

Research Paper

Green hydrogen in the Alps: Mapping local stakeholders perspectives and identifying opportunities for decarbonization

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ABSTRACT

The effects of climate change and reliance on fossil fuels in the Alps highlight the need for energy sufficiency, improved efficiency, and renewable energy deployment to support decarbonization goals. Hydrogen has gained attention as a versatile, zero-emission energy carrier with the potential to drive cleaner energy solutions and sustainable tourism in Alpine regions. This study shares findings from a hydrogen survey conducted within the Interreg Alpine Space AMETHyST project, which included questionnaires and roundtable discussions across Alpine territories. The survey explored hydrogen's role in decarbonizing the Alps, gathering insights from local stakeholders about their knowledge, expertise, needs, and targets for hydrogen solutions. It also mapped existing hydrogen initiatives. Results revealed strong interest in hydrogen implementation, with many territories eager to launch projects. However, high investment and operational costs, along with associated risks, are key barriers. The absence of clear local hydrogen strategies and of a comprehensive regulatory framework also poses significant challenges. Incentivization schemes could facilitate initiatives and foster local hydrogen economies. The most promising application areas for hydrogen in the Alps are private and public mobility sectors. The residential sector, particularly in tourist accommodations, also presents potential. Regardless of specific uses, developing renewable energy capacity and infrastructure is essential to create green hydrogen ecosystems that can store excess renewable energy from intermittent sources for later use.

1. Introduction

Since the 1998 Kyoto Protocol, which identified global warming as a human-made risk (Breidenich et al., 1998), global actions have been aimed at contrasting climate change. The Paris Agreement, negotiated at the United Nations Climate Change Conference in 2015 (United Nations Environment Programme, 2015), reinforced this commitment, setting a goal to keep the global temperature increase below 2 K above pre-industrial levels, aspiring to keep it within 1.5 K. Emissions contributing to climate change are associated mainly with sectors such as industry, power production, and transport. However, emissions attributable to tourism can reach 8 % of total emissions (Lenzen et al., 2018) and their effect on climate change could be detrimental for the tourism sector itself. Winter mountain tourism in particular is at stake under the current trajectories of global warming, because it heavily relies on natural resources and attractions that are extremely vulnerable to shifts in climate conditions (Hudson, Simon, 1996; Steiger et al., 2022; Hock et al., 2019). This aspect should motivate local stakeholders in mountainous regions to enhance energy self-sufficiency and efficiency

measures, promote the adoption of renewables, and advance the decarbonization of these areas, all while supported by adequate policies. Studies have been carried out with the intent of assessing smart integration of energy efficiency measures and renewable energy capacity within ski resorts and mountainous regions energy systems, trying to identify the issues hindering the development of renewable energy production technologies, storage technologies, and to the identification of energy demand, and which specific technologies are appropriate for this sector (Viesi et al., 2023; Polderman et al., 2021; Polderman et al., 2020; Farrell, 2019; Papada and Kaliampakos, 2015; Hočevar et al., 2019). The findings of such studies show how such intervention strategies can positively affect the environmental sustainability of resorts and, more generally, mountain destinations. However, challenges remain due to the governance structure of resorts and the absence of specific national and regional policies to support this energy transition. Additionally, resorts often face financial and technical difficulties in developing and executing low-carbon energy strategies. Financial, land and community barriers are, in fact, the most limiting factors to the integration of renewable energy systems in mountain regions.

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In recent years, hydrogen has emerged as a versatile, zero-emission energy carrier that can support the transition to cleaner and more sustainable energy solutions (Kovač et al., 2021; Trattner et al., 2022) that are also fostering environmental sustainability of tourism-prone destinations that rely on natural resources (Matera et al., 2009), such as the Alpine regions. Moreover, the utilization of hydrogen as an energy vector can improve energy security, preserve natural sources, and promote sustainable economic growth (Dincer and Aydin, 2023). Similarly to what has been witnessed with the now established sustainable energy generation technologies, hydrogen solutions development must also be guided by adequate policy frameworks, such as incentive schemes (Nastasi and Mazzoni, 2023; Henry et al., 2023), which in return will kindle economies of scale effects to positively impact on the currently disadvantaged economics of hydrogen projects (Bhandari and Shah, 2021; Ajanovic et al., 2021; Ajanovic and Haas, 2021). Complementarily, a careful planning and design of systems is of paramount importance to ensure optimal operation and minimum costs (Petrollese et al., 2022). A further aspect to be considered when introducing novel technologies such as hydrogen solutions is their social acceptance. Through stakeholder interviews Schönauer and Glanz (Schönauer and Glanz, 2022) investigated the social acceptance of energy transition. While it is accepted that the transition is positive, acceptance of the means to obtain the transition is not uniform throughout society. The role of hydrogen within the transition sparks contradictory opinions among stakeholders. Major concerns regard security of supply and economic feasibility and a diffuse NIMBY (Not In My Backyard) sentiment towards the necessary infrastructure (Schönauer and Glanz, 2022). The primary focus should therefore be on addressing legislative issues, securing appropriate markets, readying industry, society and economies for the expansion of hydrogen-based systems, and fostering global interconnectivity and cooperation (Kovač et al., 2021).

The Interreg Alpine Space AMETHyST project ('AMETHyST - A MultipurposE and Tran Sectorial HYdrogen Support for Decarbonized Alpine Territories', 2022) focuses on the possibility of implementing green hydrogen applications in touristic mountain areas and on supporting the launch of local green hydrogen ecosystems, providing tools for assessing and actualizing the deployment of hydrogen in the Alps. This study presents the results of a survey that was carried out through questionnaires and local roundtable discussions across the Alpine territories aimed at identifying the role that green hydrogen can take on in the decarbonization of these regions, identifying key needs and mapping existing hydrogen initiatives in the Alpine regions. The creation of local energy communities integrating hydrogen applications can, in fact, enable collective actions for supporting the clean energy transition and contribute to increasing public acceptance of renewable energy and hydrogen projects, encouraging also private investments in the decarbonization process of the Alps. Similar survey- and interview-based studies have been conducted to evaluate public perception and social acceptance of renewable (Vuichard et al., 2021; Spiess et al., 2015; Grilli et al., 2016; Michel et al., 2015) and sustainable solutions (Casasso et al., 2017; Scuttari et al., 2016) as well as other operations tied to mountain tourism (Pütz et al., 2011).

The survey revealed a strong interest in implementing hydrogen, with most of the surveyed Alpine territories eager to initiate new hydrogen projects. The main obstacle to advancing hydrogen initiatives is the high investment and operational costs, along with the associated risks. Additionally, the lack of defined local hydrogen strategies and a comprehensive regulatory framework is seen as a critical challenge to address in fostering the development of an integrated hydrogen supply and demand network. The promotion of a multi-level approach (local, national, and cross-border) can support an efficient roll-out of hydrogen applications. Introducing targeted incentive schemes could further support the launch of initiatives and the establishment of a local hydrogen economy. Regardless of the application, expanding renewable energy capacity and infrastructure is also essential for building green hydrogen ecosystems. Such ecosystems can efficiently store surplus

energy produced by intermittent renewable sources for future use.

This paper provides an overview of the role that green hydrogen could play in the sustainable development of Alpine territories and in supporting the decarbonization of mountain tourism destinations. Given the peculiarities of these territories, it is crucial to open a discussion with local players and understand what is the state-of-the-art as well as the main obstacles to reach the decarbonization targets and build resilient Alpine ecosystems. Only by building this benchmark it is possible to develop a unified strategy shared among Alpine territories and create local and sustainable hydrogen ecosystems.

2. Methodological approach

To determine the primary needs and objectives for deploying hydrogen solutions in the Alpine regions, a preliminary stakeholder mapping was conducted. This process categorized relevant actors across all sectors of the triple-helix: academia, industry, and government. The study engaged potential customers, end-users, businesses (such as manufacturers, service providers, and consultants), and policymakers involved in or potentially interested in various hydrogen sectors, namely production, use, storage, transport, and distribution. Additionally, sectoral agencies (e.g., tourism and energy agencies, innovation and development clusters), business support organizations, higher education and research institutions, infrastructure and public service providers, and enterprises were identified. These stakeholders were invited to complete a structured questionnaire on hydrogen, and, in selected cases, to participate in local roundtable discussions held in selected Alpine territories that were chosen as case studies for implementing green hydrogen solutions in the assessed regions. Survey- and interview-based data collection was guided by the principle that local stakeholder involvement is critical for shaping sustainable pathways in mountainous regions (Svadlenak-Gomez et al., 2014). The questionnaire and roundtable discussions aimed to gather insights into the current state, challenges, and opportunities for hydrogen deployment in the Alpine region. Participants provided information on existing hydrogen initiatives, barriers to adoption, potential use cases, and the role of various stakeholders. The collected data was then analyzed to extract common themes and, challenges, and opportunities, thereby contributing to a comprehensive understanding of the regional hydrogen landscape.

