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Alpine Space

H2MA

Fondazione Lombardia per l'Ambiente

Deliverable D.2.3.2

Green H2 Masterplan for Alpine Space

Activity 2.3

September 2024

The H2MA project is co-funded by the European Union through the Interreg Alpine Space programme

DOCUMENT CONTROL SHEET

Project reference	
Project title	Green Hydrogen Mobility for Alpine Region Transportation
Acronym	H2MA
Programme priority	Carbon neutral and resource sensitive Alpine region
Specific objective	SO 2.1: Promoting energy efficiency and reducing greenhouse gas emissions
Duration	01.11.2022 – 31.10.2025
Project website	https://www.alpine-space.eu/project/h2ma/
Lead partner	KSSENA

Short description

H2MA brings together 11 partners from all 5 Interreg Alpine Space EU countries (SI, IT, DE, FR, AT), to coordinate and accelerate the transnational roll-out of green hydrogen (H2) infrastructure for transport and mobility in the Alpine region. Through the joint development of cooperation mechanisms, strategies, tools, and resources, H2MA will increase the capacities of territorial public authorities and stakeholders to overcome existing barriers and collaboratively plan and pilot test transalpine zero-emission H2 routes.

Document details	
Full document's title	Green H2 Masterplan for Alpine Space
Version	V2
Author/s	Domenico Vito, Mita Lapi, Antonio Ballarin Denti, Carlo Santoro
Organization/s responsible	Lombardy Foundation for Environment (FLA)
Delivery period	4

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IMPRINT

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EXECUTIVE SUMMARY

The Green H2 Hydrogen Masterplan for the Alpine Space (H2MA) focuses on advancing green hydrogen infrastructure to decarbonize freight and public transport across the Alpine region. As heavy-duty transport (HDT) is a major contributor to regional emissions and challenging to electrify, green hydrogen provides a sustainable solution for trucks, buses, and other heavy-duty vehicles. The H2MA project brings together 11 partners from five Interreg Alpine Space countries (Slovenia, Italy, Germany, France, and Austria) to coordinate the transnational roll-out of hydrogen infrastructure.

H2MA fosters collaboration among public authorities, energy and transport agencies, hydrogen infrastructure providers, and renewable energy producers. The project integrates hydrogen production with renewable energy sources and harmonizes policies across the region. Through joint strategies, tools, and cooperation mechanisms, it aims to enhance the capacity of stakeholders to overcome current barriers and pilot zero-emission hydrogen routes in the region.

This document provides an overview of hydrogen route planning in the Alpine regions, aligning with existing EU regulations and initiatives. It incorporates feedback from peer reviews and stakeholders, offering recommendations for future planning. Additionally, it addresses the synergies with current EU plans, providing a comprehensive roadmap for the region's transition to green hydrogen mobility. Limitations and broader considerations are also discussed to guide informed decision-making and ensure effective implementation.

1. Introduction

1.1 The H2MA Project

The H2MA (Green Hydrogen Masterplan for Alpine Space) project focuses on advancing green hydrogen (H2) infrastructure to reduce greenhouse gas emissions from freight and public transport in the Alpine region. H2MA will foster transnational collaboration among public authorities, energy and transport agencies, H2 infrastructure providers, and renewable energy producers to create zero-emission hydrogen routes and urban mobility solutions.

Heavy-duty transport (HDT), a significant contributor to Alpine emissions, is difficult to electrify. Green hydrogen offers a sustainable decarbonization pathway for trucks, buses, and other HDVs. H2MA addresses the current lack of policy knowledge, coordination, and resource sharing needed to scale up green H2 solutions. The project aims to streamline H2 roll-out plans, connecting hydrogen production with renewable energy sources and creating harmonized policies for the region.

By integrating transnational and urban infrastructure planning, H2MA will develop a critical mass for green hydrogen in commercial applications. The project builds on existing H2 initiatives in Germany, France, Austria, and Italy, aiming to decarbonize heavy-duty mobility across the Alpine region, including trucks, trains, and planes.

H2MA brings together 11 partners from all the 5 Interreg Alpine Space EU countries (SI, IT, DE, FR, AT), to coordinate and accelerate the transnational roll-out of green hydrogen (HYDROGEN) infrastructure for transport and mobility in the Alpine region. Through the joint development of cooperation mechanisms, strategies, tools, and resources, H2MA will increase the capacities of territorial public authorities and stakeholders to overcome existing barriers and collaboratively plan and pilot test transalpine zero-emission HYDROGEN routes

1.2 Goals of this document

- Provide an integrated overview of the H2 routes planning in the regions involved into H2MA
- Inform about synergies with the existing EU plans and regulations and other initiatives in the Alpine Space
- Provide recommendations and suggestions coming from the peer review process useful for planning
- Provide feedback from stakeholders (LWGS)
- Communicate limitations and overall remarks

2. Background : the European Hydrogen Scenario

2.1 The Renewable Energy Directive (RED III)

A starting point to talk about zero-emission HYDROGEN routes stands surely in the framework proposed by the *Renewable Energy Directive (RED III).*

RED III plays a vital role in setting the agenda for hydrogen development in Europe by establishing clear targets for RFNBOs, thereby promoting the use of renewable hydrogen in both industry and transport. The starting point for the Renewable Energy Directive (RED III) is a critical policy framework driving the development of renewable energy in Europe, with a strong focus on hydrogen as a key energy carrier. Its objective is to accelerate the transition towards a more sustainable and carbon-neutral energy system. By setting binding targets for renewable energy consumption across sectors, RED III ensures that renewable fuels, including hydrogen, play a central role in decarbonizing both industrial processes and transportation.

A pivotal aspect of RED III is its clear emphasis on **Renewable Fuels of Non-Biological Origin (RFNBOs)**. RFNBOs are fuels derived from renewable electricity, typically in the form of hydrogen or hydrogen-based fuels like ammonia or synthetic methane.

These fuels are considered vital in achieving the decarbonization of sectors where direct electrification is difficult or less efficient, particularly in industries and transport.

For hydrogen, RED III sets ambitious targets to promote its penetration in both the industrial and transport sectors. In the industrial sector, RED III mandates that RFNBOs should account for 42% of energy consumption by 2030, rising to 60% by 2035. This target reflects the significant role that renewable hydrogen is expected to play in replacing fossil fuels, especially in energy-intensive sectors like steelmaking, chemicals, and refining, where alternative decarbonization options are limited [1].

In the transport sector, the directive sets a target for RFNBOs to comprise at least 1% of the total energy consumed by 2030. While this percentage may seem modest, it reflects the relatively early stage of hydrogen adoption in transport, which currently faces challenges such as limited refueling infrastructure and the higher costs of hydrogen production. However, achieving this target would represent a significant shift towards cleaner mobility solutions, particularly for heavy-duty vehicles, shipping, and aviation where hydrogen-based fuels offer the most promising alternatives to fossil fuels [2].

RED III also emphasizes the sustainability criteria for hydrogen production, ensuring that hydrogen classified as an RFNBO is produced using renewable electricity while satisfying the principles of additional and temporal and geographical correlation. This focus on sustainable production is crucial to ensure that hydrogen development contributes to overall greenhouse gas emissions reductions, rather than shifting emissions from one sector to another [3].

2.2 The role of H2 in decarbonizing the transport sector

The transport sector plays a critical role in the decarbonization of Europe's energy system, accounting for over 25% of the region's total energy consumption and carbon emissions. Within this sector, road transportation, particularly road vehicles, represents the largest share of energy use and emissions (Figure 1).

