Interreg
Co-funded by the European Union
Alpine Space

AMETHyS
T

Deliverable D.1.1.1

GREEN HYDROGEN IN THE ALPS

Activity A.1.1: Identification of needs and targets for the deployment of green H2 solutions with a focus on touristic uses

European Regional Development Fund Support from the European Union: € 1,349.279,62

DOCUMENT CONTROL SHEET

Project reference	
Full title of the project	AMultipurposE and Tran sectorial Hydrogen Support for decarbonized alpine Territories
Acronym	AMETHyST
Contract agreement n.	ASP0100032 – AMETHyST
Duration	01.11.2022 – 31.10.2025
Project website	https://www.alpine-space.eu/project/amethyst
Project coordinator	AURA-EE (Auvergne-Rhône-Alpes Energy Environment Agency)

Short Description
This report reviews the state-of-the-art of green hydrogen solutions for application in the Alpine Space area and identifies the role of hydrogen in these territories by mapping the knowledge of local stakeholders on hydrogen and their experience in the sector. Hydrogen-related projects and initiatives are identified, for discussing the needs of local territories and the main gaps that hinder the development of a hydrogen economy in the Alps.

Document Details	
Title of document	Green Hydrogen in the Alps
Action	Activity A.1.1: Identification of needs and targets for the deployment of green H2 solutions with a focus on touristic uses
Deliverable	D.1.1.1
Delivery date	31/10/2023
File name	AMETHyST_D.1.1.1
Reviewers	Project partners
Dissemination	Public

Version	**Date**	**Author(s)**	**Organization**	**Description**
1.0	24/10/2023	Eleonora Cordioli, Jacopo de Maigret	Fondazione Bruno Kessler	Report reviewing needs and targets for hydrogen application in the Alpine Space area
2.0				
3.0				

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

RESPONSIBLE PARTNER

Fondazione Bruno Kessler, Center for Sustainable Energy

Via Sommarive 18, 38123 Trento, Italy

Eleonora Cordioli, ecordioli@fbk.eu
Jacopo de Maigret, jdemaigret@fbk.eu

PROJECT LEAD PARTNER

Auvergne-Rhône-Alpes Energy Environment Agency

Rue Gabriel Péri 18, 69100 Villeurbanne, France

Etienne Vienot, etienne.vienot@auvergnerhonealpes-ee.fr
Noemie Bichon, noemie.bichon@auvergnerhonealpes-ee.fr

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Executive summary

Hydrogen as an energy carrier can be a key element in the transition towards sustainable and clean energy solutions, even in the context of touristic Alpine regions. This report provides an overview of possible applications of green and low carbon hydrogen within the Alpine environment, as well as an assessment of the knowledge and expertise of local stakeholders regarding hydrogen technologies. The primary objective of is twofold. Firstly, the study aims to map the level of interest and commitment of local communities and authorities in pursuing higher sustainable development objectives. Secondly, it seeks to identify their specific needs for the implementation of hydrogen-based pilot initiatives. The analysis is intended to outline the role of hydrogen in the Alpine territories, informing and sharing knowledge among local stakeholders, thus paving the way to the creation of Alpine hydrogen ecosystems.

The overview of state-of-the-art hydrogen solutions for application in Alpine contexts includes the analysis of each step of the hydrogen value chain: production, use, storage, transport, and distribution. The whole range of possibilities is covered, providing information on all potential applications of hydrogen and on the latest development of specific technologies. This can support local authorities and stakeholders involved in the energy transition of Alpine regions as well as local communities to increase their knowledge of hydrogen and get acquainted with the main solutions available.

Through questionnaires and roundtable discussions, a survey of local stakeholders about their knowledge of and expertise on hydrogen was conducted in order to identify the main needs and targets for the deployment of hydrogen solutions and to map existing hydrogen initiatives in the Alpine regions. There is a strong interest in the implementation of hydrogen and most of the Alpine Space territories are keen to launch new initiatives. The primary barrier is of an economic nature. The high investment costs and the corresponding investment risks, as well as the operational costs, are the main challenges to overcome for the development of hydrogen projects. The absence of a defined local hydrogen strategy and of a comprehensive regulatory framework is also perceived as a very crucial point to overcome for facilitating the growth of an integrated supply and demand network. In addition, the presence of dedicated incentivization schemes could support the launching of initiatives and the development of a local hydrogen economy.

As regards the specific technological applications, the greatest potential for H2 implementation in the Alpine context is seen in the private and public mobility sector (both light-duty and heavy-duty vehicles). The use of hydrogen for the residential sector is also considered as an interesting possibility, especially for accommodation facilities in touristic areas. Regardless of the end-use application, the development of renewable energy capacity and infrastructure is fundamental for supporting the creation of a green hydrogen ecosystem, capable of efficiently storing excess energy generated by intermittent sources for future use.

The widespread adoption and integration of hydrogen-based technologies within local energy systems can support the decarbonization of Alpine territories, enhance energy security and self-sufficiency, and drive economic growth of touristic destinations, thereby amplifying their sustainability image and attractiveness to tourists.

Contents

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

1 Introduction

The effects of climate change and massive use of fossil fuels in the Alps should encourage Alpine actors to strengthen measures for energy sufficiency and efficiency, and the deployment of renewable energies to support the decarbonization of these territories. In recent years, hydrogen has emerged as a pivotal player in the global effort to transition towards cleaner and more sustainable energy solutions. With its potential to serve as a versatile, zero-emission energy carrier, hydrogen has garnered significant attention across industries, from transportation to power generation and beyond, and can support the energy transition and the development of a sustainable tourism in the Alpine regions.

In this context, the AMETHyST project aims to investigate the potential application of green and low carbon hydrogen in touristic mountain areas and to support the deployment of local Alpine green hydrogen ecosystems, paving the way to the implementation of Alpine hydrogen valleys and an Alpine post-carbon lifestyle.

This report aims at identifying the role of hydrogen in the decarbonization of the Alps, by mapping the state-of-the-art green hydrogen solutions and their potential application in the Alpine context. The actual implementation of hydrogen and the creation of hydrogen-based ecosystems can only result from synergies and collaboration among several types of stakeholders both public and private (public authorities, technology providers, consultants, research organizations, sectoral agencies, business support organizations). Their engagement is crucial to identifying the needs of local territories and authorities and to define the scope and priorities of ongoing and future H2-based pilot actions. Moreover, knowledge sharing and the exchange of expertise can propel the widespread adoption and successful deployment of hydrogen solutions.

2 State-of-the-art of hydrogen solutions

This introduction delves into the current state of hydrogen solutions, exploring the cutting-edge technologies, applications, and initiatives driving the widespread implementation of hydrogen and its pivotal role in shaping green hydrogen Alpine ecosystems, with a particular focus on possible applications in the tourist sector. In the following, hydrogen production, use, storage, and transport and distribution solutions will be assessed in detail.

2.1 Hydrogen production

Electrolysis

Electrolysis is a chemical process used to produce green hydrogen from water and electric power produced from renewable sources. Electrolyzers split water (H_2O) into its constituents (hydrogen and oxygen) when an electric potential is applied, thanks to the presence of an electrolyte. The nature of the electrolyte determines different types of electrolyzers with different techno-economic parameters. Currently, the most established types of electrolyzers are the proton exchange membrane water electrolyzer (PEM-WEL) and the alkaline water electrolyzer (A-WEL) (**Figure 1**). PEM-WEL electrolyzers utilize a polymer membrane as an electrolyte, that allows transport of hydrogen ions. The environment in the PEM-WEL cell is therefore acidic and requires the need for more costly materials and catalysts. The main advantages of PEM-WEL are the higher output pressure, ensured by the polymer membrane higher resistance to gas transport. This aspect also allows for rapid cold start, a broad operational range, and good response to electricity input variation. Lastly, PEM-WEL electrolyzers only require pure water to produce hydrogen, requiring less performing (and costly) balance of plant instrumentations (tanks, piping, pumps, etc.) compared to AEM-WELs. AEM-WELs make use of a liquid electrolyte represented by the KOH solution. This allows to utilize less costly catalysts and separation membranes. The latter are not resistant to gas transport and this limits the operational range of this technology as well as its ability to quickly respond to load variations (as well as limiting the maximum output pressures).

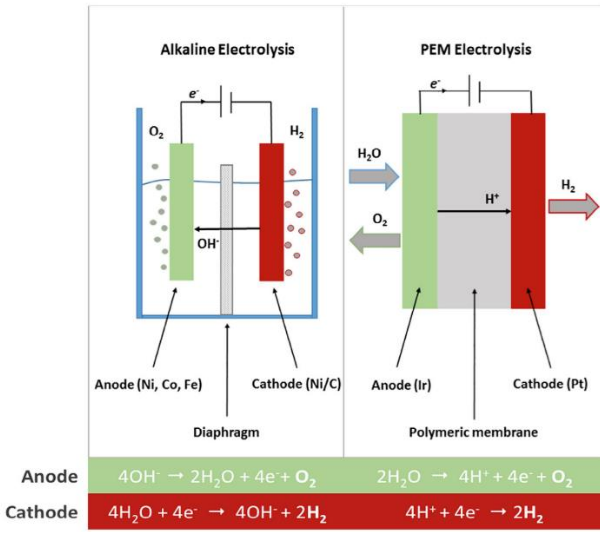


***Figure 1**. Simplified scheme of basic operation of alkaline and PEM electrolyzers* (Sapountzi et al., 2017).

In terms of investment costs, A-WELs are generally cheaper than PEM-WELs because of their slightly higher maturity and lack of expensive electrode catalysts. However, PEM-WELs outperform A-WELs under certain types of operating conditions. For example, PEM-WELs are able to quickly ramp up (or down) their operating point as a function of the electricity input, other than being able to fully cover the operating range (0 – 100%).

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

For this reason, PEM-WELs are deemed as more suitable to follow the intermittent nature of renewable power generated from wind or solar. However, A-WELs development in the years to come will likely allow to close the performance gap between the technologies (Hydrogen Europe, 2020).

The cost per kilogram of hydrogen produced by an electrolyzer is mostly attributable in equal amounts to the electrolyzer CAPEX (**Figure 2**) and the cost of the electricity (levelized cost of electricity, LCOE) fed to the electrolyzer. Therefore, a fundamental technical parameter needed for the assessment of the cost of hydrogen production is the electrolyzer efficiency, calculated as the ratio of the heating value of the hydrogen produced to the electrical energy input (**Figure 3**). The efficiency describes the amount of electric energy needed to produce one kilogram of hydrogen. If this value is compared with the energy contained in one kilogram of hydrogen, the efficiency can be expressed as a percentage of either the higher or lower heating value of hydrogen. Differently from fuel cells, electrolyzer electric efficiency is typically calculated with respect to the higher heating value (HHV) (**Figure 4**). The reason for this convention is that all the energetic content of the hydrogen gas being produced by the electrolyzer is assumed to be available. For fuel cells, on the other hand, it is assumed that the difference between the lower heating value (LHV) and the HHV, that is the latent heat of water vaporization, does not contribute to electric production. Therefore, electric efficiency of fuel cells is calculated considering the LHV as the energetic input to the system.

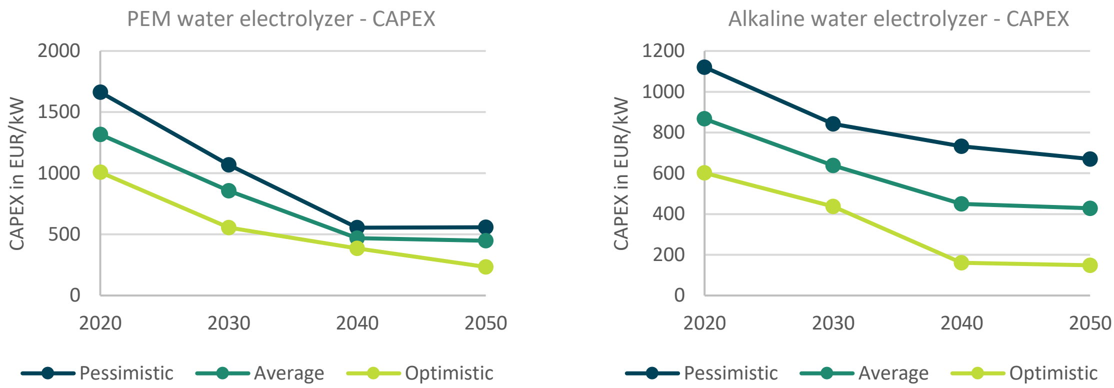
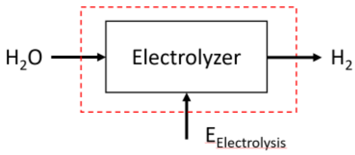


***Figure 2**. PEM-WEL (left) and A-WEL (right) CAPEX. The values represented summarize the values found in the following references:* (Brändle et al., 2021) *(IEA, 2019b)* (Böhm et al., 2019)*(Hydrogen Europe, 2020)*(Glenk & Reichelstein, 2019)(Smolinka et al., 2018)(Bertuccioli et al., 2014)(Holst et al., 2021)(Böhm et al., 2020) (Janssen et al., 2022)(Vartiainen et al., 2021) *(IRENA, 2020)* (Zauner et al., 2022).



$$\eta = \frac{HHV_{H2}\left[\frac{kWh}{kg_{H2}}\right]}{E_{Electrolysis}\left[\frac{kWh_{el}}{kg_{H2}}\right]}$$

***Figure 3**. Electrolyzer boundaries (left) for efficiency calculation (right)*

Electrolyzers are still a developing technology. This implies that the increase of capacity deployment will not only enable learn-by-doing and learn-by-researching effects on the costs of this technology, but also on the efficiency. According to literature-based forecasts, the electric energy needed to produce one kilogram of hydrogen will decrease by 10 – 17% for PEM-WELs and 9 – 10% for A-WELs by 2050. PEM-WELs will pass from consuming 55 – 52 kWh/kg_{H2} to 49 – 45 kWh/kg_{H2}, while A-WELs will decrease from 53 – 49 kWh/kg_{H2} to 49 – 45 kWh/kg_{H2}.

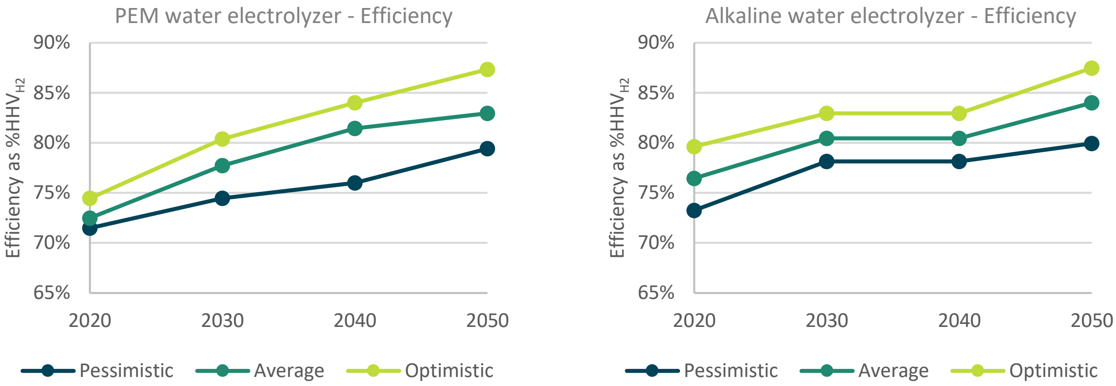


***Figure 4**. PEM-WEL (left) and A-WEL (right) efficiency. The values represented summarize the values found in the following references:* (Brändle et al., 2021) *(IEA, 2019b) (Hydrogen Europe, 2020)* (Smolinka et al., 2018) (Bertuccioli et al., 2014) (Holst et al., 2021) (Janssen et al., 2022) (Vartiainen et al., 2021) *(IRENA, 2020)*

Variable operation and maintenance costs (VOM) are attributable to the stack components of the electrolyzer having a different useful life compared to the electrolyzer system. The more hydrogen is produced the more often the stack needs replacement due to its degradation. The stack life is usually provided in hours and its duration is also affected by the technological development forecasted for the next decades. PEM-WEL stack life is forecasted to improve from 30,000 – 90,000 hours today to 100,000 – 150,000 hours in 2050, with a similar improvement for A-WELs from 60,000 – 90,000 hours today to 100,000 – 150,000 hours in 2050 (IEA, 2019b). Bearing in mind that the CAPEX of the stack represents around 50% of the total CAPEX for the electrolyzer system (IRENA, 2020), it is possible to determine the necessary stack replacement costs as a function of the operating hours of the system. Regarding electrolyzers coupled with renewable energy sources, it was estimated that the VOM costs associated with stack replacement decrease from 0.158 – 0.045 EUR/kWh_{H2} to 0.024 – 0.005 EUR/kWh_{H2} by 2050 for PEM-WELs, and from 0.063 – 0.020 EUR/kWh_{H2} to 0.019 – 0.005 EUR/kWh_{H2} for A-WELs.

Steam Methane Reforming

Hydrogen production through Steam Methane reforming (SMR) is a widely used industrial process to generate hydrogen from fossil fuels like natural gas or methane. Currently, most of the hydrogen produced worldwide derives from reforming of fossil fuels (grey hydrogen), generating a significant amount of CO_2 that is released into the atmosphere, thus contributing to greenhouse emissions and climate change. In combination with carbon capture and storage systems, the production of hydrogen from fossil fuels (blue hydrogen) can work as a valid alternative to hydrogen produced via electrolysis.

The primary feedstock for SMR is pure methane (CH_4) or natural gas, which primarily consists of methane (**Figure 5**); then steam (H_2O) is introduced into the reactor, where the following main reaction occurs:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

The process occurs typically at 700 – 1000 °C and is highly endothermic, meaning it requires a substantial input of heat to proceed. This heat can come from various sources, such as natural gas combustion or electricity. Inside the SMR reactor, the methane and steam mixture passes over a catalyst, usually a nickel-based catalyst, that facilitates the chemical reactions required for hydrogen production.

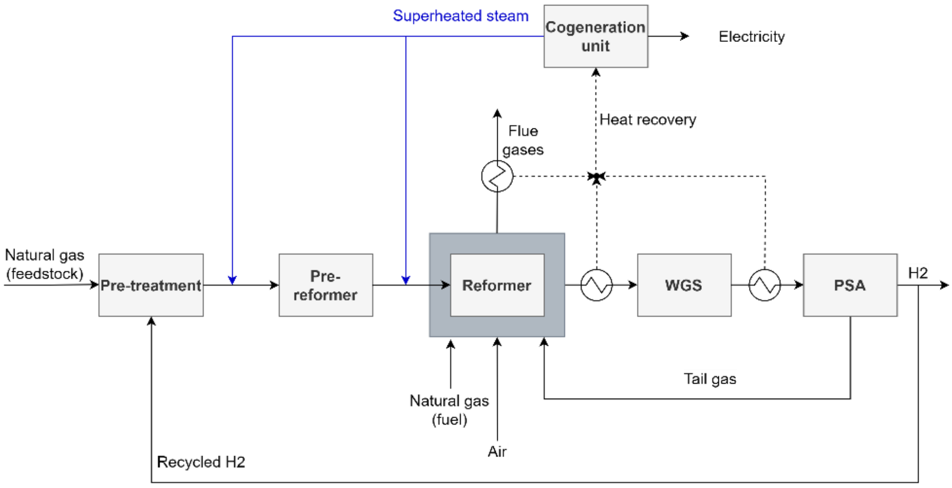


Figure 5. *Schematic diagram of typical SMR process.*

The product gas from the SMR reactor contains mainly hydrogen and carbon monoxide, but also carbon dioxide and other trace impurities. The gas goes through a series of cleanup processes to increase the hydrogen yield through the water shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

and to remove impurities, particularly carbon monoxide, to obtain high-purity hydrogen. After the cleanup, the remaining gas primarily consists of hydrogen and some residual methane. Various techniques like pressure swing adsorption (PSA) or membrane separation are used to recover and purify the hydrogen further, separating it from any remaining impurities (up to 99.999%vol H2 purity). Carbon dioxide is one of the byproducts of SMR, and it is typically captured and either stored or utilized to prevent it from being released into the atmosphere as a greenhouse gas (blue hydrogen).

Steam Methane Reforming is an established and efficient method for large-scale hydrogen production. However, it does produce carbon dioxide as a byproduct, and this carbon footprint can be a concern. To address this issue, there is ongoing research into technologies like carbon capture and utilization (CCU) and carbon capture and storage (CCS) to reduce the environmental impact of hydrogen production via SMR.

Biomass or waste pyrolysis/gasification

Obtaining hydrogen from biomass (pellets, woodchips, agricultural or forestry residue) or waste (municipal solid waste) through pyrolysis or gasification involves a series of thermochemical processes that convert the organic material in the feedstock into a mixture of gases called syngas, which consists mainly of hydrogen and carbon monoxide, with small concentrations of carbon dioxide and other gases.

In pyrolysis, the feedstock is heated in the absence of oxygen (or with limited oxygen) at moderate to high temperatures (typically 300 – 800 °C). This thermal decomposition process breaks down the organic matter into three main products: syngas; biochar (solid residue); bio-oil (liquid product).

In gasification, the feedstock is partially oxidized with a controlled amount of oxygen or steam at higher temperatures (typically 700 – 1000°C). This process produces primarily syngas, with small amounts of char (solid residue) and tar (liquid product). The gasification process is more versatile and can yield more syngas and a higher hydrogen content in the syngas compared to pyrolysis.

The syngas produced in either pyrolysis or gasification contains impurities, such as tar, particulates, and sulfur compounds. These impurities need to be removed to prevent damage to downstream equipment and to meet purity requirements for hydrogen production. Once the syngas is cleaned, it can be converted into hydrogen through the water gas shift reaction (WGS) to convert the carbon monoxide in the syngas into carbon dioxide and hydrogen, and then the hydrogen is purified through pressure swing adsorption (PSA) or membrane separation processes. The hydrogen obtained from the syngas conversion step may still contain trace impurities, so further purification steps may be necessary. The purified hydrogen can then be compressed to the desired pressure for storage or use.

It is important to note that the efficiency and hydrogen yield in biomass or waste pyrolysis or gasification can vary based on factors such as the type of feedstock, operating conditions, and the specific process employed. Additionally, the choice of technology and equipment used for syngas cleanup and hydrogen separation can affect the overall efficiency and economics of the hydrogen production process.

2.2 Hydrogen use

Fuel Cell Electric Vehicles

Fuel cell electric vehicles, or FCEVs, make use of fuel cell technology to power on-board electric motors. This typology of drivetrain can be used to drive both light-duty vehicles (e.g., passenger cars), and heavy-duty vehicles (e.g., trucks, buses, snow groomers), and trains. In addition, this technology is foreseen to also play a role in aviation.

Light-duty Fuel Cell Electric Vehicles

Regarding light-duty road transport vehicles, fuel cell cars (**Figure 6**) can potentially provide a transport service comparable to conventional internal combustion engine vehicles today. Assuming a large-scale deployment of the necessary infrastructure to guarantee reliability of hydrogen as a mobility energy vector (mainly hydrogen refueling stations and hydrogen supply chain), FCEVs can ensure long range travel (600 km) and short refueling times. Hydrogen is stored directly on board the vehicle in pressurized tanks, which can contain about 6 kg_{H2} at 700 bar (with an overall weight of 125 kg and volume of 260 liters) (Viesi et al., 2017). Unit costs of FCEVs are generally higher (for the same category of vehicle) than fossil-fuel ICE (internal combustion engine) vehicles today. However, following the decreasing trend of PEM fuel cells and general cost reduction effect enabled by large scale deployment, costs may become somewhat comparable by 2030. A similar decreasing trend can also be expected for the specific hydrogen consumption per unit distance driven.

Figure 6*. Commercially available FCEVs. (Left) Toyota Mirai[1]. (Right) Hyundai Nexo[2].*

[1] https://www.toyota.com/mirai/photo-gallery/360-views/
[2] https://www.hyundaimotorgroup.com/news/CONT0000000000032283

Heavy-duty Fuel Cell Electric Vehicles

Heavy-duty vehicles comprise truck, buses, and coaches (**Figure 7**), that is freight vehicles of more than 3.5 tons (trucks) or passenger transport vehicles of more than 8 seats (buses and coaches), but also snow groomers and other operating machines.

Long-haul transport trucks are deemed particularly suitable for fuel cell technology when compared to their battery electric counter parts. For gross weight ratings (total weight of a full loaded truck) greater than 16 tons and delivery routes greater than 300 – 400 km, fuel cell technology becomes the predominant decarbonized means of transport (H2IT, 2019). According to the ICCT (2022b), the hydrogen capacity of a single truck can be of up to 55 kg_{H2} at 700 bar, which can guarantee up to 660 km of range. Information regarding the unit cost of a single unit is sparse. Today, unit cost range between kEUR 148/unit (Cunanan et al., 2021) and kEUR 450/unit (Kumar, 2022). However, according to the International Council on Clean Transportation, ICCT (2022b), unit costs could decrease (according to the same rationale as illustrated for passenger cars) to about kEUR 205/unit. Regarding the specific consumption of FC powered trucks, value were found to range between 3.76 kWh_{H2}/km (Cunanan et al., 2021) and 2.16 kWh_{H2}/km (IEA, 2019a). Under the assumption that the increase of PEM fuel cells efficiency will also affect specific consumption, values are estimated to drop to a range of between 1.43 kWh_{H2}/km and 1.74 kWh_{H2}/km.

Buses and coaches are already being deployed among the public transport fleets in Europe. They allow for a comparable service to traditional ICE vehicles and for quick refueling times from centralized refueling stations, which are usually placed in dedicated depots. The hydrogen capacity of the vehicle is similar to that of a fuel cell truck totaling 30 – 50 kg_{H2}. However, the pressure at which the hydrogen is stored is lower due to less strict spatial constraints, allowing tanks at pressure of 350 bar to be placed on the roof of the bus/coach (FCHJU, 2017). The unit costs of hydrogen fuel cell buses today are higher than those of their fossil-based ICE counterparts. However, as reported in literature and in accordance with the rationale applied for both passenger cars and trucks, the costs are forecasted to decrease. Today's values range between kEUR 687/unit and kEUR 572/unit (Ajanovic et al., 2021). The low cost of kEUR 350/unit reported by Zhang, Zhang and Xie (2020) is specific for China and not realistically applicable to Europe, however these cost levels are likely to be reached by 2030.

***Figure 7**. (Left) Fuel cell electric tractor truck by Hyzon[3]. (Right) 13m fuel cell electric bus by Rampini[4].*

Regarding the specific consumption of buses, the values found in literature are in general higher than those of trucks, even if only considering 12/13 m buses and excluding 18 m buses. As for passenger cars and trucks, values are likely to decrease from between 4 kWh_{H2}/km (FCHJU, 2017) and 2.66 kWh_{H2}/km (Zhang et al., 2020) to between 2.43 kWh_{H2}/km (H2IT, 2019)(Viesi et al., 2017) and 2 kWh_{H2}/km (Zhang et al., 2020) in 2030.

[3] https://www.hyzonmotors.com/vehicles/hyzon-hymax-series

[4] https://www.rampini.it/it/autobus-mezzi-speciali_4/prodotti/hydron_102/

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Fuel cell electric buses represent a competitive alternative to the diesel- and natural gas-powered counterparts in mountainous areas. To guarantee the service offered by public transport companies in the mountainous regions, vehicles must face long distance travel, significant elevation differences, and potentially low temperatures. It is believed that fuel cell buses represent a viable and reliable option to satisfy these requirements (Sparber et al., 2023).

Snow groomers diesel fuel consumption represents an important share of mountainous areas' energy demand, along with the associated emissions. Striving to achieve zero emissions in this area, there are multiple factors to consider such as specific applications, power requirements (slope), and range. When comparing battery and hydrogen systems, the former proves to be suitable for applications with low power requirements, offering limited range which makes them ideal for ski halls, small slopes, and cross-country skiing areas. On the other hand, H2 meets the needs of high-power requirements, with the added advantage of quick and easy refueling. As reported by snow groomer manufacturer Prinoth, the fuel cell system (**Figure 8**) functions with the electric motor powering the hydraulic drive. Fuel cells are not only efficient, with a performance up to 15% better than H2 internal combustion engines (covered in the next section) but can also be paired with a full electric drive for heightened efficiency. Emitting nothing but water vapor, they are a truly zero-emission solution. However, challenges such as low temperature resistance and inclination adaptability still need addressing. In terms of the H2 storage, the system features tanks made of composite material and equipped with a plastic liner. These tanks, designed for high pressure at 700 bar, can store 49 kg of H2 overall. The tanks can be refilled at a maximum pressure of 700 bar in 15 – 30 minutes, representing an advantage over long-duration battery charging.

Figure 8*. Example of H2 fuel cell electric snow groomer. Model: Leitwolf H2 Motion manufactured (prototypal stage) by Prinoth[5].*

H2 ICE vehicles

Hydrogen internal combustion engine (ICE) vehicles are an alternative to fossil-fuel ICE vehicles, designed to burn hydrogen gas in a traditional internal combustion engine to generate power and propel the vehicle. They present the same advantages as FCEVs in terms of emissions while requiring lower hydrogen purity. Additionally, H2 ICEs present the advantage over their conventional counterparts of a higher overall efficiency of the propulsion systems (Wróbel et al., 2022). The primary byproduct of burning hydrogen in an internal combustion engine is water vapor, so no carbon dioxide emissions are associated with their use. The minimal source of pollution comes from the combustion of the fraction of consumed lubricant as well as from the reaction of the urea injected into the exhaust gas post-treatment system. Even with these considerations, the total CO_2 emissions remain below 1 g/kWh, enabling the possibility to certify the vehicle as a zero emissions vehicle (European Parliament and Council of the European Union, 2019a)(European Parliament and Council of the European Union, 2019b). However, due to the higher combustion temperatures with respect to conventional ICEs, the emission stream also contains higher levels of NOx. This apparent drawback

[5] https://www.prinoth.com/en/snow-groomers/products/co2-free-groomers/leitwolf-h2motion-773/

can be addressed through exhaust treatment, such as gas recirculation, or by selective catalytic reduction which employs ammonia to reduce nitrogen oxides.

The field of application of H2 ICEs mostly coincides with that of conventional combustion vehicles. As for passenger vehicles, manufacturers such as Ford, BMW, Mazda, Chevrolet, and Toyota have already produced prototypes in numbers ranging from 20 to 100. This indicates the early stage of this application. In a similar direction, Kawasaki has taken steps in the direction of prototyping an H2 ICE motorcycle. Some examples are reported in **Figure 9**.

Figure 9*. Examples of hydrogen internal combustion engine passenger cars (BMW and Mazda)*(Wróbel et al., 2022) *and motorcycles (Kawasaki)*[6].

H2 ICE applications can go beyond road transport. Manufacturer Prinoth pioneered a H2 ICE snow groomer and deemed it a necessary transitional step towards the fuel cell counterpart machine, which is also a Prinoth prototype. Other applications are suggested by manufacturer EVS Hydrogen. Their H2 ICE can be utilized, for example, instead of Diesel ICEs for construction machinery in CO2-sensitive urban areas; as range extenders for battery electric vehicles (functioning as a mobile charger); as recovery drive for electricity and heat from hydrogen storage systems; or to satisfy industrial mechanical energy demand (industrial engines) (**Figure 10**).

Repowering: Diesel to H2

As mentioned in the previous section, combustion of hydrogen does not produce CO_2. Nitrogen oxides are the only residual emission from an H2 ICE, that can be reduced by exhaust treatment such as gas recirculation or by selective catalytic reduction, which employs ammonia.

The possibility of carrying out a "repowering" by feeding hydrogen to a vehicle originally powered by Diesel oil is quite recent. Hydrogen combustion in an internal combustion engine requires a specific system layout.