2.1. Questionnaire on hydrogen in the Alps

The *Hydrogen in the Alps* questionnaire was developed to gather insights into the relationship between local stakeholders and the hydrogen economy. The objective is to provide a structured way to collect diverse viewpoints from stakeholders across various sectors and regions, helping to create a more inclusive and representative framework for decision-making. Stakeholders were invited to participate via email, with the email template translated into their local languages by AMETHyST project partners to encourage participation. However, the questions were kept in English to streamline data collection and processing. Hundreds of invitations were sent out to direct contacts and other potentially interested stakeholders to maximize response rates and engage stakeholders from various Alpine Space regions and all triple-helix sectors.

The questionnaire included both multiple-choice and open-text questions, structured as follows:

1. Respondent affiliation and location;
2. Respondent categorization, that is sector of operation;
3. Respondent's self-assessment on knowledge of hydrogen, collecting information about their knowledge of hydrogen solutions, in particular regarding technical, regulatory, and financial aspects;
4. Opinions and comments of the respondent on the potential role of the hydrogen economy in the sustainable development of mountain areas;

5. Expertise and interest in hydrogen initiatives, for identifying stakeholders who play a role in hydrogen initiatives and are keen to support the implementation of hydrogen solutions;
6. Respondent's opinions on the gaps and barriers that impede the deployment of hydrogen.

In assessing the stakeholders' knowledge of hydrogen applications, the entire hydrogen supply chain has been considered. Specific technologies for hydrogen production, use, storage, transport, and distribution were included in the questions, thus stressing the importance of assuming a holistic approach and not focusing on a single step of the process (Yue et al., 2021; Kindra et al., 2023). The most common and advanced hydrogen technologies have been considered, from the production of hydrogen through electrolysis (Kumar and Himabindu, 2019; Brauns and Turek, 2020; Ursua et al., 2012; Chi and Yu, 2018) or pyrolysis/gasification (Cao et al., 2020), to the use of hydrogen for light-duty and heavy-duty vehicles (Grube et al., 2021; He et al., 2021; Chen and Melaina, 2019; Basma and Yuanrong Zhou, n.d.; (Cunanan et al., 2021; Coleman et al., 2020), stationary power generation (Cigolotti et al., 2021), as a substitute for natural gas, and fuels production (Yue et al., 2021). Attention has been paid to the entire supply chain, including hydrogen storage, transport, and distribution technologies (e.g., liquid and gaseous hydrogen storage solutions (Makridis and Sofoklis, 2016), seasonal storage solutions for renewable energy surplus (Mehrerjerd et al., 2019), hydrogen refuelling stations (Mayer et al., 2019), hydrogen blending into the natural gas grid (Quarton and Sam-sati, 2018).

The questionnaire results were analysed and grouped by stakeholder category and other key parameters, to get useful insights into the potential role of hydrogen in Alpine territories.

2.2. Roundtable discussions

Roundtable discussions were held to facilitate knowledge sharing among stakeholders and better understand the needs of local territories and authorities. These discussions play a crucial role in fostering multi-disciplinary collaboration, knowledge exchange, and problem-solving among diverse stakeholders. A total of 14 meetings were organized, either online or in person, across pilot regions that were selected as case study Alpine areas for the potential development of hydrogen-based ecosystems. These areas included Auvergne-Rhône-Alpes in France, Friuli Venezia Giulia, Trentino, and South Tyrol in Italy, Oberbayern in Germany, Tyrol in Austria, and Valais in Switzerland. The roundtables gathered local stakeholders from various sectors, such as local authorities, companies, sectoral agencies, research institutions, infrastructure and public service providers, and business support organizations, inviting them to share their insights, experiences, and expertise. Two main discussion topics were encouraged:

1. Identifying gaps and barriers in the implementation of green hydrogen solutions in the Alps and exploring potential solutions to address them;
2. Sharing experiences and best practices for applying hydrogen in Alpine environments.

These discussions help identify barriers to implementation, such as regulatory hurdles, funding challenges, or technological limitations, creating a platform for stakeholders to collaboratively explore possible solutions, helping to overcome obstacles, and informing policy-making and strategic planning. Each region has its unique characteristics, yet Alpine areas all share common features, such as geographical conditions, climate, and energy infrastructure, that allow for the drawing of general conclusions. Consequently, the roundtables identified potential hydrogen applications and key obstacles to address, while also discussing how these regions could serve as models for the implementation of hydrogen-based solutions in other similar areas.

3. Results

3.1. Questionnaire results

The *Hydrogen in the Alps* survey gathers insights from Alpine stakeholders on the opportunities and the challenges associated with hydrogen solutions in the Alpine regions. The information collected included the location and sector of operation of the responding stakeholders to allow for their identification and categorization, as well as their background knowledge of/expertise on hydrogen solutions. By combining this profiling information with stakeholders' responses on opportunities and barriers, the survey facilitates the derivation of more informed conclusions, enhancing decision-making processes and serving as baseline for monitoring progress and assessing the effectiveness of future implemented strategies.

The questionnaire received responses from 124 participants representing 118 distinct stakeholder organizations distributed across the Alpine Space countries and subregions as illustrated in Fig. 1, and across the triple-helix sectors, as depicted in Table 1. The survey also explored stakeholders' roles in the energy transition process, revealing that 81 % of respondents actively contribute to this transition. To further characterize stakeholders, a multi-select question allowed participants to indicate their involvement in various sectors. The most represented sectors were Energy (68 respondents) and Mobility (45 respondents), followed by Industry (32 respondents), Tourism (19 respondents), and Environment (3 respondents). Certain trends were observed within stakeholder categories. For example, higher education institutions predominantly operate within the energy sector, while infrastructure/public service providers and SMEs/large companies are mainly involved in energy and mobility. Sectoral agencies showed additional involvement in tourism, alongside energy and mobility. For other stakeholder categories, the sample size was insufficient to draw definitive conclusions. Overall, the survey achieved a well-balanced representation of stakeholder types and areas of interest, supporting a comprehensive analysis of hydrogen's role in the region.

The perspective of stakeholders on the potential implementation of hydrogen technologies in their regions is also assessed. Certain hydrogen applications could be perceived as easier or more practical to implement, depending on a variety of contextual factors, including the availability of energy sources, the presence of suitable infrastructure, local regulatory frameworks, and regional socio-economic conditions. For instance, regions with abundant renewable energy resources, such as hydropower, wind, or solar energy, may find it more feasible to produce green hydrogen via electrolysis. Infrastructure plays a pivotal role as well. Regions with well-developed transportation networks or pre-existing natural gas pipelines may perceive hydrogen as easier to integrate into existing systems, blending it with natural gas. Conversely, remote areas lacking this infrastructure might consider these applications more challenging. Lastly, stakeholders' perceptions are influenced by the maturity and scalability of specific hydrogen applications. For example, applications like hydrogen fuel cell buses, trucks, or trains may be considered more straightforward to implement, especially in regions with high mobility demands and fleet operation systems. The respondents were presented with multiple-choice options, listed in Table 2, and could select more than one response. Table 2 illustrates the frequency of stakeholder preferences across Alpine Space countries. The data highlights a strong consensus on the potential of hydrogen production via electrolysis and the use of hydrogen for heavy-duty fuel-cell electric vehicles (FCEVs). This reflects stakeholders' recognition of green hydrogen's role in decarbonized energy systems and the limited appeal of grey hydrogen from steam methane reforming, which relies on fossil fuels. Additionally, the survey indicates significant potential for hydrogen-powered applications such as fuel-cell buses, trucks, trains, and even snow groomers. Across regions, stakeholders identified the mobility sector as holding the greatest potential for hydrogen applications.