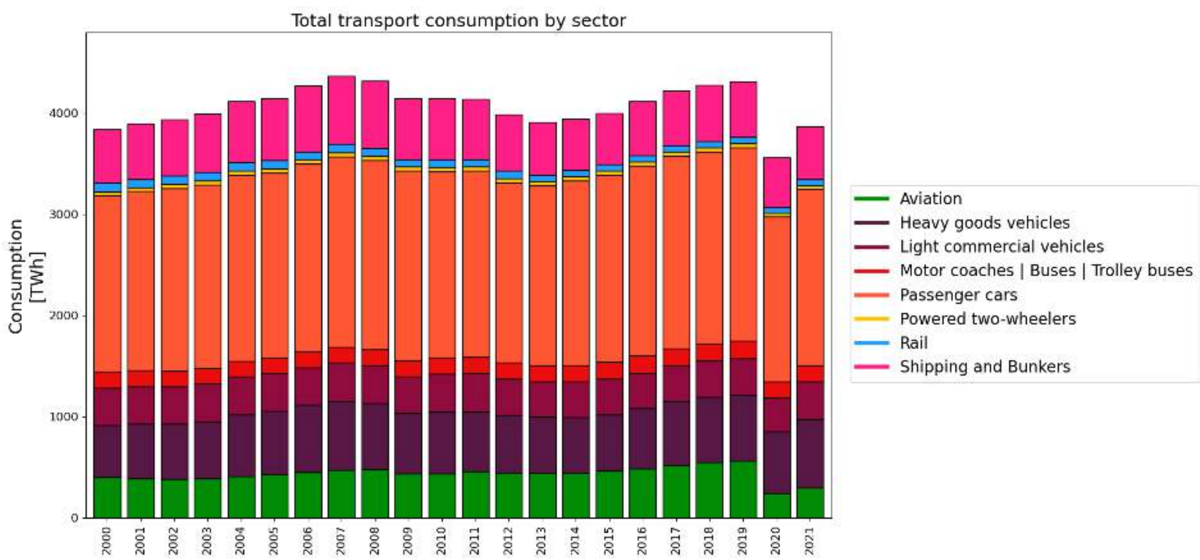

Figure 1 - Total consumption in the transport sector in the EU.
(Source: JRC-IDEES-2021 (2024)[4])

Fossil fuels continue to dominate all transport subsectors, with the exception of rail, which is largely powered by electricity in many regions. Depending on the subsector, alternative technologies are emerging, and in some cases, are spreading rapidly. For instance, private passenger vehicles and light-duty commercial vehicles are transitioning toward electric mobility, with battery electric powertrains readily available on the market and charging infrastructure expanding to support this shift from traditional to electric mobility.

In certain subsectors, however, no single technology has emerged as the dominant solution. These sectors often include those that are hard to decarbonize or face challenges to direct electrification. Although direct electrification can provide greater system efficiency and lower supply chain costs, its adoption is not straightforward in every segment. In these cases, hydrogen may offer a promising alternative to direct electrification.

Direct electrification faces challenges due to the low energy density associated with storing electricity, which leads to technical limitations in sectors where energy density is crucial. For instance, aviation relies on energy-dense fuels due to the limited space available on aircraft and the need to maximize payload capacity. This same reasoning applies to shipping and heavy-duty trucks. Electric battery storage devices have a low energy density, which can be significantly improved by using fuel tanks that store liquid or gaseous hydrogen-derived fuels.

Moreover, the dimensions of the infrastructure cannot be overlooked. In some contexts, the electricity grid would require substantial upgrades to accommodate distributed charging capacity, especially since many regions in Europe are experiencing significant congestion problems (e.g., the Netherlands). Hydrogen can play a role in alleviating stress on medium- to high-voltage electricity infrastructure by leveraging different strategies, such as local production of green hydrogen, utilizing dedicated pipelines, or even blending hydrogen into natural gas networks. This approach optimizes hydrogen production when residual demand is low while taking advantage of relatively inexpensive hydrogen storage facilities compared to stationary batteries.

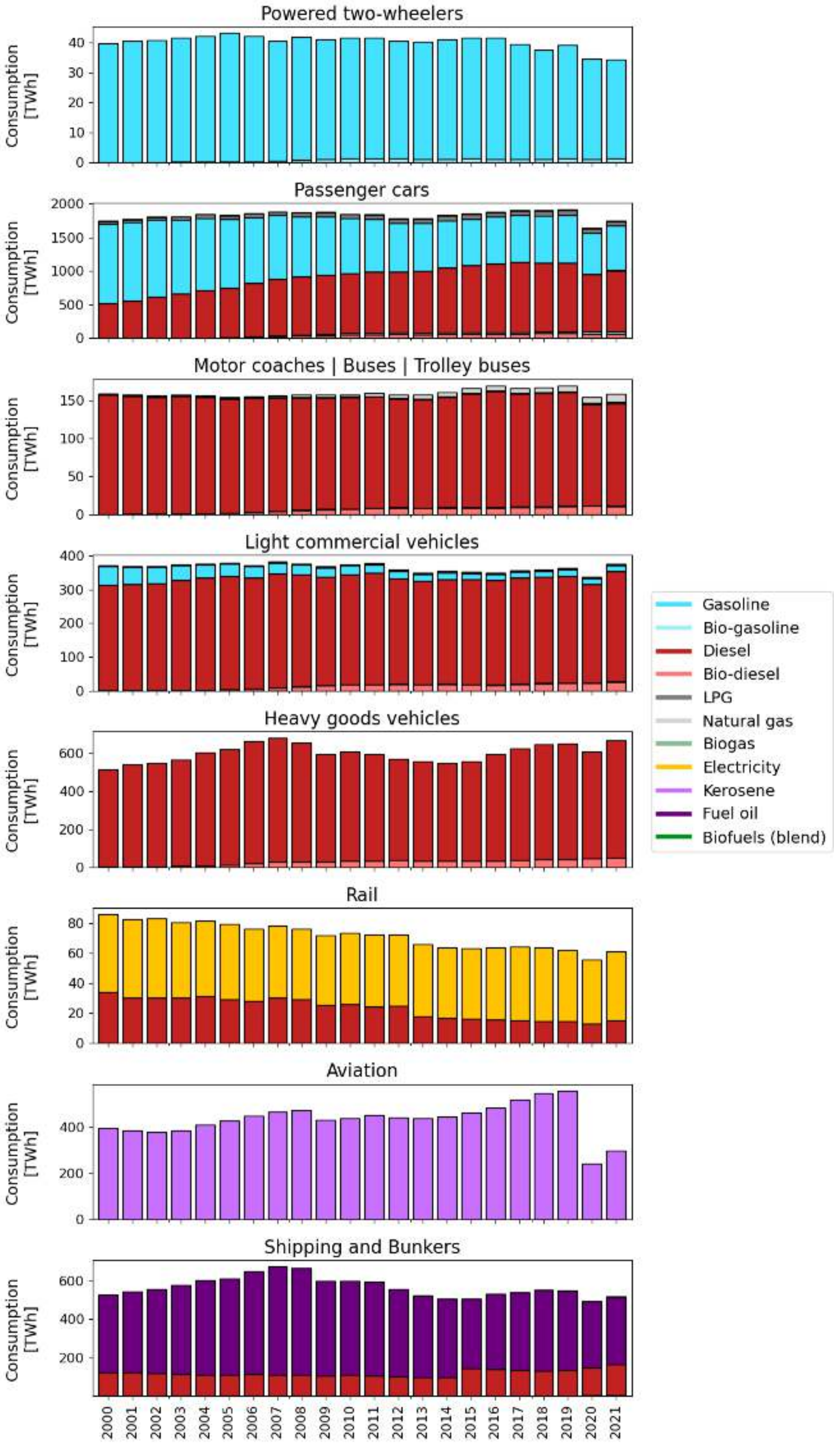

Figure 2 -Transport subsector consumption by fuel in EU.
(Source: JRC-IDEES-2021 .2024 [4])

For all the above-mentioned reasons, hydrogen is a promising candidate for decarbonizing a wide range of end uses, which can be broadly categorized into several sectors:

Direct use of hydrogen involves Fuel Cell Electric Vehicles (FCEVs) and Internal Combustion Engine Vehicles (ICEVs) powered by hydrogen. FCEVs are powered by hydrogen fuel cells that convert hydrogen into electricity, emitting only water vapor as a byproduct. These vehicles are particularly promising for heavy-duty road transport, such as trucks and buses, where battery-electric solutions face challenges related to range and refueling time. FCEVs offer quick refueling times and longer driving ranges compared to battery electric vehicles (BEVs), making them a practical option for long-haul transportation [5]. Hydrogen-powered ICEVs, though less common, are another direct-use option. These vehicles burn hydrogen in modified internal combustion engines, providing a transition technology for industries already heavily invested in internal combustion infrastructure.