The conversion of a classic Diesel engine to one powered by hydrogen requires a modification to the engine itself, mainly focused on certain components:

- an efficient supercharging system (turbocharger and exhaust gas recirculation circuit), to guarantee the high demand for air;
- optimization of the size of the injectors and resizing of the intake manifold for the correct introduction of the fuel;
- modification of the piston rings to limit and reduce the leakage of H2;
- the engine head undergoes reworking of the diesel injector seats to allow the installation of central spark plugs.

The intake and exhaust ports, water and oil passages, are borrowed from the Diesel engine; however, the entire diesel fuel system is removed and replaced by H2 injection and ignition systems (fuel rail, injectors, spark plugs, coils and hydrogen piping).

[6] https://www.cyclenews.com/2022/11/article/kawasaki-announces-carbon-neutrality-plans-at-eicma/

In terms of cost, there are no quotations or estimates of the costs incurred for a repowering with ICE-H2 technology, given the innovative nature of the option. However, some preliminary studies (Westport Fuel Systems, 2022) compare the 5-year TCO (Total Cost of Ownership) of the repowering to H2 ICE solution, with that of a fuel cell system and a new diesel engine, suggesting this solution as an interesting option to battery repowering in terms of cost sustained during operational service.

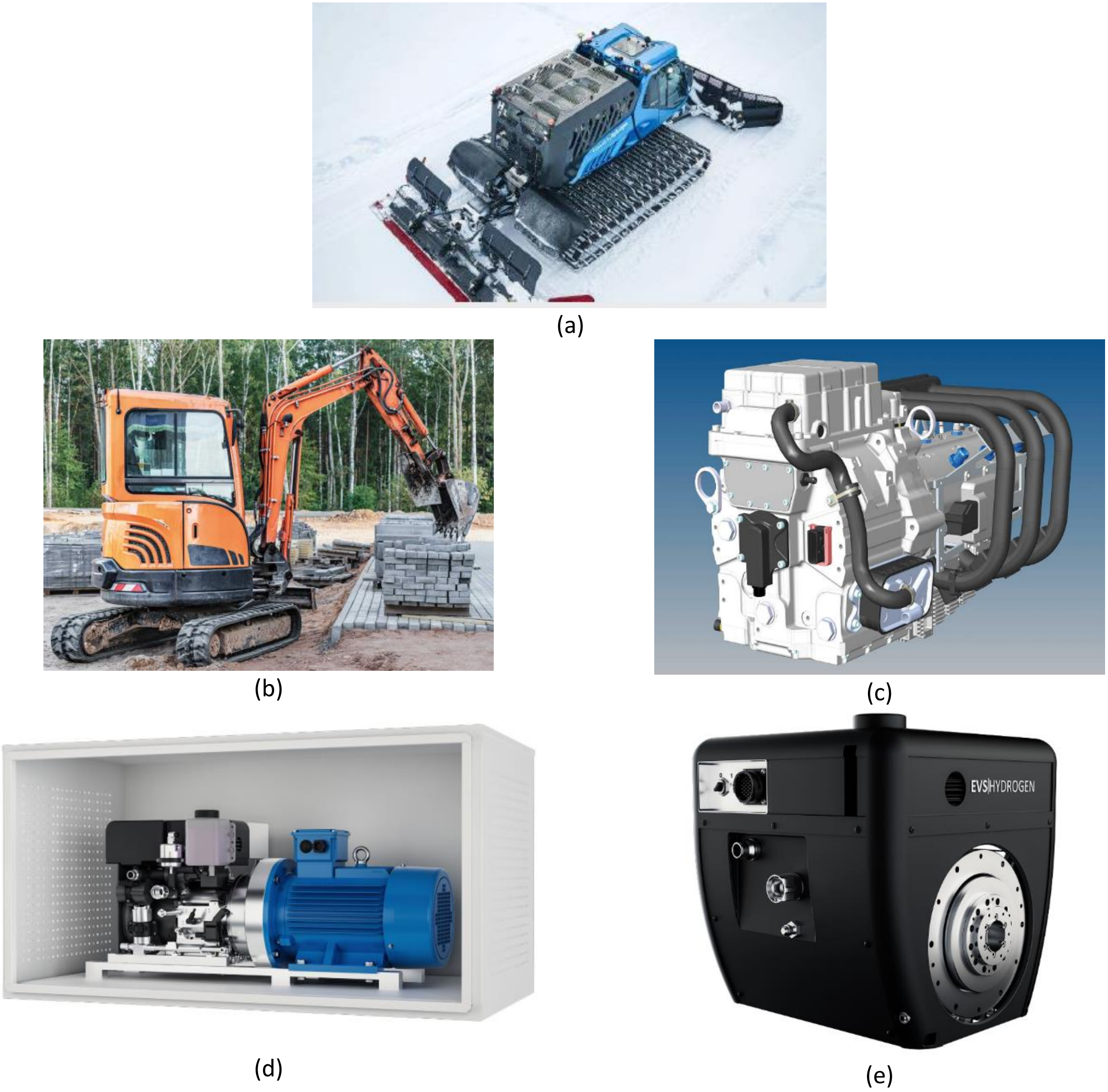


Figure 10*. (a) Prinoth H2 ICE snow groomer. (b) Construction machine powered by H2 ICE. (c) H2-based electric vehicle range extender. (d) H2-based recovery drive for electricity and heat from hydrogen storage systems. (e) H2 industrial engine [7].*

Stationary power generation

Hydrogen can be used for stationary power generation in various applications: gas turbines, stationary fuel cells, combustion engines, energy storage, cogeneration (combined heat and power).

Hydrogen gas turbines

Gas turbines are well-known in power production and typically use natural gas as fuel. However, blending of hydrogen gas and methane is common in certain applications. For example, refineries employ gas turbines

[7] https://www.evs-hydrogen.de/

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

with specific designs that allows them to be fired by-product gas streams with high hydrogen contents (for example from catalytic cracking units with 15 – 20%vol H2 [Mukherjee and Singh, 2021]). Building onto this knowledge, many manufacturers are now looking to produce turbines able to run high hydrogen content gas streams if not solely on hydrogen gas (Ansaldo Energia, Baker Hughes, General Electric, Siemens Energy, **Figure 11**). The challenges faced by research and development are due both to hydrogen gas handling and to the nature of hydrogen combustion. The gas handling systems require materials that are not prone to degradation in the presence of hydrogen and must be leak-resistant. As regards combustion, hydrogen differs from natural gas as hydrogen is more reactive, which may cause phenomena known as autoignition (when the mixture ignites in the premixing chamber as opposed to the combustion chamber) and flashback (when the flame speed is higher that the stream injection velocity, so that the flame front travels back into the burner tube). Lastly, higher flame temperatures also cause higher NOx emissions, therefore extra design steps must be undertaken in order to either decrease the flame temperature or abate the NOx in the flue gas streams (ETN Global, 2020).

***Figure 11**. Hydrogen ready gas turbine by Siemens[8].*

Techno-economic data is presented for both open circuit gas turbines (OCGT) and combined cycle gas turbines (CCGT) designed to run on 100% hydrogen gas. The first typology is characterized by a power-producing gas turbine discharging its flue gases into the atmosphere and therefore not utilizing their heat content for further power production. The second typology utilizes a heat recovery steam generator to exploit the heat content of the flue gases for further power generation in a secondary steam power plant. According to Öberg, Odenberger and Johnsson (2022), investment costs for a new 100% H2 OCGT vary between EUR 536/kW_{el} and EUR 583/kW_{el} while for a new 100% H2 CCGT they vary between EUR 1,072/kW_{el} and EUR 1,165/kW_{el}. The efficiencies of the two typologies are between 27% and 32% (considering the electrical output) for the OCGT, and between 58% and 62% (considering the electrical output and the thermal recovery) for the CCGT (DNV GL, 2019). Regarding non-fuel variable costs, these vary between EUR 0.002/kWh_{el} and EUR 0.015/kWh_{el} for the OCGT and between EUR 0.001/kWh_{el} and EUR 0.006/kWh_{el} (Grosse *et al.*, 2017; Oh, Lee and Lee, 2021).

Stationary Fuel Cells

Fuel cells allow to convert hydrogen gas to electric energy through an electrochemical reaction (inverse reaction to electrolysis). There are a variety of typologies of fuel cells differing on the nature of the materials (electrodes, membranes), operating temperatures and gases accepted. Some fuel cells are able to process not only pure hydrogen, but also other hydrogen-containing gases that, through high temperatures, are cracked/reformed to isolate the hydrogen gas prior to the power generating electrochemical reaction.

Considering the different typologies of fuel cells (alkaline fuel cells, phosphoric acid fuel cell, molten carbonate fuel cell, proton exchange membrane fuel cell, and solid oxide fuel cell), the most suitable for

[8] https://www.siemens-energy.com/global/en/home/products-services/product/sgt-800.html#/

stationary power generation are proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs). PEM fuel cells (**Figure 12**) benefit from the maturity of the technology, low maintenance costs (due to the solid electrolyte), high efficiencies and low temperatures. However, relatively low temperatures (80 – 200°C) also require a better performing, thus more expensive, catalyst. For this reason, the more innovative SOFCs are also assessed, which with their high operating temperatures (700 – 800°C) require less performing catalyst for the electrochemical reaction (Cigolotti & Genovese, 2021).

According to data gathered by Cigolotti and Genovese (2021) and the forecasts presented by Hydrogen Europe (2020), PEMFCs specific investment costs decrease from between EUR 2,858/kW_{el} and EUR 5,255/kW_{el} in 2020 to EUR 1,000/kW_{el} and EUR 3,000/kW_{el} in 2030. Further forecasts were determined assuming that cost reduction phenomena occurring in PEM electrolyzers would also impact cost reduction in PEMFCs. By applying this rationale, specific investment costs were determined to fall to a range of EUR 722/kW_{el} and EUR 195/kW_{el} in 2050. Regarding the electrical efficiency of PEMFC systems, the value increases from between 35% and 42% (calculated with respect to the lower heating value of hydrogen) to 53% and 58%. With a reasoning like the one adopted for the specific investment, the efficiency improvements may ensure values of between 56% and 65% in 2050.

***Figure 12**. PEM stationary fuel cell by Proton Motor[9].*

Regarding SOFCs, the specific investment costs found in literature are in general higher than those of PEMFCs, with 2020 values varying between EUR 4,224/kW_{el} and EUR 11,100/kW_{el} (Cigolotti and Genovese, 2021; Safari and Ali, 2020; Al-Khori, Bicer and Koç, 2021), but are forecasted to decrease, as reported by Hydrogen Europe (2020), to between EUR 2,220/kW_{el} and EUR 3,885/kW_{el} by 2030. As for efficiency, the value varies between 35% and 55% (calculated with respect to the lower heating value of methane) in 2020 and 55% to 65% in 2030. For this technology, the values are provided as a percentage of the lower heating value of methane because the necessary reforming to obtain hydrogen from methane occurs within the fuel cell due to the high operating temperatures available.

Substitute for natural gas

Industrial heat supply

Another application of hydrogen gas is its use as fuel for heat generation in industry. Industrial heat demand accounts for one-fifth of global energy consumption and, since it is mostly satisfied with fossil fuels, it is responsible for 12% of global CO_2 emissions (DENA, 2019). This shows the potential substitution of fossil fuels for heat generation in industry with green hydrogen could have significant impact in emissions abatement.

[9] https://www.proton-motor.com/en/hyshelter/

On this matter, Element Energy (2019) conducted a study on quantifying challenges and efforts of the conversion of industrial heat generation equipment from natural gas fired to hydrogen fired. The study finds that most industrial equipment can be retrofitted to become hydrogen fired. However, the different combustion characteristics of hydrogen (heat transfer characteristics, high concentrations of NOx and moisture in the flue gases) might in some cases interfere with the final product quality, especially for direct fired heaters. For example, glass furnaces and kilns are sensitive to the moisture content in the flue gases as well as the radiant heat transfer to product. On the other hand, indirect fired equipment, such as water boilers, are less susceptible to changes in the combustion characteristics.

Residential heat supply

Hydrogen emerges as an important element in the quest to decarbonize the building sector, given the ambitions of achieving widespread green hydrogen production by 2050. Introducing hydrogen into the residential heating market represents a promising solution to reduce overall system costs. Despite this potential, there are uncertainties regarding complete decarbonization of the building industry through hydrogen, especially finding itself in competition with alternative solutions like heat pumps.

Domestic gas boilers can function with a hydrogen-natural gas blend of up to 20%vol, but any increase in hydrogen concentration would require a redesign of the burner. However, boilers designed to run on pure hydrogen are forecast to align in cost with their natural gas counterparts, and the process to retrofit current models is anticipated to be straightforward.

Also fuel cells have been identified as suitable for residential use due to their efficiency and reduced emissions in combined heat and power operation (**Figure 13**). These systems can be very versatile, operating either on natural gas or on pure hydrogen. However, it is worth noting that heating solutions employing hydrogen are currently less efficient compared to heat pumps, demanding 150% more primary energy (Knosala et al., 2022).

Figure 13*. (Left) Solydera's solution of a residential high-temperature fuel cell for heat and power cogeneration[10]. (Right) Pure-hydrogen water boiler by Baxi[11].*

[10] https://bluegen.eu/en/

[11] https://www.baxi.it/news-eventi/caldaia-idrogeno

E-fuels production

Hydrogen can be used for the production of synthetic fuels such as gasoline, kerosene and diesel, which could be directly used in the existing transport infrastructure replacing fossil fuels in internal combustion engine (ICE) vehicles without the need for new powertrains.

E-fuels are synthetic fuels produced using electricity (typically generated from renewable sources) from the combination of hydrogen and CO_2 (e.g., captured from the atmosphere) through various chemical reactions, such as Fischer-Tropsch (FT) synthesis. Under high pressure and using catalysts, the hydrogen binds with the CO_2, producing a liquid energy carrier, that is the e-fuel, easy to store and simple to transport. Through FT both methanol and long-chain hydrocarbons can be obtained. After refining processes, e-fuels can be used as gasoline, diesel, or kerosene, and completely replace conventional fuels using existing logistics, distribution and refueling infrastructures. However, e-fuels also face challenges, including high energy input requirements for production, cost, and the need for significant renewable energy sources to make the process environmentally beneficial. The production of e-fuels is an area of ongoing research and development, with the aim of making the process more efficient, cost-effective, and environmentally friendly to help address climate change and reduce dependence on fossil fuels.

Zang, Sun, A. A. Elgowainy, *et al.* (2021) conducted a simulation study of a Fischer-Tropsch system and found that the energy needs of e-fuel production via the FT route are, for the most part, embodied in compression and heating needs for the process to occur. Regarding the cost of production of e-kerosene and e-diesel, the value is sensitive to the variation of the price of H_2 than the price of CO_2. Increasing the cost of input hydrogen from EUR 2/kg_{H2} to EUR 4/kg_{H2} (fixing the cost of CO_2 to EUR 17.3/t_{CO2}) causes the price of e-kerosene to rise from EUR 0.38/kWh to EUR 0.65/kWh and the price of e-diesel from EUR 0.62/kWh to EUR 1.06/kWh (+71% in both cases). On the other hand, increasing the price of CO_2 from EUR 17.3/t_{CO2} to EUR 34.6/t_{CO2} (fixing the cost of H_2 to EUR 2/t_{H2}) causes the price of e-kerosene to rise from EUR 0.38/kWh to EUR 0.41/kWh and the price of e-diesel from EUR 0.62/kWh to EUR 0.66/kWh (+6% in both cases). For comparison, it is useful to report that the 2023 prices of jet-A1 fuel (kerosene) and diesel are EUR 0.08/kWh_{Kero} and EUR 0.17/kWh_{Diesel}.

The forecasts of the cost of FT e-fuels, do show that there is cost reduction potential, both because of improvements in the TRL (Technology Readiness Level) of the process, that is currently around 5 – 7 (Bazzanella et al., 2017), and because the cost of raw materials (hydrogen and carbon dioxide) is likely to decrease between now and 2050.

2.3 Hydrogen storage

Hydrogen can be stored in either gaseous or liquid form, depending on the intended use, its transportation, and both volumes and safety considerations.

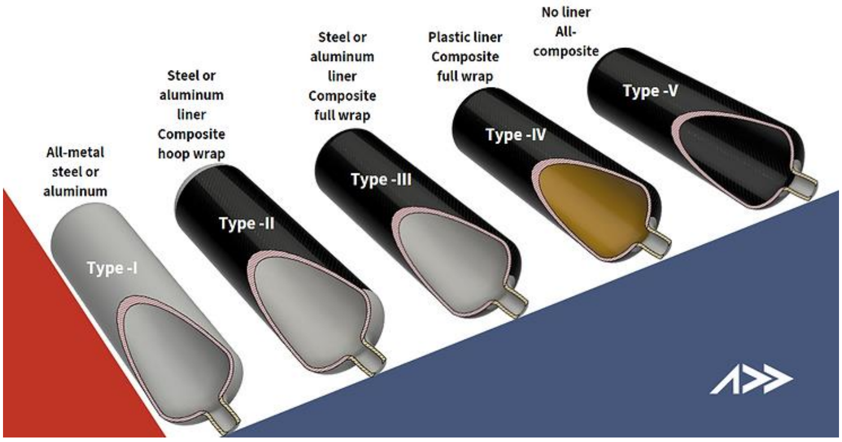
Gaseous hydrogen storage

Gaseous hydrogen storage involves storing hydrogen in its gaseous state, typically at high pressures to achieve the necessary storage density. This method is commonly used for smaller-scale applications, including fuel cell vehicles and some industrial processes.

Pressurized hydrogen vessels

Hydrogen gas can be stored in vessels designed to withstand the high pressures required for gaseous H2 storage, typically between 350 and 700 bar. This is a relatively simple and mature technology, besides providing a relatively high energy density. Storage pressure up to 1,000 bar is possible, although achieving such pressures entails high operating costs. Scaling up the capacity of the vessel also increases the initial investment due to the special material needed for its manufacturing. Metallic and polymer materials are suitable for intermediate pressures, while new and innovative composite materials allow to reach storage pressures of up to 1000 bar (DNV GL, 2019).

Different hydrogen storage tanks are categorized into five categories which are indicated through roman numerals (I, II, III, IV, V). Each category is certified to withstand a certain level of pressure and therefore able to contain different amounts of hydrogen per unit volume. The categories and respective pressures are depicted in **Figure 14**.



Type	Materials	Pressures	H2 storage density	Applications
I	Metal	200 - 300 bar	15 g/liter	Industrial
II	Composite: aluminum with glass/carbon fiber filament windings	≤ 350 bar	20 g/liter	Industrial
III	Composite: glass/carbon fiber filament windings as outer casing and metal lining	≤ 450 bar	25 g/liter	vehicles
IV	Composite: glass/carbon fiber filament windings as outer casing and polymeric lining	≤ 700 bar	40 g/liter	vehicles
V	Liner-less, all-composite construction	≤ 700 bar	40 g/liter	vehicles

Figure 14*. Schematic representation of Types I-V of pressurized hydrogen storage tanks (Addcomposites*[12]*) along with the technical specifics of each category* (Usman, 2022).

In order for such systems to be economically attractive (i.e., to provide a competitive levelized cost of storage) it is advised to design small to medium sized storage capacities (around 500 kg_{H2} at 200 bar) with charge/discharge cycles lasting hours up to months (ENTEC, 2022) (DNV GL, 2019). Potential applications could be encountered in industrial sites or hydrogen refueling stations in the form of stationary tube racks or transportable tube trailers. Element Energy (2018) assesses the use of distributed compressed hydrogen vessels as a balancing element in a hydrogen transmission network, allowing to absorb and release hydrogen following low and high demand.

Two storage vessels are discussed hereby. First, large vertical tanks operating at transmission network pressure (50 – 80 bar) that require no (additional) compression. These may hold up to 405 kg_{H2} each and are envisioned to be installed in groups of ten. Their specific cost amounts to EUR 483/kg_{H2}. High pressure storage vessels (430 bar) assembled in batteries of steel tubes would require compression from transmission pressure levels. Compression needs and more resistant vessels would require higher investment cost of EUR 2,318 – 3,119/kg_{H2}. Considering the pressure range at which the different vessels operate, the overall installed cost can range between EUR 421/kg_{H2} and EUR 1,940/kg_{H2} (Hystories, 2022)(JRC, 2022).

[12] https://www.addcomposites.com/

Pipe systems

Pipe system storage of compressed hydrogen sees gas stored in an underground, localized, and interconnected pipe system. An advantage of pipe storage over above-ground storage is that it has no (or negligible) footprint, which could enable the utilization of the ground for other purposes (e.g., for agriculture). A few meters below the surface hydrogen pipelines, with diameters of 1.4 m (DN 1400), are welded together in parallel to form a single storage unit of up to 6,300 m^3 of free volume (which corresponds to a cumulative length of the pipe system storage of 4 km) (Welder et al., 2018). Smaller interconnector pipes are used to better distribute the pressure and temperature gradients. However, floating bearings are needed to accommodate any thermal dilation of the piping during injection and withdrawal phases. The whole system is slightly inclined to ensure that any accumulation of water can be gathered and bled with a valve. Such technology is used for short term hydrogen storage to satisfy peak demand, as the capacity is not comparable to natural underground formations for seasonal storage. The investment costs mostly relate to the procurement of the pipelines/compressor and the site excavation, with additional costs for the installation of the pipelines (welding) and the re-earthing of the site. Surface components comprise compression and metering system, while no treatment unit is needed because the quality of the withdrawn hydrogen is delivery ready (HyUnder, 2013). The operating pressure range is suggested by Welder *et al.* (2018) to be between 7 bar and 100 bar, potentially accumulating 1.5 GWh of hydrogen, with injection rates of 63 MW (which ensures the complete emptying of the storage in 24 hours). Differently from underground storage in geological formations, the minimum pressure value is not set to guarantee thermal/structural stability of the storage, but rather to maintain reasonable operating conditions of the compressor for delivery into the transmission network (HyUnder, 2013). Considering the abovementioned factor, this assessment proposes a CAPEX for this storage technology to vary between EUR 9.14/kWh_{H2} and EUR 10.5/kWh_{H2} (or EUR 304-350/kg_{H2}), a fixed OPEX of around 19% of the CAPEX per year and a lifespan of 30 year (Welder et al., 2018)(HyUnder, 2013).

Line packing

Line packing is a practice widely used in the natural gas transmission/distribution networks (Element Energy, 2018). The principle is that of exploiting the existing pipeline infrastructure for storage of the gas. By widening the operational pressure range of the pipelines, it is possible to inject and withdraw (and therefore store) a larger quantity of gas within a section of the network. This technique could be transferable to hydrogen transmission/distribution networks (hydrogen backbone), and could be able to accommodate hourly supply and demand fluctuations (Guidehouse, 2021b) (ENTEC, 2022) (Wijk & Wouters, 2021) (Agora Energiewende, 2021). Hydrogen gas line packing could be thought of as a type of distributed storage, and encouraged near demand centers (Element Energy, 2018). According to ENTEC (2022), a 24 inch pipe with a length of 100 km could store up to 43 tons of hydrogen if the pressure is increased from 50 bar to 60 bar.

Metal hydrides hydrogen storage

Hydrogen storage through absorption in metal hydrides is a promising hydrogen storage method suitable for various uses. This technique provides high energy storage capacities by volume and is very safe because the hydrogen is chemically bound at pressures lower than the compressed storage counterpart. Metal hydrides (alloys such as MgH_2, TiFe, $TiMn_2$, $LaNi_5$, $NaAlH_4$, $LiBH_4$) are materials that are able to absorb hydrogen at low temperatures (0 – 15°C, depending on the specific alloy) and release it at higher temperatures (40 – 100°C, depending on the specific alloy) (**Figure 15**). Additionally, various metal hydrides can be employed for diverse applications, from minor to major scales and for both short-term and long-term energy storage.

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

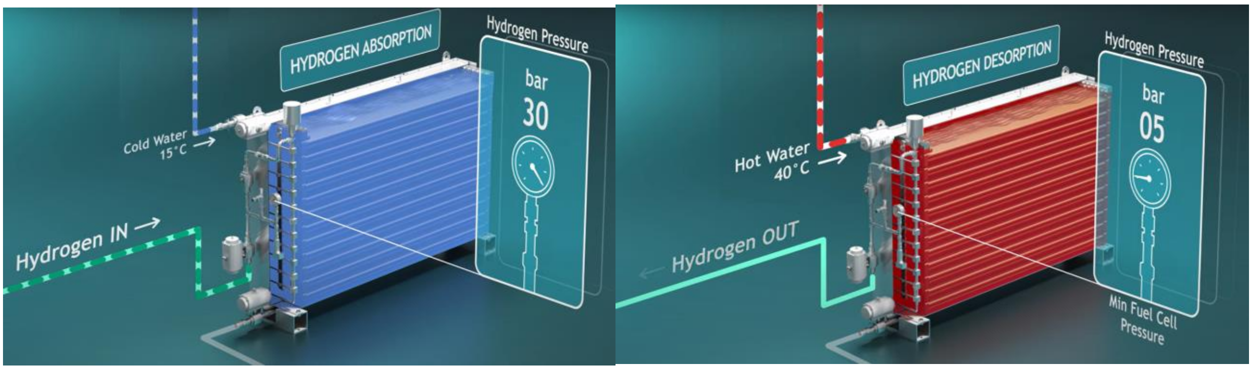


***Figure 15**. MetHydor's metal hydride hydrogen storage solution[13]. Absorption phase through water mains cold water (left) and desorption through mid-range temperature water from other sources (right).*

The main advantages of hydrogen storage in metal hydrides for stationary applications are the high volumetric energy density and lower operating pressure compared to gaseous hydrogen storage. These pressure levels are also conveniently compliant with those of PEM electrolyzer outlet (30 bar) and fuel cell inlet (3 – 5 bar), making it possible to avoid the use of a dedicated compressor for storage. Moreover, lower pressure level also translates into increased safety and maintenance requirements, which contribute to lowering the overall cost. Moreover, this technology benefits from a good scalability and low hydrogen losses in time, making it a suitable solution for small- and large-scale applications for both short- and long-term storage (**Figure 16**) (Klopčič et al., 2023).

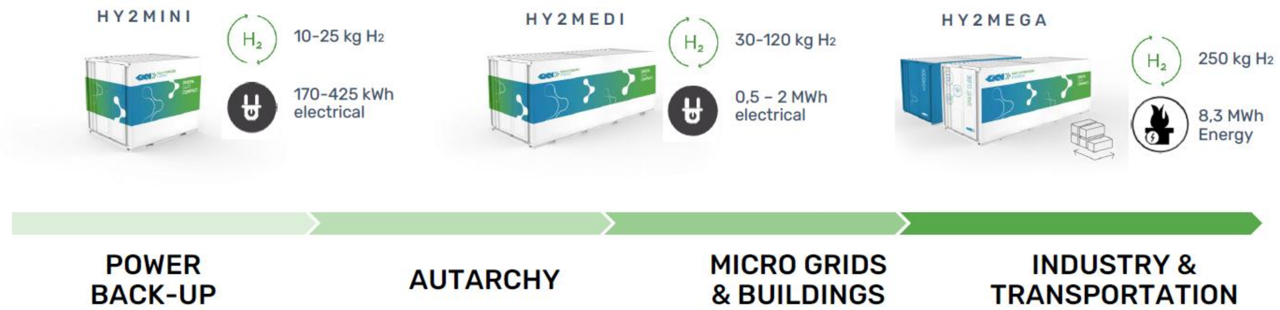


***Figure 16**. GKN Hydrogen metal hydride H2 storage solutions at different scales, for different applications[14].*

Underground storage

The assessment of large-scale hydrogen storage is of particular interest because it could potentially enable storage of energy for periods of months to seasons. Therefore, large-scale hydrogen storage could play an important enabling role in reducing the curtailment of renewable energy produced by solar and wind. Electrolyzers could absorb the surplus energy resulting from the mismatch between low power demand and high renewable energy supply that would otherwise be curtailed, to produce green hydrogen which, once compressed, can be stored for later use when demand exceeds supply (BNEF, 2020). Seasonal storage of energy in the form of hydrogen to satisfy regional demands requires very large storage capacities (hundreds of millions to billions of Sm^3) and for this reason, its implementation cannot realistically be envisioned in a conventional storage vessel (be it a pressurized tank, ammonia, LOHC, liquid hydrogen tanks) as this would require too much aboveground space, meet with unacceptable health, safety and environmental risks, and be too expensive. The means by which large-scale hydrogen storage is possible is by exploiting particular – favorable – conditions in the subsurface. There are four main typologies of geological storage reservoirs that

[13] https://methydor.com/

[14] https://www.gknhydrogen.com/product/

allow for such great volumes of gas to be stored safely: hydrocarbon reservoirs, aquifers, salt caverns, and lined rock caverns (Lord et al., 2014).

Salt caverns are man-made cavities in underground salt deposits. Salt deposits may exist either in the form of bedded salts or salt domes. Bedded salts are commonly laterally continuous, and their internal composition is "predictable", however their thickness can be a limiting factor for cavern development. Salt domes are laterally not continuous, and their internal composition is not "predictable", but they are not height-limiting for cavern development, i.e., higher caverns can be created. It has been proven that salt is effectively impermeable, i.e., it does not allow fluids to flow through it. As such, salt caverns can be seen as perfect storage containers for long-term storage of gases and liquids. In a single salt cavern, made by solution mining of salt, a volume of one hundred million Sm^3 of gas can typically be stored. Salt cavern storage is a proven technology for natural gas and has great potential for the storage of green hydrogen (Caglayan et al., 2020).

The two main differences between **pore storages** and salt caverns are, firstly, that salt caverns are man-made cavities while porous reservoirs are naturally occurring in the subsurface. The second difference lies in the structure of the subsurface storage element. Salt caverns are essentially large voids of space, whereas porous reservoirs are rock formations with high enough and interconnected (to ensure gas permeability) porosity. As already mentioned, such formations are naturally occurring and are host to hydrocarbons (hydrocarbon reservoirs) and/or water (aquifers). The reservoirs' tightness to the fluid they are bearing is proven simply by the occurrence of the fluid, that has been contained in the reservoir for many years prior to their discovery. The porous reservoirs' tightness is guaranteed by the presence of a sealing caprock which prevents the hydrocarbons or water diffusing towards the surface, and lateral sealing which allows to contain the hydrocarbon or water in a confined in space.

Oil and natural gas fields have been the subject of assessment for many decades due to the interest in the exploitation of their hydrocarbon content. The concept of gas storage in such reservoirs is based on the utilization of the fields once the hydrocarbon extraction is considered completed. Gas storage in depleted oil reservoirs has been trialed in a few cases and resulted in production and treatment issues, and will therefore be excluded (HyUnder, 2013). Differently from gas fields, aquifers can potentially be used as gas storage systems without the need for depletion of the reservoir. However, it is necessary to assess and ensure that the porous formation, originally hosting water, is suitable for gas storage. In both cases it is of paramount importance to assess and verify that the storage of high-pressure gas does not affect the geology/lithology surrounding the reservoir, which could potentially jeopardize its tightness to the gas.

The majority of porous reservoirs that are in use for gas storage today lie at depths of 500 – 2,500 m (with some reservoirs at depths of up to 3,500 m, in particular in the North Sea region), have relatively high porosities of 10 – 30%, and widely ranging permeabilities of 20 – 2,000 mD [15] (Cavanagh et al., 2022). These elements are verified through geological characterization of a site, an activity well-known from decades of exploration in the oil and gas industry. Depleted natural gas fields have been successfully converted into natural gas storage and are the most prominent typology of large-scale storage. The main reason of this is the advantage presented by prior knowledge about the reservoir, and the re-use of existing infrastructure (production wells, some surface components) (Hanson et al., 2022). However, in order to convert the production site to a gas storage site, additional production (and monitoring) wells may have to be drilled. The number of storage wells required typically depends on the intended functions of the storage facility, i.e., short term storage cycles (storage for days to weeks) with usually higher rates of injection and withdrawal

[15] mD unit of measure represents the millidarcy, where 1 Darcy ≈ 10^{-12} m^2.

requiring more wells vs. long-term storage cycles (intra-to-interseasonal and/or strategic storage) requiring lower rates of injection and withdrawal.