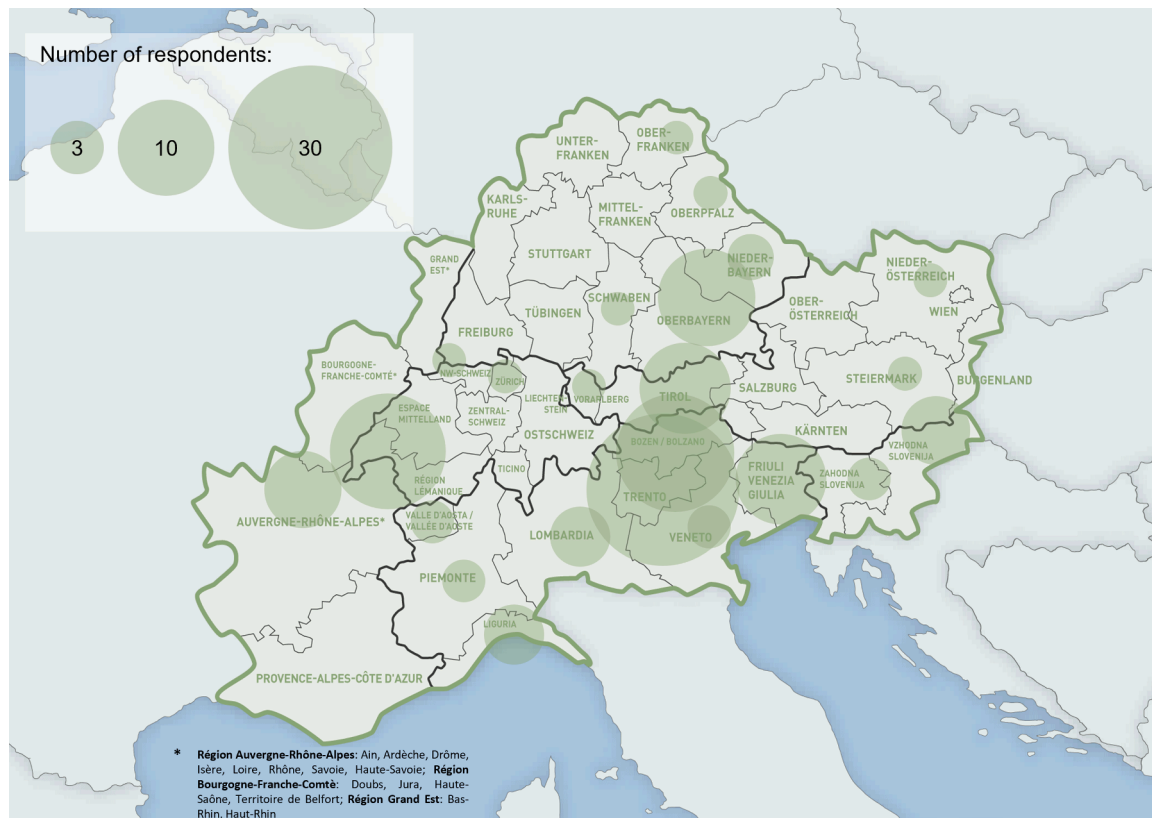


Fig. 1. Stakeholders mapping. Geographical distribution in the Alpine Space regions of stakeholders responding to the questionnaire “Hydrogen in the Alps”.

Table 1
Stakeholders participation in *Hydrogen in the Alps* questionnaire, divided by triple-helix sectors (academia, industry, government).

Triple-helix sectors	Stakeholder category	Representativeness in the survey	Specific sectors involvement
Academia	Higher education or research organisation	14 %	Energy, Mobility, Industry
Industry	SME / large company	38 %	Energy, Tourism, Mobility, Industry
	Business support organisation	5 %	
	Other (projects developer, investor)	2 %	
Government	Infrastructure and public service provider	20 %	Energy, Environment, Tourism, Mobility, Industry
	Sectoral agency	15 %	
	Local or regional public authority	5 %	
	Other (public healthcare provider, political institution)	2 %	

The survey also explored stakeholders’ interest in the hydrogen sector, identifying the specific stages of the hydrogen value chain, where they could potentially contribute. Although many stakeholders have currently limited experience with hydrogen technologies, they expressed strong interest in its applications and potential for decarbonizing Alpine environments. A radar graph in Fig. 2 visualizes the distribution of stakeholder interest across various sectors, with percentages representing the frequency of each sector being identified as an area of interest by stakeholders.

Table 2
Local stakeholders’ perception of hydrogen applications and technologies with the highest potential to be implemented in the short-term in Alpine regions. Numbers indicate the number of times that a specific application/technology is mentioned by interviewed stakeholders.

Hydrogen applications and technologies	Frequency of stakeholder preferences
Production of hydrogen by electrolysis	93
Production of hydrogen by pyrolysis/gasification of biomass or waste	41
Use of hydrogen for heavy-duty FCEVs	84
Use of hydrogen for light-duty FCEVs	33
Use of hydrogen for seasonal storage solutions	50
Use of hydrogen as substitute for natural gas	31
Use of hydrogen in internal combustion engines	24
Production of hydrogen by steam methane reforming	11
Use of hydrogen for stationary power generation	35
Use of hydrogen for e-fuels	22

Stakeholders showed significant interest in hydrogen use, production, and storage, highlighting their relevance in decarbonization pathways for Alpine regions. While hydrogen use and production are established focal areas, the growing interest in hydrogen storage is particularly noteworthy. This trend may reflect an increasing awareness of hydrogen’s role as seasonal storage for surplus renewable electricity, a critical component for achieving energy stability and self-sufficiency, especially in Alpine regions. The interest in hydrogen storage and use was evenly distributed among stakeholders, while higher education and research institutions leaned towards production, and public authorities and infrastructure providers prioritized hydrogen transport. This alignment reflects their expected operational roles, with authorities likely overseeing regulated transport frameworks. Interestingly, hydrogen transport and distribution garnered the least interest despite

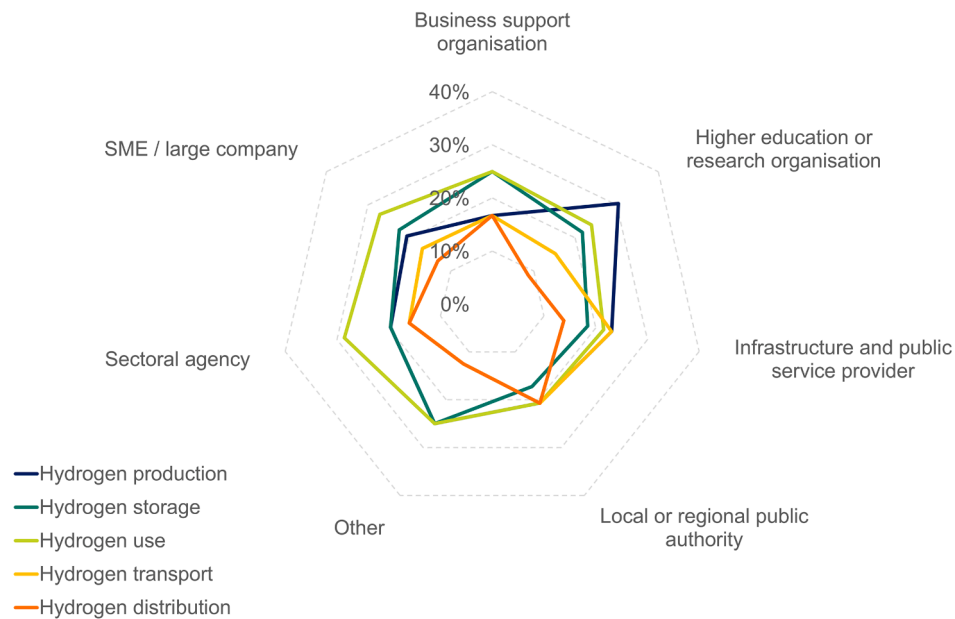


Fig. 2. Stakeholder typology and areas within the hydrogen sector for which interest was expressed. Percentages represent the frequency with which a specific sector was mentioned by each stakeholder typology as their area of interest. The “Other” category encompasses public healthcare providers, investors, and project developers.

their vital role in enabling ecosystem functionality by linking supply and demand. These activities, which include tube trailers for compressed gas transport, refueling stations for mobility, and hydrogen injection into gas grids, remain foundational for achieving a connected and efficient hydrogen network.