The ***indirect use*** of hydrogen in transport involves the production of hydrogen-derived fuels. These synthetic fuels, often referred to as e-fuels, include liquid or gaseous carbon-based fuels like synthetic natural gas (SNG), dimethyl ether (DME), methanol (MeOH), and Fischer-Tropsch (FT) diesel equivalents. These fuels are produced through the hydrogenation of CO_2, creating a carbon-neutral energy vector when renewable hydrogen is used in the process. E-fuels can be used in existing internal combustion engines with minimal modifications, offering a low-carbon solution for the transport sector without requiring a complete overhaul of the current vehicle fleet [6]. E-fuels are particularly relevant for sectors such as aviation, shipping, and heavy-duty trucking, where electrification poses significant technical and economic challenges.

Standing the definition given by the RED III, hydrogen can be considered as RFNBO if it is produced with Renewable Energy Sources (RES) that meet the criteria of:

- *Additionality*: from 2028 electricity coming from RES which have not received incentives and newly installed (installed maximum 36 months before the electrolysis system)
- *Geographical correlation*: electricity generated in the same bidding zone or in zones
- interconnections to the area of use
- *Temporal correlation*: electricity produced in the same month of use until 2030,
- at the same time from 2030.
- *Reduction of greenhouse gas emissions by 70%* compared to fossil fuels (94 gCO2/MJ)
- *use of electricity* from the grid with renewable penetration >90%
- *use of electricity* from the grid in areas with emissions < 18 gCO2/MJ)

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However, the widespread adoption of hydrogen in transport faces challenges related to storage and reliability. Storing hydrogen in a vehicle requires significant space, as hydrogen has a low energy density by volume, even in its compressed or liquefied forms. This makes storage a more critical issue for long-distance and heavy-duty applications compared to weight, which is less of a concern for hydrogen.Infrastructure development is becoming indeed an essential factor in hydrogen diffusion for transport. A robust network of hydrogen refueling stations and supply chains is required to support hydrogen-powered vehicles, especially in large-scale applications like shipping, which rely heavily on harbor infrastructure. Without significant investment in these areas, the widespread adoption of hydrogen for transport will remain limited.Hydrogen presents a viable path for decarbonizing the transport sector, particularly in applications that face difficulties with direct electrification (hard -to abate sectors). However, its successful diffusion will depend on overcoming challenges related to storage, reliability, and infrastructure development.

2.3 The European Roadmap

The European strategy for hydrogen focuses on developing large-scale production of green hydrogen to meet both domestic energy needs and decarbonization goals. Producing the hydrogen required today would demand 3600 TWh/year of electricity, more than the EU's current energy production. Green hydrogen, produced via electrolysis using renewable energy, is central to this strategy. Key projects, such as Shell's Holland Hydrogen I, demonstrate Europe's commitment to expanding capacity. This 200 MW electrolysis plant, connected to an offshore wind farm, is set to become operational in 2025, marking a significant step in scaling up hydrogen production.

The EU's REPowerEU strategy targets the production of 10 million tons (Mt) of hydrogen annually by 2030, with an additional 10 Mt imported. To meet these goals, Europe is ramping up manufacturing capacity, reaching 3.9 GW/year in 2023, with a potential output of 23.4 GW by 2030. However, this still falls short by 40%, indicating that further investment and innovation will be needed to achieve the targets .

The current roadmap based its fundamentals on 3 main policy packages set in following years.

The EU hydrogen strategy (2020), Fit-for-55; RePower EU.

The **EU Hydrogen Strategy,** introduced in 2020, marked a pivotal step toward achieving a climate-neutral Europe by 2050. The strategy identifies hydrogen as a key enabler of decarbonization across various sectors, particularly those difficult to electrify, such as heavy industry and transport. The EU outlined a comprehensive framework of political actions, emphasizing the need for coordinated investment, fostering hydrogen production, and creating robust market structures and infrastructure. Key objectives are grouped into five main areas: implementing investment plans; supporting production; ensuring demand growth and infrastructure development; and fostering research and innovation in hydrogen technologies [7].

The **Fit for 55** package, launched in 2021, serves as a cornerstone of the EU's efforts to reduce greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. It promotes cooperation both within Europe and with international partners to meet its ambitious climate goals. Several legislative initiatives stem from this package, such as the:

- *Alternative Fuels Infrastructure Regulation* (AFIR), CO2 standards for vehicles, and
- *Renewable Energy Directive* (RED III).

The Hydrogen and Decarbonised Gas Market Package, introduced under the *Fit for 55* framework, is critical for establishing regulatory certainty, fostering cross-border hydrogen trade, and developing infrastructure across Europe [8].

The **RePower EU plan**, introduced in 2022, complements the EU Hydrogen Strategy by accelerating the deployment of renewable hydrogen and its derivatives, such as ammonia, particularly in sectors that are hard to decarbonize. This initiative aims to reduce the EU's dependence on Russian fossil fuels while accelerating the green transition. The Recovery and Resilience Facility (RRF) allocates at least 37% of its funding to green transition measures, including hydrogen. Key hydrogen initiatives under RePower EU include IPCEI projects like *Hy2Tech*, *Hy2Use*, and upcoming projects like *Hy2Infra* and *Hy2Move*. Additionally, the establishment of the *Hydrogen Bank* seeks to create a functioning market for renewable hydrogen and attract investments [9].

2.3.1 The EU Hydrogen Strategy

Hydrogen is a key element of the EU's Green Deal and its "Energy System Integration Strategy." The focus is on developing renewable hydrogen, with projected investments ranging from €180 to €470 billion by 2050. The EU expects this green hydrogen economy to generate 1 million high-skilled jobs by 2030 and 5.4 million by 2050.
The "2×40 GW Green Hydrogen Initiative," launched by Hydrogen Europe in 2020, aims to scale up hydrogen production, targeting 40 GW (173 TWh) within the EU and an additional 40 GW (118 TWh) in Ukraine and North Africa. Total investment is estimated at €430 billion, including €145 billion in grants and subsidies.Germany's national hydrogen strategy, introduced in June 2020, commits €9 billion to green hydrogen projects. €7 billion will support domestic efforts, while €2 billion will fund projects in Ukraine and Morocco. The country aims to establish 5 GW of electrolyser capacity by 2030 but faces high costs, raising concerns among experts about the economic viability of green hydrogen from intermittent renewable sources. The European Union's hydrogen strategy, adopted in July 2020 (COM/2020/301), outlines a comprehensive plan to foster the growth of renewable hydrogen as a cornerstone of Europe's decarbonization goals. This strategy focuses on advancing hydrogen technologies, increasing demand, and establishing a competitive hydrogen market, with the ultimate goal of achieving climate neutrality by 2050[10].

The newly adopted EU regulatory framework for hydrogen is a complex combination of economic and legal instruments to fight climate change and support the energy transition, ranging from the establishment of binding targets rules and standards (i.a RED and Delegated Acts), putting a price on carbon emissions (EU ETS and CBAM) or establishing financial incentives (i.a. EU Hydrogen Bank):