Liquid hydrogen storage

For larger-scale applications, hydrogen can be stored as a cryogenic liquid at extremely low temperatures (around -253°C or -423°F). Specialized storage tanks are required for this purpose (DNV GL, 2019), but these are also a well-known technology, due to their deployment in the aerospace industry for many decades. NASA already owns large-scale spherical storages of liquefied hydrogen with capacities of 3,200 m^3 and 4,700 m^3 (227 and 334 tons of hydrogen, respectively), and Kawasaki Heavy Industries has a 10,000 m^3 vessel planned (IRENA, 2022). An advantage of liquid hydrogen storage (at ambient pressure) is the high volumetric energy density, which is four times that of gaseous hydrogen at 200 bar (ENTEC, 2022). A major issue of storing hydrogen in its liquefied form is the inevitable losses due to boil-off. It is necessary to dispose of the evaporated hydrogen since the constant volume of the vessel leads to potentially dangerous overpressures (maximum allowed pressure 1.2MPa) (JRC, 2022). These losses occur despite the high insulation of the tanks and amount to between 0.05% and 2.5% per day. The boil-off stream could potentially be re-liquefied and pumped back to the storage, but this presents a high energy expenditure (IRENA, 2022). In order to minimize the boil-off losses highly insulated vessels are designed. The majority of such vessels are double-hulled allowing for a vacuum pumped gap packed with additional insulating material (IRENA, 2022) (JRC, 2022). Another technique in limiting the boil-off losses lies in the spherical shape that liquid hydrogen vessels have (**Figure 17**). Thanks to the geometrical properties of the sphere, the exposed surface to volume ratio is minimized along with the overall heat absorption. However, this particular shape presents manufacturing challenges and therefore has higher costs (IRENA, 2022). A cheaper but slightly less effective alternative is represented by cylindrical vessels. Costs of liquefied hydrogen vessels are determined by the material necessary and manufacturing techniques and range between EUR 2.7/kWh_{H2} and EUR 5.2/kWh_{H2} (DNV GL, 2019; ENTEC, 2022; Guidehouse, 2021a; JRC, 2022).

***Figure 17**. Large-scale spherical liquid hydrogen storage tanks employed by NASA[16].*

[16] https://www.energy.gov/sites/default/files/2021-10/new-lh2-sphere.pdf

Liquid organic hydrogen carriers

Liquid organic hydrogen carriers (LOHCs) are organic chemical compounds which can be loaded with hydrogen under determined conditions of high pressures. The hydrogen can be retrieved from the LOHC through high temperatures and low pressures after being transported or stored. There are a variety of organic chemical compounds suitable to be used as hydrogen carriers which benefit from a well-established industry developed in the past decades. LOHCs present conventional oil product behavior, such as being in liquid form in atmospheric conditions and other properties like flammability (IRENA, 2022). Therefore, LOHCs can be stored in conventional liquid fuel tanks (Niermann et al., 2019) (Raab et al., 2021), which additionally benefit from the little to no geographical constraints on their placement and medium-scale storage capabilities (ENTEC, 2022).

LOHCs stay hydrogenated for a long period of time without great costs and the only losses witnessed are due to some side reactions that cause 3% loss per year (and a complete lack of boil-off losses) (IRENA, 2022). Characteristic costs of LOHC tanks are found to be EUR ~7/kg_{H2} (EUR 0.21/kWh_{H2}). Such costs are lower compared to other hydrogen derivatives storage tanks despite the low percentage of hydrogen contained in such carriers (4-7%wt for LOHC, and 12.5%wt for methanol) (IRENA, 2022).

2.4 Hydrogen transport and distribution

Compressed hydrogen can be transported using tube trailers, which are specially designed trucks or trailers equipped with high-pressure cylinders, or through hydrogen pipelines that transport H2 from production facilities to distribution points and end-users. Liquid hydrogen can be transported in cryogenic tankers that are well-insulated to maintain extremely low temperatures.

For the distribution, hydrogen refueling stations can be used for fuel cell vehicles and other hydrogen-powered devices, while in industrial and commercial settings, hydrogen can be distributed through pipelines, cylinders, or specialized containers, depending on the specific requirements of the application. In specific cases and conditions, hydrogen can also be injected into the natural gas grid at controlled concentrations to blend with natural gas or serve as a renewable gas source.

Tube trailers

Compressed gaseous hydrogen is transported on roads using tube trailer technology. These are special trailers equipped to hold large, pressurized vessels, which trucks tow to their destinations. The amount of hydrogen transported in a single trip varies based on the vessel type and the packing method used on the trailer. Tubes can carry up to 250 kg of hydrogen at 200 bar pressure or up to 1000 kg at 500 bar pressure (Reddi et al., 2018). Due to cost and safety constraints however, these trailers are set to operate at a maximum pressure of 250 bar. In the context of early Fuel Cell Electric Vehicle (FCEV) markets, when the Hydrogen Refueling Station (HRS) daily demand is relatively low (up to about 500 kg/day), utilizing these trailers proves to be the most economical option. The materials used for these trailers are typically steel or composites. However, it is important to note that steel tube trailers have a limited capacity due to on-road weight restrictions. For the transportation of hydrogen over short distances of 100-200 kilometers, to relatively small demand centers, trailers are the most suitable option(Yang et al., 2023) (Elgowainy et al., 2014). The trailers most commonly used for this purpose are Type III vessels (presented in **Figure 14**), which are horizontally bundled together, as can be seen in **Figure 18**.

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Figure 18*. Example of a towed tuber trailer for transporting hydrogen at 250 bar* (Cussons, 2019)*.*

Hydrogen refueling stations

A hydrogen refueling station (HRS) is a station to refill fuel cell vehicles just like a petrol or diesel vehicle. However, its backend operations are entirely different, and these are supported by several key components that are critical for the safe and effective functioning of the refueling station. A regular HRS consists of hydrogen storage tanks, hydrogen gas compressors, a pre-cooling system and a hydrogen dispenser, which dispenses hydrogen to pressures of 350 bar, 700 bar or dual pressure dispensing, depending on the type of vehicle being refueled. A typical hydrogen car will be refueled in approximately three minutes and a bus in seven minutes.

The key components of a HRS are the following (**Figure 19**):

- Hydrogen storage system for storing hydrogen to meet daily demand;
- High-pressure buffer storage system, to deliver gaseous hydrogen to the vehicle tank;
- Compressor, for pressurizing hydrogen from the storage source pressure to the buffer storage pressure (typically higher than vehicle's maximum service pressure);
- Refrigeration system, for pre-cooling the hydrogen gas being dispensed into the vehicle's tank;
- Dispenser, managing the flow of hydrogen to the vehicle's tank;
- Controls and safety equipment.

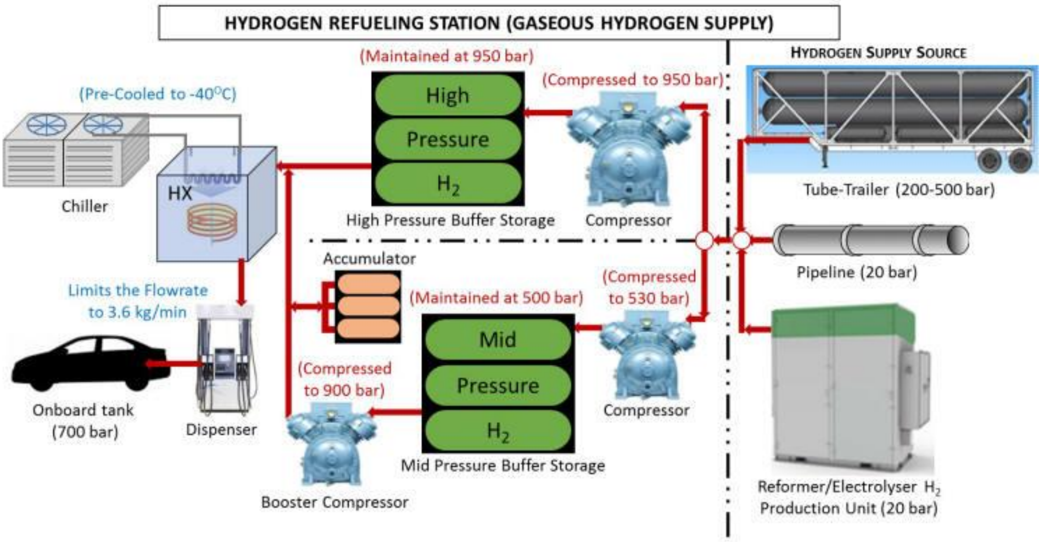


Figure 19. *Gaseous hydrogen supply refueling configuration.*

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Ensuring a minimum density of hydrogen refueling stations is a fundamental prerequisite to capture consumer interest and guarantee a broad market for FCEVs. They can be exclusively for hydrogen or be part of a multi-fuel station.

The design characteristics of a hydrogen refueling station are determined by the daily demand for hydrogen, the way hydrogen is stored on board the vehicles (for example, the pressure at 350 bar or 700 bar), and the way hydrogen is delivered or produced at the station. Moreover, determining the optimal size of a station is a crucial step. For passenger cars, very small stations with a capacity of 50 – 100 kg/day of hydrogen might be sufficient in the initial stages; in a mature market, stations of at least 500 kg/day will be required.

Designing and building a station involves significant financial risks, mainly related to the pace of FCEV market penetration and the consequent demand for hydrogen. The investment risk associated with the development of refueling stations is primarily due to the high capital investment and operating costs, as well as the underutilization of the facilities during the initial phase of the FCEV market development, which can lead to a negative cash flow in the first 10 – 15 years, that could be supported by public funding.

Clustering hydrogen stations around major demand centers and key connection corridors during the FCEV vehicle roll-out phase can ensure the maximization of usage rates.

As of 2023 there are 756 operational stations globally. The bulk of this number is located in Asia: 250 in China, 161 in Japan and 141 in South Korea. In Europe, Germany leads the rank with 93 stations loosely followed by France, Switzerland, and the Netherlands with 21, 13 and 11 stations, respectively. Lastly, Austria and Italy have 5 and 1 stations, respectively (Hydrogen Tools, 2023).

The main components of a hydrogen refueling station are a compressor, hydrogen storage, equipment for pre-cooling/refrigeration, and dispensers. Cost assumptions are derived from various European studies by H2Mobility, UK TINA (Low Carbon Innovation Coordination Group, 2014), and quotes received directly from supplier companies. The current and forecasted investment costs up to 2050 are shown in **Table 1** and include investment costs in infrastructure (compressor, hydrogen storage, equipment for pre-cooling/refrigeration, dispensers), civil costs for preparing the station area, and design costs. The investment costs of the reference hydrogen stations are expected to decrease by about 50% by 2030, reflecting optimizations in design and increases in market volumes and the number of industry operators.

HRS Type	2015	2020	2030 – 2050
50 kg/day	1,250,000 €	850,000 €	550,000 €
100 kg/day	1,350,000 €	900,000 €	600,000 €
200 kg/ day	1,500,000 €	1,000,000 €	700,000 €
500 kg/ day	2,000,000 €	1,300,000 €	1,000,000 €
1000 kg/ day	3,000,000 €	2,000,000 €	1,500,000 €

Table 1. *Hydrogen refueling station (HRS) CAPEX forecasts as a function of daily hydrogen delivery capacity.*

Operational costs are indicated in **Table 2**. As with investment costs, operational costs will also be subject to significant reduction, thanks to a more efficient supply chain, the use of local labor for maintenance, and an increase in the lifespan of components. In designing hydrogen refueling stations, the harmonization of European standards is desirable. Without compromising safety, costs can be reduced, even significantly, if regulatory requirements are lessened.

HRS Type	2015	2020	2030 – 2050
50 kg/day	1.2 €/kg_{H2}	0.9 €/kg_{H2}	0.7 €/kg_{H2}
100 kg/ day	1.1 €/kg_{H2}	0.8 €/kg_{H2}	0.6 €/kg_{H2}
200 kg/ day	1 €/kg_{H2}	0.7 €/kg_{H2}	0.5 €/kg_{H2}
500 kg/ day	0.9 €/kg_{H2}	0.6 €/kg_{H2}	0.4 €/kg_{H2}
1000 kg/ day	0.8 €/kg_{H2}	0.5 €/kg_{H2}	0.3 €/kg_{H2}

***Table 2**. Variable operation and maintenance costs per kg of dispensed H2 (at the nozzle) forecasts as a function of daily hydrogen delivery capacity.*

Lastly, it will be essential to ensure efficiency in the authorization procedures, avoiding lengthy bureaucratic delays that might discourage industry operators and slow down the transition towards sustainable mobility.

Gas grid injection

The injection of hydrogen into the natural gas network has the potential to decarbonize the network, reducing the emissions directly attributable to the use of natural gas, thus meeting the objectives imposed by the decarbonization policies of the European Union. The reduction of emissions may vary between a partial substitution of natural gas to the use of pure hydrogen. The degree of emission abatement is a function of the volumetric fraction of hydrogen and of the process through which the hydrogen is produced. Zero or low emission hydrogen, such as green and blue hydrogen, present benefits in terms of emission abatements at nearly all blending percentages. Utilizing grey or yellow hydrogen[17], on the other hand, increases the emissions compared to pure natural gas.

A more accurate assessment of the emissions reduction percentage can be obtained from **Figure 20**, in which the emission percentages of the various mixes compared to the natural gas reference value are reported. In this case, only green H2 and blue H2 are reported. It is interesting to note that, with a volume percentage of 20% hydrogen, the emission reduction stands at about 3%, 6%, and 8% of the original emissions for the cases of "Blue - 60%", "Blue – 90%" and green hydrogen. The reduction would be more marked if we assumed a 50% mix, with 10%, 20%, and 24% respectively. A total substitution, on the other hand, would result in a decrease in emissions of 40%, 95%, and 100% respectively.

Hydrogen has the ability to penetrate and diffuse, more easily than natural gas, into the crystal lattice of the steels used for the construction of transport and distribution pipelines. This phenomenon can cause a decrease in the ductility of the steels (embrittlement), as well as an increase in the speed of propagation of defects existing in them (GRTgaz, 2019). There are multiple degradation mechanisms of engineering-use alloys related to the presence of H2 in the working environment.

Carbon steels appear to be the ones with the least resistance to hydrogen embrittlement under high pressure conditions (≥ 100 bar). However, at pressures close to atmospheric pressure and temperatures close to room temperature, embrittlement phenomena are expected to be of little significance even for carbon steels (Blanchard & Briottet, 2020). The materials that show very high sensitivity to the presence of hydrogen, and therefore should be avoided, are instead Ti and its alloys and Ni and its alloys (contrary to what happens for stainless steels)(Barthélémy, 2006).

[17] Grey hydrogen refers to hydrogen gas produced through steam methane reforming (SMR) of natural gas or other hydrocarbons. Yellow hydrogen is the electrolytical H2 produced through electricity sourced from national grid, considering the emissions attributable to the generation mix (ISPRA, 2022).

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

The structural differences, at the molecular level, between hydrogen and natural gas lead to variations in the thermodynamic, physical, and chemical properties of the H2-natural gas mixture, compared to the case of pure natural gas, depending on the mixing rate. For this reason, it is of fundamental importance to study the variation of the main characteristic properties of the fluid, depending on the volumetric content of hydrogen. Most importantly, as the volumetric percentage of hydrogen increases, the energy content per unit volume decreases. Given the volumetric flow rate, an H2-natural gas mixture will be less energetic than pure natural gas. Therefore, to deliver the same amount of energy per unit time, the flow rate must be increased (Abbas et al., 2021).

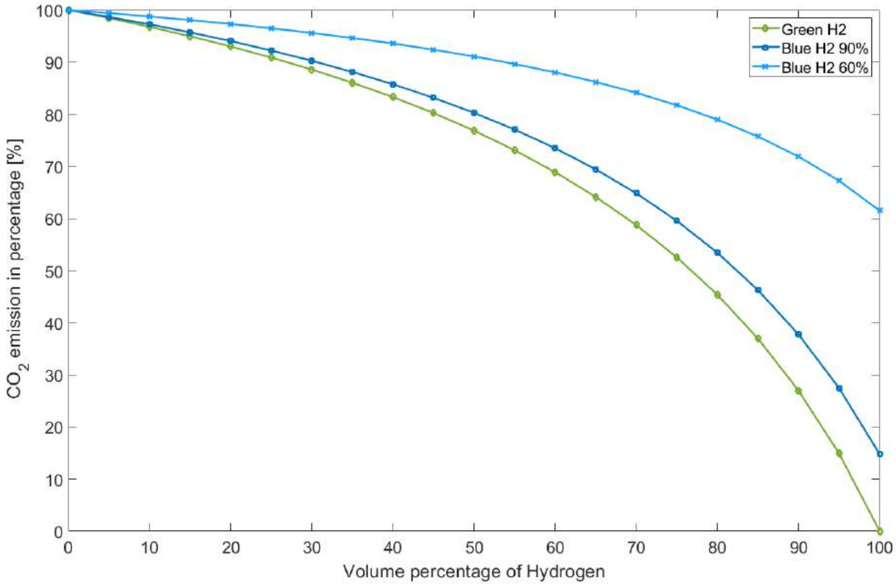


Figure 20. *Emissions reduction with respect to pure natural gas as function of volumetric percentage of hydrogen blending and source of hydrogen.*

3 Methodological approach for collection of information on H2 in the Alps

The present chapter describes the adopted methodology to identify the main needs and targets for the deployment of hydrogen solutions and to map existing hydrogen initiatives in the Alpine regions. It was first necessary to carry out a preliminary assessment aimed at identifying and classifying the stakeholders to engage in the analysis.

Potential customers, end users, business activities (manufacturers, service providers, consultants, etc.) and policy makers involved or potentially interested in specific hydrogen sectors (production, use, storage, transport, and distribution) were identified. Thanks to a close collaboration with AMETHyST project partners and their presence throughout the Alpine regions, a list has therefore been drawn up with a focus on potential beneficiaries of hydrogen economy, including but not limited to the tourism sector. Engaged stakeholders include sectoral agencies (e.g., tourism agencies, energy agencies, innovation and development clusters), business support organizations, higher education or research organizations, infrastructure and public service providers, enterprises.

The identified stakeholders were involved in the project in different ways, mostly through the submission of questionnaires, but some of them were included also into local roundtable discussions or embraced into a pilot territory, serving as case study for the implementation of green H2 solutions in the Alps.

The survey was divided into two steps. A first questionnaire, “Hydrogen in the Alps”, was drawn up with a more generic approach, with the aim of collecting information on the relationship between stakeholders and the hydrogen economy. A second questionnaire, “Hydrogen projects and initiatives in the Alps”, was exclusively addressed to stakeholders with direct experience in hydrogen applications and initiatives, in order to gather further details on projects and initiatives in which they are involved.

Furthermore, within the AMETHyST project, pilot territories were identified and set as cornerstone for roundtable discussions around a specific territory and hydrogen application.

3.1 Questionnaires

Local stakeholders were involved in taking part in questionnaires via email. Thanks to the support of project partners, the email template was translated into the local language of stakeholders, in order to encourage their involvement, although it was decided to keep both questionnaires in English for facilitating the collection and processing of information.

The first questionnaire, “Hydrogen in the Alps”, that was sent to all the identified stakeholders, can be found in **Annex I**. In the following, the questionnaire structure is briefly described:

1. Stakeholder identification and location.
2. Stakeholder categorization. This step will simplify and improve results discussion.
3. Self-assessment on knowledge of hydrogen (Questions 1 – 4). This section provides valuable information about the interviewee's technical, regulatory, and financial knowledge of hydrogen solutions.
4. Interviewee opinions and comments on hydrogen economy (Questions 5 – 9).
5. Expertise and experience on hydrogen initiatives evaluation (Questions 10 – 14). The answers will be exploited to identify stakeholders who played a significant role in hydrogen projects and initiatives.
6. Interviewee opinions on gaps and barriers that hinder hydrogen deployment (Questions 15 – 16).

The second questionnaire, “Hydrogen projects and initiatives in the Alps”, is properly devoted to collecting specific information on hydrogen projects and initiatives, and it was sent only to those stakeholders that showed a direct involvement in this field through the first questionnaire. The full questionnaire is included in

Annex II. The survey was designed as a project sheet to be drafted multiple times, one for each H2 project or initiative the stakeholder is part of. In addition to the main features required to identify a project, the questionnaire collects the following additional characteristics:

1. The presence, and location, if applicable, of pilot test cases.
2. State of advancement of the project or initiative.
3. Source of funding.
4. The belonging to pre-established types of projects. Considering also whether initiatives can have potential impacts on the tourism sector. This step will be useful to compare and discuss results.

The results of this second questionnaire helped map the state-of-the-art of implemented and planned green hydrogen solutions in the Alpine Space regions, defining what is the engagement of territories for the creation of local hydrogen ecosystems. The specifics of collected projects will be discussed in detail in a dedicated report, as part of deliverable D.1.2.1. "Map of green hydrogen initiatives in the Alps".

3.2 Pilot territories and roundtables

As mentioned, the AMETHyST project involves the definition of pilot territories that support the application of hydrogen-based solutions in the Alps and will help define a model Alpine hydrogen ecosystem, thus fostering the decarbonization of Alpine areas. These territories represent ideal sites for initiating the implementation of hydrogen technologies in the Alps and for revealing the potential role of these areas in the energy transition.

In the following, a brief description of the pilot territories identified within AMETHyST is provided.

1. Pilot territory in Auvergne-Rhône-Alpes (France). The pilot territory is located in the Savoie department, in the Auvergne-Rhône-Alpes region, southeastern France. Its territory develops around the main valley of Isère and the Doron valley, and it is composed of:
   - Assemblée de Pays Tarantaise Vanoise, a joint association of 30 municipalities and 5 groups of local authorities.
   - Arlysere, a grouping of 39 municipalities.

   The region has a powerful tourist economy but also significant territorial disparities (north/south slopes, villages, resorts, valley floor). Over 25% of the territory is covered by the Vanoise National Park, nature reserves and Natura 2000 sites. Its demographic growth is based on a positive natural balance. In this territory there is a strong local political will to develop H2 solutions with an already existing H2 refueling station in Moûtiers. It has big potential for many touristic uses of H2 related with mobility, for instance snow groomers, coaches, waste trucks, and bikes.

2. Pilot territory in Friuli Venezia Giulia (Italy). The AMETHyST pilot project would be the first green H2 production and usage site in the region. The goal is to set up a local value chain in the Bût Alpine Valley, where the right conditions to kickstart such a project are all present within a few kilometers. In fact, the local energy cooperative society SECAB owns six hydropower plants, a large photovoltaic (PV) plant and the distribution grid. This results in some periods of the year with 100% renewable electricity surplus in the area. At the same time, in the same area, the Zoncolan ski resort is a major touristic attraction in the area, with great impact on the local economy. PromoTurismoFVG, the regional body who runs the resort, owns and manages five more ski resorts in the region. Being the ski lifts already supplied directly by SECAB, the emissions of the Zoncolan ski resort are already one of the lowest in the Alpine range. The pilot project aims at using the surplus of renewable energy from SECA's plants to produce green hydrogen, to be used first of all by a snow groomer of the ski resort. If the pilot project proves to be economically sustainable, the goal is to substitute the entire snow groomers fleet with H2-powered snow groomers and make Zoncolan a zero-emission ski resort.

3. Pilot territory in Oberbayern (Germany). The pilot project is a self-sufficient hydrogen house in the municipality of Icking, to promote decentralized energy management for the housing sector. The 230 m^2 PV system installed on the roof of the house collects the excessive energy in battery storage units and converts it into hydrogen by using an electrolyzer so that the house can self-sufficiently get through the winter and meet its own energy needs without any connection to the national grid. With larger or high-pressure H2 storage more energy could be stored, but high investment costs are needed.

4. Pilot territory in Tyrol (Austria). The WIVA P&G HyWest project (ongoing since 2018) aims at the establishment of the first business case driven, regional, green hydrogen economy in central Europe. This project is mainly based on the logistic principle and is a result of synergies between three ongoing projects:
    - "Green Hydrogen for MPREIS, Tyrol and Europe" (MPREIS Hydrogen), initiated in the frame of the European project "Demo4Grid" and ongoing since 2016 with the aim to implement a 3 MW pressurized alkaline electrolyzer (PAE) at the production facility of supermarket chain MPREIS, in Völs (Tyrol, Austria) to provide grid balancing services. Large quantities of green hydrogen for industrial use in the food production sector as well as for heavy-duty mobility applications are supplied.
    - "Hydrogen Valley Zillertal" starting with the Zillertalbahn 2020+ energy autonomous" project ongoing since 2017, in which a holistic approach including required hydrogen infrastructure and business cases for the implementation of hydrogen electric trains is employed.
    - "Power2X Kufstein" ongoing since 2019, in which the construction of an innovative sector coupling (P2X) plant with a hydrogen center in the southwest of Kufstein near the TIWAG (Tiroler Wasserkraft AG) hydropower plant in Langkampfen in Tyrol, is planned.

    The main elements of the developed green hydrogen logistic within "MPREIS Hydrogen" are a 3MW pressurized alkaline water electrolysis system complemented by three hydrogen storage vessels and heavy-duty HRS operating at 350 bar including pre-cooling and a trailer filling station, MEGCs (Multiple Element Hydrogen Gas Containers, 20-foot hydrogen storage containers), and a hydrogen semi-trailer truck (tractor plus trailer) from Hyzon Motors, operational as of January 2023 for food distribution in the region of Tyrol.

    In the framework of the "Hydrogen Valley Zillertal" project, test drives with a Hyundai ElecCity hydrogen bus (made available by Graz Linien, Graz, Austria) were performed in alpine terrain. The refueling of the hydrogen bus in use with the MPREIS heavy-duty HRS further validated the functionality of this refueling station. The monitoring and collection of required parameters for the operation optimization of the hydrogen buses under various conditions (especially in alpine regions), such as fuel cell system power, H2 tank pressure, buffer battery power, traction motor power, temperature, voltage, and current, is currently ongoing. A hydrogen distribution system based on MEGCs via road transport could be the most promising solution with the aim to guarantee a high green hydrogen availability in the region. Additional technical research topics in this regard are under development regarding the connectivity between hydrogen containers and hydrogen filling stations in the three hydrogen production sites.

5. Pilot territory in Trentino (Italy) - Madonna di Campiglio ski area. The ski area of Funivie Madonna di Campiglio represents the center of the Campiglio Dolomiti di Brenta ski area and provides 60 km of slopes connected by 19 ski lift systems. The managing company has 500 employees and 50 snow groomers, serving around 3 million skiers each year. In 2022 the total energy consumption was equal to 3607 toe (tons of oil equivalent), of which 84% was electricity, 13% fossil fuels, 3% biomass (pellets). 91% of the fossil fuel share was used for the supply of snow groomers. Several hydrogen applications could be implemented in the ski area:

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

- Production of H2 via electrolysis for seasonal storage of renewable energy. Use of surplus renewable energy (e.g., from PV) seems to be the optimal solution for producing H2. PV panels will be installed in the ski area in the next years, hence production of H2 from excess energy could be considered.
- H2 for mobility (snow groomers, ski buses, operating machines, cars). Both fuel-cell snow groomers and H2 internal combustion engine snow groomers are options.
- Other options of H2 integration in the ski area are not excluded: fuel cells for (distributed) cogeneration of heat and electricity; hydrogen boilers for buildings heating.

6. Pilot territory in Trentino (Italy) – Mountain tourist municipalities in the Province of Trento. The pilot project will be the realization of a feasibility study for the implementation of green hydrogen as an energy vector in an integrated system serving a non-methanized mountain tourist village. The case studies identified for the realization of the study are of three different types. The first one involves the implementation of a new integrated system of hydrogen production, storage, and distribution to users. The second one refers to the implementation of hydrogen where there is already an existing island network, fueled by LPG (liquefied petroleum gas) or LNG (liquefied natural gas). The third case study considers the presence of a biomass district heating system where hydrogen could be integrated replacing the fuel used for the backup system (e.g., diesel).

7. Pilot territory in South Tyrol (Italy) – Arieshof tourist accommodation. The Arieshof is a tourist accommodation with a strong focus on sustainability, in ST. Lorenzen, a mountain area near Brunico, in the Province of Bolzano. In order to achieve maximum possible energy autonomy and reduce its carbon footprint, it uses a combination of photovoltaic electricity generation system, a wood chips cogeneration plant, and an electrolyzer and fuel cell to store and utilize hydrogen according to the energy demand. Hydrogen can be seasonally stored in innovative metal-hydride batteries. The Arieshof is therefore a case study for the stationary utilization of hydrogen as one element of a smart, interconnected energy system. The evaluation of this pilot case will provide insights into how touristic accommodation services, with their strong seasonal energy fluctuations and wide range of guest services, can benefit from the integration of hydrogen into their energy supply systems.
8. Pilot territory in Valais (Switzerland). Verbier 4 Vallèes, located in the municipality of Val de Bagnes in the Valais canton, is the biggest ski area in Switzerland, with 410km of linked tracks accessed by 93 ski lifts. The ski terrain starts at 1,250m and tops out at 3,330m at the summit of Mont Fort. The case-study aims at studying the feasibility of using hydrogen for powering the snow groomers and the buses of the Verbier ski resort, thus reducing its carbon footprint. Local production of green hydrogen will also be considered.

In order to share knowledge and help identify the needs of local territories and authorities, roundtable discussions were organized in each pilot territory. All roundtables brought together local stakeholders of different backgrounds (e.g., local authorities, companies, sectoral agencies, research institutions, infrastructure and public service providers, business support organizations), fostering the discussion around two main topics:

1) Gaps and barriers in the implementation of H2 solutions in the Alps and possible solutions to overcome them.
2) Sharing experiences and best practices in the application of H2 in an Alpine environment.

Considering the specific features of each pilot territory, roundtables brought out possible applications of hydrogen in the area and main obstacles to be tackled, as well as a discussion on how the pilot could serve as model for the implementation of hydrogen-based solutions elsewhere.

4 Results

4.1 Questionnaires results

Questionnaire 1 – “Hydrogen in the Alps”

Analysis of closed-ended questions

Recalling the objectives of Questionnaire 1 (see description in section 3.1), the aim of the survey is to inquire Alpine Space stakeholders on opportunities and barriers of hydrogen solutions in the Alps. Moreover, the questionnaire is designed for stakeholder identification in terms of place of origin, sector of operation, and background knowledge/expertise on H2 solutions. Coupling such information with the respective responses on opportunities and barriers enables more informed conclusions to be derived from questionnaire responses, in that any kind of statement will always be reported alongside respondent characterization.

Questionnaire 1 saw a total of 124 respondents from 118 different stakeholder organizations, scattered across the Alpine Space countries and subregions as can be seen in **Figure 21**. However, no significant trends in any of the metrics assessed and presented in this section have been noted as region-dependent.