These results reflect the perception and interest of local stakeholders towards the potential application of hydrogen technologies in the Alpine

regions. Although this does not translate into actual feasibility of the proposed solutions, it provides valuable insight into regional priorities, perceived benefits, and potential barriers that could influence policy direction and investment strategies. The alignment of stakeholders’ perceptions with broader decarbonization objectives suggests the willingness to explore and adopt green hydrogen technologies. Nevertheless, implementation will necessarily depend on technological readiness,

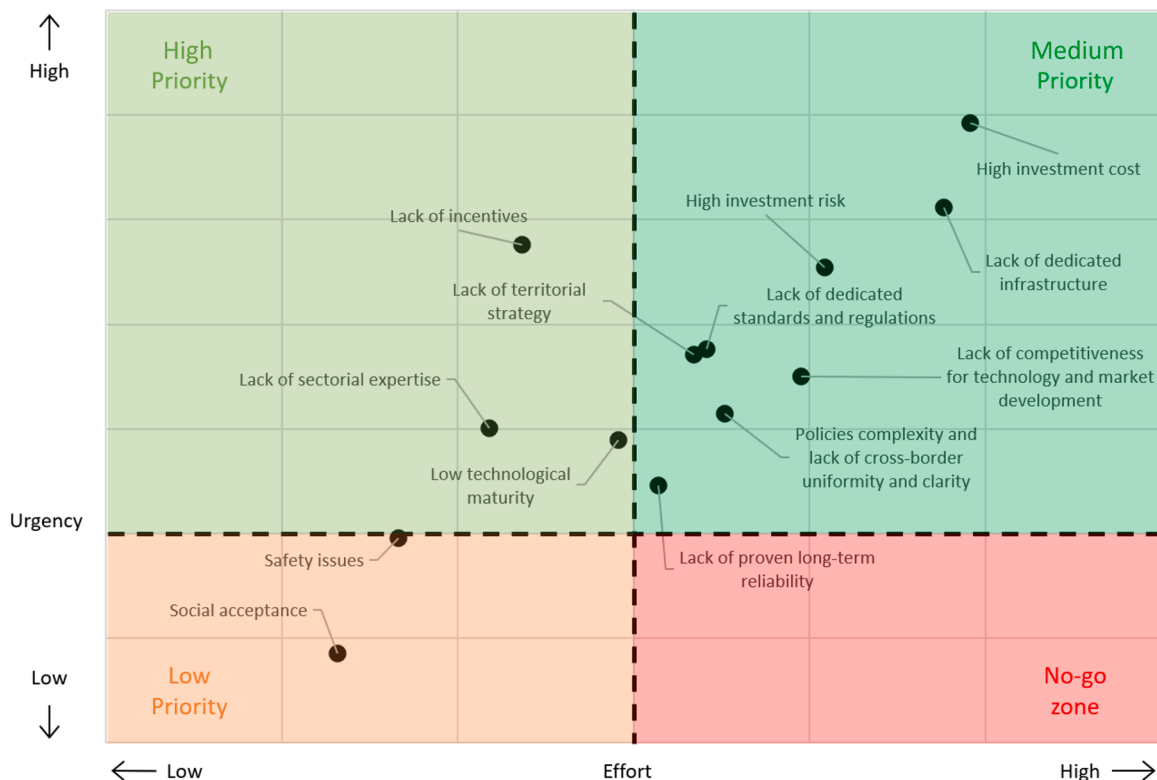


Fig. 3. Urgency-Effort matrix. Combination of stakeholder responses on urgency and efforts of gaps and barriers to hydrogen solutions implementation in the Alpine Space regions.

economic viability, and supportive policy frameworks, as well as on cross-regional cooperation.

The survey additionally examined stakeholders' perceptions of barriers to hydrogen ecosystem implementation, covering economic, societal, technical, and regulatory challenges. Stakeholders evaluated these barriers based on their criticality (how urgent and impactful the barrier is) and the effort required to resolve them, yielding insights into resource allocation priorities. This allows for a strategic approach to addressing obstacles, ensuring that both immediate and long-term challenges are tackled in the most efficient way possible. Specific barriers were categorized into four quadrants, reported in Fig. 3:

1. High-urgency, easy to solve (low-hanging fruits): these gaps, like incentivization schemes, sectorial expertise, and technological immaturity, offer immediate opportunities for positive impact with limited effort (high priority).
2. High urgency, challenging to solve (high-impact barriers): issues such as high investment costs, infrastructure and regulatory deficits, require substantial resources but are pivotal to long-term success (medium priority).
3. Low urgency, easy to solve: addressing these gaps is secondary and only pursued if resource allocation is minimal (low priority).
4. Low urgency, challenging to solve (no-go zone): these are non-critical barriers that require significant resources and may be deprioritized.

Key high-priority barriers include the lack of incentives, sector-specific expertise, and low technological maturity of some hydrogen solutions, while medium-priority barriers revolved around economic risks, infrastructure deficits, and the absence of harmonized regulations, each of which plays a crucial role in hindering the development and scalability of hydrogen ecosystems.

Among stakeholders, there was a strong consensus that economic considerations represent one of the most pressing challenges. High investment costs and financial uncertainties associated with hydrogen technologies are frequently cited as significant concerns for stakeholders, especially for private sector actors. The economic risks stem from the substantial upfront capital required for infrastructure development, such as hydrogen production facilities, storage systems, and distribution networks. These costs are compounded by the long payback periods and the perceived financial uncertainty surrounding the market's maturity. As a result, stakeholders are wary of making substantial investments without clear and reliable financial incentives or guarantees. A lack of necessary infrastructure remains a major challenge. The hydrogen ecosystem relies heavily on the development of production, storage, and distribution networks to connect supply with demand. However, the existing infrastructure in many regions is either insufficient or completely absent. This gap is particularly evident in remote or mountainous areas, where the cost of developing the required infrastructure can be prohibitive. Without a robust network of refuelling stations, pipelines, and storage facilities, hydrogen adoption will be severely limited, especially in sectors like transportation and industry, where infrastructure is critical for daily operations. The complexity of navigating different national and regional standards, policies, and legal frameworks can also create confusion and inefficiencies. The absence of dedicated, clear and harmonized regulations makes it difficult for businesses to operate across borders and hinders collaboration on cross-border hydrogen projects, especially where territorial strategies are missing. Moreover, inconsistent regulations can slow down the certification and commercialization of new hydrogen technologies, limiting their market acceptance and scale-up potential. The uncertainty of long-term reliability of hydrogen technologies, which is connected to their technological maturity is also classified as a medium-priority barrier. Stakeholders are concerned about the risks associated with early adoption and the potential for unforeseen technical failures or inefficiencies.

The economic challenges associated with hydrogen technologies can

be addressed through coordinated legislative action from governmental institutions. The absence of a unified territorial strategy, alongside the lack of dedicated standards and regulations, coupled with the complexity of existing policies, hampers efforts to effectively tackle the issue of costly and risky investments. Establishing incentive schemes could alleviate financial challenges, especially at the earlier stage, and support the commercial viability of hydrogen projects, including infrastructure development, thus enabling the large-scale deployment of hydrogen technologies. These actions should, nevertheless, keep into consideration the specific territorial requirements of Alpine regions. The scaling up of manufacturing and deployment can reduce costs by capitalizing on learn-by-doing effects and economies of scale. Consequently, the growth of hydrogen ecosystems will likely be initially driven by incentive programs, eventually transitioning to a self-sustaining model as projects become more economically viable and integrate into competitive business frameworks. This reduction in costs from large-scale adoption also extends to the technologies themselves, with technological maturity expected to improve as sector experience accumulates. Additionally, the increasing demand for a specialized workforce will need to be addressed through targeted training programs for engineers and technicians, equipping them with the necessary knowledge of regulations, codes, and standards to safely operate in this evolving market.

Stakeholders classified social acceptance and safety concerns as low-priority issues, identifying them as non-critical barriers to the development of hydrogen ecosystems. This result is very likely due to increasing public awareness and confidence in hydrogen's role in sustainable energy systems. However, this perception may understate the significance of safety as one of the key socio-economic deterrents to the widespread adoption of hydrogen technologies. These two factors – social acceptance and safety – are intrinsically connected, as negative public perception of hydrogen or of any emerging technology often correlates with concerns about its safety. To effectively address these challenges, improving social perception should begin with providing the public with clear, factual information about hydrogen, its benefits, and its safety measures. A transparent approach that openly discusses potential hazards and how they are mitigated is crucial to building trust. In addition to public education, it is equally important to establish and promote comprehensive safety regulations and standards. These efforts would help reassure stakeholders and the general public, fostering a more positive outlook toward hydrogen technologies and their integration into the energy landscape.