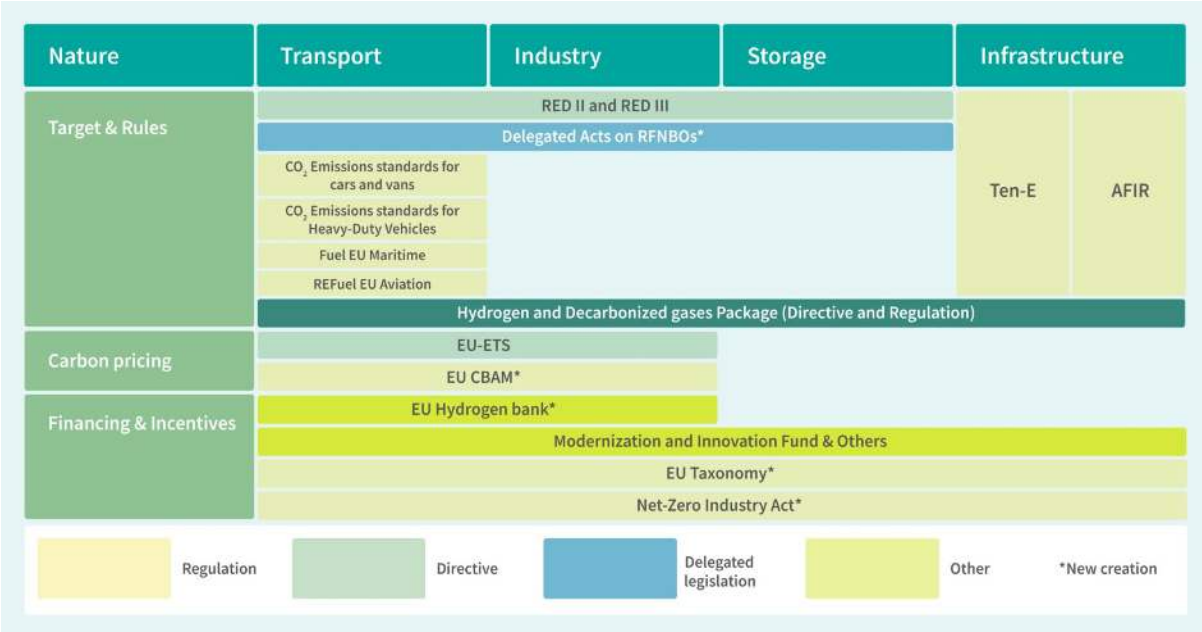

Figure 3: The EU hydrogen strategy framework
(*Source* http://ptx-hub.org *[10]*)

Key Actions:

The strategy outlines 20 key actions to accelerate hydrogen adoption across the EU. It includes large-scale investments, with plans to mobilize up to €430 billion by 2030. Among these, the European Clean Hydrogen Alliance is a central initiative aimed at bringing together stakeholders from the private and public sectors to implement hydrogen projects. Furthermore, hydrogen plays a significant role in national recovery and resilience plans of several member states, reflecting the importance of hydrogen in their energy transition efforts (Table 1).

Renewable Hydrogen Production and Demand:

The strategy sets ambitious goals for renewable hydrogen production, particularly through the Renewable Energy Directive (RED III), which promotes renewable energy use across industries. In addition, initiatives like the Alternative Fuel Infrastructure Regulation (AFIR) and the European Hydrogen Backbone emphasize the development of hydrogen infrastructure, including pipelines and refueling stations, to support growing demand.

Market Creation and Cooperation:

Creating a robust hydrogen market requires regulatory frameworks and financial mechanisms. The European Hydrogen Bank is proposed to ensure market liquidity, while the review of the EU Emissions Trading System (EU ETS) and carbon contracts foster competitiveness. The Clean Hydrogen Partnership, with €1 billion from Horizon Europe and another €1 billion from industry partners, supports R&D efforts. Additionally, the S3 Partnership for Hydrogen Valleys integrates regional and industrial actors to create hydrogen hubs.

Global Cooperation:

The EU also aims to promote hydrogen in international partnerships, such as the Africa-EU Green Energy Initiative, and to play a leadership role in the Clean Hydrogen Mission, supporting projects in over 30 countries.

Table 1: 20 key actions in the European hydrogen strategy (COM/2020/301)

20 key actions in the European hydrogen strategy (COM/2020/301)
Investment plans to stimulate hydrogen adoption
• European Clean Hydrogen Alliance
• National recovery and resilience plans (hydrogen present in individual country plans)
Initiatives to increase the demand and production of renewable hydrogen
• Strategy for sustainable and intelligent mobility
• Renewable Energy Directive (RED III)
• Review of Carbon Contracts and Emissions Trading System - EU ETS
Support the creation of the hydrogen market and foster European cooperation
• Trans-European Energy Infrastructure/European Hydrogen Backbone Regulations
• Alternative Fuel Infrastructure Standard (AFIR)
• European Parliament directive for internal hydrogen markets
• European Hydrogen Bank
• Creation of the Clean Hydrogen Partnership (1000 M€ from Horizon & 1000 M€ from partners
• industrial)
• S3 Partnership for Hydrogen Valleys
Promote international cooperation
• Increase European guidance for the definition of standards, regulations
• Co-leader in the Clean Hydrogen Mission (83 projects on Hydrogen Valley projects in 33 countries)
• Production of renewable hydrogen under the Africa-EU Green Energy Initiative
• Increase the strength of the Euro in international transactions

2.3.2 EU Hydrogen distribution networks

Continental network

The development of continental networks dedicated to hydrogen is essential to the European Union's objective of creating a robust hydrogen economy.

Five main corridors are planned for hydrogen supply (Figure 2): North Africa to Southern Europe, Southwestern Europe to North Africa, the North Sea region, the

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Nordic and Baltic regions, and Eastern to Southeastern Europe. The project is evolving rapidly, with significant growth expected in the northern and eastern regions of Europe. A major initiative within this framework is the **South H2 Corridor (Corridor A),** a Project of Common Interest (PCI), which will span 3,300 km.
This pipeline system will transport hydrogen from North Africa to Italy, Austria, and Germany.

Figure 4: 5 main continental corridors for EU H2 supply (Source http://ehb.eu)

Italy, through SNAM and its well-developed national infrastructure, is poised to play a critical role, particularly in achieving the EU's target of importing 4 million tonnes per annum (Mtpa) of hydrogen from North Africa, which will account for 40% of the EU's total hydrogen import target. The integration of European hydrogen valleys with those in Italy and non-EU regions will further solidify this network, making it fundamental to Europe's clean energy future.

The European Hydrogen Backbone (EHB)

One key initiative is the European Hydrogen Backbone (EHB), launched in 2020, which involves SNAM and 10 other European infrastructure operators. This network aims to connect hydrogen production and consumption areas across Europe, with plans for expansion into non-EU regions.

The European Hydrogen Backbone (EHB) offers a pathway to accelerate the decarbonization of the energy sector by enabling the integration of large volumes of renewable and low-carbon energy. It also connects regions with abundant supply to major demand centers. The EHB can further revitalize Europe's industrial sector while enhancing energy system resilience, independence, and security of supply across the continent.

Achieving this vision cost-effectively requires close cooperation between EU Member States and neighboring countries, along with a stable, supportive, and flexible regulatory framework to facilitate its implementation. The proposed infrastructure pathway to 2040 reflects the vision of 32 European network operators, grounded in national analyses of existing natural gas infrastructure, anticipated natural gas market trends, and future hydrogen market developments within an ambitious climate scenario. However, the final infrastructure solution will largely depend on evolving supply and demand dynamics in the integrated energy system, encompassing natural gas, hydrogen, electricity, and heat. As hydrogen supply and demand grow and energy system integration deepens, alternative or additional routes may emerge, potentially shifting the timelines of some routes proposed for 2030 and 2040.

The EHB initiative welcomes discussions on its vision with stakeholders, including policymakers, companies, and other actors in the hydrogen value chain.

EHB[1] is a project aiming to establish a trans-European hydrogen transport network by repurposing existing natural gas pipelines and constructing new ones. This network will enable the transportation of renewable hydrogen across Europe, supporting the decarbonisation of the sector. The EHB project is a key step towards achieving the European Union's goal of becoming climate-neutral by 2050.

Key lessons learned include reducing costs by using existing infrastructure for hydrogen transport, effective cross-border coordination among EU member states, and designing the network with scalability for gradual expansion.

The vision of the EHB is to provide a**:** connective hydrogen infrastructure provides the most cost-effective solution for supplying the hydrogen economy, with a pan-European network projected to save €330B as compared to a clustered

[1] EHB (2023). Implementation roadmap -Cross border projects and costs update. Source: EHB-2023-Implementation-Roadmap-Part-1.pdf

approach [11] (Figure 3)

Figure 5. The vision of hydrogen pan-European network underneath EHB.

Additionally, the EHB project highlights the importance of collaboration between the public and private sectors to drive innovation and investment in sustainable energy solutions. By using the existing natural gas infrastructure, the transition to renewable hydrogen can be accelerated, paving the way for a greener future in Europe.