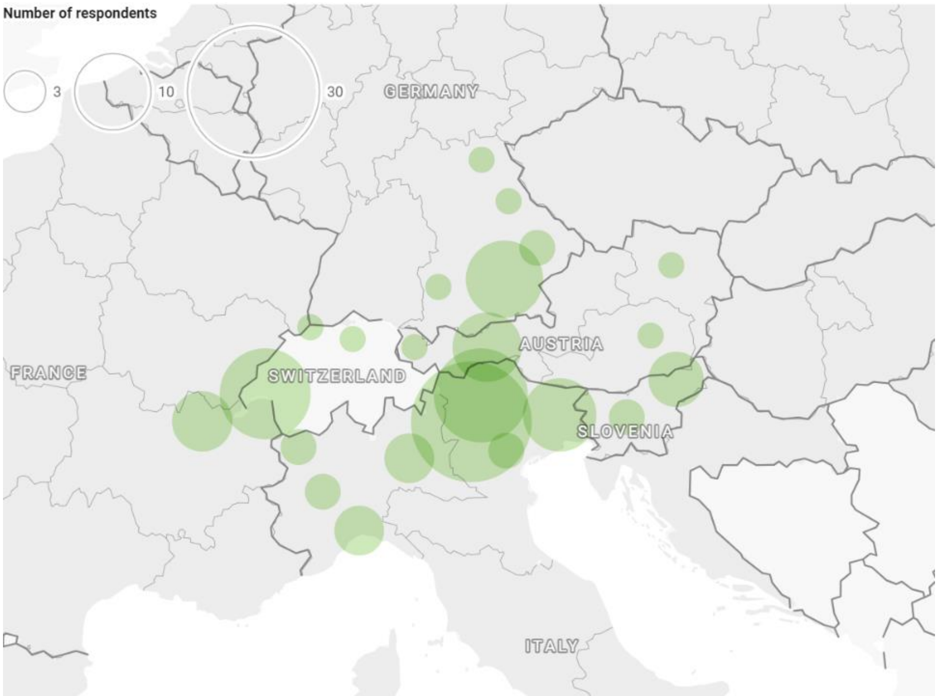


Figure 21*. Geographical distribution map of respondent stakeholders in the Alpine space.*

Efforts to cover the Alpine Space have proved to be successful. All countries, except for Liechtenstein, have provided responses and in the case of Italy and Slovenia, all Alpine Space regions have participated in the survey.

In **Figure 22** the typology characterization of the respondents is reported. Almost half of the respondents are represented by small-medium enterprises and large companies followed by infrastructure and public service providers (such as energy companies), higher education or research organizations, and sectoral agencies. Further characterizing the stakeholders, the questionnaire probes their involvement in the energy transition process. In this regard, results show that 81% of respondents play an active role in the transition. As a last profiling question, a multi-select multiple choice question allowed to characterize the stakeholders based on what sectors they claim to be involved in. The results are reported in **Table 3**.

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

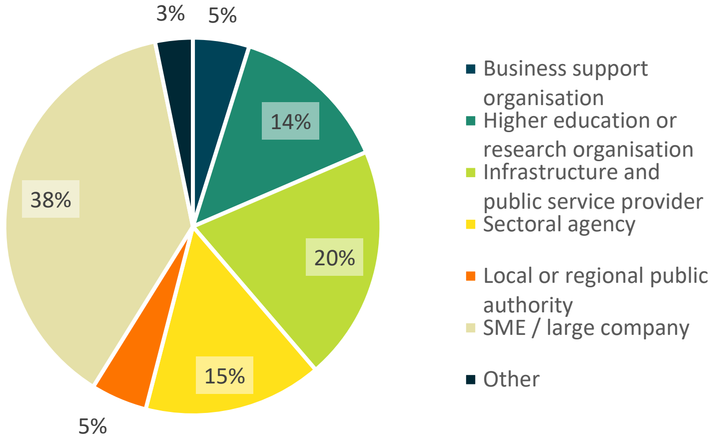


***Figure 22**. Stakeholder typology distribution across all Alpine space. Labels report stakeholder typology, number of respondents, and percentage with respect to the total.*

Stakeholder Typology	Sector of Operation				
	Energy	Environment	Tourism	Mobility	Industry
Business support organization	3	0	1	3	4
Higher education or research organization	14	1	1	4	5
Infrastructure and public service provider	13	0	2	12	1
Local or regional public authority	4	0	0	1	0
Sectoral agency	12	2	7	7	2
SME / large company	20	0	8	18	19
Other	2	0	0	0	1
Total	**68**	**3**	**19**	**45**	**32**

***Table 3**. Stakeholder typology and sector of operation across the Alpine Space area. Labels report sector and the number of times that a specific sector was mentioned by stakeholders as their area of involvement. Note that the numbers do not refer to the number of stakeholders. The "Other" category encompasses public healthcare providers, investors, and project developers.*

The sectors of operation in which most stakeholders are involved are Energy (68) and Mobility (45), followed by Industry (32), Tourism (19) and lastly Environment (3). Among the stakeholder typologies, respondents from higher education present a strong unbalance in the distribution of their sector of operation, mostly operating in the energy sector. Infrastructure/public service providers and SME / large companies also present a non-uniform distribution of sector involvement, as most respondents claim to be involved in only two sectors: energy and mobility. Sectoral agency respondents are also involved in tourism, other than energy and mobility, suggesting how tourism sectoral agencies have been targeted successfully within AMETHyST scope. The remaining stakeholder typologies have too few overall respondents to draw conclusions.

The following figures (**Figure 23**, **Figure 24**, and **Figure 25**) are dedicated to the analysis of the survey responses regarding stakeholder knowledge in the three main sections of the hydrogen value chain: end-uses, production, and transport and storage. An initial assessment of stakeholder overall knowledge led to the necessity of further refining the available results. In this regard, stakeholder knowledge was analyzed disaggregated per stakeholder typology. The full analysis is reported in **Annex III** and provides interesting insights on the differences between stakeholder typologies' level of knowledge. Higher education and research organizations together with SMEs and large industries are ranked highest in terms of knowledge in nearly all hydrogen technologies. Conversely, infrastructure and service public providers, along with sectoral agencies, demonstrate the highest number of low-knowledge respondents.

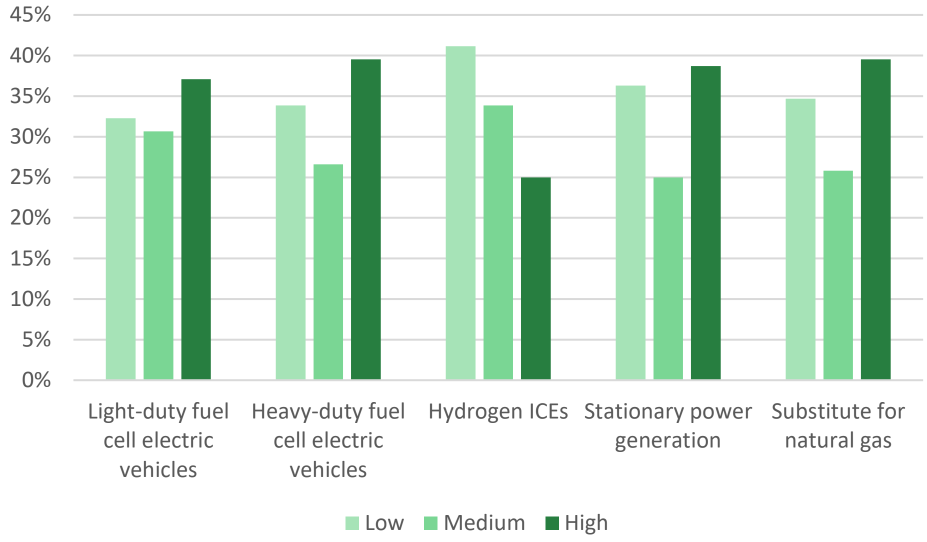


Figure 23*. Stakeholders responses distribution on their knowledge of final uses of hydrogen. ICEs: internal combustion engines.*

The first macro-category probed for stakeholder knowledge (hydrogen use) encompasses various technologies for final uses of hydrogen as an energy vector. The results of the survey have been processed and are synthesized in **Figure 23**. The technologies for hydrogen use (extensively covered in Section **2.2**) identified as relevant in the Alpine Space are:

- Light-duty fuel cell electric vehicles (LFCEV). Mainly passenger vehicles for private transport.
- Heavy-duty fuel cell electric vehicles (HFCEV). Mainly trucks, buses, and snow groomers.
- Hydrogen internal combustion engines (H2 ICEs). This category only regards the engine which can be potentially applied to drive multiple types of vehicles or other devices that require mechanical energy (e.g., power generators).
- Stationary power generation. This category refers to the use of hydrogen in electrical energy generation through gas turbines and stationary fuel cells.
- Substitute for natural gas. Refers to the substitution of natural gas for heat generation either at a distributed, residential, scale or concentrated, industrial, level.

What emerges from the survey is that whilst the majority of respondents express a high level of knowledge in LFCEV, and HFCEV, closely followed by stationary power generation and substitution for natural gas, a low level of knowledge is found for H2 ICEs. This hints at a broad range of backgrounds of stakeholders. On the other hand, as mentioned above, and with reference to the hydrogen final uses section in **Annex III**, the low level of knowledge is mostly attributable to infrastructure and service public providers along with sectoral agencies. Complementarily, a high level of knowledge is attributed to higher education and research organizations together with SMEs and large industries.

The second macro-category probed for stakeholder knowledge (hydrogen production) encompasses three technologies for hydrogen production. The results of the survey have been processed and are synthesized in **Figure 24**.

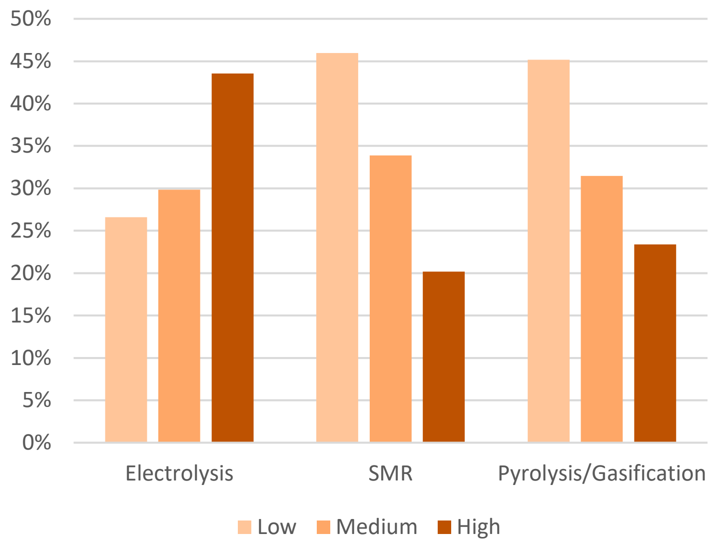


***Figure 24**. Stakeholders responses distribution on their knowledge of production of hydrogen. SMR stands for steam methane reforming, which produces the so-called grey hydrogen.*

The technologies for hydrogen production (extensively covered in Section **2.1**) identified as relevant in the Alpine Space are:

- Electrolysis. Process of separation of water through an electrolyzer using electricity, independently of the source of power.
- Steam methane reforming (SMR). Process of separating methane into hydrogen and carbon monoxide, through water vapor and heat.
- Pyrolysis/gasification. Thermochemical process for turning biomass into syngas, to be upgraded to a pure hydrogen stream.

The survey shows how the stakeholders are more familiar with electrolysis compared to SMR and biomass pyrolysis or gasification. By looking at the knowledge of the single stakeholder typology groups (**Annex III**) it can be seen that high knowledge in electrolysis is mostly expressed by higher education and research organizations together with SMEs and large industries, similar to what is witnessed in the end-use sector. Differently, for SMR and biomass pyrolysis or gasification, only higher education and research organizations reported having a high knowledge, while the majority of SMEs and large industries, infrastructure and service public providers, along with sectoral agencies, all manifested medium to low knowledge.

The last of the three macro-categories of the hydrogen value chain regards means of transportation and storage of hydrogen. The survey results are reported in **Figure 25**. The storage and transportation technologies, presented and discussed in Sections **2.3** and **2.4**, and identified as relevant in the Alpine Space are:

- Liquefied hydrogen. With a greater energy density per unit volume compared to pressurized gaseous hydrogen, it represents a promising way to store and transport large quantities of hydrogen. The downside is represented by the cost of liquefaction and boil-off losses.
- Gaseous hydrogen. Most used means of transport and storage. Compressed gaseous hydrogen can be injected into hydrogen-ready pipelines, tanks, and tube trailers.
- Seasonal storage. Method that assesses the issue of mismatch between production of renewables and electricity demand. Excess production can be converted to hydrogen and stored for later conversion into electricity in case of a deficit of renewable supply.

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

- Hydrogen refueling stations (HRS). A form of local distribution of hydrogen for mobility applications such as fuel cell passenger cars, trucks, buses, and also snow groomers.
- Blending of hydrogen in the natural gas grid. Enables distributed hydrogen supply for heat production for both residential and industry players.

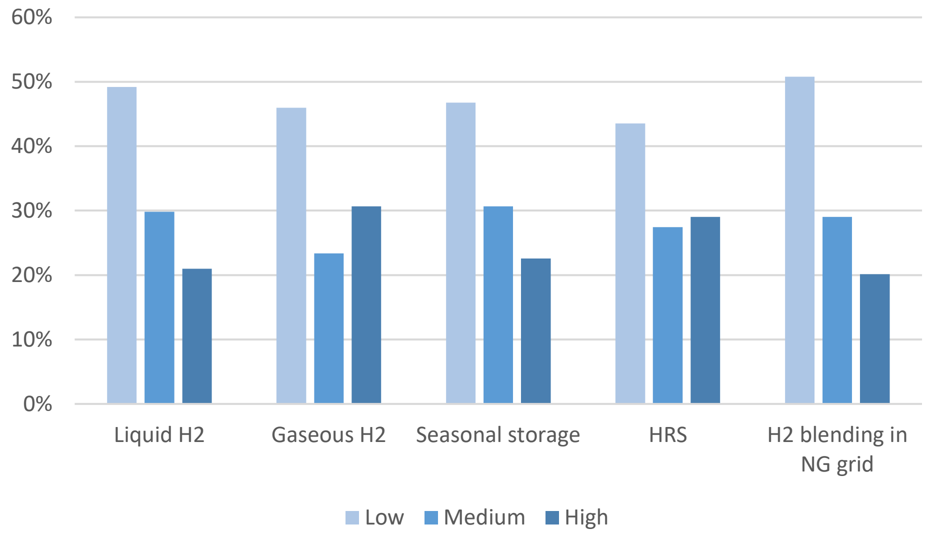


***Figure 25**. Stakeholders responses distribution on their knowledge of transportation and storage of hydrogen. HRS: hydrogen refueling station; NG: natural gas.*

The questionnaire results reported in **Figure 25** suggest that there is an overall low level of knowledge regarding hydrogen transport and storage. Gaseous hydrogen leads in terms of high knowledge probably due to the technological affinity with natural gas and other existing process gases such as nitrogen and oxygen. Hydrogen refueling stations show the second highest level of knowledge driven mostly by SMEs and large companies (**Annex III**). This might be attributable to the potential business case this technology represents, enhanced by the growing promoted public image. The lowest level of knowledge regards hydrogen blending in natural gas grids. This technology appears to be less known across all stakeholder typologies, probably due to its innovative nature and the limited number of players that can take advantage of it as a business case. Similarly to what is witnessed in the majority of the hydrogen technologies of the previous two macro-areas of the hydrogen value chain, higher education and research organizations together with SMEs and large industries are ranked highest in terms of knowledge in nearly all hydrogen technologies. Conversely, infrastructure and service public providers along with sectoral agencies demonstrate the highest number of low-knowledge respondents (**Annex III**).

Having probed the survey respondents' knowledge of hydrogen technologies applicable in the Alpine Space area, it is also useful to assess their knowledge of the legislative and institutional landscape supporting hydrogen development. The landscape is presented to the stakeholder with the bundle of the three terms laws, directives, and strategies. These encompass all legislative and political factors that guide and affect the development of a hydrogen economy. A distinction is made between three geographical levels: European, national, and local. Results are synthesized in **Figure 26** and highlight how stakeholders are more aware of political and legislative actions that might affect them directly at a local level. National and European political and legislative action are equal in terms of high stakeholder knowledge but show a discrepancy in terms of low and medium knowledge in that stakeholders seem to be more aware of national actions. In conclusion, stakeholders are more attentive to political and legislative actions that are attributable to authorities geographically closer to them.

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

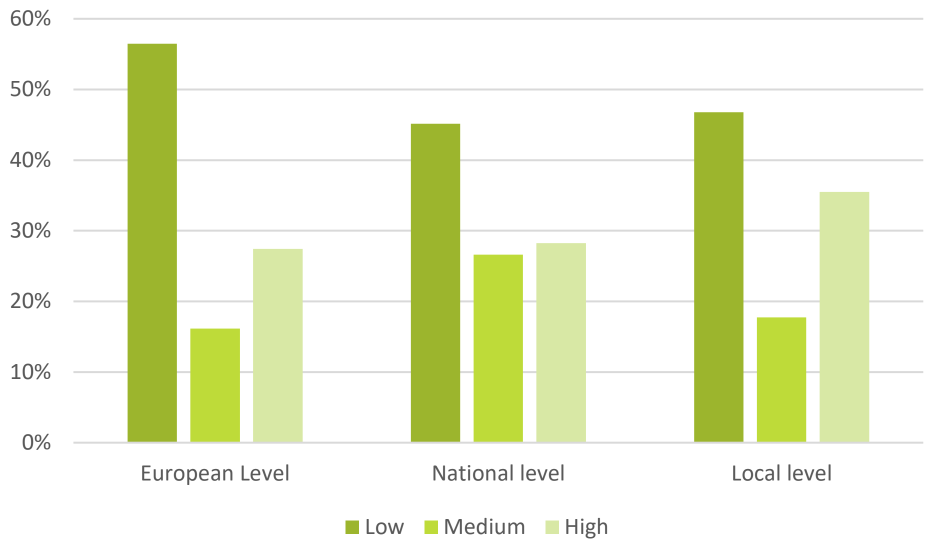


Figure 26*. Stakeholders responses distribution on their knowledge of laws, directives, and strategies aimed at hydrogen economy development and/or support at European, national, and local level.*

A piece of information useful to capture stakeholder perception of hydrogen ecosystems comes from the assessment of their judgment of the suitability of the current regulatory framework (or legislative landscape) and financing tools in support of hydrogen. The results of this assessment are reported in **Figure 27**. It is necessary to add that the stakeholders were presented with four options. Other than the three reported in the legend of the figure, a fourth option allowed stakeholders to express that the current regulatory framework or financing tools are fully adequate. However, this last choice was only chosen by 3 stakeholders out of 124. Merging this information with that deducible from **Figure 27** it becomes clear how the vast majority of stakeholders see regulatory frameworks and financing tools currently in place as inadequate. One could also speculate that the low level of knowledge witnessed in **Figure 26** might be directly due to the inadequacy of the current regulatory frameworks and financing tools. Lastly, there seems to be a general consensus among stakeholders regarding efforts that are being made to progress the development of regulatory frameworks (53% respondents) and financing tools (45% respondents).

Stakeholders' view on the potentiality of hydrogen technologies implementations in their respective regions is also assessed. The respondents were presented with multiple choices, reported in the leftmost column of **Table 4**, and were given the possibility of selecting more than one choice. Therefore, the table represents the number of times each hydrogen technology was deemed by the stakeholders to have potential use in their territories. In addition, **Table 4** presents results under geographical disaggregation between the countries of the Alpine Space area. With the aid of a color gradient (green: more mentions, red: less mentions) it can be observed which hydrogen technologies are believed to have potential in the various countries by local players. Immediately standing out, is the general recognition across countries of the high potential of production of hydrogen by electrolysis as well as of use for heavy-duty FCEVs. This demonstrates firstly the awareness of the role of green hydrogen in future decarbonized energy systems, further confirmed by the low popularity of steam methane reforming, typically based on the use of fossil fuels (grey hydrogen). Secondly, it is possible to conclude that Alpine Space regions have room for the development of fuel cell bus fleets, trucks, trains, and even snow groomers.

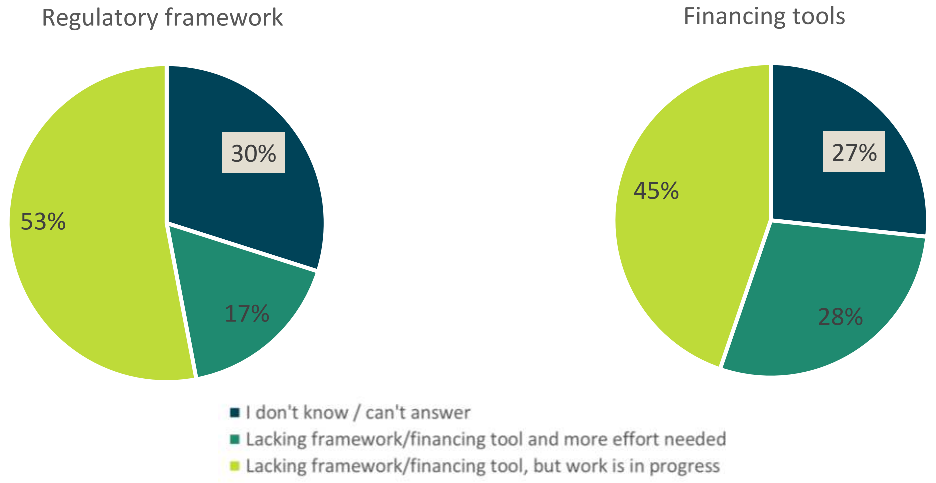


Figure 27*. Stakeholders' evaluation of the suitability of the current regulatory framework (left) and financing tools (right) aimed at hydrogen economy development and/or support.*

	Austria	France	Germany	Italy	Slovenia	Switzerland	Total
Production by electrolysis	10	6	13	51	3	10	93
Production by pyrolysis/gasification of biomass or waste	2	2	6	25	3	3	41
Use for heavy-duty FCEV	10	5	10	44	4	11	84
Use for light-duty FCEV	5	1	5	19	0	3	33
Use for seasonal storage solutions	6	4	10	22	3	5	50
Use as substitute for natural gas	6	3	3	13	4	2	31
Use in internal combustion engines	4	2	5	10	1	2	24
Production by steam methane reforming	0	0	3	6	1	1	11
Use for stationary power generation	5	2	9	15	1	3	35
Use for e-fuels	1	1	2	12	0	6	22

Table 4*. Hydrogen applications or technologies that have the highest potential to be implemented in the short term in the respondent's territory, disaggregated per stakeholder country. Numbers indicate the number of times that a specific application or technology is mentioned.*

Another metric considered important for characterizing stakeholders is their level of expertise in the hydrogen sector, meaning any activity related to the matter. The results of the dedicated survey question are reported in **Figure 28**. It can be seen how the highest expertise (Expert) and higher intermediate (Competent) levels are mostly found among higher education or research organizations and SMEs or large companies groups. On the other hand, infrastructure, and service public providers along with sectoral agencies and especially local/regional public authorities claim to have less expert and competent players and mostly advanced beginners in the hydrogen sector. This distribution somewhat reflects the results of the survey questions on knowledge in hydrogen technologies, which can be found in **Annex III**.

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

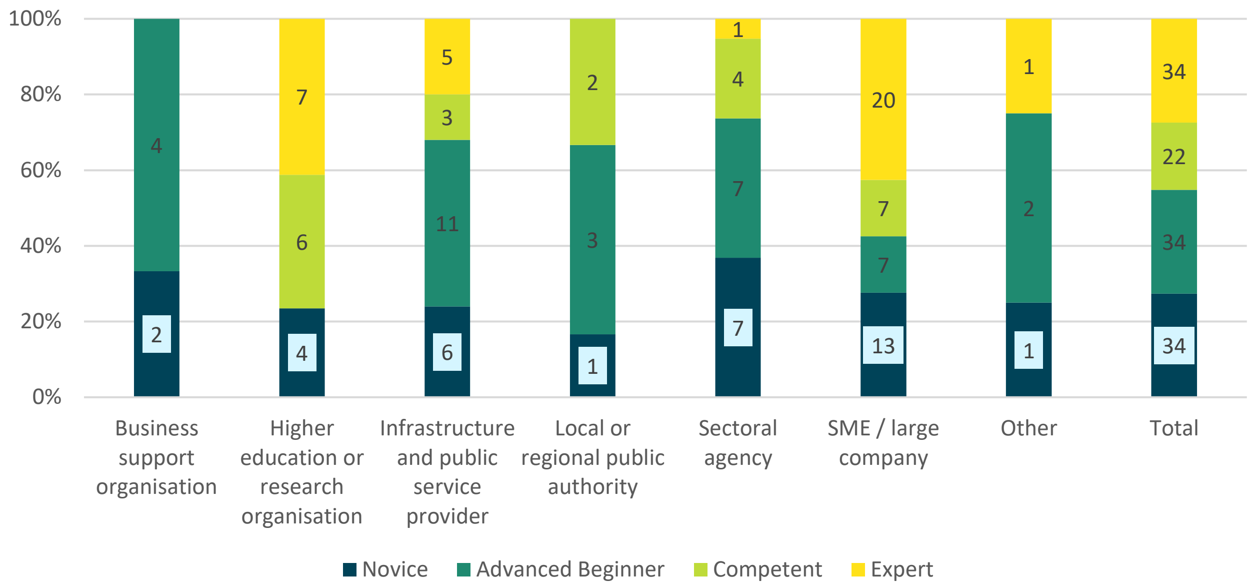


***Figure 28**. Stakeholders level of expertise (self-proclaimed), divided per stakeholder typology. Numbers within the bars represent the number of stakeholders that provided the response. The "Other" category encompasses public healthcare providers, investors, and project developers.*

Having gained an insight into the stakeholders' degree of expertise in the hydrogen sector, it is useful to assess which general macro-area they are actively involved in. The stakeholders were provided with multiple choices, reported in the topmost row of **Table 5** (production, storage, use, transport, distribution), and were given the possibility of selecting more than one choice. Therefore, the table represents the number of times each macro-area of the hydrogen sector was claimed by stakeholders to be in their field of involvement. For sake of completeness, this specific question also allowed to express no involvement in the hydrogen sector. However, it was only claimed twice and is therefore excluded from the representation. With the aid of the color gradient (green: more claims, red: fewer claims) it can be stated that the sector in which most stakeholders are involved is hydrogen production, followed by hydrogen use and hydrogen transport. By analyzing the table from a stakeholder typology perspective, it can be seen that higher education or research organizations are involved only in hydrogen production, while infrastructure and public service providers and local or regional public authorities claim involvement also in hydrogen use and hydrogen transport. Lastly, SMEs and large companies show a more homogeneous spread of involvement across all hydrogen sectors.

	Production	Storage	Use	Transport	Distribution	Other
Business support organization	2	1	1	2	1	1
Higher education or research organization	11	6	7	7	4	5
Infrastructure and public service provider	8	5	9	5	7	0
Local or regional public authority	4	2	3	4	3	1
Sectoral agency	3	3	3	4	4	4
SME / large company	16	17	20	11	8	4
Other	1	2	1	0	0	2
Total	45	36	44	33	27	17

***Table 5**. Stakeholders' typology and area of involvement within the hydrogen sector. Labels report sector and the number of times that a specific sector was mentioned by stakeholders as their area of involvement. Note that the numbers do not refer to the number of stakeholders. The "Other" stakeholder category refers to stakeholders involved in research, education, or consulting. The "Other" sector of involvement refers to environmental compliance of hydrogen solution studies, dissemination, and demand prediction assessments.*

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Interest in the hydrogen sector was also assessed through a dedicated question in the survey. The stakeholders were provided with multiple choices, reported at the apices of the radar graph **Figure 29**, and were given the possibility of selecting more than one choice. Therefore, the percentages in the graph represent the frequency with which a specific sector was mentioned by each stakeholders typology as their area of interest. It can be deduced that the most popular areas of interest for stakeholders are hydrogen use, production, and, interestingly, storage. While the first two broadly reflect the insights produced from **Table 4** and **Table 5** (in that these two sectors are sought after as having the most potential and involvement), the popularity of hydrogen storage might still be gaining momentum. A hypothesis on the reason for this phenomenon might be the emerging role of hydrogen as infra- and intra-seasonal storage of renewable electricity, and therefore the importance of storage. At stakeholder level, it can be observed that there is a relatively even distribution of interest in hydrogen use and hydrogen storage. Following, higher education or research institutions expressed more interest in hydrogen production, while local or regional public authorities and infrastructure and public service providers express more interest in hydrogen transport. This phenomenon is somehow expected as hydrogen transport is likely to be regulated and operated by these two players. Lastly, the category of least interest is represented by hydrogen distribution.

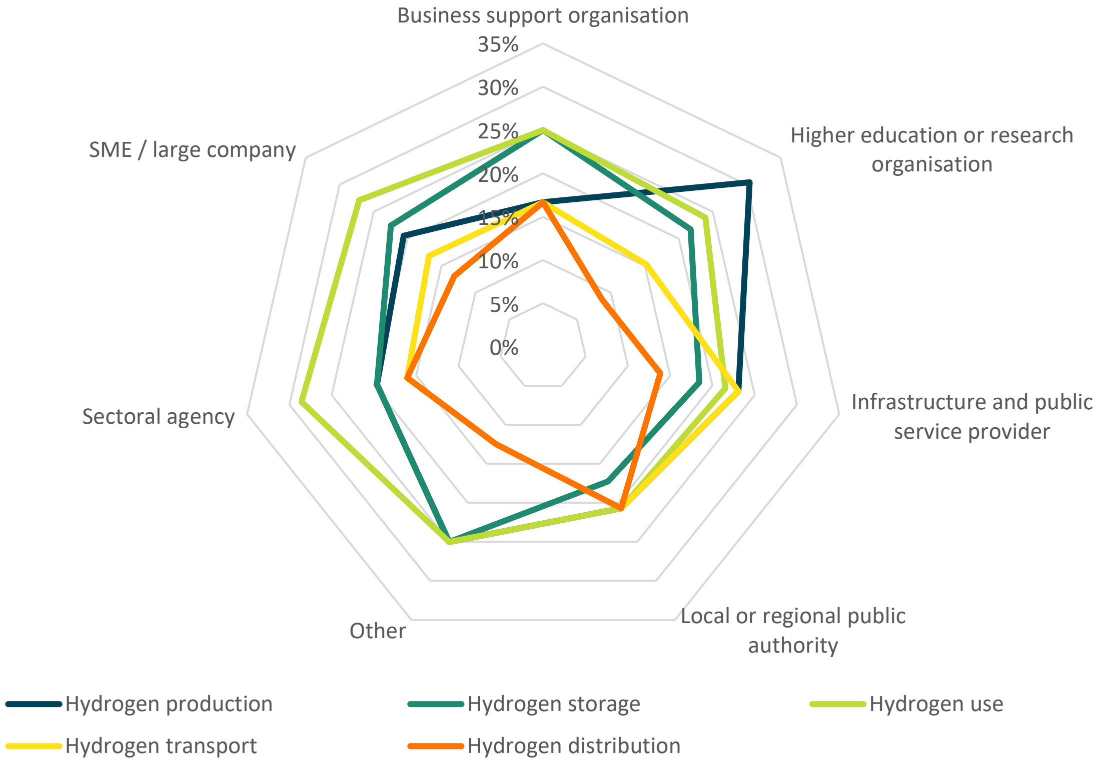


Figure 29. *Stakeholder typology and areas within the hydrogen sector for which interest was expressed. Percentages represent the frequency with which a specific sector was mentioned by each stakeholder typology as their area of interest. The "Other" category encompasses public healthcare providers, investors, and project developers.*

In connection with the scope of deliverable D.1.2.1 of the AMETHyST project, which aims at mapping all hydrogen projects or initiatives of the Alpine Space area, stakeholders were also probed for their involvement (active, past, and future) in projects or initiatives related to low-carbon hydrogen. The survey question could be answered through three different answers:

- Yes, our organization is involved.
- No, but our organization is aware of projects and/or initiatives.
- No, our organization is neither involved nor aware of projects and/or initiatives.

Out of the 124 respondents, the majority replied by selecting either of the first two choices. Only 21 respondents stated that they are neither involved nor aware of hydrogen projects and/or initiatives. The subdivision between the first two answer choices is reported in **Figure 30**.