No assessed barrier falls within the *low urgency, challenging to solve* category, underlining the perceived feasibility of hydrogen application in the specific context of Alpine territories.

It is important to emphasize that no significant region-specific trends were observed in the analysed results. All the parameters assessed and presented consistently yielded outcomes that are largely independent of the specific territory. This highlights the shared characteristics and overarching commonalities among Alpine regions, particularly in the context of their decarbonization efforts. The findings suggest that while each region possesses unique geographical and socio-economic attributes, the fundamental challenges and opportunities associated with the adoption of hydrogen solutions and other decarbonization strategies are strikingly similar across the Alpine Space. This uniformity underscores the interconnected nature of Alpine regions, characterized by similar energy demands, environmental concerns, and economic dependencies on sectors like mobility, industry, and tourism. Moreover, the lack of territory-dependent variations in the data strengthens the argument for developing harmonized, cross-regional approaches to decarbonization. These shared challenges create a strong foundation for collaborative efforts, enabling the pooling of resources, knowledge, and best practices across Alpine regions. The uniformity also suggests that successful pilot projects or innovations in one territory can be readily adapted and replicated in others, accelerating the collective progress towards a sustainable, low-carbon future.

Open-text questions in the survey examined more deeply the potential of hydrogen in Alpine areas. Focusing on their specific territory, local stakeholders were asked to define how the application of hydrogen could help the decarbonization of their territory and, in particular, the tourism sector. The main results are presented in Table 3, where advantages and criticalities mentioned by the stakeholders are reported. The analysis of the survey responses was primarily exploratory, aimed at understanding the perspectives and attitudes of local stakeholders rather than providing a detailed explanation or description. The objective was to capture the range of opinions expressed by stakeholders without seeking to offer conclusive explanations. Overall, no significant differences in opinions or attitudes toward hydrogen were observed based on regional, national, or organizational factors. This suggests a common viewpoint among stakeholders across the Alpine region. However, from the collected responses, broader generalizations could be made, which are applicable to the entire Alpine territory, reflecting shared perceptions and insights on the potential role of hydrogen in these areas.

Hydrogen production pathways. The most mentioned method for producing green hydrogen to support the decarbonization of Alpine territories is the electrolysis of water using renewable energy sources (solar, hydroelectric, and wind power). Additionally, a small number of stakeholders cited alternative routes for hydrogen production, such as biomass and waste-based processes. These include dark fermentation

and pyrolysis/gasification, which convert organic materials into hydrogen. These methods could be particularly interesting and promising for regions with abundant biomass resources, offering a potential complement to electrolysis in the hydrogen production landscape.

Hydrogen end-uses. Survey respondents generally indicated hydrogen applications in the mobility and residential sectors as valuable tools for decarbonizing their territories. Alpine areas, particularly those in remote or mountainous regions, frequently face challenges in connecting to conventional gas and electricity grids due to their geographical isolation and rugged terrain. These areas often lack the necessary infrastructure to support stable and consistent energy supply, making them heavily reliant on off-grid solutions for their energy needs. In this context, hydrogen could be used for both heating and electricity generation.

In terms of mobility, hydrogen as a fuel is also seen as a promising solution. Respondents frequently mentioned its potential in local public transport, with buses, light rail, and trains in mountain areas identified as prime candidates for hydrogen deployment. Additionally, hydrogen could facilitate the creation of a sustainable, extensive logistics network in valleys that lack railway infrastructure. Other lesser-cited hydrogen applications within the mobility sector included its use for ski-lifts and ropeways, waste collection vehicles, heavy-duty machinery (such as construction vehicles), and “last-mile delivery” vehicles.

Table 3

Results of questionnaire on hydrogen. Hydrogen technologies and processes that, according to interviewed stakeholders, can support the decarbonization of their territories, with indication of corresponding opportunities and criticalities mentioned in the replies to the open-text questions in the survey. LNG: Liquefied Natural Gas.

Hydrogen production				
Technology/process	Electrolysis of water		Biomass-based processes (pyrolysis/gasification; dark fermentation)	
Sources	Electricity from renewable energy sources (solar; wind power; hydroelectric)		Biomass/waste	
Target	Off-grid systems in remote Alpine areas		Alternative to electrolysis in regions with abundant biomass resources	
Opportunities	<ul style="list-style-type: none"> Storage of surplus intermittent renewable energy sources Regional green energy self-sufficiency 		Exploitation of local resources	
Criticalities	<ul style="list-style-type: none"> Limited renewable energy penetration and saturation of hydroelectric power capacity Lack of surplus energy 		Not identified	
Hydrogen uses				
Technology	Fuel-cell electric vehicles	Internal combustion engine vehicles	Fuel-cells for stationary power generation	Stationary power generation through gas turbines, fuel-cells, combustion engines
Product	Electricity to power electric motor	Mechanical work	Heat/electricity	Heat/electricity
Target application	Mobility: local public transport (buses, light rail, and trains), logistics network (trucks), other mobility solutions: snow groomers, snowmobiles, ski-lifts, ropeways, waste collection vehicles, heavy-duty machinery such as construction vehicles, “last-mile delivery” vehicles, bicycles, scooters, kick-scooters)		Residential sector: tourist accommodations (Alpine retreats, hotels, B&Bs) and off-grid remote areas	Industry: hard-to-abate industries
Opportunities	<ul style="list-style-type: none"> Enhanced accessibility and transportation reach of remote areas Sustainable mobility and reduction of environmental impact (pollution, noise) Better performance than electric or LNG vehicles in contexts with challenging slopes and temperatures 		<ul style="list-style-type: none"> Alternative to conventional gas/electricity grids where infrastructure is missing Enhancement of territory energy autonomy Decarbonization of tourism sector Market as sustainable or eco-tourism destinations 	<ul style="list-style-type: none"> Contribution to decarbonization of territories
Criticalities	<ul style="list-style-type: none"> Competition with electric, LNG or biomethane vehicles, especially for private transportation 		<ul style="list-style-type: none"> Competition with direct electrification of systems 	<ul style="list-style-type: none"> Specific applications to be identified High effort for decarbonization of small-scale industries typical of Alpine areas

Hydrogen potential in the industrial sector was also noted, with many respondents recognizing its importance for decarbonizing Alpine regions, where hard-to-abate industrial activities often contribute significantly to carbon emissions. However, specific industrial applications (e.g., steel industry) were less frequently mentioned in the survey’s open-ended responses. This could be due to several factors. Firstly, stakeholders may not have been fully aware of all the possible industrial applications of hydrogen or might have focused more on the immediate and tangible benefits of hydrogen in sectors like mobility, residential energy, and renewable energy storage. Secondly, the industrial sector can be complex and diverse, and respondents may have found it challenging to pinpoint precise industrial applications for hydrogen that would be relevant to the unique characteristics of the Alpine region. For example, industries in the Alps may differ from those in other regions in terms of scale, infrastructure, and energy needs.

Septicism and critical issues. The survey also captured some scepticism regarding the potential of hydrogen for decarbonization, both in general and specifically within the tourism sector and mountain areas. Sceptics question the economic sustainability of hydrogen applications and claim that other sustainable alternatives, such as direct electrification or use of biomethane for transportation, can be more cost-effective. They point to the significant initial investment costs, the lack of a comprehensive legal and strategic framework, and the underdeveloped hydrogen market as factors limiting hydrogen’s true potential. This is especially recognized for mountain contexts, where there is less room for an impactful decarbonization, and existing financing programs are not easily applicable because of the peculiar characteristic of these areas. Furthermore, the decarbonization potential of hydrogen is closely tied to the advancement of renewable energy sources. Challenges such as limited renewable energy penetration, the lack of surplus energy, and the saturation of existing hydroelectric power capacity are seen as significant barriers to fully realizing hydrogen’s potential in certain Alpine regions.