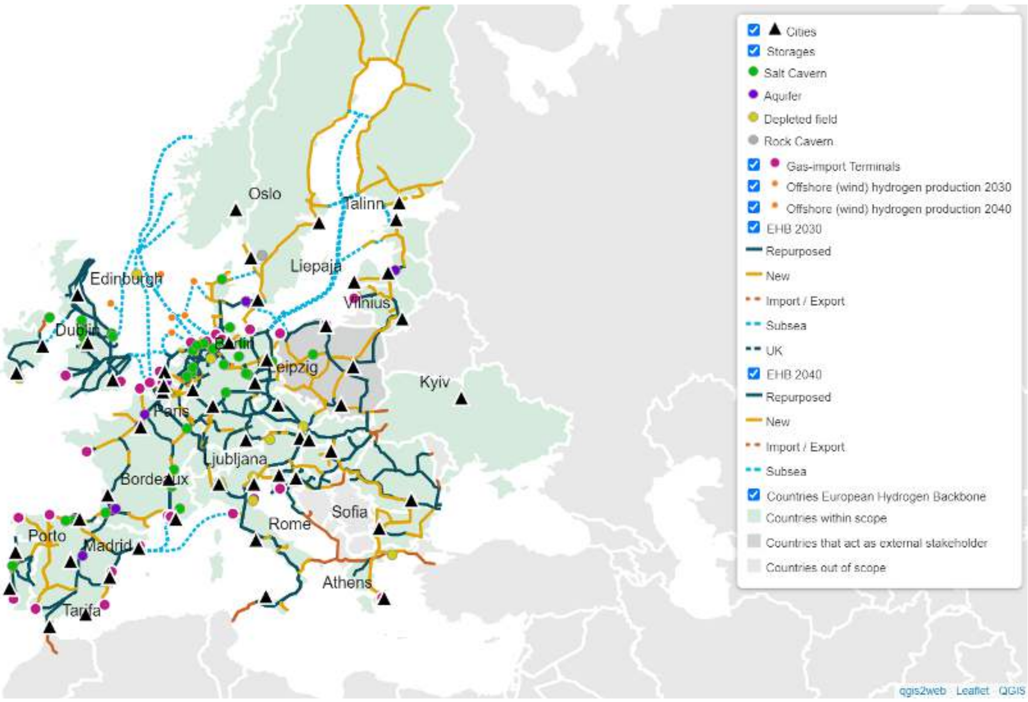


Figure 6. The European Hydrogen Backbone EHB

(Source : https://ehb.eu/maps/202307/index.html#4/53.00/13.01)

However, large-scale infrastructure projects like EHB require substantial financial investment, which can be challenging to secure, especially for cross-border initiatives involving multiple stakeholders. The main strategy involves leveraging a combination of public-private partnerships, EU funding mechanisms, and strategic investments from member states.

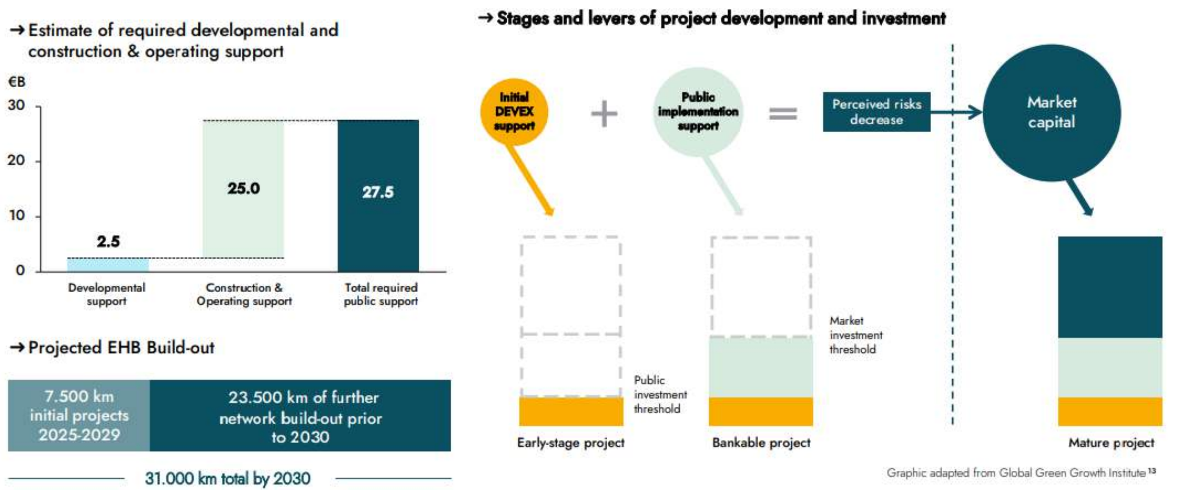


Figure 7. Financial plans for the implementation of the EHB [12]

Hydrogen Infrastructure Map

The hydrogen infrastructure projects (distribution, transport, storage) have been mapped into one interactive map, the «Hydrogen Infrastructure Map» (www.h2inframap.eu).

The "Hydrogen Infrastructure Map" (www.h2inframap.eu) offers a comprehensive, interactive platform that consolidates key hydrogen infrastructure projects across Europe. It provides a detailed overview of the various initiatives related to hydrogen distribution, transport, and storage. By mapping out these projects, the platform allows users to visualize the interconnectedness of the hydrogen economy, helping to identify gaps, opportunities, and progress in infrastructure development. The map is particularly useful for policymakers, industry stakeholders, and researchers looking to assess the readiness and expansion of hydrogen networks. It promotes collaboration by making essential data on pipelines, storage facilities, and transport routes easily accessible. As Europe pushes towards a more sustainable energy future, this map serves as a vital tool in tracking and fostering the growth of the hydrogen sector, supporting the region's ambition to lead in clean energy innovation.

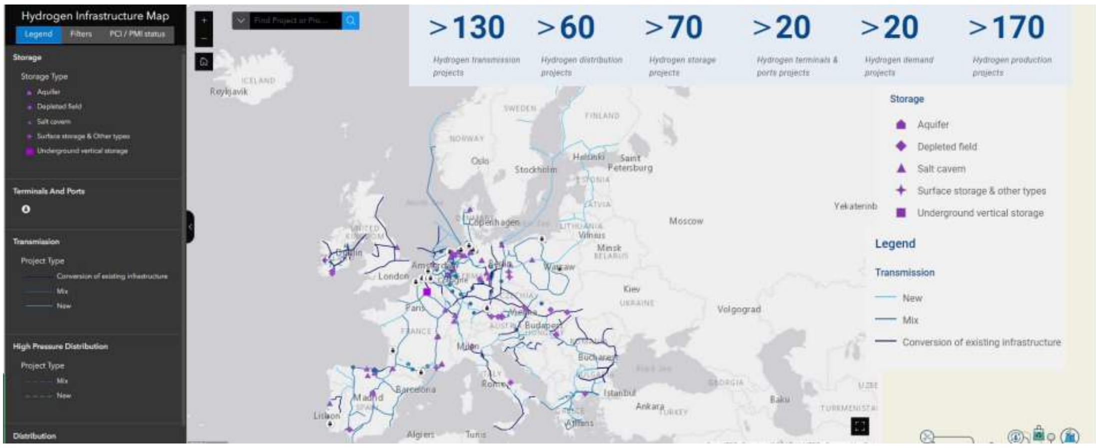


Figure 8. The «Hydrogen Infrastructure Map» and some statistics regarding the mapped infrastructures (Source : www.h2inframap.eu)

Future development plans for EHB

REPowerEU: production target of 10 million tonnes of renewable hydrogen in the EU and import of others 10 million tonnes by 2030.

The «European Hydrogen Backbone» initiative (www.ehb.eu) aims to create a transport system and distribution of hydrogen in Europe, identifying several hydrogen corridors.

The strategy for EHB development focuses on increasing green hydrogen production and infrastructure to meet ambitious energy targets.

In 2021, the European Commission set a goal of producing 5.6 million tons of sustainable hydrogen by 2030 under the "Fit for 55" initiative. However, in response to the energy crisis caused by the curtailment of Russian gas supplies, the REPowerEU program significantly raised this target in 2022 to 20 million tons. This includes 10 million tons of domestic production and 10 million tons from imports.

To achieve this, the hydrogen infrastructure will be developed in three phases [13].

