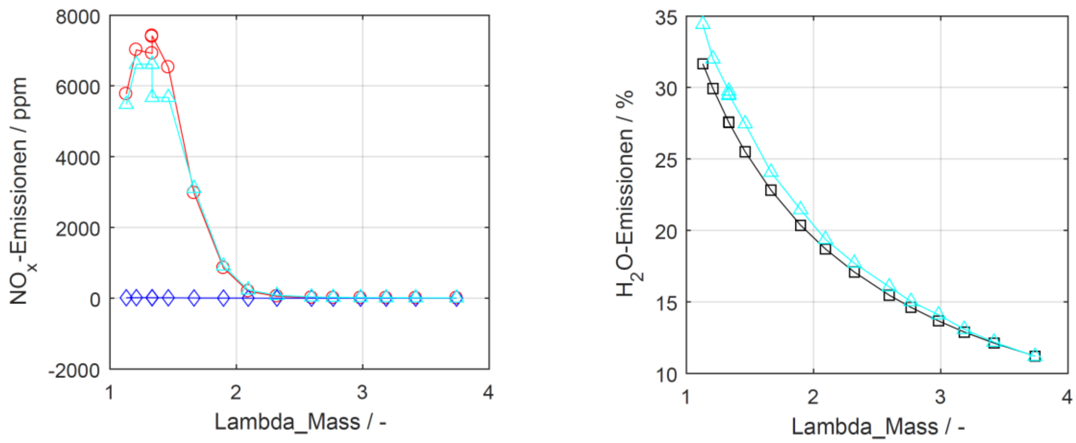


Figure 70 - Nox Emission Vs Lambda [31]

Let's examine the differences between a Diesel Internal Combustion Engine (ICE) testbed and a Hydrogen ICE test cell. Essentially, three actions should be considered:

1- **Capability Check:** Assess the system's capability to accommodate hydrogen-specific requirements.
2- **Development of Specific Functions for H2 Application:** Create and integrate functions that are specifically designed for hydrogen applications.
3- **Adaptation of Safety Measures**: Modify and enhance safety protocols to address the unique aspects of hydrogen testing.