By analysing the scepticism about hydrogen in the answers to the questionnaire, no pattern emerged according to the regional and organization type distribution of stakeholders. Sceptics are evenly spread across different Alpine regions and organizational types. As reported in Fig. 4, considering the specific application of hydrogen for powering fuel-cell or internal combustion engine vehicles, most stakeholders who express scepticism without providing reasons also report having very little knowledge of this application. Conversely, sceptics who do provide justification for their doubts tend to claim a high level of understanding

of the subject. A similar pattern is observed in the context of hydrogen use for stationary power generation. Conversely, when examining the use of hydrogen as substitute for natural gas, sceptics frequently assert a high level of knowledge of the topic, especially those who do not offer any justification to their scepticism.

Cross-referencing open-text answers revealing scepticism about hydrogen with the expertise of the respondents in the sector, it is possible to infer that scepticism is, at least partially, associated with a lack of expertise. In this regard, it emerged that most sceptics have little or no expertise in the implementation of hydrogen. This means that although some stakeholders claim to have a high knowledge level on the subject, this does not necessarily correspond to a high level of expertise.

It is essential to emphasize that the analysis conducted was exploratory in nature. The data collection method employed was not designed to comprehensively categorize all forms of scepticism, and it cannot be assumed that every individual with doubts about hydrogen’s potential in decarbonizing mountain regions was identified. As a result, the findings of the analysis should not be viewed as universally applicable. However, they provide valuable insights into the views of stakeholders who chose to openly express their scepticism while completing the questionnaire, offering a partial but useful understanding of the concerns that exist within the community and supporting the definition of existing barriers to be overcome.

Strategies. In response to open-text questions, several stakeholders shared their perspectives on the urgent strategies needed to address critical challenges and maximize hydrogen’s potential in Alpine regions. A recurring theme is the necessity of adopting a holistic, systemic approach to energy management and decarbonization. Many stakeholders emphasized that treating hydrogen applications as isolated interventions would be inefficient and ineffective. Instead, they advocate for a coordinated approach that considers the broader regional context, particularly the integration of hydrogen solutions with local renewable energy production, as well as the establishment of a clear and supportive legal framework.

Moreover, stakeholders underscored the importance of creating "smart communities", that is energy communities that leverage information and communication technology (ICT) to optimize energy use, foster collaboration, and ensure efficient resource allocation. These communities could play a crucial role in the successful integration of hydrogen technologies by facilitating shared resources, such as hydrogen production, storage, and distribution. In this context, energy communities are seen not just as a means of decarbonizing individual

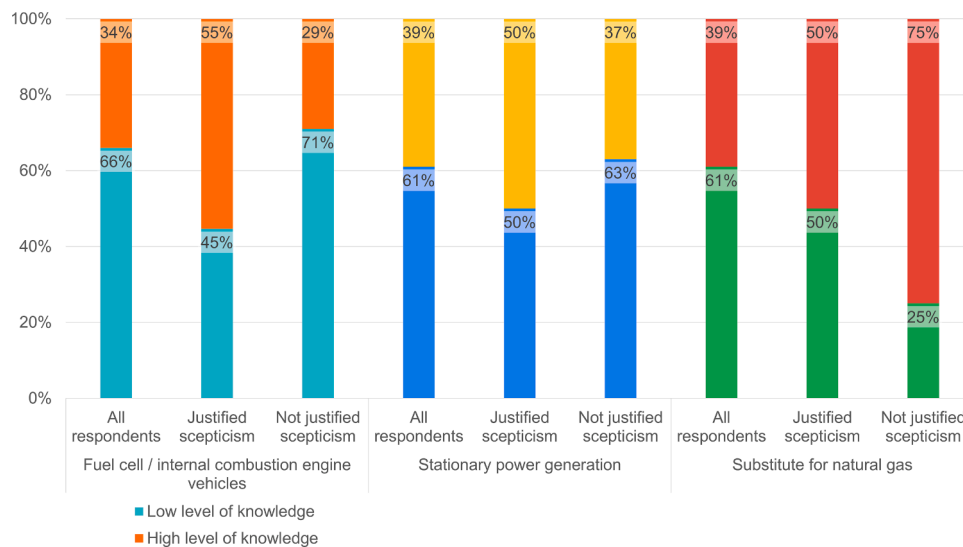


Fig. 4. Distribution of stakeholders claiming to have high or low level of knowledge in the hydrogen sector. The distribution is shown for all respondents, sceptics with reasoned answers and sceptics with not motivated answers, divided per specific hydrogen application: use for fuel cell or internal combustion engines vehicles, use for stationary power generation, use as substitute for natural gas.

households or sectors but also as a foundational element for establishing a resilient, decentralized energy system in mountain areas.

Another key aspect highlighted by respondents is the need to tailor hydrogen technologies to the unique characteristics of mountain regions. The seasonality of energy demand, extreme temperatures, challenging terrain, and the sparsely populated nature of these areas present specific challenges that require careful consideration. For instance, technologies that work efficiently in urban or flat areas may not be suitable for the Alpine context. As such, stakeholders called for the evaluation of hydrogen solutions based on the region’s specific needs and conditions.

An important point raised was the need for funding schemes that align with the scale and context of mountain territories. For example, large-scale electrolyzers may not be practical or financially viable in small, remote mountain ecosystems. Instead, funding mechanisms should be adapted to the realities of these regions, providing support for smaller, decentralized projects that are better suited to local energy demands. This would help foster the growth of localized hydrogen production, distribution, and storage systems that align with the capacity and needs of the region, rather than relying on large-scale infrastructures that may not be feasible in remote, less populated areas.

3.2. Roundtable discussions results

Roundtable discussions were organized in key territories of the Alpine regions covered in the AMETHyST project (Auvergne-Rhône-Alpes, Friuli Venezia Giulia, Trentino, South Tyrol, Oberbayern, Tyrol, and Valais) and provided a platform to explore the opportunities green hydrogen presents for these regions and its potential role in Alpine contexts in general. Local manufacturers, operators, and institutions representatives engaged in debates focusing on practical applications of hydrogen and the main barriers to implementing hydrogen-based

solutions in Alpine regions. The main hydrogen technologies, covering the entire value chain from the production to the end-uses, were addressed to discuss possible coordinated activities and initiatives that could lead to establishing green hydrogen ecosystems. Participants also shared practical experiences and best practices from their involvement in hydrogen projects, highlighting technical, managerial, and administrative challenges. While discussions were tailored to address local needs and priorities, overarching insights emerged.

The main outputs of the discussions are reported in Fig. 5. A key conclusion of stakeholders roundtables was that mobility represents the most significant potential application for hydrogen solutions in the Alps, spanning both heavy-duty and light-duty transport solutions. These include buses for extra-urban routes, shuttle buses for ski areas, snow groomers, garbage trucks, and private vehicles, as an alternative to battery-based solutions like battery electric vehicles (BEVs). In remote areas and low-temperature environments, electrification is not always feasible. Specifically, battery-powered heavy-duty vehicles such as snow groomers and snowmobiles face operational challenges in extreme cold and steep terrains, which can impair battery performance. In contrast, hydrogen-powered vehicles, utilizing either fuel cells or hydrogen internal combustion engines, offer a viable and robust alternative. Beyond reducing carbon dioxide emissions, hydrogen-powered vehicles are advantageous for their flexibility and resilience to low temperatures, which are critical in mountainous regions. From a technical standpoint, concerns were raised about the efficiency and the range of fuel cells, which is the distance hydrogen vehicles can travel before refueling, as they are influenced by factors such as driving style, terrain, slope, weather conditions, and payload. These variables are particularly pronounced in mountain transport applications, where routes often involve significant elevation changes and adverse weather. Refueling infrastructure also requires careful planning to ensure operational efficiency. Hydrogen refueling stations must be strategically located to support