- **Phase 1:** (today to 2030) involves the construction of 11,600 km of hydrogen pipelines, connecting 21 European countries. Main corridors will link high green hydrogen production areas, such as Northern Europe, with major industrial and urban consumption centers.
- **Phase 2:** (2030–2040) expands the network to 39,700 km, covering nearly all of Europe and enhancing cross-border connections.
- **Phase 3:** (post-2040) envisions a fully integrated 50,000 km network that supports widespread hydrogen distribution and trading, fully integrating with other energy systems.

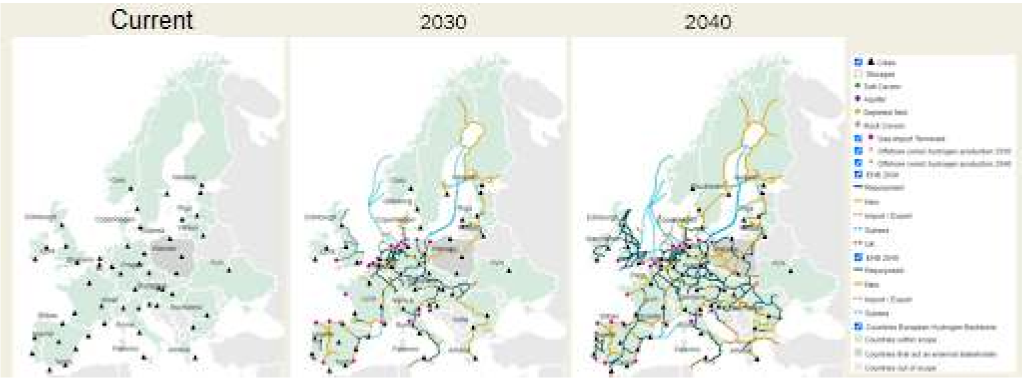


Figure 9. Different phases of the EHB Development Strategy
(Source : [12])

The ENTSOG Roadmap 2050

Even if not of strict interest for the green hydrogen production, in term of distribution networks also for a transition phase can be interesting the ENTSOG Roadmap 2050:
ENTSOG, the European Network of Transmission System Operators for Gas, represents operators of natural gas transmission systems in the EU and neighboring countries. Established in 2009, its key roles include:

- **Network development plans**: ENTSOG develops the Ten-Year Network Development Plan (TYNDP), identifying future infrastructure needs.
- **Grid codes**: It implements harmonized grid codes to ensure smooth cross-border gas transmission.

- **Transparency**: ENTSOG promotes openness about network capacity, gas supply, demand, and cross-border flows.
- **Operator cooperation**: It fosters collaboration among transmission operators to improve system safety and efficiency.
- **EU energy policy support**: ENTSOG supports EU energy goals, including supply security, sustainability, and competitiveness.

The ENTSOG Roadmap 2050 focuses on four main drivers:

- **Decarbonizing gas networks**: Gas systems will play a key role in the energy transition.
- **Incorporation of biomethane, hydrogen, and CCUS**: These technologies are vital to achieving a low-carbon future.
- **Ongoing role of natural gas**: It remains essential in the energy mix, offering potential to reduce CO2 emissions and pollution.
- **Hybrid energy systems**: Synergies between electricity and gas infrastructure will address energy transport, storage, supply security, and system resilience.

The ENTSOG Roadmap 2050 plays a crucial role in supporting hydrogen development in Europe by leveraging the existing gas infrastructure to facilitate a smoother and more cost-effective energy transition. Thus, ENTSOG's focus on infrastructure efficiency and collaboration across energy sectors directly supports the expansion and sustainability of hydrogen in Europe's energy future.

2.3.3 Other project and Case studies for the development of H2

Case study 2: Hydrogen Infrastructure for European Transport (H2ME)

H2ME[2] is a large-scale European initiative (run 2015-2022) that focused on expanding hydrogen refueling infrastructure across multiple countries. It aims to create a unified network to support hydrogen transport and usage across Europe. The H2ME project has revealed both progress and challenges in the adoption of Fuel Cell Electric Vehicles (FCEVs) and Hydrogen Refuelling Stations (HRS). The main challenges the H2ME project faced included scarcity of refueling infrastructure, permitting bottlenecks, limited vehicle offerings from Original Equipment Manufacturer (OEMs), high costs compared to Battery Electric Vehicles (BEVs), low utilization levels of existing HRS, and regulatory uncertainties.

[2] https://h2me.eu/about/hydrogen-refuelling-infrastructure/

Figure 10. Hydrogen Infrastructure for European Transport (H2ME)
Source: https://h2me.eu/about/hydrogen-refuelling-infrastructure/

Recommendations derived from stakeholder insights and project analyses emphasize the imperative for scale to drive down costs, sustained financial support for the roll-out of FCEVs and HRS, consistent policy frameworks, and clear market signals to instill OEM confidence in scaling production. Furthermore, calls are made for strategic HRS deployment plans to prepare for AFIR, enhanced equipment reliability, and designs tailored to high utilization to meet fleet expectations effectively. These insights demonstrate the ongoing need for collaborative efforts and sustained financial support beyond the H2ME project to overcome barriers and propel the widespread adoption of hydrogen mobility solutions to decarbonise transport across Europe.

Case study 3: North Sea Wind Power Hub (NSWPH)

NSWPH is a proposed project aiming to create a large-scale renewable energy hub in the North Sea. The project includes the production of green hydrogen and its transportation across multiple European countries including the Netherlands, Germany, and Denmark. The NSWPH masterplan outlines a roadmap for establishing a major hydrogen transport route across Europe, emphasizing the importance of regional cooperation and integrated planning in developing a sustainable hydrogen network. It involves collaboration between governments and major energy companies, extensive feasibility studies, and a comprehensive infrastructure plan including offshore wind farms, hydrogen production facilities, and transnational pipelines.

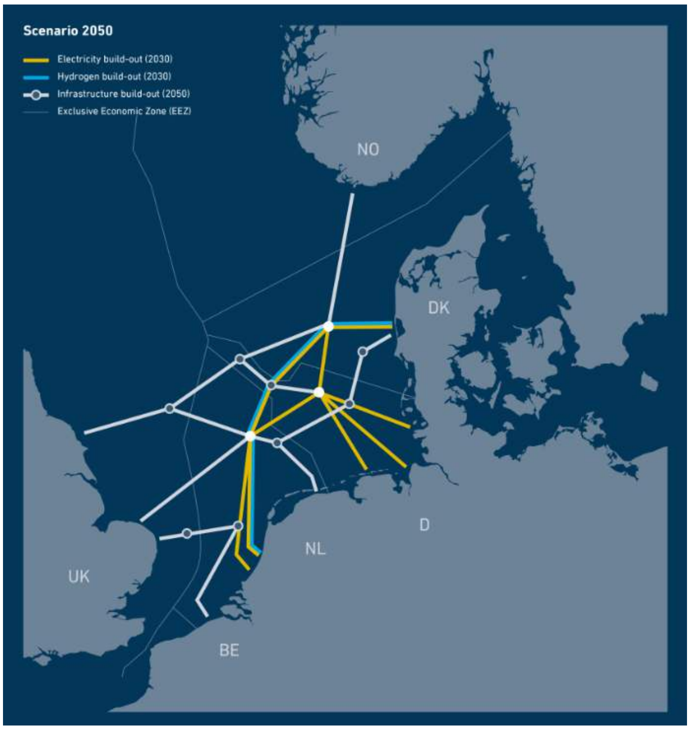


Figure 11. NSWPH masterplan

Source: https://northseawindpowerhub.eu/a-blueprint-the-new-energy-highways

The project is organized focusing on four overarching topics: system integration, technical feasibility, cost and benefits, and regulation and market design:

- System integration involves identifying multiple electricity corridors in the North Sea to connect offshore wind locations and transport energy via hubs to shore.
- Technical feasibility involves determining the technical design principles for individual system elements of a hub-and-spoke project, including substructure, high voltage direct current (HVDC) infrastructure, offshore electrolysis, and hydrogen infrastructure.

The H2MA project is co-funded by the European Union through the Interreg Alpine Space programme

- Cost and benefits calculations are done using cost-benefit analysis methodologies developed for the hub-and-spoke concept.
- Regulation and market design decisions are made by national and European governments to provide sufficient investment clarity for hub-and-spoke projects and offshore wind roll-out.