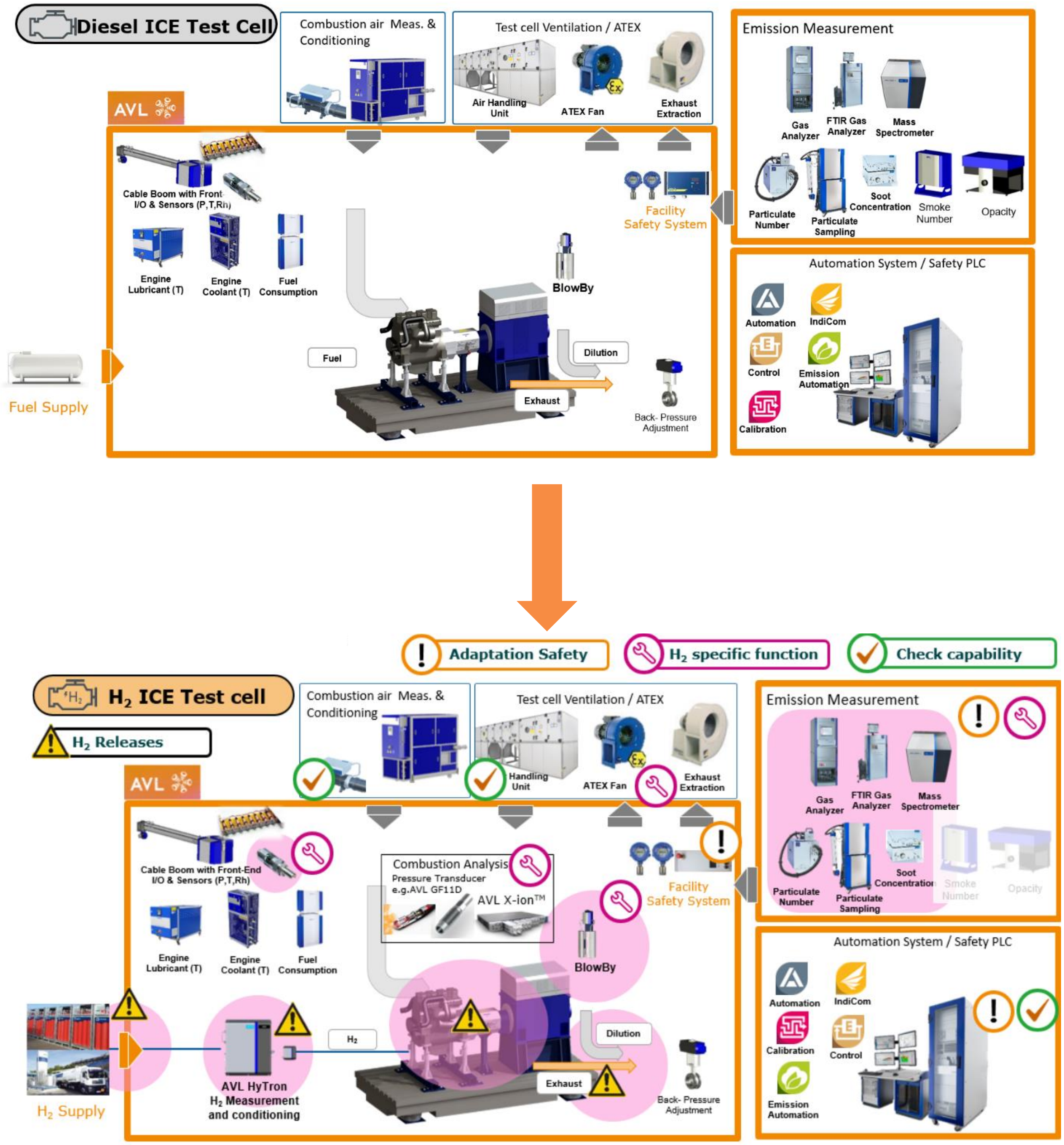


Figure 71 – From Diesel ICE Testbed to H2 ICE Testbed Adapatation in AVL [31]

1. At first, we should think about H2 Measurement and conditioning system. In the test cell, AVL implements its standardized device which is the HyTron.
2. A second step is to check the capability of the combustion air supply (excess of air is needed) and ventilation capabilities (it’s important because it is one of the primary protection measures in the testbed)
3. Identify the H2 releases in the test cell and where them are, because if the correct measures are not taken in the test cell, the hydrogen releases will create an explosive atmosphere and it’s very dangerous.
4. Special attention is required to the equipment in contact with pure hydrogen or mixed with hydrogen and air (this is the case for example of the AVL BlowBy meter or the emission equipments, both particulate and gaseous emissions)

Moreover, there is the need of implementing special functions to protect the instrumentation and equipment. This because is important to assure an optimal measurement quality.

The Test Cell will require important Safety Integrated Functions that are integrated also in the automation system (in AVL is called PUMA) and Organisational Measures to be able to work in a non-hazardous environment.

For what concerns the Fuel Cell testbed instead:

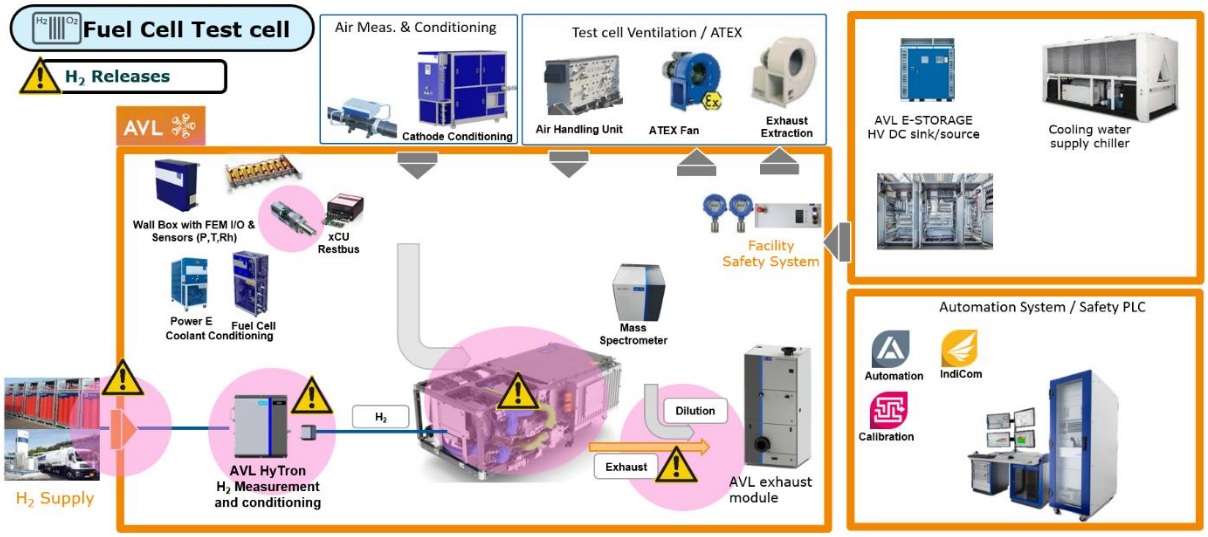


Figure 72 - Fuel Cell Testbed, Hazardous Zones [31]

The Figure 72 depicts a fuel cell testbed with its associated modules. Positioned centrally is the Fuel Cell System, which requires a supply of hydrogen and air. Hydrogen is conveyed from the facility to the test cell, facilitated by a dedicated module for hydrogen supply as previously mentioned. The HyTron manages the measurement and conditioning of the supplied hydrogen, while air is drawn from the test cell. Energy and heat generated by the Fuel Cell (FC) are managed by load and cooling conditioning units. The overall intelligence of the entire testbed is centralized in the automation system, specifically AVL PUMA 2 Fuel Cell. The figure highlights potential hydrogen release points, including those from the supply, the Fuel Cell System itself, or in the exhaust module.

Conclusions

In both theory and practical application, the significance of hydrogen in driving energy transformation and aligning with the objectives outlined in the Paris Agreement has become evident. The proper distribution of hydrogen demand across various industries requires a thoughtful consideration of the renewable energy capacity required for hydrogen production.

Central to the success of hydrogen projects is the management of electricity prices, constituting a substantial cost component. Renewable electricity emerges as a pivotal factor in facilitating the decarbonization of industries such as iron and steel.

The momentum toward green hydrogen, coupled with initiatives supporting hydrogen injection into the gas network, enjoys backing from both research entities and governmental bodies as a strategic means of achieving their targets.

Policy support plays a crucial role in steering innovation and fostering investment in emerging technologies. Simultaneously, efforts are needed to drive down the costs of electrolysers, with a focus on enhancing efficiency to produce the same volume of hydrogen with reduced resources. The collective pursuit of these strategies is essential for realizing the full potential of hydrogen in advancing sustainable energy solutions.

The cost and efficiency of a hydrogen plant depend on the sources of hydrogen production. Costs can be minimized if the plant is situated near its natural resources. Therefore, the consideration of source locations is crucial in the development of a hydrogen plant.

This eco-friendly energy has no impact on the environment, making it appealing for the development of hydrogen vehicles by the automotive industry. Hydrogen comes with various benefits for combustion in internal combustion engines. However, designing engines requires special attention to prevent abnormal combustion, which is a significant challenge in hydrogen engines. As a result, improvements should be seen in engine efficiency, power production, and the reduction of NOx emissions.