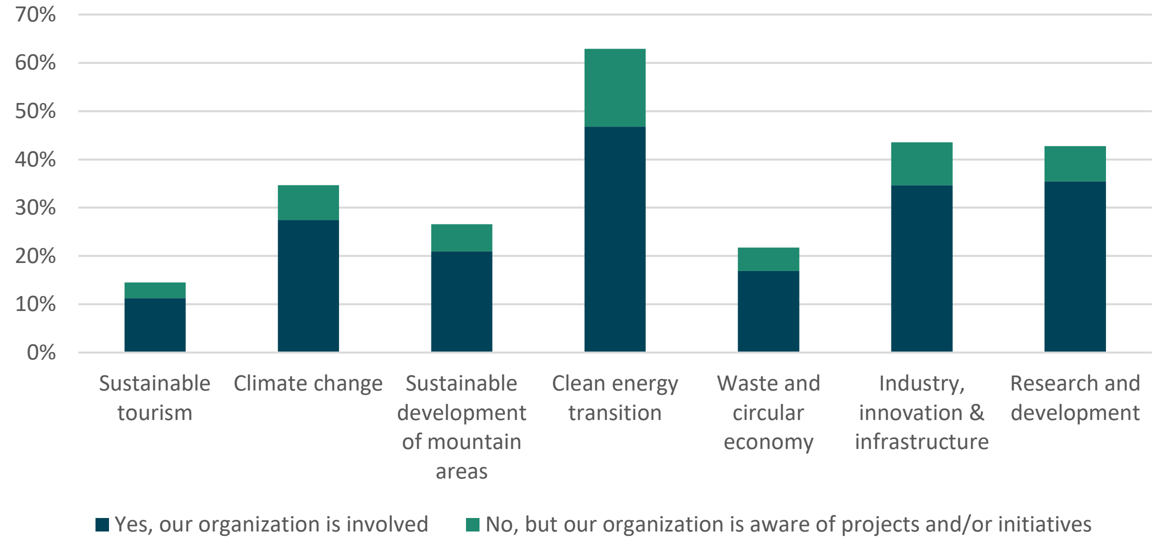


Figure 30*. Stakeholders involvement in projects and/or initiatives related to green or low-carbon hydrogen, further divided into specific scopes of the project and/or initiative. Percentages represent the frequency with which a specific sector was mentioned by each stakeholder's typology as their area of involvement.*

Respondents who stated their involvement in or awareness of projects and/or initiatives were then provided with a second question to define the scopes and goals of the projects and/or initiatives. The stakeholders were provided with multiple choices, reported in **Figure 30**, and were given the possibility of selecting more than one choice. Therefore, the percentages in the graph represent the frequency with which a specific scope and goal was mentioned by the respondents. It can be seen how most of the projects and/or initiatives regard the clean energy transition, followed at equal levels by climate change, industry, innovation & infrastructure, and research & development. Lastly, it can be noted that projects and/or initiatives regarding sustainable tourism and sustainable development of mountain areas are not very common.

The last set of questions assesses the stakeholders views on gaps and barriers that might hinder the implementation of hydrogen solutions in their respective territories. The set of gaps and barriers, reported in **Figure 31** and **Figure 32**, encompasses economic, social, technical, and regulatory issues faced by the development of hydrogen ecosystems. The intention of the survey is to characterize each gap and barrier in terms of both its criticality and the effort needed to solve it. **Figure 31** shows what level of urgency stakeholders attribute to each gap or barrier. Here, "high urgency" indicates an urgent need to overcome a gap or barrier. What emerges from this first graph is the significant urgency of economic aspects underlying hydrogen ecosystems. Most of the stakeholders' concerns regard high investment costs, amplified by high investment risks. These two aspects intrinsically cause business models for hydrogen solutions to be less competitive and attractive for the market. Stakeholders also recognize the importance of incentives, a legislative and strategic measure, probably due to the potentiality of mitigating the two abovementioned issues. Likely as a consequence of the risky and costly economics of hydrogen projects, stakeholders identified a lack of infrastructure for hydrogen, which is also tied to technical difficulties of its realization.

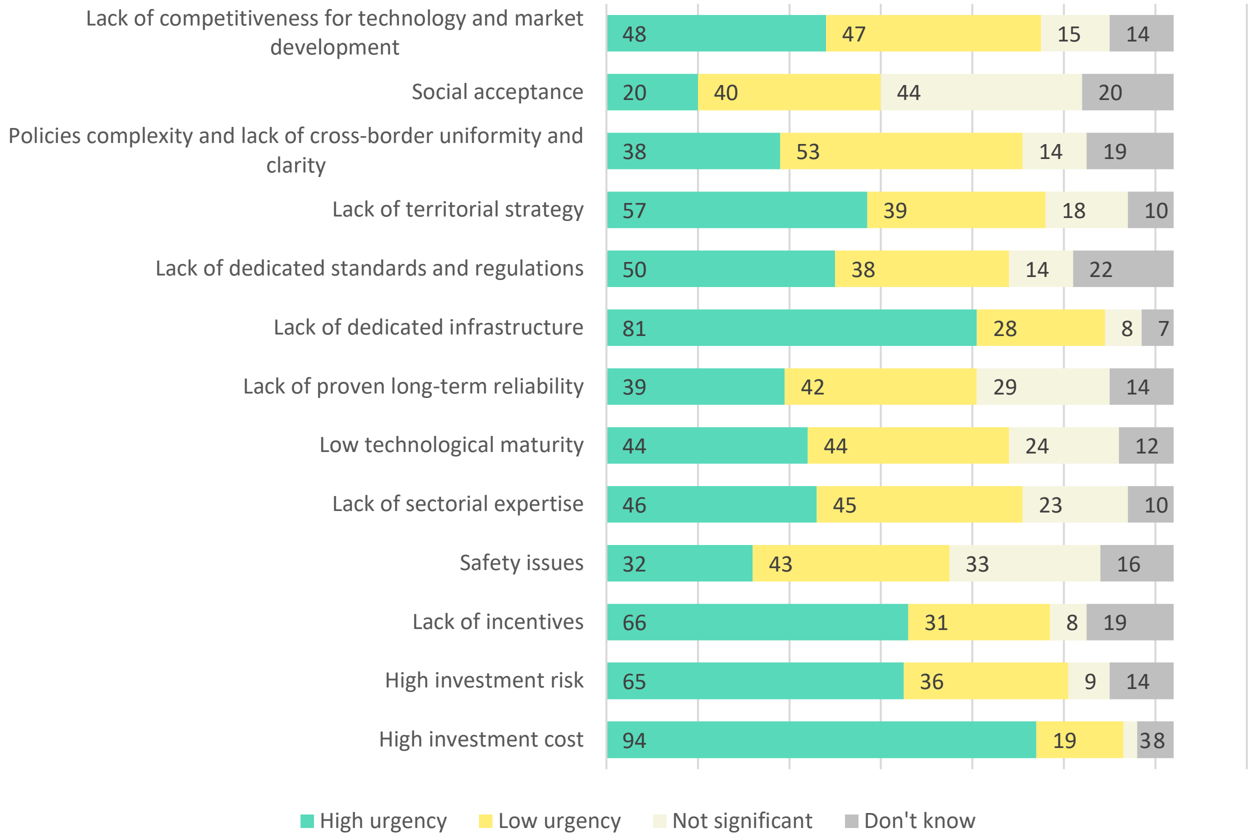


***Figure 31**. Stakeholder evaluation of urgency of gaps and barriers that hinder the implementation of green or low-carbon hydrogen solutions.*

Second, primary economic barriers are the lack and uncertainty of legislative measures supporting hydrogen ecosystems. Stakeholders believe that coordinating territorial strategies is essential for the development of hydrogen ecosystems. These strategies should also be based on clear, dedicated standards and regulations. Additionally, the presence of adequate incentive schemes is a complementary support to the development of the territorial strategies. Solving these economic and legislative drawbacks might enable a pick-up of the development of hydrogen ecosystems. Subsequently, other less critical gaps and barriers can be addressed.

Figure 32 reports the difficulty attributed to the solution of each gap or barrier. Here, "very challenging" indicates a high amount of effort needed to overcome the gap or barrier. Some of the most critical gaps and barriers of **Figure 31** are also deemed as the most difficult to overcome. Lowering high investment costs and de-risking investments are believed to be very challenging to tackle by stakeholders. Consequently, the lack of costly infrastructure and the economic unattractiveness of hydrogen projects are also high-effort barriers. Conversely, the legislative tool represented by incentivization schemes that might facilitate the development of hydrogen ecosystems is not perceived as very challenging to achieve. This suggests the relevance of such tools in the growth of the development of hydrogen economies. Similarly to what shown in **Figure 31**, barriers encompassing the lack and uncertainty of legislative measures supporting hydrogen ecosystems are second - in terms of efforts needed - to the economic ones.

Overall, **Figure 32** highlights how the listed gaps and barriers are considered by stakeholders as mostly "challenging" and not "very challenging". This aspect suggests a general confidence in the ability to overcome gaps and barriers.

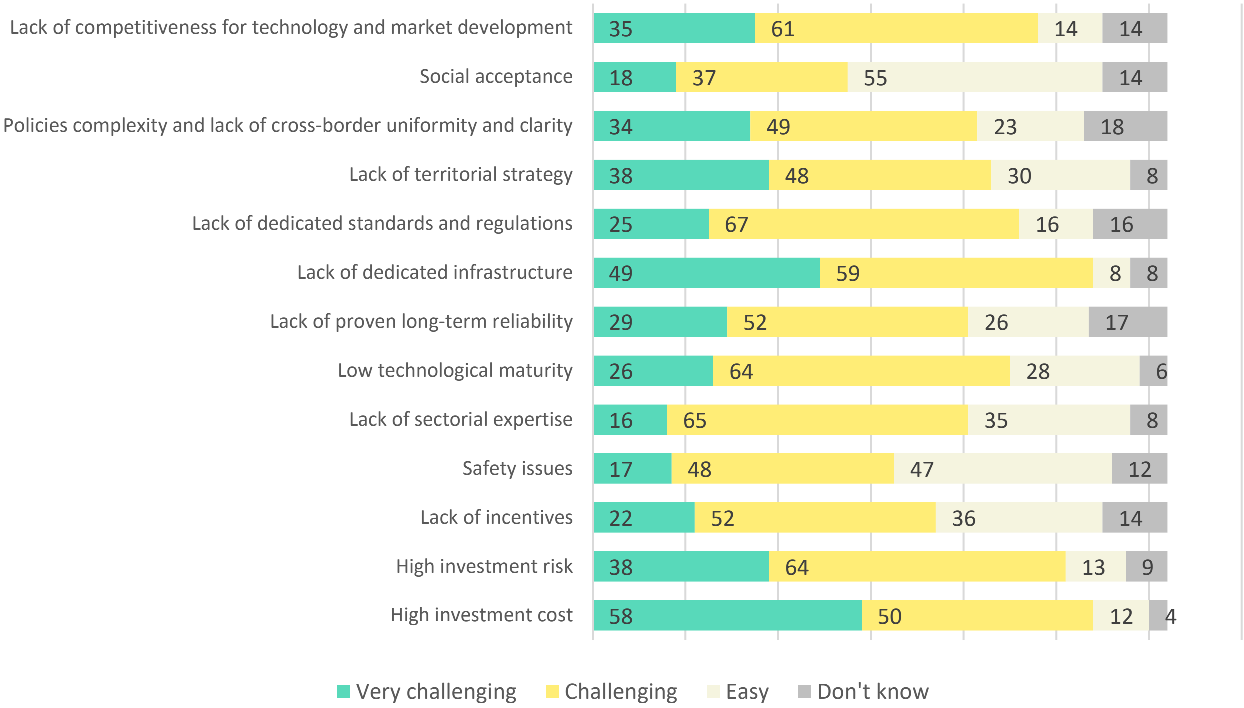


Figure 32*. Stakeholders' evaluation of the difficulty of surpassing and/or solving gaps and barriers that hinder the implementation of green or low-carbon hydrogen solutions.*

A final analysis regards the combination of the information gathered on stakeholders' perception of gaps and barriers to hydrogen ecosystems and presented in **Figure 31** and **Figure 32**. By assigning weights to the different degrees of urgency and effort of the gaps and barriers and considering the number of replies for each stakeholders category, it was possible to combine the information to produce the graph in **Figure 33**. The main insight is that of establishing where resources should be ultimately allocated to be most effective. Depending on the degree of difficulty to solve (x-axis) and urgency (y-axis) of each barrier, four quadrants can be identified on the graph. A high urgency barrier could be perceived either as very challenging or easy to solve. This difference leads to conferring two different natures to the barrier. A high urgency but easy-to-solve gap or barrier can be referred to as a "low-hanging fruit", with high priority. This translates to a great positive impact relative to a small resource allocation. On the other hand, for the same level of high urgency, very challenging-to-solve barriers can be defined as "high-impact", with medium priority. These require more resource allocation to observe a positive impact. To high urgency gaps and barriers, which should be tackled under both easy and very challenging conditions, less-significant gaps and barriers should only be resolved if the resource allocation required is low. These are intrinsically not critical and with low priority, so should be secondary in relevance with respect to the medium and high priority gaps or barriers. Lastly, gaps and barriers that are not significant and that require more resources to be solved should be the last to be assessed, if not assessed at all ("**no-go zone**").

The high- priority zone of the graph of **Figure 33** confirms that investment costs and the associated risks are both urgent and very challenging to solve. On the same level is the lack of infrastructure necessary to enable interconnection between hydrogen supply and demand of hydrogen ecosystems. The infrastructure deficit is likely caused by the unfavorable economic conditions for its development, representing a poor business case. The challenging economic aspects of hydrogen technologies can be overcome starting from legislative coordination. The lack of a unified territorial strategy and of dedicated standards and regulations, as well as the complexity of current policies, do not allow to effectively tackle the problem of costly and risky investments. One solution that stakeholders have identified as a high priority is, in fact, a legislative one. The establishment of incentive schemes could resolve cost issues and favor commercial hydrogen projects (including infrastructure), enabling large-scale deployment of hydrogen technologies. Large-scale manufacturing and deployment will drive down costs, leveraging learn-by-doing effects as well as economies of scale mechanisms. Therefore, the expansion of hydrogen ecosystems will likely be driven initially by incentive schemes and will transition to become self-sustaining as projects become more economically feasible, finding their place in competitive business plans. The positive effect on costs of large-scale adoption of hydrogen solutions is also mirrored in the technologies. Technological maturity will be in any case achieved as experience in the sector grows. Lastly, the growing demand for specialized workforce will have to be addressed with dedicated programs for engineers and technicians. These groups will have to be educated on regulations, codes, and standards to safely operate in this growing market.

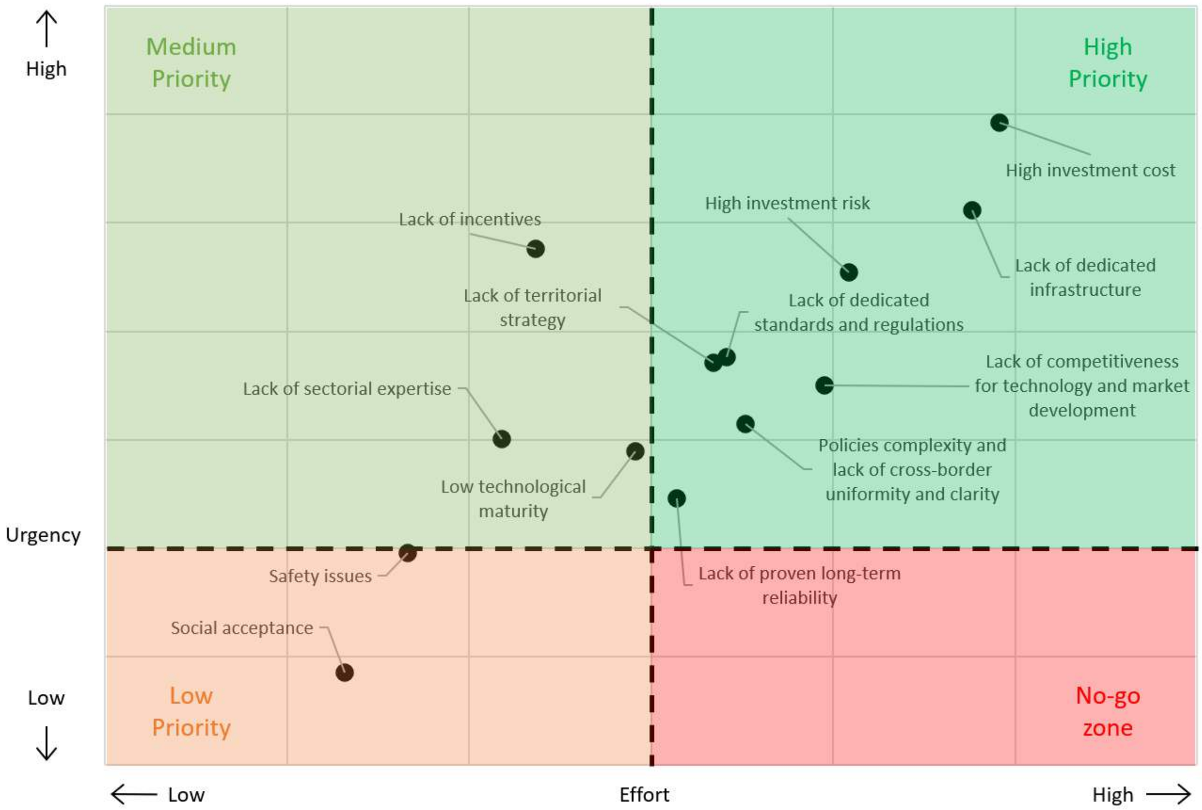


Figure 33. Combination of stakeholder responses regarding urgency and efforts of gaps and barriers to hydrogen solutions implementation in the Alpine Space area.

Social acceptance and safety issues are not regarded by the stakeholders as critical barriers to the development of hydrogen ecosystems (low priority). These two aspects are related to one another in that negative social perception of hydrogen (or any other innovation) is directly proportional to the safety issues that burden it. Addressing the social perception of hydrogen coincides firstly with providing the public with factual information on the matter. Secondly, dedicated codes and standards on safety measures must also be publicized.

Analysis of open-ended questions

To explore and compare open-text answers of the 124 responses to Questionnaire 1 – "Hydrogen in the Alps", text data was codified with the support of the software Atlas.ti. In Atlas.ti, codes are short text lines identifying a concept, an attitude, or an argument inside the answer. By linking codes to each open-text answer, it is possible to cross-analyze answers of all respondents detecting similar attitudes and lines of reasoning from different respondents, highlighting co-occurrence of codes, organizing the analysis through thematic grouping of codes (e.g., "Hydrogen applications", "Critical Issues"), and bringing out the most frequently cited concepts.

The analysis here had an explorative rather than an explicative or descriptive purpose. Open-text questions were focused on possible hydrogen applications for the decarbonization of local territories. Other than that, the analysis involved different themes and concepts brought out autonomously by stakeholders. For these reasons, the analysis cannot have a descriptive purpose. Questions limited the scope of the answers, and it is not possible to have a comprehensive picture of all stakeholders' opinions and attitudes regarding most of the themes analyzed. In line with the scope of the AMETHyST project, our purpose was, then, explorative. What respondents brought out in the answers was collected organically and organized in themes, be it strictly related to the question or not.

In order to compare open-text answers from different groups of respondents, three categorial variables referred to the questionnaire respondent were integrated into the analysis: Organization's Country, Organization's Region, and Organization's Type. Grouping respondents on the basis of these variables, patterns in the distribution of Atlas.ti codes between groups could be found, in order to reveal regional, national, or organizational differences in stakeholders' opinions and attitudes towards specific hydrogen applications. The analysis of regional, national, and organizational variables had also the same explorative purpose. Trying to explain differences in stakeholders' opinions and attitudes with the regional or organizational variables, besides being theoretically questionable, would have been wrong because of the not representative character of the stakeholders' sample. Anyways, no regional, national, or organizational differences in stakeholders' opinions and attitudes towards hydrogen could be detected. Codes were homogeneously distributed between the respondents.

Output of the Atlas.ti analysis is then an explorative report of opinions, attitudes, used concepts, and lines of reasoning detected in the open answers of the questionnaire, organized by theme. In line with this approach, frequencies have been considered only in a qualitative way, reporting, for each theme, first what has been told by the stakeholders more frequently.

Production

Electrolysis of water with renewable energy is, by far, the most-cited way to produce hydrogen to sustain decarbonization. A few respondents talk about the production of hydrogen by biomass/waste (dark fermentation, pyrolysis/gasification).

Applications

Answering the questionnaire, respondents generally indicated hydrogen applications to be useful for decarbonizing their territories.

Production of hydrogen with surplus renewable energy for energy storage is by far the most cited application. Integration with renewable energy production is identified by many as the fundamental step for hydrogen decarbonization potential. A case cited by several respondents is the integration of energy to the poor hydroelectric production during winter; according to some respondents, this could help to decarbonize tourism in mountain areas, making renewable energy more independent from fossil fuel usage.

Renewable energy storage with hydrogen is also related to regional green energy self-sufficiency, since hydrogen can be used for energy storage in off-grid systems. This is identified as particularly useful for alpine tourism since remote areas unreached by gas and electricity grids can rely on hydrogen for both heating and electricity generation. Lastly, hydrogen as a fuel in the mobility sector is also among the most cited final usages.

Local public transport in particular is identified by many respondents as a great opportunity for hydrogen deployment in mountain areas. In this regard:

- Hydrogen is considered a good solution that lies in-between the utility-sustainability nexus. Some respondents highlight accessibility as one of the major issues with mountain areas (geographical conformation, lack of infrastructure). Improving the quality and quantity of public transportation is important for both the tourists and the local population. Hydrogen is interpreted as an opportunity to improve the capillarity of public transportation and facilitate access to remote areas in a sustainable way.
- The usage of hydrogen for buses is cited by many as a way to decarbonize the tourism sector in the mountains.
- Another advantage of the implementation of a hydrogen public transport system identified by some respondents is that hydrogen buses (with fuel-cell or combustion engines) work better than electric or GNL buses considering the slope and temperature conditions of mountain areas.
- Public transportation means identified as potential targets for hydrogen implementation are buses, light rails, trains, and also ships.

Mobility in general is cited by many of the respondents, often without specification.

- Many respondents are positive about the possibility of helping alpine tourism decarbonization through the implementation of hydrogen-fueled snow groomers and snowmobiles. For some respondents, hydrogen-powered fuel-cell snowmobiles could be easily implemented.
- Use for heavy mobility is indicated both in relation to the tourism sector and the logistics sector.
- Use for light vehicles is mentioned by very few respondents, and it seems that, for private transport, the alternative of battery electric vehicles is considered preferable.
- Similar to what was reported above for the public passenger transport system, some respondents say hydrogen could sustain the transition to a sustainable capillary logistic network in valleys not reached by railways, through the implementation of hydrogen trucks.
- Implementation of hydrogen mobility can be positive not only for the decarbonization of the territory but also for the reduction of the impact (pollution, noise) on the fragile alpine environment.
- One of the respondents indicates the possibility of implementing a hydrogen small mobility system (e.g., bicycles, scooters, kick-scooters), especially useful for the tourism sector decarbonization.

Residential uses of hydrogen are cited by many, especially for the decarbonization of touristic accommodation facilities:

- Residential uses are associated with the decarbonization potential of hydrogen in remote areas of the alpine territory; hydrogen can be used in off-grid systems for heating and electric generation in alpine retreats, hotels, and B&Bs not reached by the natural gas grid (some stakeholders talk about "energy autarky of hotels"). At the same time, according to respondents, distributing hydrogen through the existing infrastructure is the way to go in areas reached by the natural gas grid.
- Some say that the decarbonization potential of residential usage of hydrogen is great as heating is what consumes most energy in the alpine territories, especially during winter.
- Finally, some respondents notice that decarbonizing alpine touristic structures can economically boost the sector through the "sustainable accommodation" (or "eco-tourism") label, making the touristic offer more attractive for conscious customers.

The usage of hydrogen in the industry sector is another most-cited application.

Other less-cited hydrogen applications are:

- Usage for ski-lifts
- Usage for vehicles for waste collection
- Usage for heavy-duty machinery (construction vehicles)
- Usage for "last-mile delivery" vehicles
- Usage to "capture" CO_2 emissions from industrial processes
- Usage in hydrogenotrophic methanogenesis
- Usage for ropeways

Skepticism and critical issues

Skepticism about the hydrogen potential for decarbonization both in general or specifically for the tourism sector or mountain areas is often unjustified in the answers; other times it is supported by diverse arguments:

- There is no economic sustainability for hydrogen applications; other alternatives, such as direct electrification for transports, are more cost-effective;
- Alternative technologies, such as those based on biomethane or an electric transport system, are more efficient;
- "There is no room for significant CO_2 save" in the mountain areas;
- It is difficult to implement hydrogen in the mountain areas;
- A respondent says hydrogen mobility works better in non-mountainous areas;

Cross-referencing open-text answers with the questionnaire's multiple-choice answers, the attributes/opinions of those who explicitly affirmed a skeptical attitude towards the decarbonization potential of hydrogen can be further analyzed.

Before going on, it is important to highlight once more that such analysis has only an explorative scope. In fact, the method used to collect the data did not enable an exhaustive categorization of the skeptics, since the open questions of the questionnaire, whose answers were used for the categorization, focused on something other than the attitude towards hydrogen decarbonization (in particular, they concerned hydrogen applications). It cannot be guaranteed that all skeptics have been identified, and it is also uncertain whether those categorized as such may hold additional, unexpressed reasons for their skepticism regarding the limited potential of hydrogen for decarbonization. For this reason, and for what was stated above about the not representative character of the stakeholders' sample, the results of the analysis cannot be generalized, but they can still inform on the stakeholders who wanted to make explicit, in one way or another, their skepticism in completing the questionnaire.

Regarding regional and organization type distribution, a pattern does not emerge. Skeptics are homogeneously distributed among Alpine regions and organization types.

In order to grasp something about possible causes of explicit skepticism, skeptics' level of knowledge about the uses of hydrogen was analyzed, referencing the answers provided to the questionnaire's multiple-choice question: "How would you describe your level of knowledge of the following technologies for the use of hydrogen?". The question concerned 5 technologies for the use of hydrogen: Light-duty fuel-cell vehicles, Heavy-duty fuel-cell vehicles, Hydrogen Internal Combustion Engines, Stationary power generation, and Substitute for natural gas. For each of them, the respondent indicated their level of knowledge by selecting one of the following options: No knowledge, Novice, Advanced beginner, Competent, Highly knowledgeable. The overall results and analysis of this question can be found in **Figure 23**, while the full analysis disaggregated by stakeholder typology is in **Annex III**.

Comparing the answers of the skeptics in general with those of all the respondents, no great differences seem to emerge. The distribution of skeptics in the level of knowledge categories reflects that of respondents in general. Skeptics were further differentiated between *reasoned* and *not reasoned* answers. Reasoned answers, as mentioned above, concerned alternative technologies, economic sustainability, and Alpine territory specificities. Hypothesizing that open-ended answers expressing not reasoned skepticism about hydrogen's potential for decarbonization may be caused by a lack of knowledge about hydrogen technologies, the distribution of not reasoned answers skeptics between level of knowledge categories was compared with that of respondents in general.

As it can be seen in **Figure 34**, the results are mixed. The hypothesis is partially confirmed for the knowledge of light- and heavy-duty fuel-cell vehicles; not reasoned skepticism is not present in the group of fuel-cell vehicles' highly knowledgeable respondents, 13% of total stakeholders. The pattern isn't that clear: the "novice" and "competent" categories frequency does not support the hypothesis, since in the total number of respondents there are proportionally slightly more "novices" and less "competent" than in the category of skeptics. However, half of the skeptics define themselves as "advanced beginner" regarding both light-duty and heavy-duty fuel-cell vehicles. It is possible to think that skepticism about the hydrogen decarbonization potential by these stakeholders is partially due to a lack of knowledge regarding these technologies. Comparing knowledge categories distribution for the other three technologies doesn't reveal any pattern clear enough to support any conclusion.

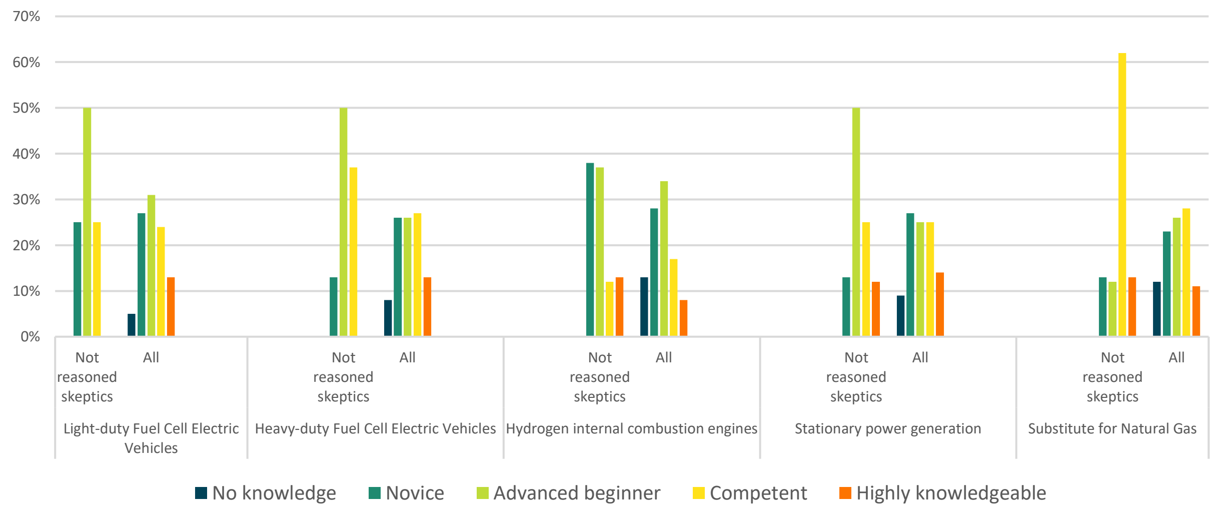


Figure 34*. Stakeholder level of knowledge on hydrogen final uses subdivided into not reasoned answer skeptics and total respondents.*

The same comparison has been made for hydrogen expertise level (**Figure 35**). Expertise level categories, as defined in the multiple-choice question of the questionnaire, were: Novice, no or little experience; Advanced Beginner, little experience, very recently started being involved in activities related to H2; Competent, moderate amount of experience in hydrogen-related technologies; Expert, a significant amount of experience.

As it was done for knowledge levels, the distribution of expertise levels in the groups of skeptics and not reasoned skeptics was compared against the distribution for the totality of respondents. Results are similar to those concerning the level of knowledge of fuel-cell vehicles. In the skeptics and, more importantly, in the not reasoned skeptics groups, stakeholders are concentrated in the "advanced beginner" expertise level, against a more equal stakeholder distribution for the totality of respondents. Again, half of those who expressed not reasoned skepticism in answering the open-text question was "advanced beginner". This could indicate that the skepticism of these particular stakeholders is due, at least partially, to a lack of experience with hydrogen.