Case study 4: H2Med project

H2Med project[3] aims to establish a hydrogen corridor connecting Southern Europe with Central and Northern Europe, utilising the existing natural gas infrastructure for hydrogen transport. H2Med intends to connect significant hydrogen production locations in Southern Europe, mainly Spain and Portugal, with key industrial hubs and hydrogen consumption centres throughout Europe. This geographical coverage is critical for maintaining a consistent supply of hydrogen to high-demand areas.

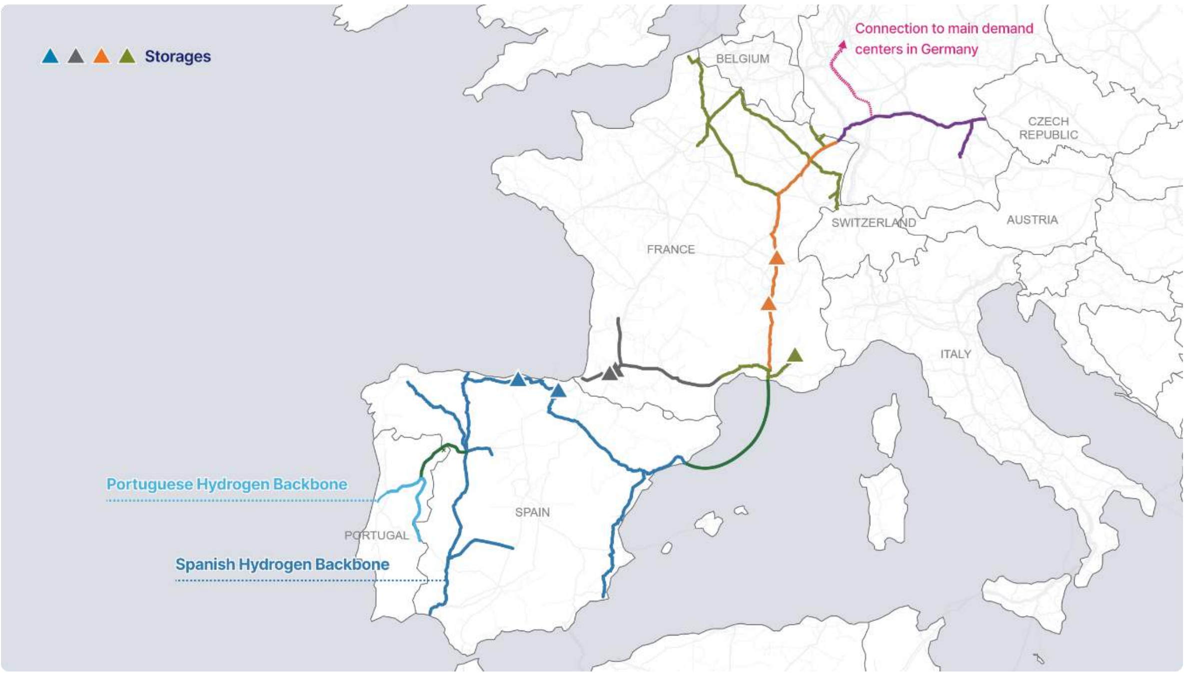


Figure 12. Identification of the routes proposed by the H2Med project
(Source: https://h2medproject.com/the-h2med-project/)

The project focuses on the creation of green hydrogen with renewable energy sources such as solar and wind power. This integration contributes to minimising the carbon footprint and aligning with the EU's decarbonisation objectives.

H2Med receives strong regulatory and policy support on both the national and EU levels. This assistance comprises financial incentives, accelerated permitting processes, and harmonised legislation to facilitate cross-border hydrogen transportation. The project is

3 https://h2medproject.com/

designed to be scalable and flexible, allowing for gradual development and expansion based on demand.

In this context, the H2Med project could offer some insights for partners in peer review and masterplan development including utilising existing infrastructure, ensuring strategic coverage of production and consumption areas, integrating renewable energy, utilizing regulatory support, planning for scalability, and fostering cross-border collaboration.

Case study 5: AMETHySТ

AMETHySТ aims to support the deployment of local Alpine green hydrogen ecosystems to pave the way for a post-carbon lifestyle in the Alps. The project wants to reinforce the role of public authorities by increasing their capacity, designing support services to roll out green hydrogen solutions and including green hydrogen in local and regional energy strategies and plans.

AmeThyst is delivering:

- **Piloting H2 Territorial Ecosystem**: This output defines and details the concept of local Alpine green hydrogen ecosystems. For each pilot project, an implementation plan covers objectives, activities, technical solutions, and cost estimates. It focuses on green hydrogen production, storage, grid services, distribution, and multi-use in tourism areas.
- **Development Guideline for Local Alpine Green Hydrogen Ecosystems**: A step-by-step methodology (OT2.2) is being developed to guide the design, experimentation, and evaluation of green hydrogen applications in local Alpine ecosystems. It includes a review of suitable hydrogen technologies, a techno-economic feasibility assessment, and an evaluation of environmental and social impacts. Based on pilot testing from WP2, this guideline helps upscale projects to other Alpine regions. It is targeted at public authorities and hydrogen project developers and will be available in Alpine languages on the WP1 platform.
- **Financial Evaluation Toolkit for Alpine Green H2 Ecosystems**: A toolbox is being created to assess the financial planning of green hydrogen projects, using a techno-financial model applied to various end-uses like transportation, snow groomers, production, and storage. With site-specific data, the toolkit evaluates project sustainability and emissions reductions. It will be embedded in WP1 and shared with municipalities and associations.
- **Policy Guidelines for Implementing Local Alpine Green Hydrogen Ecosystems**: Policy guidelines are being developed to help regional and local authorities integrate green hydrogen into energy planning and foster local ecosystems. These

will be broadly disseminated and shared with public authorities at the Final Conference.

Case study 6: H2iseO Hydrogen Valley

The “” is a project realised by FNM, FERROVIENORD and Trenord. The objective of the project is to foster hydrogen diffusion and decarbonization of the Brescia-Iseo-Edolo railway line with the construction of infrastructures for the production and distribution of hydrogen in the area, to support the local economic and industrial sector.
More at: https://www.fnmgroup.it/h2iseo_hydrogen_valley/

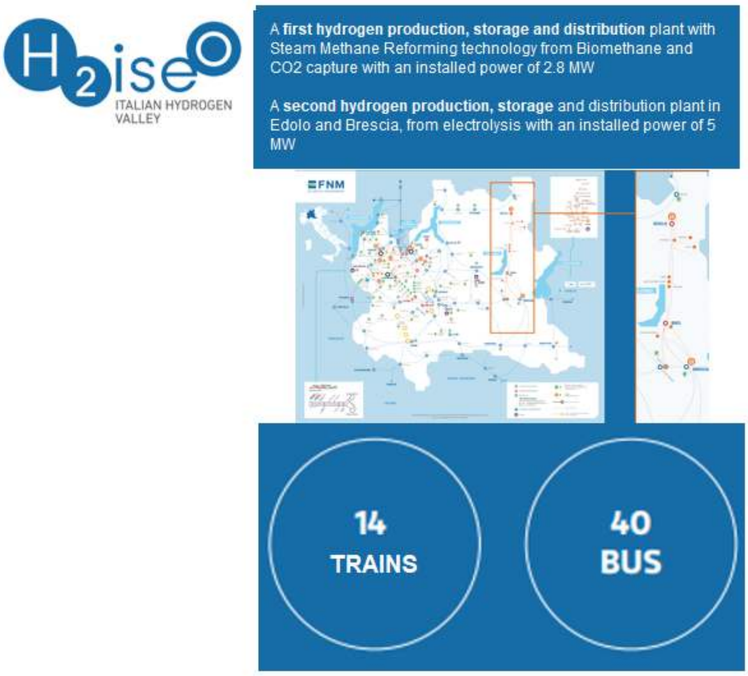


Figure 13 -H2iseO Hydrogen Valley Concept
(Source - Regione Lombardia and
https://www.fnmgroup.it/h2iseo_hydrogen_valley/)

2. Methods and Process for developing the H2MA Masterplan

2.1 Local Working Groups and regional routes

The Green H2 Mobility Masterplan for the Alpine Space has been generated through a collaborative and codesign process involving Local Working Groups (LWG) in each region of the project beneficiaries. Each region's LWG was tasked with developing regional routes and strategies, ensuring that the masterplan reflects localized needs and solutions while contributing to the broader transalpine vision.