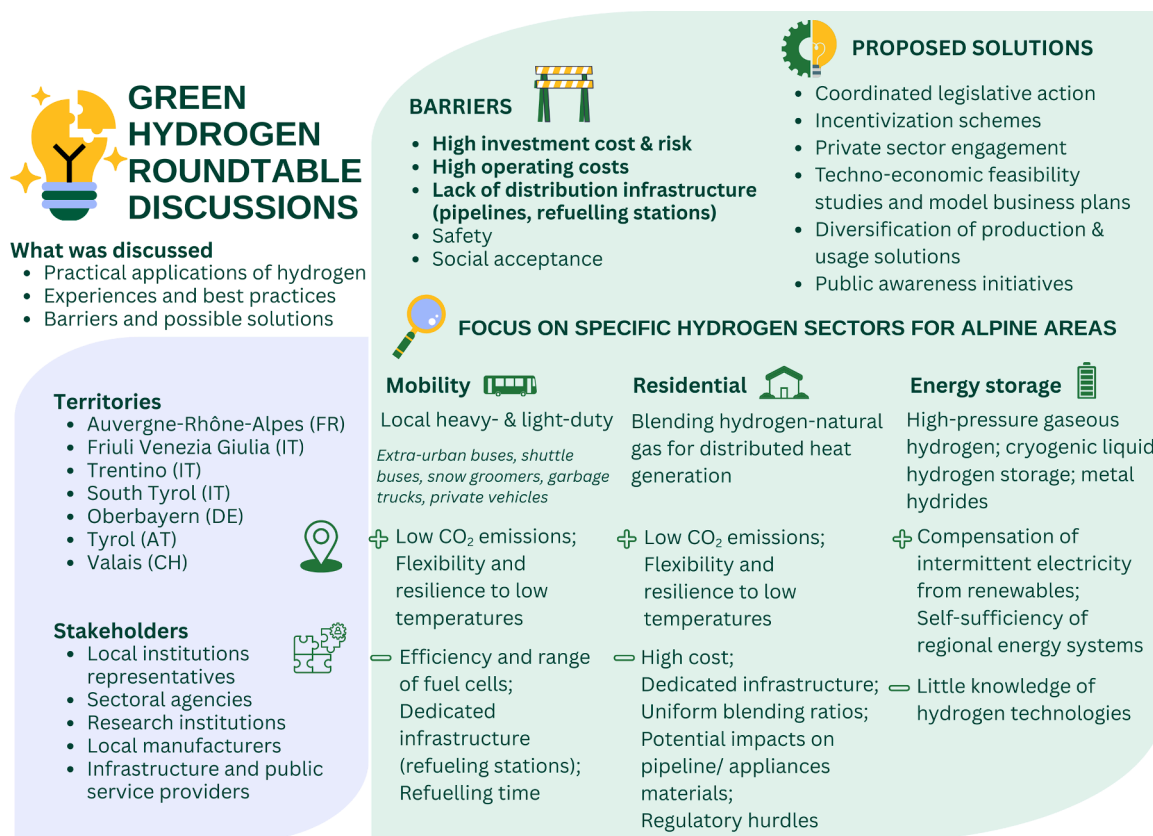


Fig. 5. Results of roundtable discussions on green hydrogen applications in Alpine Areas: territories and stakeholders involved, barriers and proposed solutions, advantages and disadvantages of specific applications.

vehicles operating in remote and dispersed areas. Moreover, the time required for refueling could necessitate adjustments in operational schedules and vehicle management procedures, particularly for fleet operations like buses and snow groomers that have demanding and time-sensitive usage patterns.

The residential sector is seen as a potential area for hydrogen application, but it presents challenges due to the need for dedicated infrastructure and the high costs associated with hydrogen technologies. Electrification (e.g., heat pumps) could be the preferred solution in this sector, but some stakeholders suggested that blending hydrogen with natural gas in existing gas infrastructure could be a practical approach in areas already connected to the natural gas grid, particularly for distributed heat generation. This approach leverages the existing infrastructure, reducing the need for substantial upfront investment in new distribution systems. The benefits include lowering carbon emissions by reducing the proportion of natural gas used, while maintaining energy reliability and flexibility. However, challenges such as ensuring uniform blending ratios, potential impacts on pipeline and appliances materials, and regulatory hurdles must be addressed. Moreover, burning hydrogen for residential heat generation would not be the most efficient pathway of exploiting this energy carrier. Energy communities could play a crucial role in overcoming these obstacles by pooling resources for collective investments in shared infrastructure, thereby reducing individual financial burdens. By distributing costs among members and fostering local collaboration, energy communities can enable the adoption of hydrogen technologies in residential areas. Additionally, these communities can support infrastructure development through shared ownership models and coordinated planning, making hydrogen solutions more accessible and economically viable.

An interesting finding of roundtables was the widespread interest among stakeholders in hydrogen storage technologies, alongside its production and use. Conventional methods, such as high-pressure gaseous hydrogen storage and cryogenic liquid hydrogen storage, as well as more innovative solutions like metal hydrides were discussed. In general, although knowledge of storage technologies lags behind that of production methods (e.g., electrolysis) and usage (e.g., fuel cells), many stakeholders emphasized the importance of integrating intermittent renewable energy sources, such as photovoltaic systems and hydropower, with hydrogen storage, in order to compensate for daily and seasonal variations of electric energy availability. This integration would allow surplus energy to be stored and utilized when demand exceeds supply. Hydrogen storage could play a pivotal role in supporting renewable energy integration within Alpine energy systems, enhancing the penetration of renewables in the local energy mix, facilitating regional decarbonization, and enabling self-sufficient energy systems.

Despite the recognized potential of hydrogen solutions, stakeholders identified and shared several barriers to developing hydrogen ecosystems in Alpine territories. One of the primary obstacles is the high cost of investments and associated risks, stemming from the currently limited market and supply of hydrogen technologies. Operating costs are also significant, with green hydrogen being considerably more expensive than traditional fossil fuels, including natural gas. Another critical issue is the lack of dedicated hydrogen distribution infrastructure, such as hydrogen pipelines for industries or households and refueling stations for private light-duty mobility, but also heavy-duty transport. This particularly hinders the alignment of hydrogen supply with demand and is exacerbated by the unfavorable economic conditions for infrastructure development and the weak business cases resulting from them. The tight connection between the implementation of hydrogen solutions and the expansion of renewable energy capacity further adds to the complexity and costs to the necessary infrastructure.

Addressing the economic challenges of hydrogen technologies requires coordinated legislative action within and among territories. A systemic approach to integrating hydrogen technologies into local energy systems must be supported by a harmonized legislative framework. The absence of unified territorial strategies, clear standards, and

streamlined regulations complicates the landscape, deterring investments and delaying project implementation. Moreover, complex and time-consuming permitting processes further discourage stakeholders. To overcome cost-related barriers and enable commercial hydrogen projects, stakeholders suggested the establishment of incentive schemes, in the form of subsidies, grants, or low-interest loans. These incentives would support infrastructure development, create local hydrogen markets and value chains, and facilitate large-scale deployment that will drive down the cost of production and consumption. Initially, public funding and incentives are critical to supporting the transition, but private-sector engagement is equally important to build interconnected supply and demand networks. Neither local authorities nor private entities alone can ensure widespread hydrogen implementation.

Techno-economic feasibility studies and model business plans can provide a roadmap for gradual hydrogen adoption, starting with small-scale projects to gather data, build experience, and eventually scale up or replicate successful models. Diversifying production and usage solutions is also vital to developing structured and resilient hydrogen ecosystems. Safety concerns, while not considered a major barrier, were noted by some participants due to stringent regulations surrounding hydrogen storage and usage. Dedicated depots for hydrogen-powered vehicles, such as buses and snow groomers, are necessary. These issues, however, can be effectively addressed with clear and well-defined standards and regulations. As already observed in the questionnaire results, social acceptance is not perceived as a significant obstacle to hydrogen ecosystem development. Hydrogen is often seen as an opportunity to enhance the sustainability and attractiveness of tourist destinations. While skepticism may exist in remote areas, public awareness initiatives are essential to inform and educate local communities. Stakeholders believe that using hydrogen in public mobility can bolster confidence in this technology and its benefits.

4. Discussion

The results of the survey presented in this work show that green hydrogen holds a great potential for application in Alpine areas. Local stakeholders see it as an opportunity for the sustainability of their territories. Obviously, technical feasibility should be checked first for each specific application, to guarantee appropriate implementation of the technologies and actually contribute to the decarbonization of local energy or mobility systems.