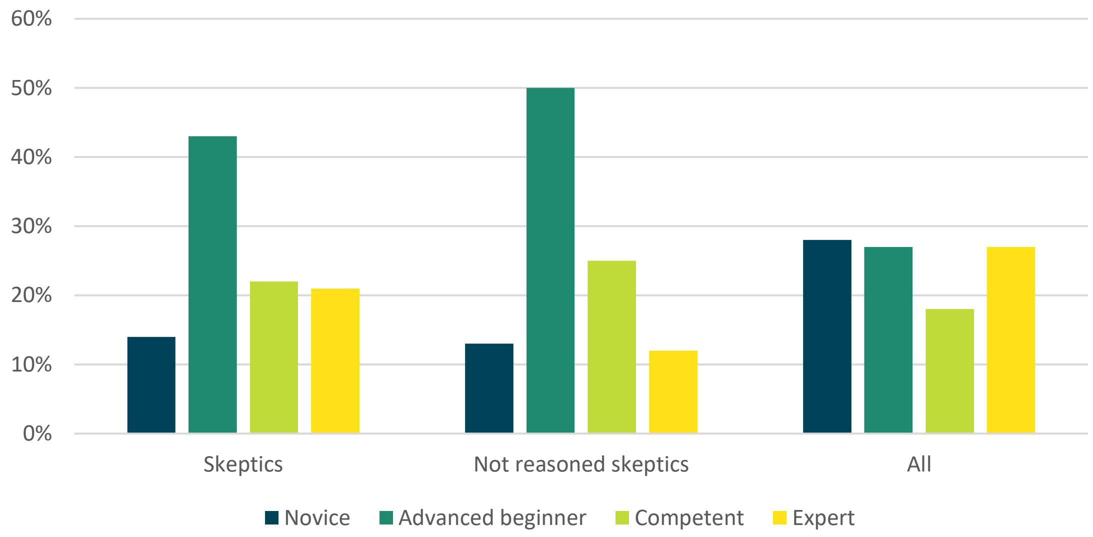


Figure 35. *Stakeholder expertise in the hydrogen sector subdivided into skeptics, not reasoned answer skeptics, and total respondents.*

Other than general skepticism, critical issues that need to be addressed have emerged. Critical issues brought on by respondents are reported below from the most to the least frequent:

- Hydrogen potential for decarbonization is necessarily dependent on renewable energy development. Low renewable energy penetration in the territory, absence of surplus, and reached production capacity limit of hydroelectric power in the mountains are presented as obstacles to the hydrogen potential;
- Even if positive about hydrogen potential, some respondents highlight the high costs of applications and the economic sustainability barrier;
- High investment risk, related to a missing legal framework / unclear strategy at a political level, and uncertainty about demand development. Those who bring on the latter as the key obstacle to hydrogen implementation advocate for public support for the demand of hydrogen-based technologies;
- The dependence of hydrogen potential for decarbonization on renewable energy penetration makes the lack of infrastructures in the mountain areas problematic; in remote areas, the lack of infrastructures makes hydrogen application difficult and the mountain tourism sector a target for fossil fuels usage;
- Lack of information about regulations and actual possibilities for implementation;
- Lack of effort by public authorities;
- Financing programs requirements are not suitable for specific characteristics of mountain areas
- The development of the hydrogen vehicles market is poor.

<u>Strategies</u>

In answering open-text questions, some stakeholders indicated their opinion on urgent strategies to overcome critical issues or to best exploit hydrogen potential in their area:

- Systemic approach: to optimize energy efficiency and decarbonization, stakeholders affirm it is fundamental to integrate hydrogen applications with a systemic approach. Many of them, in one way or another, state the inefficiency of considering hydrogen applications as single interventions. There is a need to consider: - regional integration, with participation in regional initiatives; - the fundamental integration with renewable energy production; - the construction of a clear legal framework; - the spreading of information and building of "smart communities" (community collaboration through ICT technologies);

- Some stakeholders highlight how important it is to evaluate which technologies are suitable to specific characteristics of mountain areas (seasonality of uses, temperature, slope, population, etc.). A related issue regards funding scheme requirements, that have to be suitable to mountain territories (for example, as pointed out by a respondent, a high minimum power for the electrolyzer may not be suitable for a small mountain ecosystem).

Questionnaire 2 – "Hydrogen projects and initiatives in the Alps"

Through the second questionnaire developed and shared with stakeholders already involved in hydrogen ("Hydrogen projects and initiatives in the Alps"), a total of 40 replies were collected, with details on specific hydrogen projects and initiatives developed within the Alpine Space region. 60% of these projects or initiatives involve the implementation of hydrogen-based technologies in a specific location, including demonstration sites, pilot plants, or case studies. The specific location and further features of these projects are displayed and discussed in detail in a dedicated report, as part of deliverable D.1.2.1. "Map of green hydrogen initiatives in the Alps".

In the following the main findings of the survey are presented.

- **State of advancement.** Most of the gathered projects are on-going, only a few of them are already concluded or are in the planning stage but have not yet started (**Figure 36**). This implies that hydrogen deployment in the Alpine regions is currently in a continuous development phase, with numerous initiatives in progress, and will deliver outputs and H2 applications in the years ahead.

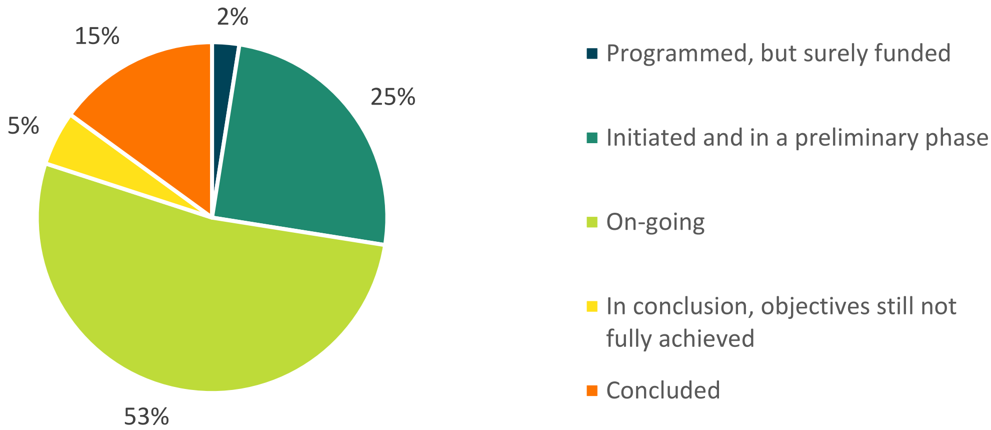


***Figure 36**. State of advancement of collected H2 projects and initiatives.*

- **Source of funding.** Most projects are funded by the European Union (e.g., Horizon 2020, Horizon Europe), state governments or private funding (**Figure 37**); multiple funding sources is a very common strategy for guaranteeing the economic feasibility and sustainability of innovative projects. The source of funding for hydrogen projects also suggests the presence or absence of a local or regional strategy supporting the creation of a green hydrogen economy. In general, it can be inferred that the presence of a shared hydrogen strategy at European level is not necessarily reflected on a local level, and that many projects still need to rely on private investments.

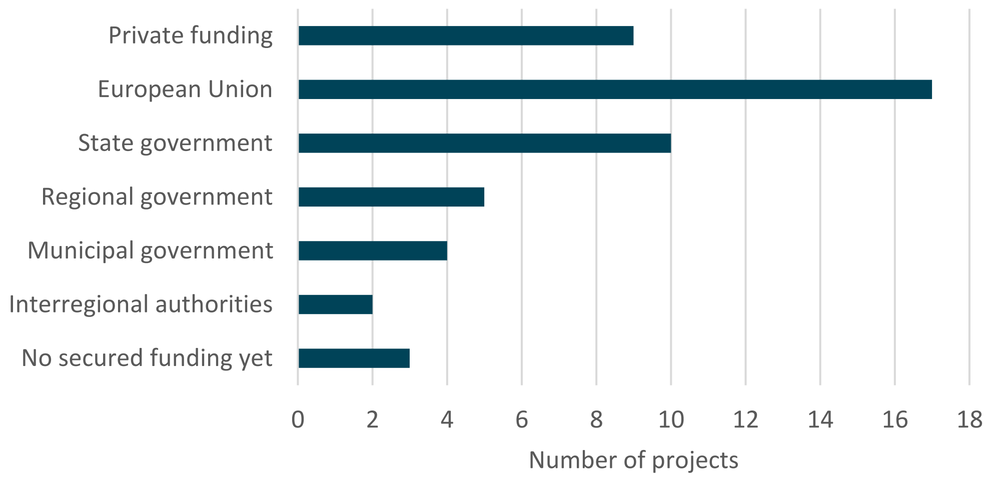


Figure 37. *Source of funding of collected H2 projects. Single projects may have multiple funding sources.*

- **Hydrogen source.** As regards the hydrogen produced/used/sored/distributed, 33 of the collected projects concern hydrogen that is produced from renewable energy sources (green hydrogen). Only in a few projects the hydrogen that is produced, used, stored, or distributed is either derived from electricity from the grid or from fossil fuels; in some cases, multiple hydrogen sources were indicated by stakeholders.
- **Area of interest.** A distinction was made based on the primary focus of the projects, as illustrated in **Figure 38**. The majority of projects aim at creating, modifying, implementing, or improving a hydrogen-based system or solution (31 technical projects), but many also include economic feasibility or market research (21 projects). Beyond these categories, there are also projects that address critical aspects such as social acceptance (12 projects), policy development and implementation (8 projects), and educational initiatives (1 project).

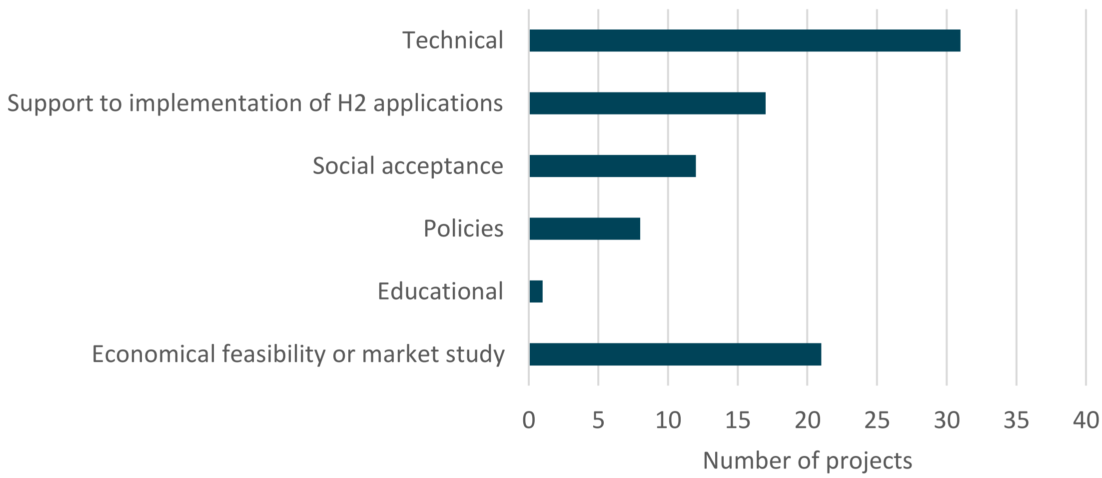


Figure 38. *Area of interest of collected H2 projects.*

- **Scopes and goals.** The primary scope of the collected projects is related to clean energy transition (35 projects), but, more specifically, climate change is also a concern for 22 projects. Additionally, a substantial number of projects are dedicated to research and development, while others contribute to the advancement of industry, innovation, and infrastructure. In addition, sustainable mobility stands out as a prominent and shared goal, with 17 projects actively working toward this vision

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

(**Figure 39**). Only 10% of projects address tourism directly, but 42% of them can have implications for the tourism industry (**Figure 40**). As an example, an initiative may not directly introduce tourist or shuttle buses, but instead may feature H2-powered buses serving vital commercial routes (e.g., airport-to-city-center routes); hydrogen produced in a specific touristic location could significantly enhance its sustainability reputation and attract investments for use of the produced H2 in the tourism sector, for mobility or heating purposes.

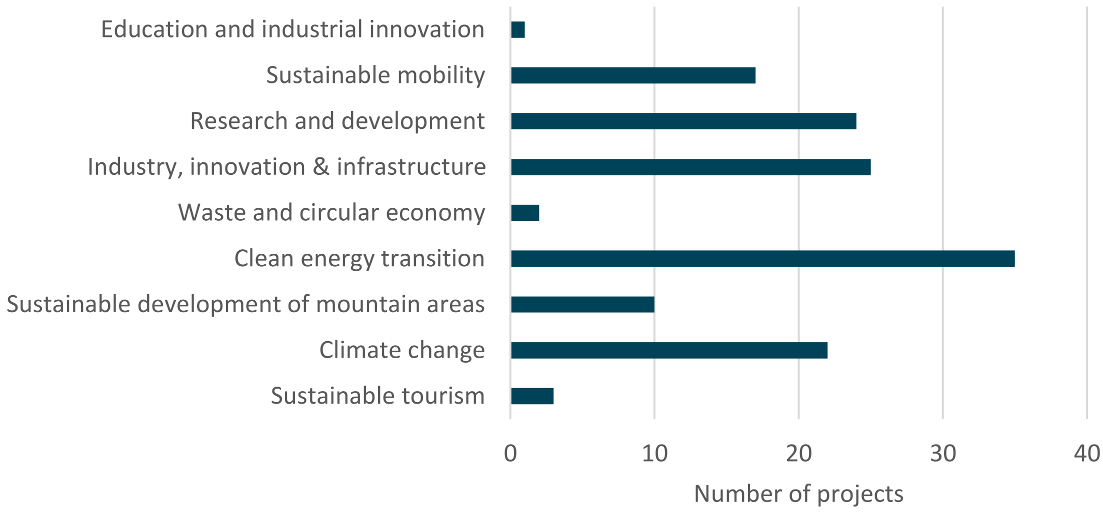


Figure 39*. Scopes and goals of collected H2 projects.*

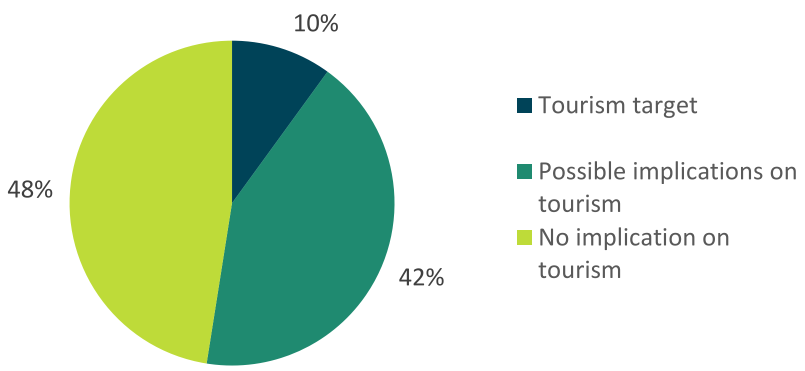


Figure 40*. Focus on tourism of collected H2 projects.*

- **Technology Readiness Level (TRL). Figure 41** reports the TRL of projects at their starting and ending points. For simplicity, TRL scale was divided into the following categories:
    - Basic technology research (TRL 1 – 2)
    - Technology development (TRL 3 – 5)
    - System/subsystem development (TRL 6 – 8)
    - System proven in operational environment (TRL 9)
    - Not applicable (e.g., crosscutting projects, with focus on policies development or promoting technological integration)

  The distribution of collected H2 projects shows a relatively balanced spread across the defined TRL categories, with the exception of basic technology research, which is almost uncovered. However, a discernible trend pointing towards application of H2 solutions in operational settings can be clearly outlined.

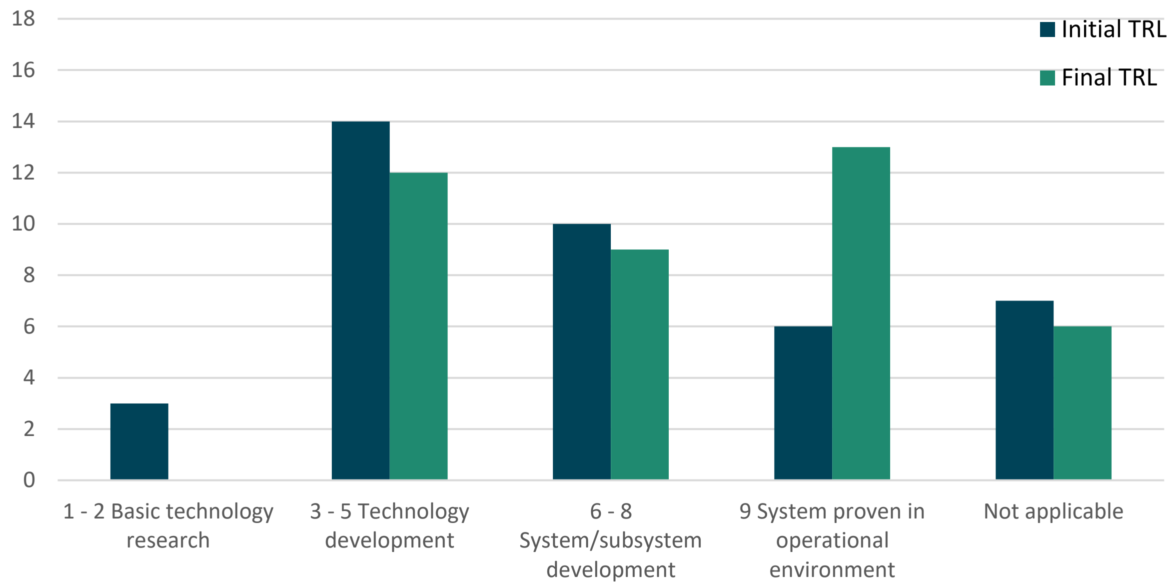


Figure 41*. Initial and final TRL of collected H2 projects.*

- **Sector of implementation.** Going more into detail of the specific role of hydrogen within individual projects (**Figure 42**), it emerged that the majority of these activities deal with the production of green or low carbon hydrogen and/or with the use of hydrogen for clean mobility (26 and 22 projects, respectively). A great interest and commitment in power/heat generation applications could also be observed, as well as in the storage of hydrogen, that can serve as support and incentive for the integration of renewable energy sources compensating for their intermittency. Very few mapped projects commit to raise social acceptance and awareness (only 2 projects) or aim at using hydrogen as feedstock for the production of e-fuels, ammonia or other energy vectors (only 3 projects).

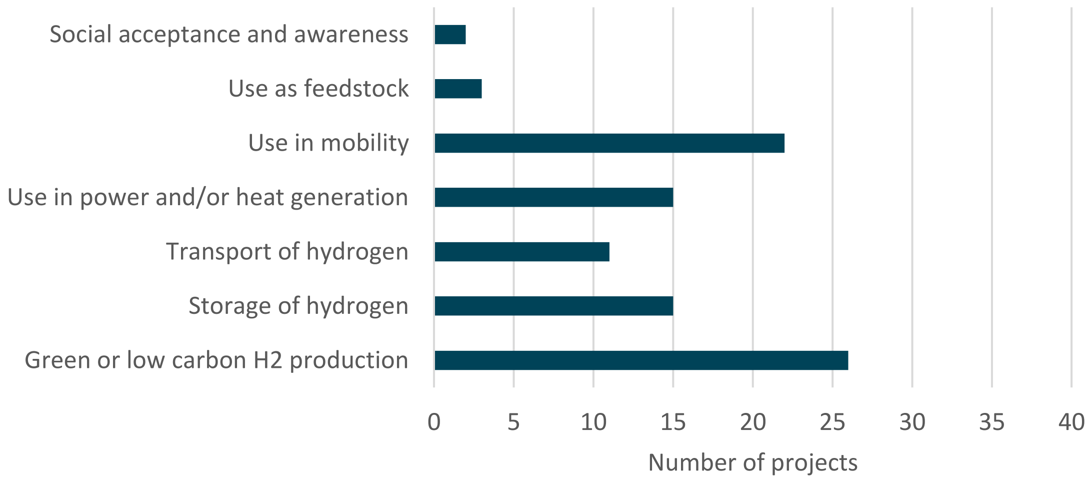


Figure 42*. Sector of implementation.*

This questionnaire helped map the state-of-the-art of implemented and planned green hydrogen solutions in the Alpine regions, with detailed information of each individual project. The mapping is, of course, not comprehensive, but provides an overview of the main focus of hydrogen projects launched in Alpine regions, including the development stage of specific applications.

4.2 Roundtables results

The roundtable discussions held within AMETHyST provided the occasion for discussing locally the opportunities offered by hydrogen and the role it could play in Alpine contexts. The debate among local institutions and operators focused on the potential applications of hydrogen and on the main obstacles that hinder the implementation of H2-based solutions in Alpine regions. Moreover, practical experiences and best practices were shared, bringing out technical, management and administrative challenges. Although each discussion focused on local needs and priorities, general keynotes can be drawn.

Auvergne-Rhône-Alpes (France)

Roundtables location: Moûtiers, France
Organizing project partners: Auvergne Rhône-Alpes Energy Environment Agency (AURA-EE); Cluster Technologies New Energies Renewable Energies Rhône-Alpes (Tenerrdis)

The Auvergne-Rhône-Alpes region has already shown a strong inclination to politically encourage the local implementation of H2 solutions, supporting, for instance, the installation of hydrogen refueling stations for private mobility. Local stakeholders participating in the roundtables are already involved in hydrogen projects and initiatives for the decarbonization of local industry and tourism, especially in the mobility sector. What emerged is an interest in the use of hydrogen especially for local mobility (e.g., shuttle buses connecting ski areas, snow groomers, private cars) and for stationary power generation (e.g., for events). Furthermore, hydrogen could significantly support the integration of renewable energy into the actual energy system (hydrogen-based storage solutions for surplus renewable energy).

As regards hydrogen mobility, its advantages over fossil fuel and electric vehicles are acknowledged, with particular attention paid to CO_2 emissions reduction, flexibility of application, and resistance to low temperatures, that could be very critical in mountain areas.

Another plus point for hydrogen is its complementarity with electricity production from renewable energy sources that can strongly support both the decarbonization of the region and the creation of self-sufficient off-grid energy systems.

One of the main barriers to the deployment of hydrogen in the territory can be the limited market and supply of vehicles, linked to high investment and operating costs (H2 is still very expensive). Safety issues are also a concern for operators, since hydrogen-related regulations are very strict and dedicated depots (e.g., for buses or snow groomers) are needed. It is noted, also, a lack of information on hydrogen-powered vehicles management, in particular as regards recharging and maintenance.

Moreover, hydrogen production may require significant use of land and water, and that could be critical in mountain remote areas.

Assessing the economic sustainability of hydrogen solutions, substantial financial support (e.g., public funding) is needed, combined with specific information on technical-economic aspects, to help territories and stakeholders define a business plan and a strategy (e.g., starting from a single small unit and upscaling to larger production/use capacities). In this regard, the AMETHyST pilot territory in the Auvergne-Rhône-Alpes region can surely help build a new ecosystem model and a new business model to serve as an input for replication in other territories. This would also support the creation of a supply and demand market, hence of an interconnected production-use network. In this framework, both institutional and industrial players are needed, because local authorities alone cannot afford a widespread implementation of H2 solutions.

Friuli Venezia Giulia (Italy)

Roundtables location: Martignacco, Udine (Italy)
Organizing project partner: Energy Management Agency of Friuli Venezia Giulia (APE FVG)

All stakeholders participating in the roundtables are involved in hydrogen-related projects, for applications both in the industrial and in the residential sectors, and have expertise in the development, design, and deployment of H2 solutions (production, storage, use). The tourism sector is not directly assessed, but the creation of a strong network and sharing of know-how can certainly help mountain territories of the region to develop their own initiatives.

In the specific context of the Zoncolan ski area, the most critical barrier to the implementation of hydrogen solutions is the high cost of green H2 and of H2 vehicles (e.g., fuel-cell snow groomers) compared to diesel ones. From a technical point of view some concerns are raised as regards the fuel cell range, that is the distance the vehicle can travel before it requires refueling, affected by driving style, terrain, slope, weather conditions, and payload. In addition, refueling time might require a redefinition of operational and management procedures, and adequate training for operators is needed, implying additional costs.

Given the high expected investment and operational costs, the current lack of incentives is perceived as an obstacle to widespread distribution of H2 applications and their upscaling. The lack of regulations for both hydrogen production and storage also makes the transition to hydrogen-powered mobility less smooth.

Clear national and regional strategies with defined milestones need to be set, supported by an effective regulatory and incentivization framework that can help the creation of a local hydrogen market and of a resilient hydrogen supply chain with multiple players at any stage (production, distribution, storage, use). Moreover, adequate financing tools should be granted to support investments in the long term.

The collection of energy data and the development of accurate models and scenarios is crucial for initiating small projects that can then lead to optimization of models to be used for upscaling and replication in other areas. Starting from the AMETHyST pilot territory in Friuli Venezia Giulia, as PromoTurismoFVG is a regional agency that manages many ski resorts in the area, the same approach to H2 implementation could be applied to other ski resorts with renewable energy production plants nearby that can guarantee green hydrogen production. Furthermore, the H2 usage could be expanded from the ski area to other local sectors, such as local public transport or local industries (e.g., forestry, mining).

Oberbayern (Germany)

Roundtables location: Landratsamt Bad Tölz
Organizing project partner: Civic Foundation Energiewende Oberland (EWO)

The AMETHyST pilot project in this territory is a self-sufficient hydrogen house, but the focus of hydrogen production in the region is currently clearly on the expansion in the mobility sector and on the integration of hydrogen into the energy sector at industrial level. The greatest potential for hydrogen is, in fact, identified in the mobility sector, and especially in heavy-duty mobility. However, there is still no clear local strategy on whether to aim for hydrogen-powered vehicles rather than battery-powered vehicles. The expansion of hydrogen use in the building sector is currently to be classified as a secondary field of interest, as well as its application in the tourism sector. Nonetheless, in Alpine areas, besides mobility, many other H2 uses should be considered, e.g., blending of hydrogen into the natural gas grid; use of H2 as energy storage medium (for storing surplus renewable energy and for balancing of peak loads); use of H2 for stationary power generation in Alpine farms or accommodation facilities; use of H2-powered ferries on Alpine lakes. No single solution can solve all problems and diversification of use in several sectors is key to a widespread deployment of H2 solutions, together with the creation of an interconnected H2 network and of a distribution infrastructure to ensure that the supply meets the demand. It is acknowledged that transition to H2 can only be slow and gradual, and in this view the simultaneous use of green H2 and natural gas, especially for the winter season, can be a temporary solution, so that an energy supply baseline is always guaranteed.

In terms of hydrogen production options, alternatives to electrolysis should also be encouraged, e.g., H2 from sewage sludge and organic residues through carbonization followed by char gasification and gas reforming. This could have great potential, especially for the agriculture sector.

The main barriers to the implementation of H2 solutions are of an economic nature. The cost of hydrogen is still very high compared to the cost of natural gas; investment costs and associated risks are also still very high (especially for storage solutions), making application particularly hard in the private mobility and residential sectors. Furthermore, the high level of maintenance needed for H2-powered vehicles and the lack of sectorial expertise, in terms of local specialized companies and skilled workers, add up to the high investment costs and slow down the launching of initiatives.

Sustainability ("green") certificates might incentivize the implementation of H2, but public funding might not be sufficient for developing a local hydrogen ecosystem. Local stakeholders also see as obstacles the long authorization procedures typically needed for new solutions, exacerbated by uncertain and complicated regulatory framework or by a lack of regulatory framework, especially at superordinate level. Support to small-medium companies, not only large companies, to municipal enterprises, or to private households should be provided, to engage territories at all levels. Sharing of knowledge and best practices among local stakeholders should be encouraged, promoting informational and educational initiatives, and providing energy consultancy services.

Social acceptance can also be an issue in certain areas, especially in the absence of existing models locally that guarantee the functioning of a system. The use of hydrogen for public mobility could, in this context, help build confidence in the sector.

Tirol (Austria)

Roundtables location: Green Energy Center, Innsbruck (Austria) and online
Organizing project partner: Standortagentur Tirol GmbH (SAT)

The AMETHyST project pilot in this region is denominated "WIVA P&G HyWest" and it involves three ongoing complementary projects: MPREIS Hydrogen, focused on hydrogen production; Hydrogen Valley Zillertal, starting with the implementation of hydrogen electric trains; and Power2X Kufstein, an innovative sector coupling (P2X) plant with a hydrogen center.

Stakeholders from mobility, logistics and food retailing clusters, as well as from R&D showed interest in supporting the transition to hydrogen, underlining that politics is the most important key for it. Presently, the political emphasis lies in ensuring the accessibility of hydrogen for the industrial sector. However, as per the insights shared during the roundtable discussions, the local energy resources may fall short in meeting the demand for hydrogen required by industries. An alternative and more viable approach could involve the local production of hydrogen for mobility purposes, while importing it to meet the industrial sector's needs. Furthermore, it is essential to highlight the synergy between batteries and hydrogen in the mobility sector, as they should ideally complement each other to achieve comprehensive solutions.

Hydrogen can support the implementation of renewable energy, dampening energy demand peaks and storing excess energy that can then be used when needed (great potential especially as short-term storage).

The major problem in mobility right now is the operating costs; the cost for H2 fuel in Austria is currently more than double the cost of diesel oil. Moreover, the lack of supply infrastructure and vehicles provision availability hinder the implementation of hydrogen solutions. These problems could be lessened by political support with incentives to industries for infrastructure, and public funding.

During discussion about the introduction of hydrogen in the pilot territory, a notable challenge that emerged was the knowledge gap. While there is a solid foundation of technical expertise, managing and executing projects in this context presented a significant unknown. Issues ranging from securing permissions and hydrogen certification to addressing delays, forming consortia, and tailoring solutions to specific circumstances all surfaced as concerns. These challenges tend to arise when embarking on the initial stages of project implementation. Another pressing concern is the financial risk involved. Project leaders have displayed remarkable courage as early adopters of this technology, but it is not realistic to expect everyone to take the same leap. Venturing into uncharted territory may entail financial losses or a delay in seeing returns on investments. Government intervention can play a pivotal role in alleviating this burden. When there is support available to mitigate some of the risks, the market becomes more enticing. This, in turn, accelerates development and fosters a competitive market environment.

The AMETHyST pilot can support the development of other projects sharing the built expertise, especially as regards permissions and requirements needed to receive certification, and the creation of a realistic timeline considering possible delays and their effects.

Trento (Italy) – Madonna di Campiglio ski area

Roundtables location: Madonna di Campiglio, Trento (Italy); Trento (Italy)
Organizing project partner: Fondazione Bruno Kessler (FBK)

Participating stakeholders are interested and/or already involved in the application of H2 solutions for the decarbonization of Alpine territories, so the potential implementation of several hydrogen applications in the ski area was discussed.

First of all, hydrogen mobility was considered. In the push to decarbonize mountain areas, H2 could play a key role as an alternative to battery-based solutions (e.g., battery electric vehicles, BEVs) that are not suitable for very cold temperature conditions. In particular, the use of H2 for fueling snow groomers seems feasible, but it is important to make a technical-economic feasibility study beforehand, to understand how many snow groomers could be introduced, with a gradual implementation, and if they could actually and efficiently substitute fossil fuel ones. Both fuel-cell snow groomers and H2 internal combustion engine snow groomers are options. The latter have lower efficiencies, but easier integration into existing snow groomers structure and more imminent market readiness; moreover, neither high voltage system nor high purity H2 is needed. In any case, some technical aspects should not be neglected: H2O emissions of hydrogen-powered vehicles might freeze under sub-zero operating conditions and clog parts of the machine; and H2 tanks occupy large volumes, that might require a non-trivial redesign of the vehicles.

Secondly, seasonal storage of renewable energy emerged as an interesting application. The use of surplus renewable energy (e.g., electricity from PV) seems to be the optimal solution for producing H2, which, on the other hand, is a great opportunity to store and supply large quantities of energy per mass unit without CO2 emissions during use. PV panels will be installed in the ski area in the next years, hence production of H2 from excess energy (in the summer) could be considered. Although it is not possible to store that much energy in summer and use it in winter (too large volumes needed), daily or weekly storage solutions could be considered.

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Other options of H2 integration in the ski area are not excluded: fuel cells for (distributed) cogeneration of heat and electricity; hydrogen boilers for buildings heating. The natural gas grid, at least initially, could be used for H2/natural gas blending, supporting a gradual deployment of H2 solutions.