In conclusion, this thesis contributes to the sustainable energy dialogue by unrevealing hydrogen's complexities. By combining theoretical knowledge with practical applications, it offers a comprehensive understanding of hydrogen's potential. As the energy landscape evolves, hydrogen emerges as a key player, promising a sustainable and resilient future.

The journey through this thesis reflects not just the current state of hydrogen technologies but also the dynamic possibilities that lie ahead in the intricate intersection of science, technology, and sustainability.

Bibliography and Webography

[1] https://www.eo-dev.com/technologies/hydrogen

[2] https://www.iea.org/reports/the-future-of-hydrogen

[3] https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

[4] "The economics and the environmental benignity of different colors of hydrogen ", A. Ajanovic, M. Sayer, R. Haas

[5] "Hydrogen Economy Outlook, March 30, 2020"– BloombergNEF

[6] "Global Hydrogen review 2023" - IEA

[7] "Ministero dello sviluppo economico. Strategia Nazionale Idrogeno Linee Guida Preliminari. 2020."
URL:https://www.mimit.gov.it/images/stories/documenti/Strategia_Nazionale_Idrogeno_Linee_guida_preliminari_nov20.pdf (visited on 2023).

[8] "Hydrogen Innovation Report 2023"by Energy & Strategy.

[9]https://www.bip-group.com/insights/hydrogen-valley-the-key-to-break-the-chicken-and-egg-deadlock/

[10] Hydrogen Valleys, ecco le proposte ammesse dalle Regioni Italiane - Hydrogen-news.it

[11] https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en

[12] The role of hydrogen for future internal combustion engines (polimi.it)

[13] GenComm Smart H2 position paper March 2018 - GENCOMM: GENerating energy secure COMMunities | Interreg NWE (nweurope.eu)

[14] "Hydrogen Fuel for FutureMobility: Challenges and Future Aspects -
Santanu Kumar Dash, Suprava Chakraborty, Michele Roccotelli, Umesh Kumar Sahu", 2022

[15] "Recent development of hydrogen and fuel cell technologies: A review"
Author links open overlay panelLixin Fan a, Zhengkai Tu a, Siew Hwa Chan b", 2021,

[16] "Understanding How a Hydrogen Fuel Cell Works: A Comprehensive Guide"
April 21, 2023; https://www.lhyfe-heroes.com/about-hydrogen/understanding-how-a-hydrogen-fuel-cell-works-a-comprehensive-guide

[17] https://www.energoclub.org/page/fuel-cell

[18] “The role of hydrogen for future internal combustion engines“International J of Engine Research 2022

[19] “A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges, 2021“

[20] “A Review of Hydrogen Direct Injection for Internal Combustion Engines: Towards Carbon-Free Combustion “, 2019 - https://www.mdpi.com/2076-3417/9/22/4842

[21]https://www.avl.com/en/press/press-release/410-hp-2-liter-displacement-prototype-h2-ice-race-engine-avl

[22] https://hyfindr.com/marketplace/systems/electrolysers/pem-electrolysers/neahytron-hypem-electrolyzer/

[23] https://www.ceew.in/cef/quick-reads/explains/types-of-electrolysers

[24] https://www.engineeringtoolbox.com/hydrogen-d_1419.html

[25] “Stoccaggio dell'idrogeno in idruro metallico” (mcter.com)

[26] https://encyclopedia.pub/entry/23402

[27] “Safe Use of Hydrogen“ [www.energy.gov]

[28] https://www.vigilfuoco.it/aspx/notizia.aspx?codnews=87588

[29] https://www.avl.com/en/about-avl

[30]https://www.vigilfuoco.it/allegati/PI/RegoleTecnicheXAttivita/COORD_DM_23_10_2018.pdf

[31] Showcase Webinar: Safety in Testbeds for FC Systems and H2ICE (gasworld.tv)

[32] https://www.h2it.it/

[33] https://www.autoscout24.it/

[34] February H2IQ Hour: Overview of Hydrogen Internal Combustion Engine (H2ICE) Technologies (energy.gov)