It is recognized that the integration of hydrogen systems needs to be supported by large investments. Incentivization schemes are seen as key especially for the development of the infrastructure necessary for developing the hydrogen value chain (Kannaiyan et al., 2023). The policy framework, both at European and regional levels, is currently under development for addressing criticalities and support the implementation of hydrogen in diverse sectors in all European regions. The European Hydrogen Strategy (European Commission, 2020), adopted by the European Commission in 2020, aims to accelerate the deployment of hydrogen from renewable energy sources across Europe, scaling up the production, investing in hydrogen refuelling stations, integration into existing gas grids, storage facilities, and supporting the creation of hydrogen demand in industry, transportation, and heating sectors. The strategy also promotes research and innovation as well as international cooperation for facilitating technology improvements and promoting the global expansion of hydrogen technologies. Moreover, the Fit-for-55 package (European Commission, 2021) and the REPowerEU Plan (European Commission, 2022) include measures for defining the role of green hydrogen as a strategic energy carrier in achieving the EU's goal of reducing greenhouse gases emissions by 55 % by 2030. The more recent Directive (EU) 2023/2413 (RED III) (European Commission, 2023) sets further ambitious targets for green hydrogen use in industry and transport. In particular, the directive aims for at least 42 % of hydrogen used in industry by 2030 and 60 % by 2035 to be RFNBO (Renewable Fuel of Non-Biological Origin). At the European level, the Clean Energy

Transition Partnership and the Clean Hydrogen Partnership focus on advancing the energy transition, contributing to EU's climate neutrality goals, and accelerating the development and deployment of the European value chain for green hydrogen, strengthening its competitiveness and supporting industries. These initiatives also support the creation of Hydrogen Valleys ([Clean Hydrogen Partnership, 2025](#)), that are specific geographic areas strategically developed to integrate and showcase hydrogen technologies across various sectors (industry, transportation, and energy), and across the entire value chain (from production to end-uses).

Since 2020 several local governments in the Alpine Space regions have adopted, or are in the process of developing, local hydrogen strategies or roadmaps for supporting the implementation of hydrogen projects and the growth of hydrogen ecosystems and value chains. At the national level, France, Germany, Austria, Italy, and Switzerland have already adopted national hydrogen strategies providing a strategic framework for developing national hydrogen markets and encouraging the launch of regional and local projects and initiatives. Moreover, cross-regional collaborations in the Alpine region, such as Euregio (Tyrol-South Tyrol-Trentino) and Arge Alp (comprising 10 states, regions, provinces, and cantons of Austria, Germany, Italy, and Switzerland), help bridging gaps in regional hydrogen value chains and reinforcing interregional cooperation.

Robust governance is crucial for establishing resilient and climate-neutral hydrogen economies that help to sustainably overcome the identified barriers and gaps. An integrated multi-level policy approach is necessary to roll-out green hydrogen in the Alps more efficiently. Based on the results of the present study, three fields of intervention can be identified for facilitating the implementation of green hydrogen in the Alpine region:

1. Promoting regional policy planning and green hydrogen strategies. By adopting hydrogen strategies within local strategic frameworks, administrations can support the implementation of hydrogen projects and the creation of sustainable green hydrogen economies. The following principles can enable the alignment with decarbonization targets:
 - Prioritize energy efficiency and renewable energy additionality, to avoid competing with other uses and ensure overall system sustainability;
 - Maximize decarbonization potential, favouring hydrogen application in areas where it offers the greatest ecological, economic and technical benefits;
 - Unlocking external expertise through private-public partnerships and multi-level governance and cooperation;
 - Implementation of targeted policy instruments for green hydrogen, like green public procurement, financial incentives, and regulatory frameworks steering investments toward sustainable hydrogen applications and avoiding reliance on non-green hydrogen pathways;
 - Policy alignment to integrate hydrogen into local and regional energy and climate policies, and follow-up monitoring for adjusting policy instruments over time;
 - Communication to increase public awareness, social acceptance and understanding of hydrogen technologies. At the same time, improve knowledge and skills to meet the future demand for skilled labour in the hydrogen sector.
2. Ensuring coordination between national and regional hydrogen policies. Other than national hydrogen strategies, in the regions of the Alpine Space individual roadmaps have been adopted by regional governments at local level, hydrogen valleys have been established, and pilot projects launched by private and public-private partnerships. In this context, it is important to establish governance structures that are able to connect decision makers and stakeholders at various levels to better steer the rollout of hydrogen policies in the long run. Therefore, it is suggested that proactive bottom-up and top-

down approaches shall be initiated from the corresponding levels, to connect regional ambition with national strategies and establish national support structures, such as one-stop shops or national stakeholder platforms.

3. Fostering transnational, transregional, and transborder cooperation, through exchange of knowledge, collaborations, and connected networks, promoting access to technical studies, funding tools, and clearer communication of EU regulations to remove legal and technical barriers to hydrogen expansion in the Alpine region. Moreover, linking existing collaborations and initiatives can prevent duplication and make more efficient use of resources.

5. Conclusions

Hydrogen, as an energy carrier, presents considerable potential for diverse applications throughout the entire value chain in Alpine regions, spanning from its production to its various end-uses. To explore this potential, surveys and roundtable discussions were conducted with local stakeholders from the Alpine Space area, helping to assess how hydrogen could contribute to the decarbonization of these regions. This process involved a comprehensive mapping of the knowledge and expertise available among local stakeholders within the hydrogen sector, as well as a thorough evaluation of the specific needs of these territories. Additionally, it highlighted the key barriers and challenges that are currently hindering the development of a robust hydrogen economy in the Alps, providing valuable insights into areas that require targeted attention and intervention.

Tourism facilities and resorts in the Alps are major energy consumers, making it crucial to explore and implement strategies to decarbonize this sector. These facilities, which include hotels, ski resorts, and other tourism-related infrastructures, rely heavily on energy, particularly during peak seasons, resulting in a considerable environmental footprint. As such, finding innovative solutions to reduce carbon emissions in this sector is essential to ensure its long-term sustainability. The case studies discussed in the roundtables share common features across Alpine areas, meaning the study's findings can be readily applied to other similar contexts. Local stakeholders, both through roundtable discussions and questionnaire responses, expressed strong interest in hydrogen applications, recognizing significant potential for its use. They believe hydrogen could support off-grid energy solutions, which would allow tourism facilities and resorts to achieve greater energy independence and self-sufficiency, and enhance the sustainability reputation of tourist destinations. However, to realize this potential, it is essential to share knowledge and expertise on hydrogen and its applications to support every stage of the hydrogen value chain's development. This knowledge transfer is essential at each stage, from production to storage, transport, distribution, and end-use. Higher education and research institutions, along with SMEs and large industries, rank highest in terms of expertise across various hydrogen technology sectors (production, transport, storage, and end-uses). In contrast, infrastructure and public service providers, as well as sectoral agencies, show the greatest number of low-knowledge responses. Sharing information and best practices will increase local stakeholders' awareness and inform them about the sustainable benefits and potential of hydrogen applications.

The greatest potential for the application of hydrogen solutions in the Alps is mobility, but also the residential sector could benefit from its implementation. In addition, integration with intermittent renewable energy sources for storing excess energy in the form of hydrogen is a viable option and particularly suited to touristic mountain areas with high seasonality of energy consumption.

The development of hydrogen ecosystems faces various challenges, though, primarily due to economic factors such as high costs and investment risks, as well as the lack of dedicated infrastructure. Overcoming these challenges requires legislative coordination and incentive schemes to drive down costs and promote commercial projects. Techno-economic feasibility studies and diversified production and usage

solutions are crucial for building structured and resilient hydrogen economies. Moreover, public and private stakeholders need to collaborate to establish interconnected supply and demand networks, thus developing local hydrogen ecosystems.

The presented survey gives an overview and provides a frame of reference for the development of hydrogen-based economies in the Alpine regions. In general, hydrogen is viewed by local stakeholders as an opportunity to enhance sustainability in touristic destinations, provided clear standards and regulations are in place. Many challenges need to be overcome, but a coordinated, multi-level governance approach aligning local, national and European strategies, and promoting synergies between public and private actors can support the deployment of green hydrogen in the Alps and contribute to the energy transition and regional decarbonization goals. Continued investment in infrastructure, policy coherence, capacity-building, and cross-border collaboration will be critical to overcoming existing barriers and unlocking the full potential of hydrogen technologies. With strategic planning and collaboration, Alpine regions can become pioneers in the integration of green energy solutions, setting a global example for sustainable development in mountain areas.

CRedit authorship contribution statement

Eleonora Cordioli: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Jacopo de Maigret:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Matteo Testi:** Supervision. **Luigi Crema:** Supervision.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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