The main challenges are the high investment and operational costs, which are not affordable by small municipalities of mountain areas, and the uncertain regulatory framework, as hydrogen is quite a new application and there are still some grey areas at normative level. Time-consuming and complicated permitting processes can also discourage local stakeholders. Incentivization policies and public funding are necessary to support the implementation of H2 technologies, at least for the initial implementation phase, and to encourage replicability. Moreover, the presence of a national and territorial hydrogen strategy would help create an integrated H2 infrastructure and a network of both producers and users (e.g., hotels, resorts, local transport) that can benefit from local H2 production and storage. Techno-economic feasibility studies are also needed to understand costs and efficiency of specific H2 projects.

Safety issues should also be taken into account and specific training for maintenance operators is needed as hydrogen is used, regardless of the specific application.

At a societal level, public awareness actions are crucial to inform and educate local communities, and to increase social acceptance, since population could be skeptical especially in remote areas.

Trento (Italy) – Mountain tourist municipalities in the Province of Trento

Roundtables location: online
Organizing project partner: Autonomous Province of Trento (PAT)

The stakeholders who participated in the roundtable, especially representatives of local administrations, showed great interest in technologies that can decarbonize the Alps and in the possibility of integrating hydrogen into the local energy system. The implementation of hydrogen in mountain territories could contribute significantly to the image of environmental sustainability, which could also be used effectively for the tourism sector that drives the economy of many of these Alpine territories.

Mobility is the sector that draws the greatest interest for H2 applications, in particular as regards the use of H2 vehicles (buses) for the extra-urban routes. Moreover, hydrogen is seen as an opportunity for storing surplus production of electric energy, e.g., from hydropower plants. However, the discussion was more focused on the possibility of building a new distribution infrastructure dedicated to hydrogen in non-methanized remote areas or of substituting fossil fuels with hydrogen in already existing gas grids or district heating plants.

In general, the main obstacle hindering the implementation of hydrogen locally is the investment cost, both for renewable energy infrastructure and for the production of hydrogen (electrolysis plant and related facilities). The financing, through public tenders, of capital costs could certainly accelerate the deployment of H2 also in mountain areas. To cut costs and increase the efficiency of hydrogen production systems, it remains essential to invest in research and experimentation. This applies to the materials used in electrolyzers (catalysts), which are rare and sometimes produced in non-EU countries, as well as to innovative technologies for H2 production, such as photocatalysis. Another problem is related to the available legislation on the hydrogen supply chain, which is still not sufficiently clear and complete. On the subject of safety, there are different regulations between European countries, which also lead to different costs for the plants. In addition, it is of paramount importance to create an integrated hydrogen ecosystem encompassing the whole supply chain from production to end-use and addressing the various needs of the territory.

Focusing on the pilot specific applications, the prior definition of the use of the hydrogen produced in the case of a new gas network or the conversion/integration of an existing gas network was mentioned as being of fundamental importance; this is to ensure that users are prepared for the use of the new energy carrier. This could give rise to very significant additional costs. For the case study combined with district heating, the possibility of hydrogen storage was also discussed to replace the fossil fuels currently used for covering peaks in demand. The space required to accommodate the storage system could be very large, but this is not perceived as a big issue, as district heating plants are typically located in large areas, far from sensitive users.

One very fundamental point is the need for a very detailed study on the compatibility of the existing infrastructure with the characteristics of the hydrogen vector. The sizing of the network according to the new energy vector should be carefully analyzed, also when considering the construction of a new hydrogen network.

Bolzano (Italy)

Roundtable location: Bolzano (Italy)
Organizing project partner: Energy Agency South Tyrol – CasaClima

The territory of the Province of Bolzano already has a fleet of H2 buses and ongoing projects for expanding it, so the roundtable discussion focused on the possible further hydrogen implementations in the tourism sector. All stakeholders participating in the roundtable are in some way involved in the energy transition and in hydrogen related projects, hence could provide first-hand knowledge of hydrogen applications.

Hydrogen has a big potential in the decarbonization of the local transport system and of high-duty vehicles along the Brenner corridor in the medium term. The local energy and transport strategy envisages a strong increase in fuel-cell electric buses from today to 2032, but the territory also showed interest in energy storage solutions.

In the local tourism sector, hydrogen could be used not only for public transport, but also for decarbonizing the skiing industry, e.g., snow groomers, energy storage for hotels or resorts, shuttle buses. The possibility of guaranteeing energy self-sufficiency of local activities (energy autarky) is perceived as a big advantage of hydrogen. The AMETHyST case study of Arieshof, in St. Lorenzen combines sustainability and hydrogen-based innovative energy storage to impressively show that future-proof and energy self-sufficient infrastructures are possible. Renewable energy sources are being used and the surplus will be stored in short- and long-term hydrogen storage units. When required, the storage returns the needed energy to power whatever is needed. The56veralll goal is to be at least 90% self-sufficient and therefore grid independent operation can be ensured.

Arieshof can surely serve as a best practice for replicability, but on a wider territorial scale more effort is needed for creating an interconnected hydrogen ecosystem. Significant challenges are identified in the high investment costs for infrastructure and in the creation of a supply/demand market. Furthermore, strong financial support and a well-defined policy and regulatory framework are needed to support investors and to guarantee the functioning of the whole ecosystem.

Valais (Switzerland)

Individual consultations with local stakeholders connected to Val de Bagnes municipality and Verbier ski area (Valais, Switzerland).
Organizing project partner: BlueArk Entremont

The municipality of Val de Bagnes exhibited a strong enthusiasm for and intends to activily engage in the development of a hydrogen economy in the area. The territory of Val de Bagnes could become a hydrogen hub in Switzerland, starting from the implementation of hydrogen in the Verbier ski resort, which is managed by the ski lift operator Téléverbieir SA. Local stakeholders involved in the discussion around AMETHyST's

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

case-study showed great interest in the application of hydrogen solutions in the alpine regions, especially as an alternative to electric vehicles that are being preferred in the lowland areas, with the support of the local cantonal government. Local transport companies, both public and private, are particularly interested in investing in hydrogen powered buses, trucks, and snow groomers; whereas energy companies are keen to further explore the potential benefits of hydrogen within the region and see an opportunity for launching green hydrogen production plants.

5 Final insights and conclusions

Hydrogen as an energy carrier has great potential for applications in Alpine areas at each step of the value chain, from production to end-uses. Through questionnaires and roundtables surveying local stakeholders from the Alpine Space area, it was possible to determine the role hydrogen could play in the decarbonization of these territories. Mapping the knowledge and the expertise of local stakeholders in the hydrogen sector, the needs of local territories, and the main gaps that hinder the development of a hydrogen economy in the Alps have been identified.

Tourist facilities and resorts in the Alps are large energy-consuming infrastructures, so it is important to find solutions to decarbonize this sector. Pilot case-studies presented in the roundtables have features that are common to all Alpine areas, therefore the outputs of AMETHyST pilots could be easily applied to any similar Alpine contexts. Local stakeholders, both during roundtables and through responses to the questionnaires, showed strong interest in H2 applications, and believe there is a strong potential for them, especially as they could not only support the implementation of off-grid solutions allowing for energy autarky, but also help build a sustainability reputation for touristic destinations. However, it is first necessary to share the knowledge and the expertise about hydrogen and its applications, to support each stage of the development of the hydrogen value chain. Higher education and research organizations together with SMEs and large industries are ranked highest in terms of knowledge and expertise in nearly all hydrogen technology sectors (production, transport, storage, and end-uses). Conversely, infrastructure and service public providers, along with sectoral agencies, demonstrate the highest number of low-knowledge respondents. Sharing information and best practices can raise awareness of local stakeholders and inform them of the sustainable benefits and potential of hydrogen applications.

The main point that emerged from the surveys and the discussion with stakeholders is that the greatest potential for the application of H2 solutions in the Alps is mobility, both for heavy-duty and light-duty transport. Electrification is not always an option because of the location (remote areas) and the low temperatures. In particular, battery-powered electric heavy-duty vehicles (e.g., snow groomers, snowmobiles) have difficulties working at low temperatures and with very steep terrain. On the contrary, H2-powered vehicles could be a viable solution, both with fuel cells and with H2 internal combustion engines.

Some stakeholders also mention distributing hydrogen through the existing gas infrastructure is the way to go in areas reached by the natural gas grid for distributed heat generation. The residential sector is in fact also perceived as a potential target for hydrogen implementation, but it is considered harder to address, because of the need for a dedicated infrastructure and the still very high costs of hydrogen solutions.

It was interesting to discover that there is a major interest in hydrogen storage technologies other than in hydrogen use and production. This seems to be true even if there is a generally lower knowledge of storage technologies compared to production (especially electrolysis) and use (especially LFCEV, HFCEV, and stationary power generation). Many stakeholders have underlined the importance of integrating intermittent renewable energy sources, such as photovoltaic (daily variations) and hydropower (seasonal variations), with hydrogen storage to utilize surplus energy when supply exceeds demand.

It is widely acknowledged that the presence of specific gaps and barriers hinders the development of hydrogen ecosystems. In general, one of the main barriers to overcome is the high cost of investments and the associated high investment risks. Following is the lack of a dedicated hydrogen infrastructure. This deficit is likely caused by the unfavorable economic conditions for its development and poor business cases that originate from it. Complementary to the economic issues, stakeholders believe hydrogen's potential for decarbonization is necessarily dependent on renewable energy capacity development. This aspect inevitably adds to the complexity and costs of the necessary infrastructure.

The challenging economics of hydrogen technologies can be overcome starting from legislative coordination. Stakeholders suggest a systemic approach to the integration of hydrogen technologies in the energy system, which can only be guided by a coordinated legislative system. The lack of a unified territorial strategy and of dedicated standards and regulations, as well as the complexity of current policies, do not help to effectively tackle the problem of costly and risky investments. The establishment of incentive schemes could resolve cost issues and favor commercial hydrogen projects (including infrastructure), enabling large-scale deployment of hydrogen technologies. Large-scale manufacturing and deployment will drive down costs, leveraging learn-by-doing effects as well as economies of scale mechanisms. Therefore, the expansion of hydrogen ecosystems will likely be driven initially by incentive schemes and will transition to become self-sustaining as projects become more economically feasible, finding their place in competitive business plans. Public funding and incentivization schemes are surely needed to support the transition on the one hand, but the engagement of both private and public stakeholders is necessary on the other, in order to build an interconnected supply and demand network. Local authorities alone cannot afford a widespread implementation of H2 solutions, nor can private individuals or companies.

Techno-economic feasibility studies and a model business plan can help support the implementation of hydrogen solutions, starting “small” to collect data and experience, build up models, and eventually upscale. Diversification of production and usage solutions should also be considered to create structured and resilient H2 ecosystems.

Social acceptance and safety issues are not regarded by the stakeholders as critical barriers to the development of hydrogen ecosystems. Indeed, hydrogen is mostly seen as an opportunity to increase the attractiveness of touristic destinations, by enhancing their sustainability commitment; while safety issues are easily assessed once dedicated and clear standards and regulations are defined.

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Bibliography

Abbas, A. J., Hassani, H., Burby, M., & John, I. J. (2021). An Investigation into the Volumetric Flow Rate Requirement of Hydrogen Transportation in Existing Natural Gas Pipelines and Its Safety Implications. *Gases*, *1*(4), 156–179. https://doi.org/10.3390/gases1040013

Agora Energiewende. (2021). No-regret hydrogen. Charting early steps for H_2 infrastructure in Europe. In *Agora Energiewende (White Paper)*. https://www.agora-energiewende.de/en/publications/no-regret-hydrogen/

Ajanovic, A., Glatt, A., & Haas, R. (2021). Prospects and impediments for hydrogen fuel cell buses. *Energy*, *235*, 121340. https://doi.org/10.1016/j.energy.2021.121340

Al-Khori, K., Bicer, Y., & Koç, M. (2021). Comparative techno-economic assessment of integrated PV-SOFC and PV-Battery hybrid system for natural gas processing plants. *Energy*, *222*, 119923. https://doi.org/10.1016/j.energy.2021.119923

Barthélémy, H. (2006). Compatibility of metallic materials with hydrogen - Review of the present knowledge. *16th World Hydrogen Energy Conference 2006, WHEC 2006*, *2*, 1306–1319. http://conference.ing.unipi.it/ichs2007/fileadmin/user_upload/CD/PAPERS/11SEPT/1.4.66.pdf

Bazzanella, A. M., Ausfelder, F., & DECHEMA. (2017). Low carbon energy and feedstock for the European chemical industry. *The European Chemical Industry Council*, 168. https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf

Bertuccioli, L., Chan, A., Hart, D., Lehner, F., Madden, B., & Standen, E. (2014). Study on development of water electrolysis in the European Union. In *Fuel Cells and hydrogen Joint Undertaking* (Vol. 1, Issue February). https://www.fch.europa.eu/sites/default/files/FCHJUElectrolysisStudy_FullReport (ID 199214).pdf

Blanchard, L., & Briottet, L. (2020). *Non-combustion related impact of hydrogen admixture-material compatibility* (Issue 874983). https://thyga-project.eu/wp-content/uploads/20200703-D2.4-Non-combustion-related-impact-of-hydrogen-admixture-material-compatibility.pdf

BNEF. (2020). Hydrogen Economy Outlook. In *Bloomberg New Energy Finance*. https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Böhm, H., Goers, S., & Zauner, A. (2019). Estimating future costs of power-to-gas – a component-based approach for technological learning. *International Journal of Hydrogen Energy*, *44*(59), 30789–30805. https://doi.org/10.1016/j.ijhydene.2019.09.230

Böhm, H., Zauner, A., Rosenfeld, D. C., & Tichler, R. (2020). Projecting cost development for future large-scale power-to-gas implementations by scaling effects. *Applied Energy*, *264*(February), 114780. https://doi.org/10.1016/j.apenergy.2020.114780

Brändle, G., Schönfisch, M., & Schulte, S. (2021). Estimating long-term global supply costs for low-carbon hydrogen. *Applied Energy*, *302*(July), 117481. https://doi.org/10.1016/j.apenergy.2021.117481

Caglayan, D. G., Weber, N., Heinrichs, H. U., Linßen, J., Robinius, M., Kukla, P. A., & Stolten, D. (2020). Technical potential of salt caverns for hydrogen storage in Europe. *International Journal of Hydrogen Energy*, *45*(11), 6793–6805. https://doi.org/10.1016/j.ijhydene.2019.12.161

Cavanagh, A., Yousefi, H., Wilkinson, M., & Groenenberg, R. (2022). *HyUSPRe Milestone MS4*.

Cigolotti, V., & Genovese, M. (2021). Stationary Fuel Cells: Current and future technologies-Costs, performances, and potential. In *IEA Technology Collaboration Programme: Advanced Fuel Cells*.

https://www.ieafuelcell.com/fileadmin/publications/2021/2021_AFCTCP_Stationary_Application_Performance.pdf

Cunanan, C., Tran, M. K., Lee, Y., Kwok, S., Leung, V., & Fowler, M. (2021). A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. *Clean Technologies*, *3*(2), 474–489. https://doi.org/10.3390/cleantechnol3020028

Cussons, R. (2019). *RHyMES Feasibility Study Final Report* (Issue February 2018).

DENA. (2019). *Powerfuels in Industry : Process Heat*. https://www.powerfuels.org/fileadmin/gap/Publikationen/Factsheets/190612_dena_FS_Process_Heat_web.pdf

DNV GL. (2019). *Hydrogen in the Electricity Value Chain*. https://www.dnv.com/Publications/hydrogen-in-the-electricity-value-chain-225850#

Element Energy. (2018). *Hydrogen supply chain evidence base* (Issue November). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf

Element Energy. (2019). Hy4Heat Work Package 6: Conversion of Industrial Heating Equipment to Hydrogen. In *Hy4Heat demonstrating hydrogen for heat*. https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/5e287d78dc5c561cf1609b3d/1579711903964/WP6+Industrial+Heating+Equipment.pdf

Elgowainy, A., Reddi, K., Sutherland, E., & Joseck, F. (2014). Tube-trailer consolidation strategy for reducing hydrogen refueling station costs. *International Journal of Hydrogen Energy*, *39*(35), 20197–20206. https://doi.org/10.1016/j.ijhydene.2014.10.030

ENTEC. (2022). The role of renewable / storage to scale up the EU deploment of renewable H2. In *Gastronomía ecuatoriana y turismo local.* (Vol. 1, Issue 69). https://doi.org/10.2833/727785

ETN Global. (2020). *Hydrogen gas turbines*. https://etn.global/wp-content/uploads/2020/01/ETN-Hydrogen-Gas-Turbines-report.pdf

European Parliament and Council of the European Union. (2019a). Directive (EU) 2019/1161 of the European Council and of the European Parliament of 20 June 2019, amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles. *Offical Journal of the European Union*, *2019*(June), 1–15. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L1161&from=EN

European Parliament and Council of the European Union. (2019b). REGULATION (EU) 2019/1242 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of th. *Official Journal of the European Union*, *198*(April), 202–240. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1242&qid=1665070521341

FCHJU. (2017). New Bus Refuelling for European Hydrogen Bus Depots: Guidance document on Large Scale Hydrogen Bus Refuelling. *Fuel Cell and Hydrogen Joint Undertaking*, *1*, 1–38. http://www.fch.europa.eu/sites/default/files/NewBusFuel Press Release 14102016 Final version.pdf#

Glenk, G., & Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. *Nature Energy*, *4*(3), 216–222. https://doi.org/10.1038/s41560-019-0326-1

Grosse, R., Christopher, B., Stefan, W., Geyer, R., & Robbi, S. (2017). *Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU*. https://doi.org/10.2760/24422

GRTgaz. (2019). *Technical and economic conditions for injecting hydrogen into natural gas networks* (Issue

June). http://inis.iaea.org/search/search.aspx?orig_q=RN:51004156

Guidehouse. (2021a). *Analysing future demand, supply, and transport of hydrogen* (Issue June). https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021_v3.pdf

Guidehouse. (2021b). *Picturing the value of underground gas storage to the European hydrogen system* (Issue June 2021). https://www.gie.eu/wp-content/uploads/filr/3517/Picturing the value of gas storage to the European hydrogen system_FINAL_140621.pdf

H2IT. (2019). *Piano Nazionale di Sviluppo: Mobilità Idrogeno Italia*. https://www.h2it.it/wp-content/uploads/2020/03/Piano-Nazionale_Mobilita-Idrogeno_integrale2019.pdf

Hanson, A. G., Kutchko, B., Lackey, G., Gulliver, D., Strazisar, B. R., Tinker, K. A., Haeri, F., Wright, R., Huerta, N., Baek, S., Bagwell, C., Toledo Camargo, J. de, Freeman, G., Kuang, W., Torgeson, J., White, J., Buscheck, T., Castelletto, N., & Smith, M. (2022). *Subsurface hydrogen and natural gas storage: state of knowledge and research recommendations report*. https://www.osti.gov/servlets/purl/1846632/

Holst, M., Aschbrenner, S., Smolinka, T., Voglstätter, C., & Grimm, G. (2021). *Cost Forecast for Low Temperature Electrolysis - Technology Driven Bottom-up Prognosis for PEM and Alkaline Water Electrolysis Systems*. https://www.ise.fraunhofer.de/en/press-media/press-releases/2022/towards-a-gw-industry-fraunhofer-ise-provides-a-deep-in-cost-analysis-for-water-electrolysis-systems.html

Hydrogen Europe. (2020). *Strategic Research and Innovation Agenda Final Draft October 2020 Contents* (Issue October). https://hydrogeneurope.eu/reports/

Hydrogen Tools. (2023). *International Hydrogen Fueling Stations*. https://h2tools.org/hyarc/hydrogen-data/international-hydrogen-fueling-stations

Hystories. (2022). *Assumptions and input parameters for modelling of the European energy system*. https://hystories.eu/wp-content/uploads/2022/05/Hystories_D5.4-0-Assumptions-and-input-parameters-for-modelling-of-the-European-energy-system.pdf

HyUnder. (2013). Overview on all known undergound storage technologies for hydrogen. In *HyUnder Deliverable D3.1*. http://hyunder.eu/wp-content/uploads/2016/01/D3.1_Overview-of-all-known-underground-storage-technologies.pdf

ICCT. (2022). *Fuel-cell hydrogen long-haul trucks in Europe: a total cost of ownership analysis* (Issue September). https://theicct.org/wp-content/uploads/2022/09/eu-hvs-fuels-evs-fuel-cell-hdvs-europe-sep22.pdf

IEA. (2019a). IEA G20 hydrogen report: Assumptions. In *The Future of Hydrogen*. https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf

IEA. (2019b). The Future of Hydrogen: Seizing today's opportunities. In *IEA Publications* (Issue June). https://www.iea.org/reports/the-future-of-hydrogen

IRENA. (2020). Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal. In */publications/2020/Dec/Green-hydrogen-cost-reduction*. /publications/2020/Dec/Green-hydrogen-cost-reduction%0Ahttps://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

IRENA. (2022). *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part II – Technology review of hydrogen carriers*. https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

ISPRA. (2022). *Indicatori di efficienza e decarbonizzazione del sistema energetico nazionale e del settore elettrico*. https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/indicatori-di-efficienza-e-decarbonizzazione-del-sistema-energetico-nazionale-e-del-settore-elettrico

Janssen, J. L. L. C. C., Weeda, M., Detz, R. J., & van der Zwaan, B. (2022). Country-specific cost projections for renewable hydrogen production through off-grid electricity systems. *Applied Energy*, *309*(December 2021), 118398. https://doi.org/10.1016/j.apenergy.2021.118398

JRC. (2022). Assessment of Hydrogen Delivery Options. In *European Comission*. https://doi.org/10.2760/869085

Klopčič, N., Grimmer, I., Winkler, F., Sartory, M., & Trattner, A. (2023). A review on metal hydride materials for hydrogen storage. *Journal of Energy Storage*, *72*(May). https://doi.org/10.1016/j.est.2023.108456

Knosala, K., Langenberg, L., Pflugradt, N., Stenzel, P., Kotzur, L., & Stolten, D. (2022). The role of hydrogen in German residential buildings. *Energy and Buildings*, *276*, 112480. https://doi.org/10.1016/j.enbuild.2022.112480

Kumar, H. (2022). *Hydrogen Powered Cars and Trucks : Is there a role for them in the electrified U . S . future ?* https://dspace.mit.edu/bitstream/handle/1721.1/143335/kumar-hemantk-sm-sdm-2022-thesis.pdf?sequence=1&isAllowed=y

Lord, A. S., Kobos, P. H., & Borns, D. J. (2014). Geologic storage of hydrogen: Scaling up to meet city transportation demands. *International Journal of Hydrogen Energy*, *39*(28), 15570–15582. https://doi.org/10.1016/j.ijhydene.2014.07.121

Low Carbon Innovation Coordination Group. (2014). Carbon Innovation Coordination Group Technology Innovation Needs Assessment (TINA) Offshore Wind Power Summary Report. *Innovation*, *February 2012*, 1–18.

Mukherjee, R., & Singh, S. (2021). Evaluating hydrogen rich fuel gas firing. *Petroleum Technology Quarterly*, *Q1*(Engineers India Limited (EIL)), 59–62. https://cdn.digitalrefining.com/data/articles/file/1002591-q1-eiGBP-copy.pdf

Niermann, M., Drünert, S., Kaltschmitt, M., & Bonhoff, K. (2019). Liquid organic hydrogen carriers (LOHCs)-techno-economic analysis of LOHCs in a defined process chain. *Energy and Environmental Science*, *12*(1), 290–307. https://doi.org/10.1039/c8ee02700e

Öberg, S., Odenberger, M., & Johnsson, F. (2022). Exploring the competitiveness of hydrogen-fueled gas turbines in future energy systems. *International Journal of Hydrogen Energy*, *47*(1), 624–644. https://doi.org/10.1016/j.ijhydene.2021.10.035

Oh, D. H., Lee, C. H., & Lee, J. C. (2021). Performance and Cost Analysis of Natural Gas Combined Cycle Plants with Chemical Looping Combustion. *ACS Omega*, *6*(32), 21043–21058. https://doi.org/10.1021/acsomega.1c02695

Raab, M., Maier, S., & Dietrich, R. U. (2021). Comparative techno-economic assessment of a large-scale hydrogen transport via liquid transport media. *International Journal of Hydrogen Energy*, *46*(21), 11956–11968. https://doi.org/10.1016/j.ijhydene.2020.12.213

Reddi, K., Elgowainy, A., Rustagi, N., & Gupta, E. (2018). Techno-economic analysis of conventional and advanced high-pressure tube trailer configurations for compressed hydrogen gas transportation and refueling. *International Journal of Hydrogen Energy*, *43*(9), 4428–4438. https://doi.org/10.1016/j.ijhydene.2018.01.049

Safari, S., & Ali, H. (2020). Electrochemical Modeling and Techno-Economic Analysis of Solid Oxide Fuel Cell for Residential Applications Journal of Renewable. *Journal of Renewable Energy and Environment*, *7*(1), 40–50.

Sapountzi, F. M., Gracia, J. M., Weststrate, C. J. (Kee. J., Fredriksson, H. O. A., & Niemantsverdriet, J. W. (Hans.

(2017). Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas. *Progress in Energy and Combustion Science*, *58*, 1–35. https://doi.org/10.1016/j.pecs.2016.09.001

Smolinka, T., Wiebe, N., Stechele, P., & Palzer, A. (2018). *Studie IndWEDe*. 1–201. https://www.ipa.fraunhofer.de/de/Publikationen/studien/studie-indWEDe.html

Sparber, W., Grotto, A., Zambelli, P., Vaccaro, R., & Zubaryeva, A. (2023). Evaluation of Different Scenarios to Switch the Whole Regional Bus Fleet of an Italian Alpine Region to Zero-Emission Buses. *World Electric Vehicle Journal*, *14*(4). https://doi.org/10.3390/wevj14040091

Usman, M. R. (2022). Hydrogen storage methods: Review and current status. *Renewable and Sustainable Energy Reviews*, *167*(July 2020), 112743. https://doi.org/10.1016/j.rser.2022.112743

Vartiainen, E., Breyer, C., Moser, D., Román Medina, E., Busto, C., Masson, G., Bosch, E., & Jäger-Waldau, A. (2021). True Cost of Solar Hydrogen. *Solar RRL*, 2100487. https://doi.org/10.1002/solr.202100487

Viesi, D., Crema, L., & Testi, M. (2017). The Italian hydrogen mobility scenario implementing the European directive on alternative fuels infrastructure (DAFI 2014/94/EU). *International Journal of Hydrogen Energy*, *42*(44), 27354–27373. https://doi.org/10.1016/j.ijhydene.2017.08.203

Welder, L., Ryberg, D. S., Kotzur, L., Grube, T., Robinius, M., & Stolten, D. (2018). Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. *Energy*, *158*, 1130–1149. https://doi.org/10.1016/j.energy.2018.05.059

Westport Fuel Systems. (2022). *H2 ICE truck cost of ownership vs diesel and fuel cell vehicles - MobilityNotes*. https://mobilitynotes.com/h2-ice-truck-cost-of-ownership-vs-diesel-and-fuel-cell-vehicles/

Wijk, A. Van, & Wouters, F. (2021). Hydrogen - The Bridge BEtween Africa and Europe. In *Shaping an Inclusive Energy Transition*. Springer International Publishing. https://doi.org/10.1007/978-3-030-74586-8

Wróbel, K., Wróbel, J., Tokarz, W., Lach, J., Podsadni, K., & Czerwiński, A. (2022). Hydrogen Internal Combustion Engine Vehicles: A Review. *Energies*, *15*(23), 1–13. https://doi.org/10.3390/en15238937

Yang, M., Hunger, R., Berrettoni, S., Sprecher, B., & Wang, B. (2023). A review of hydrogen storage and transport technologies. *Clean Energy*, *7*(1), 190–216. https://doi.org/10.1093/ce/zkad021

Zauner, A., Fazeni-Fraisl, K., Wolf-Zoellner, P., Veseli, A., Holzleitner, M. T., Lehner, M., Bauer, S., & Pichler, M. (2022). Multidisciplinary Assessment of a Novel Carbon Capture and Utilization Concept including Underground Sun Conversion. *Energies*, *15*(3). https://doi.org/10.3390/en15031021

Zhang, G., Zhang, J., & Xie, T. (2020). A solution to renewable hydrogen economy for fuel cell buses – A case study for Zhangjiakou in North China. *International Journal of Hydrogen Energy*, *45*(29), 14603–14613. https://doi.org/10.1016/j.ijhydene.2020.03.206

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Annex I

Questionnaire 1 – "Hydrogen in the Alps"

Interreg Alpine Space | Co-funded by the European Union | AMETHyST

AMETHyST Questionnaire - Hydrogen in the Alps

This questionnaire was prepared within the AMETHyST project. AMETHyST supports the deployment of Alpine green hydrogen ecosystems for a post-carbon future in the Alps. The main objectives are to increase the capacity of public authorities and to design support services to deploy green hydrogen solutions, mainly in touristic areas.

The questionnaire aims at investigating and determining the role of hydrogen in Alpine territories. Your answers will help us define the state-of-the-art of hydrogen solutions and understand the needs and targets for the development of Alpine hydrogen ecosystems.

You will need approximately **15 minutes** to complete the questionnaire. We thank you for your time and consideration.

For any further information on the questionnaire or the AMETHyST project you can contact Eleonora Cordioli at **ecordioli@fbk.eu**.

Privacy policy

Pursuant to art. 13 of EU Regulation No. 2016/679 (GDPR), we want to clarify that **the only personal data requested by this form is an email address** that may be processed for sending a follow-up questionnaire and updates on the results of the survey.

The email address shall be processed through manual, electronic and computerized means by people directly involved in the AMETHyST project, and it will be guaranteed within privacy and security standards.

Please note that the collection of your email address is necessary for the execution of tasks of public interest within the AMETHyST project and is managed by Fondazione Bruno Kessler as partner of the project and research institute conducting research and innovation activities of public interest with a high social and economic impact.

☐ I hereby confirm that I have read and understood the privacy policy.

Next | Clear form

Information on your organization

Your organization's name: *

Your answer

Please provide a valid e-mail address for further communications related to this questionnaire: *

Your answer

Your location, please select your country from the list. *

Choose

Organization info

Please select the type of organization. *

- ◯ Sectoral agency (tourism agency, energy agency, innovation and development cluster, ...)
- ◯ Business support organisation
- ◯ Higher education or research organisation
- ◯ Infrastructure and public service provider
- ◯ Small- or medium-sized enterprise
- ◯ Other:

What is your sector of operation? *

You may select one or more options.

- ☐ Tourism
- ☐ Energy
- ☐ Mobility
- ☐ Industry
- ☐ Other:

Is your organization involved in activities aimed at the sustainable development or energy transition of mountain areas? *

- ◯ Yes
- ◯ No
- ◯ Other:

This project is co-financed by the European Regional Development Fund through the Interreg Alpine Space program

Knowledge and potential implementation of hydrogen technologies

Question 1 of 16. How would you describe your level of knowledge of the following technologies for the use of hydrogen? *

Notes:

- *Light-duty Vehicles include cars, motorcycles, etc.*
- *Heavy-duty Vehicles include trucks, buses, trains, snow groomers, etc.*

	No knowledge	Novice	Advanced beginner	Competent	Highly knowledgeable
Light-duty Fuel Cell Electric Vehicles	○	○	○	○	○
Heavy-duty Fuel Cell Electric Vehicles	○	○	○	○	○
Hydrogen internal combustion engines	○	○	○	○	○
Stationary power generation	○	○	○	○	○
Substitute for natural gas	○	○	○	○	○
E-fuels or bio-fuels production	○	○	○	○	○

Question 2 of 16. How would you describe your level of knowledge of the following technologies for the production of hydrogen? *

	No knowledge	Novice	Advanced beginner	Competent	Highly knowledgeable
Electrolysis	○	○	○	○	○
Steam methane reforming	○	○	○	○	○
Biomass or waste pyrolysis/gasification	○	○	○	○	○

Question 3 of 16. How would you describe your level of knowledge of hydrogen storage, transport and distribution technologies? *

	No knowledge	Novice	Advanced beginner	Competent	Highly knowledgeable
Liquid hydrogen storage technologies	○	○	○	○	○
Gaseous hydrogen storage technologies (including metal hydrides storage)	○	○	○	○	○
Seasonal storage solutions for renewables integration	○	○	○	○	○
Hydrogen refuelling stations	○	○	○	○	○
Hydrogen blending into natural gas grid	○	○	○	○	○

Question 4 of 16. How would you define your level of knowledge of laws, directives or strategies related to the production or use of hydrogen? Do you know of any law, directive or strategy that involves or might involve hydrogen... *

	No knowledge	Novice	Advanced beginner	Competent	Highly knowledgeable
...at European level?	○	○	○	○	○
...at national level (in your country)?	○	○	○	○	○
...at local level (in your territory)?	○	○	○	○	○

Question 5 of 16. Do you think there is an adequate regulatory framework for hydrogen? *

E.g., technical standards in effect that support and regulate the implementation of hydrogen applications, etc.

- ◯ No, lacking framework and more effort needed
- ◯ No, lacking framework, but work is in progress
- ◯ Yes, the framework is adequate
- ◯ I don't know / can't answer
- ◯ Other: ____________

Question 6 of 16. Do you think there are adequate financing tools to support the implementation of hydrogen applications? *

E.g., incentives for hydrogen production, funding schemes for sustainable mobility, etc.

- ◯ No, lacking tools and more effort needed
- ◯ No, lacking tools, but work is in progress
- ◯ Yes, the tools are adequate
- ◯ I don't know / can't answer
- ◯ Other: ____________

Question 7 of 16. What do you think is the potential of hydrogen in your territory, with particular regard to the sustainable development of mountain areas? Do you think that a specific application of hydrogen could help to decarbonize your territory? *

E.g., surplus renewable energy could be used for hydrogen production, etc.

Your answer ____________

Question 8 of 16. What do you think is the potential of hydrogen in your territory, with particular regard to the tourism sector? Do you think that a specific application of hydrogen could help to decarbonize the tourism in your territory? *

E.g., use of hydrogen mobility could be easily implemented for public transport services, hydrogen-powered fuel-cell snowmobiles, etc.

Your answer ____________

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Question 9 of 16. What are, in your opinion, the hydrogen applications or technologies that have the highest potential to be implemented in your territory in the short term? Please select one or more options. *

- ☐ Production by electrolysis
- ☐ Production by steam methane reforming
- ☐ Production by pyrolysis/gasification of biomass or waste
- ☐ Use for light-duty Fuel Cell Electric Vehicles (cars, motorcycles, etc.)
- ☐ Use for heavy-duty Fuel Cell Electric Vehicles (trucks, buses, trains, snow groomers, etc.)
- ☐ Use in internal combustion engines
- ☐ Use for stationary power generation
- ☐ Use as substitute for natural gas and blending into natural gas grid
- ☐ Use for e-fuels or bio-fuels production
- ☐ Use for seasonal storage solutions for renewables integration

Local on-going and future actions in the hydrogen sector

Question 10 of 16. What is the level of expertise of your organization in the hydrogen sector? *

- ○ NOVICE level - no or little experience
- ○ ADVANCED BEGINNER level - little experience, very recently started being involved in activities related to H2
- ○ COMPETENT level - moderate amount of experience in hydrogen-related technologies
- ○ EXPERT level - significant amount of experience

Question 11 of 16. Is your organization involved in any of the following? *

You may select one or more options.

- ☐ Hydrogen production
- ☐ Hydrogen use
- ☐ Hydrogen transport
- ☐ Hydrogen distribution
- ☐ Hydrogen storage
- ☐ None
- ☐ Other: ____________

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

Question 12 of 16. Is your organization interested in any of the following? *

You may select one or more options.

- ☐ Hydrogen production
- ☐ Hydrogen use
- ☐ Hydrogen transport
- ☐ Hydrogen distribution
- ☐ Hydrogen storage
- ☐ Other: ____________

Question 13 of 16. Is your organization currently involved in projects and/or initiatives related to green or low-carbon hydrogen? *

- ◯ Yes, our organization is involved
- ◯ No, but our organization is aware of projects and/or initiatives
- ◯ No, our organization is neither involved nor aware of projects and/or initiatives

Question 14 of 16. What are the specific scopes and goals of these projects/initiatives? *

If appropriate, please select one or more options.

- ☐ Not applicable / can't answer
- ☐ Sustainable tourism
- ☐ Climate change
- ☐ Sustainable development of mountain areas
- ☐ Clean energy transition
- ☐ Waste and circular economy
- ☐ Industry, innovation & infrastructure
- ☐ Research and development
- ☐ Sustainable mobility
- ☐ Other: ____________

Gaps and barriers

Question 15 of 16. Below is a list of gaps and barriers that can hinder the implementation of green or low-carbon hydrogen solutions. If you think about your territory, how urgently should these gaps and barriers be addressed and solved? *

	High priority	Low priority	Not significant	Don't know
High investment costs	◯	◯	◯	◯
High investment risk	◯	◯	◯	◯
Lack of incentives	◯	◯	◯	◯
Safety issues	◯	◯	◯	◯
Lack of sectorial expertise	◯	◯	◯	◯
Low technological maturity	◯	◯	◯	◯
Lack of proven long-term reliability	◯	◯	◯	◯
Lack of dedicated infrastructure	◯	◯	◯	◯
Lack of dedicated standards and regulations	◯	◯	◯	◯
Lack of territorial strategy	◯	◯	◯	◯
Policies complexity and lack of cross-border uniformity and clarity	◯	◯	◯	◯
Social acceptance	◯	◯	◯	◯
Lack of competitiveness for technology and market development	◯	◯	◯	◯

Question 16 of 16. Some of the listed gaps and barries might be easier to solve than others. How do you perceive the difficulty of solving the following gaps and barriers? *

Difficulty is defined by the effort needed to overcome a specific gap or barrier.

	Easy	Challenging	Very challenging	Don't know
High investment costs	○	○	○	○
High investment risk	○	○	○	○
Lack of incentives	○	○	○	○
Safety issues	○	○	○	○
Lack of sectorial expertise	○	○	○	○
Low technological maturity	○	○	○	○
Lack of proven long-term reliability	○	○	○	○
Lack of dedicated infrastructure	○	○	○	○
Lack of dedicated standards and regulations	○	○	○	○
Lack of territorial strategy	○	○	○	○
Policies complexity and lack of cross-border uniformity and clarity	○	○	○	○
Social acceptance	○	○	○	○
Lack of competitiveness for technology and market development	○	○	○	○

This is a space for further comments you might have...

Your answer

Back **Submit** Clear form

Annex II

Questionnaire 2 – "Hydrogen projects and initiatives in the Alps"

Interreg Alpine Space | Co-funded by the European Union | AMETHyST

AMETHyST Questionnaire - Hydrogen projects and initiatives in the Alps

This form was prepared within the AMETHyST project. AMETHyST supports the deployment of Alpine green hydrogen ecosystems for a post-carbon future in the Alps. The main objectives are to increase the capacity of public authorities and to design support services to deploy green hydrogen solutions, mainly in touristic areas.

The following form aims at collecting information regarding activities, projects and best practices that support hydrogen implementation in Alpine areas.

By completing this questionnaire, you will have the chance to:

1. **Give visibility to your hydrogen projects and initiatives**
2. **Be kept in the loop of the AMETHyST project initiatives and findings**
3. **Actively participate in the energy transition of the Alpine areas**

Please compile the following questionnaire for a single hydrogen project or initiative (completed, ongoing or planned) you were or are directly involved in as coordinator or partner.

Projects or initiatives might include:

- a European, national or regional project dealing with the production, use or transportation of hydrogen
- a survey you created and proposed for collecting information related to hydrogen
- a policy or incentive scheme in support of hydrogen
- other

If you were or are involved in more than one project or initiative, **PLEASE SUBMIT MORE RESPONSES** to the questionnaire, by clicking the "**Submit another response**" button on the page that opens after you submit this questionnaire.

For any further information you can contact Eleonora Cordioli (Fondazione Bruno Kessler) at **ecordioli@fbk.eu**.

Privacy policy

Pursuant to art. 13 of EU Regulation No. 2016/679 (GDPR), we want to clarify that **the only personal data requested by this form is an email address** that may be processed for sending updates on the results of the survey.

The email address shall be processed through manual, electronic and computerized means by people directly involved in the AMETHyST project, and it will be guaranteed within privacy and security standards.

Please note that the collection of your email address is necessary for the execution of tasks of public interest within the AMETHyST project and is managed by Fondazione Bruno Kessler as partner of the project and research institute conducting research and innovation activities of public interest with a high social and economic impact.

☐ I hereby confirm that I have read and understood the privacy policy.

Information on your organization *

Your organization's name:

Your answer

Please provide a valid e-mail address for further communications related to this questionnaire: *

Your answer

Project or initiative title *

What is the name of the project or initiative? Please specify also the acronym, if available.

Your answer

Project or initiative start and end *

What are the start and end years of the project or initiative?

Your answer

Project or initiative website

Does the project or initiative have a reference website? Please specify the link to the website.

Your answer

Project or initiative location *

Does your project or initiative involve the application of hydrogen technologies in a specific town, city, valley, region, country? This means that they have demo sites or pilot plants, or that they support hydrogen implementation in a specific territory.

- ◯ Yes
- ◯ No

[Skip this if you replied "No" to the previous question]

Please specify the location, and if more locations are involved try to be as exhaustive as possible.

A detailed description of the location will allow us to present it on a map and promote your projects and initiatives.

Example 1: Purchase and deployment of hydrogen buses in the municipality of Bolzano, Italy.

Example 2: European project with several pilots or 'living labs' located in:

- *Madonna di Campiglio, Trentino, Italy.*
- *Les Orres, Provence-Alpes-Côte d'Azur, France*
- *Krvavec, Gorenjska, Slovenia*
- *Verbier, Valais, Switzerland*

Example 3: Incentive scheme or specific policy planning to support the implementation of hydrogen in a region (e.g., Tyrol) or in a country (e.g., Switzerland).

Your answer

Partners involved *

Who are the partners involved in the project or initiative?

Your answer

State of advancement *

Choose among the options available the appropriate status of your project or initiative.

- ◯ Programmed, but surely funded
- ◯ Initiated and in a preliminary phase
- ◯ On-going
- ◯ In conclusion, objectives still not fully achieved
- ◯ Concluded
- ◯ Other:

Source of funding *

What is the funding source of your project or initiative? You can select one or more options.

- ☐ Funded by EU
- ☐ Funded by state government
- ☐ Funded by interregional autorithies
- ☐ Funded by regional autorithies
- ☐ Funded by local authorities (at municipality level)
- ☐ Private funding
- ☐ Other:

Please specify by which program funding the project or initiative is supported

For example: Horizon Europe , Life, Recovery and Resilience Facility (PNRR in Italy), ERDF such as Interreg, etc.

Your answer

Project or initiative area of interest/topic *

- [ ] Technical
- [ ] Economical feasibility or market study
- [ ] Support to implementation of H2 applications (e.g., incentivization schemes)
- [ ] Policy development and implementation
- [ ] Social acceptance
- [ ] Other:

The project or initiative concerns hydrogen that is produced from...

- [ ] ...renewable energy sources (e.g., photovoltaic, hydropower, etc.).
- [ ] ...fossil fuels (e.g., steam methane reforming).
- [ ] ...electricity from the grid.
- [ ] I don't know.
- [ ] Other:

Project or initiative description *

Please tell us more about the project or initiative by providing:

- A short description (what is it about?)
- The main objectives (impact)
- The expected outcomes and results

Your answer

Project or initiative TRL (Technology Readiness Level) *

Please indicate the Technology Readiness Level within your project or initiative. This assessment is a European common method for assessing the maturity of a product or service and its relation to the market. More information can be found here.

	1 - 2 Basic technology research	3 - 5 Technology development	6 - 8 System/subsystem development	9 System proven in operational environment	Not applicable
Initial TRL	○	○	○	○	○
Final TRL	○	○	○	○	○

Scopes and goals *

What are the specific scopes and goals of your project or initiative?

- [ ] Sustainable tourism
- [ ] Climate change
- [ ] Sustainable development of mountain areas
- [ ] Clean energy transition
- [ ] Waste and circular economy
- [ ] Industry, innovation & infrastructure
- [ ] Research and development
- [ ] Sustainable mobility
- [ ] Other: ______

Does the project or initiative involve tourism? *

Choose one of the following statements and **briefly** complete it:

A. The project is meant to have a direct impact on tourism, with relevant results, for example...

B. The project could be integrated or applied to the tourism sector, because...

C. The project is totally unrelated to the tourism sector.

Your answer ______

Project or initiative sectors of implementation *

Does the project or initiative support the production, storage, transport and/or use of hydrogen?

- [ ] Green or low carbon hydrogen production
- [ ] Storage of hydrogen
- [ ] Transport of hydrogen
- [ ] Use in power and/or heat generation
- [ ] Use in mobility
- [ ] Use as feedstock (e.g., ammonia/biofuel/e-fuel production)
- [ ] Other: ______

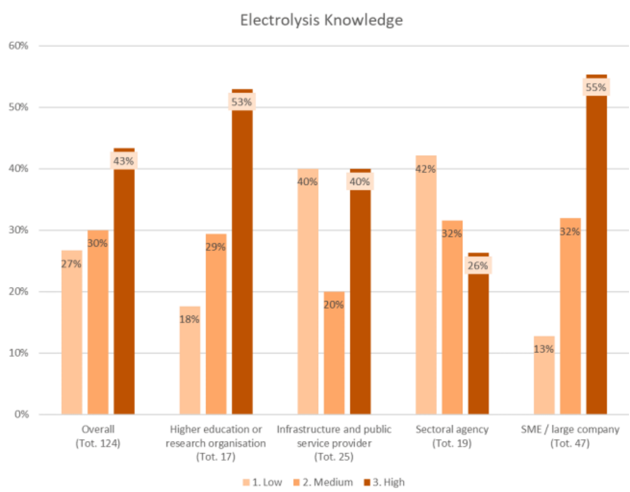
Submit | Page 1 of 1 | Clear form

Annex III

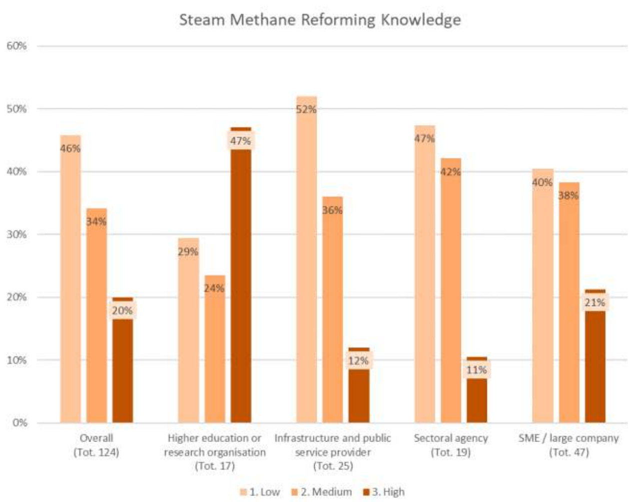
Knowledge of hydrogen technologies by stakeholder typology

This section reports a detailed analysis of the responses received to Questionnaire 1 – "Hydrogen in the Alps" related to the stakeholders knowledge of specific H2 technologies throughout the value chain (production, uses, storage and distribution). For each technology, responses were analyzed by stakeholder category. Please note that three stakeholders categories are missing from the following analysis. These are "Business support organization", "Local or regional public authorities", and "Other" (which encompasses public healthcare providers, investors, and project developers). The reason for this decision lies in the low number of respondents in each category: 6, 6, and 4, respectively. It therefore seems not correct to draw general conclusions as is done for the other categories on observable trends. Keeping in mind that other categories have 47 (SME/large company), 25 (infrastructure and public service provider), 19 (sectoral agency), 17 (higher education or research organization) respondents respectively.

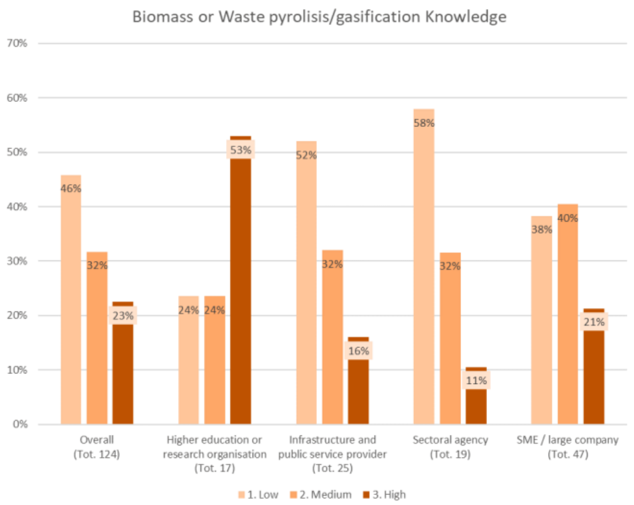
Hydrogen production:
Higher education or research organization and SME/large companies groups both demonstrate to be highly knowledgeable in electrolysis, **Figure 43 (a)**. These two stakeholder typologies share a similar characteristic in that they both present a large proportion of highly knowledgeable organizations, and a small proportion of low knowledge level. For steam methane reforming (**Figure 43 (b)**) and biomass or waste pyrolysis/gasification (**Figure 43 (c)**), higher education or research organizations are the most knowledgeable type group. This group is the only one with distributions unbalanced towards the highest level of knowledge (for both technologies). Infrastructure and public service provider and sectoral agencies type groups are less knowledgeable in all the three technologies. Compared to the overall distribution, their level of knowledge distribution is unbalanced towards the lowest level.



(a)



(b)

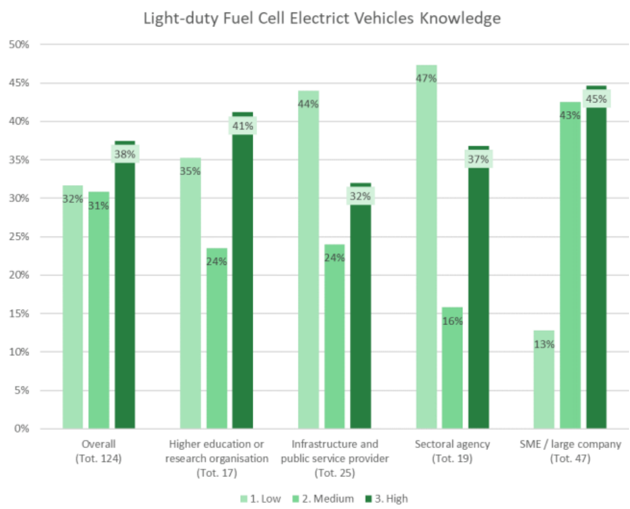


(c)

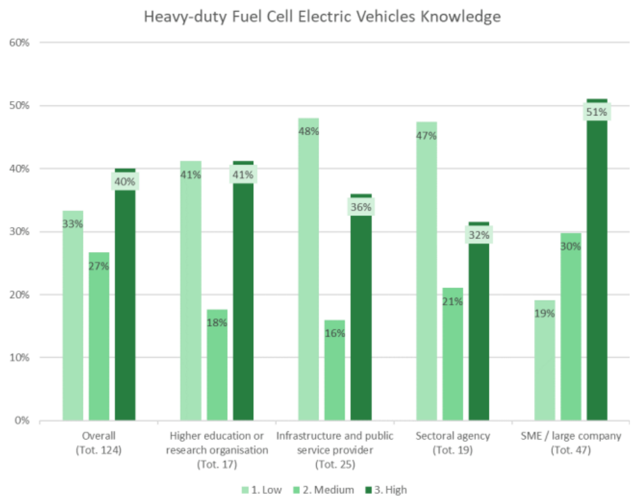
***Figure 43**. Level of knowledge in hydrogen production technologies as a function of respondent organization typology. "Overall" refers to the general distribution of knowledge among all respondent typology, as reported in **Figure 24**.*

Hydrogen uses:

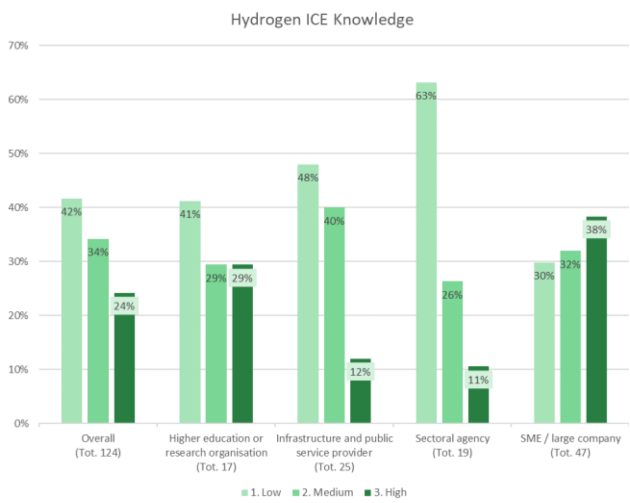
As shown in the graphs in **Figure 44**, SME/large company seems to be the most knowledgeable type group in light- and heavy-duty fuel cell electric vehicles (**Figure 44 (a)**, **Figure 44 (b)**) and ICE technologies (**Figure 44 (c)**). Higher education or research organizations follow, demonstrating a higher percentage of "high" knowledge with respect to other organizations in all the three technologies. Higher education or research organization seems to be the most knowledgeable type group in stationary power generation (**Figure 44 (d)**), substitution of natural gas(**Figure 44 (e)**) and e-fuels and bio-fuels production technologies (**Figure 44 (f)**), probably due to these hydrogen solutions' innovative nature. SME/large companies follow, with a higher-than-the-overall highest level of knowledge organizations proportion in all the three technologies. Infrastructure and public service provider and sectoral agencies type appear to be less knowledgeable in all the six technologies. As can be seen in the six graphs, their level of knowledge distribution is always unbalanced towards the lowest level compared to the overall distribution.



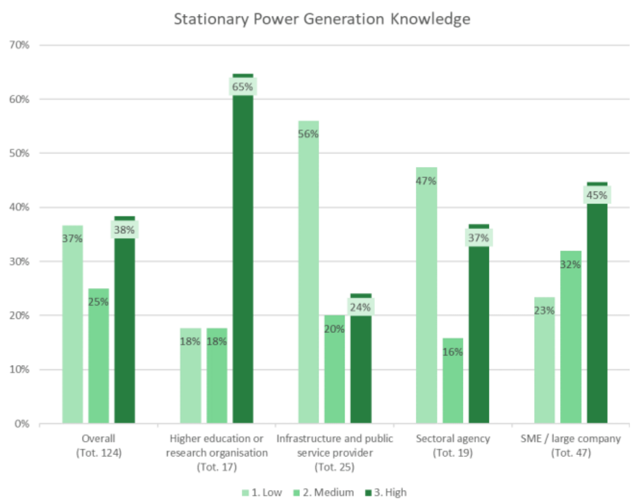
(a)



(b)

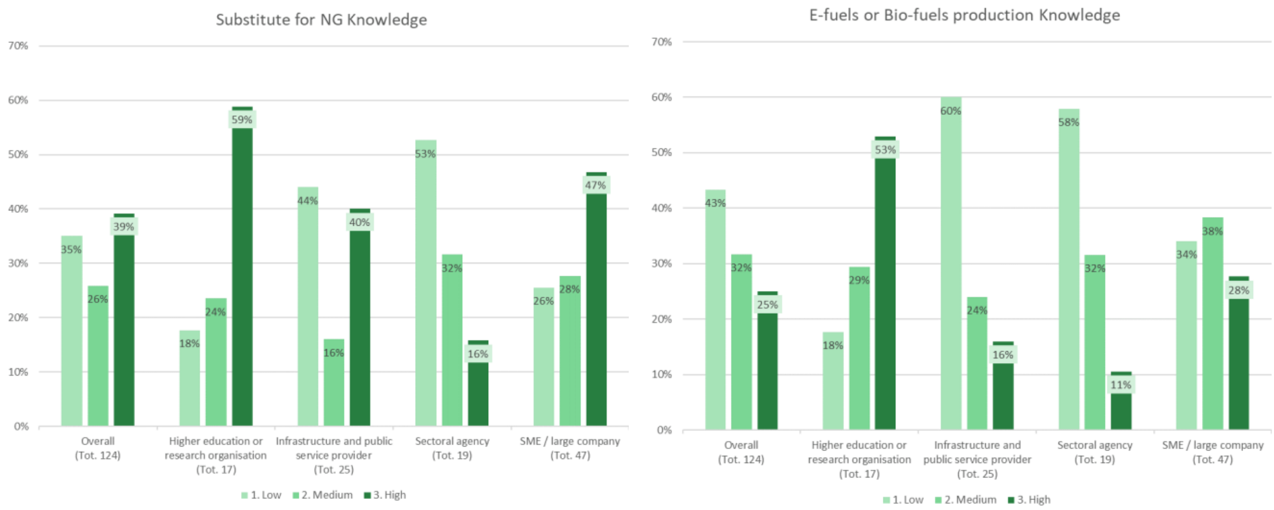


(c)



(d)

This project is co-financed by the European Regional Development Fund
through the Interreg Alpine Space program

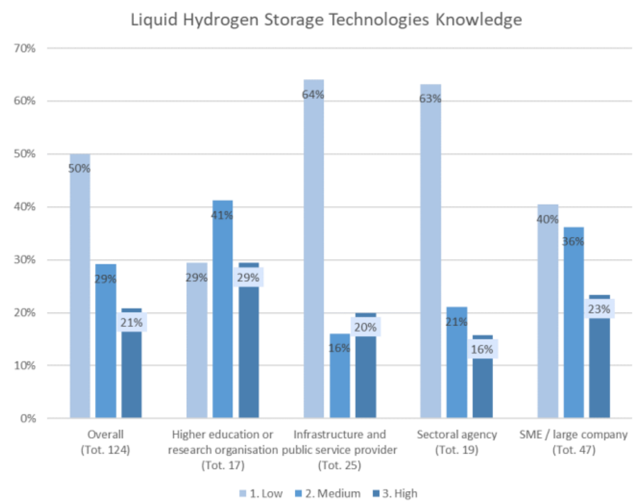


(e) (f)

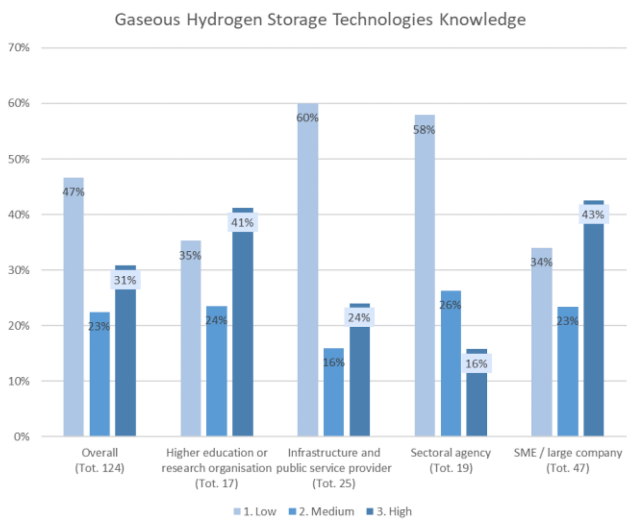
***Figure 44**. Level of knowledge in hydrogen use technologies as a function of respondent organization typology. "Overall" refers to the general distribution of knowledge among all respondent typology, as reported in **Figure 23**.*

.

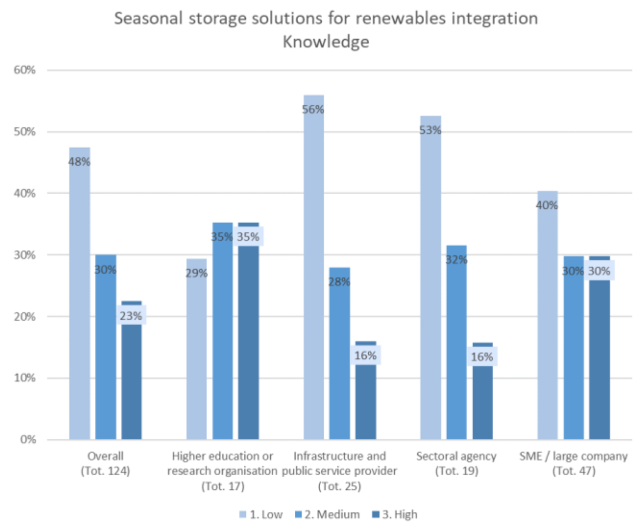
Hydrogen storage and distribution:
Differently by the other technology categories, none of the organization type groups have a large proportion of highly knowledgeable organizations in storage and distribution technologies. However, higher education or research organization group seems to be the most knowledgeable in liquid hydrogen storage technologies (**Figure 45 (a)**), seasonal storage solutions for renewable integration (**Figure 45 (c)**) and hydrogen blending into natural gas grid (**Figure 45 (e)**). On the other hand, SME/large company group have a "better" distribution for hydrogen refueling stations knowledge (**Figure 45 (d)**). The two type groups share a similar distribution between the knowledge level for gaseous hydrogen storage technologies (**Figure 45 (b)**) (unbalanced towards the highest level compared to the overall distribution). Infrastructure and public service provider and sectoral agencies type groups are less knowledgeable in all the technologies. As you can see in the graphs, compared to the overall distribution, their level of knowledge distribution is unbalanced towards the lowest level.



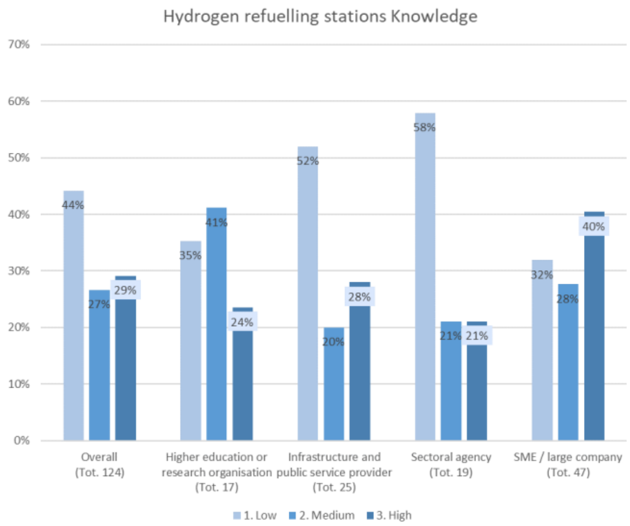
(a)



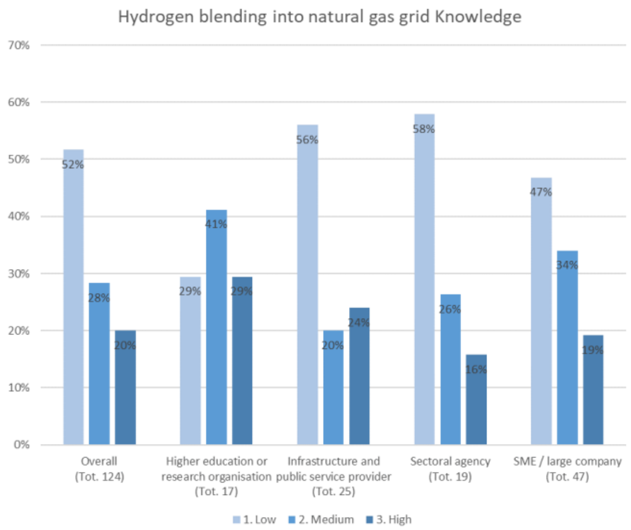
(b)



(c)



(d)



(e)

***Figure 45**. Level of knowledge in hydrogen storage and distribution technologies as a function of respondent organization typology. "Overall" refers to the general distribution of knowledge among all respondent typology, as reported in **Figure 25**.*

.