2.3.1 Process Overview:

Local Working Groups (LWGs) have played a crucial role in the development of regional strategies for green hydrogen mobility.

Their primary function has been to facilitate a bottom-up approach, ensuring that regional insights, challenges, and opportunities are integrated into broader strategic frameworks.

Each LWG has been composed of local stakeholders, including government representatives, industry experts, and other regional players who have a deep understanding of the area's specific needs and resources.

The organization of the LWGs has been structured around participatory workshops, where members collaborate to identify potential regional routes for hydrogen mobility, discuss the infrastructure requirements, and gather stakeholder feedback (Figure 12).

These workshops encouraged active dialogue, fostering collaboration between public and private sectors to ensure that the strategies developed are practical, region-specific, and aligned with the H2MA project's overall objectives.

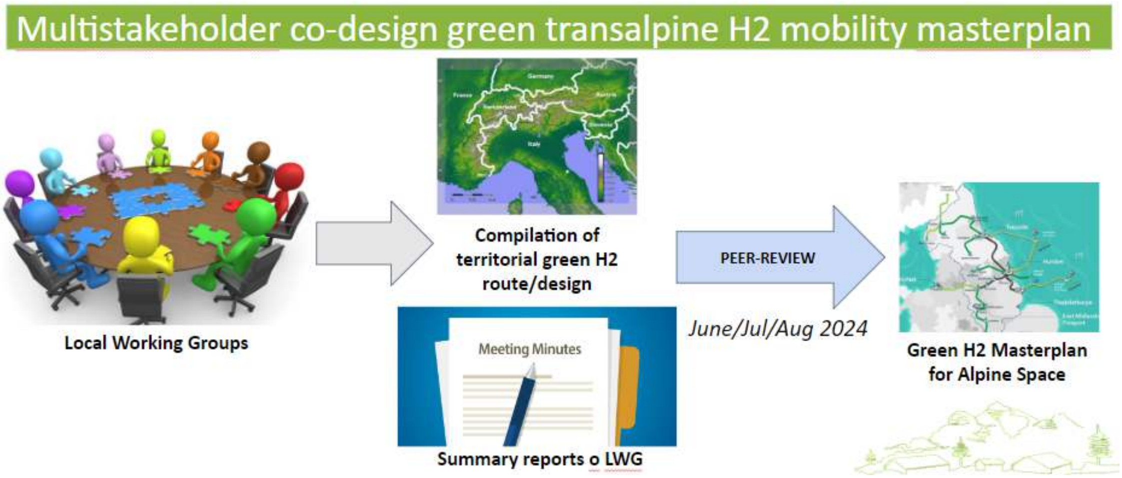


Figure 14 - Structure and Rationale of the Local Working Group (LWG)

The role of the LWGs extended beyond gathering regional data; they have also been instrumental in shaping the regional action plans that detail the steps necessary for deploying green hydrogen infrastructure.

Their work provided that the broader masterplan reflects not only the overarching goals of the H2MA project but also the unique requirements of each region.

Inputs to the LWG has been primarily the Input to *D2.1.1 Pilot Testing action plan with guidelines to establish and manage Local Working Groups* and *D2.1.2. Training package on green H2 mobility planning.* Moreover LWG has been provided of:

- **Introductory Video:** Each LWG (Local Working Group) received an introductory video that provided a comprehensive overview of the project, its objectives, and the role of the LWG. The video set the foundation by explaining key concepts, the importance of the working group's involvement, and the timeline of the project's phases.
- **Session Recordings:** Recordings of the initial Global Stakeholder Meetings were made available for review. These sessions contained important discussions from key stakeholders, offering insights into the project's expectations, challenges, and the collaborative approach. This allowed LWG members who couldn't attend the meetings live to stay informed and aligned with the broader goals.
- **Detailed Presentation Slides:** Each LWG was provided with a set of detailed presentation slides, which expanded on the project goals, methodology, and the responsibilities of the working groups. These slides served as a reference material, breaking down the technical aspects of the project and offering clear guidance on the next steps.
- **H2MA Tool Tutorial:** A tutorial for the H2MA (Hydrogen to Market Assessment) tool was shared, equipping LWG members with the knowledge needed to effectively use the tool. The tutorial covered its features, data input requirements, and how the

tool would assist in evaluating hydrogen market potentials, thereby aiding in strategic decision-making throughout the project.

As outputs, each Local Working Group (LWG) has contributed significantly to the project's progress through the following:

- **Regional Routes and Strategies:** Each LWG identified and developed regional pathways for the deployment of green hydrogen. These routes were designed to leverage local infrastructure, resources, and demand centers. The strategies outlined the key steps needed to integrate green hydrogen into the regional energy ecosystem, considering factors like transportation, storage, and distribution.
- **Stakeholder Feedback and Regional Insights:** LWGs gathered valuable input from various stakeholders, including government bodies, private sector participants, and local communities. This feedback provided a deeper understanding of the regional challenges, opportunities, and priorities regarding green hydrogen. The insights helped shape a more tailored approach, ensuring the project aligns with local needs and capabilities.

These two types of output have been collected into the H2MA deliverables *D2.2.1 Summary report of local working group meetings* and *D2.2.2 Compilation of Green Territorial H2 route plan design.*

2.3.2 H2MA tool

The work of the LWGs has been supported by the **H2MA tool**, a software developed inside the H2MA project with the support of Fondazione Politecnico di Milano.

The H2MA tool has been built with the idea of supporting local authorities in hydrogen mobility planning by identifying optimal H2 infrastructure for mobility, enhancing decision-making for sustainable transportation solutions.

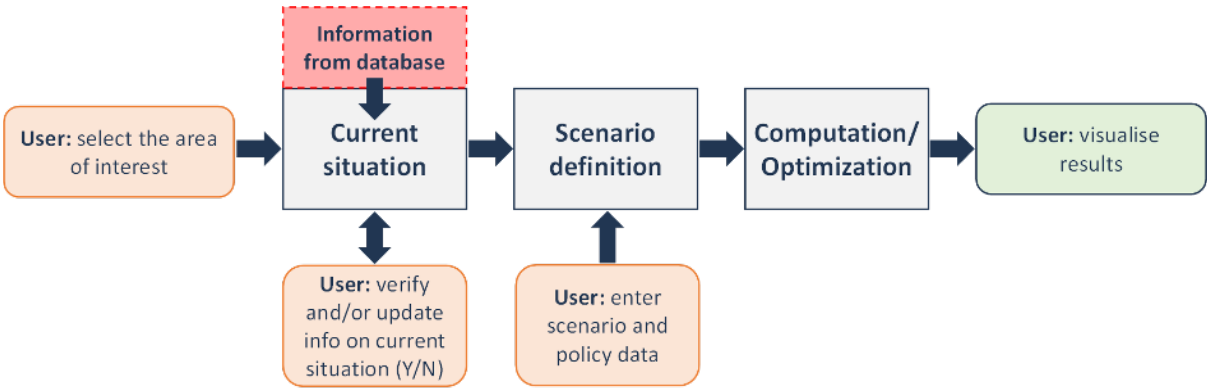


Figure 15 - *Structure of the H2MA tool*

The H2MA tool includes an integrated database of the Alpine Space region, encompassing data on existing hydrogen infrastructure, such as **production plants and refueling stations**, and **candidate networks for hydrogen delivery,** identifying potential pathways between production sites and demand areas. It also includes economic and demographic data, with assessments provided at the NUTS-2 level for the regions involved in the H2MA project (Figure 16).

The tool allows for the inclusion of new areas, provided that data are submitted in a format compatible with the H2MA database, ensuring comprehensive and consistent analysis.

Figure 16. *Subdivision of H2 routes calculation in NUTS-2 levels*

Information on existing and planned H2 production plants and HRSs accessible through an interactive map (Figure 17)

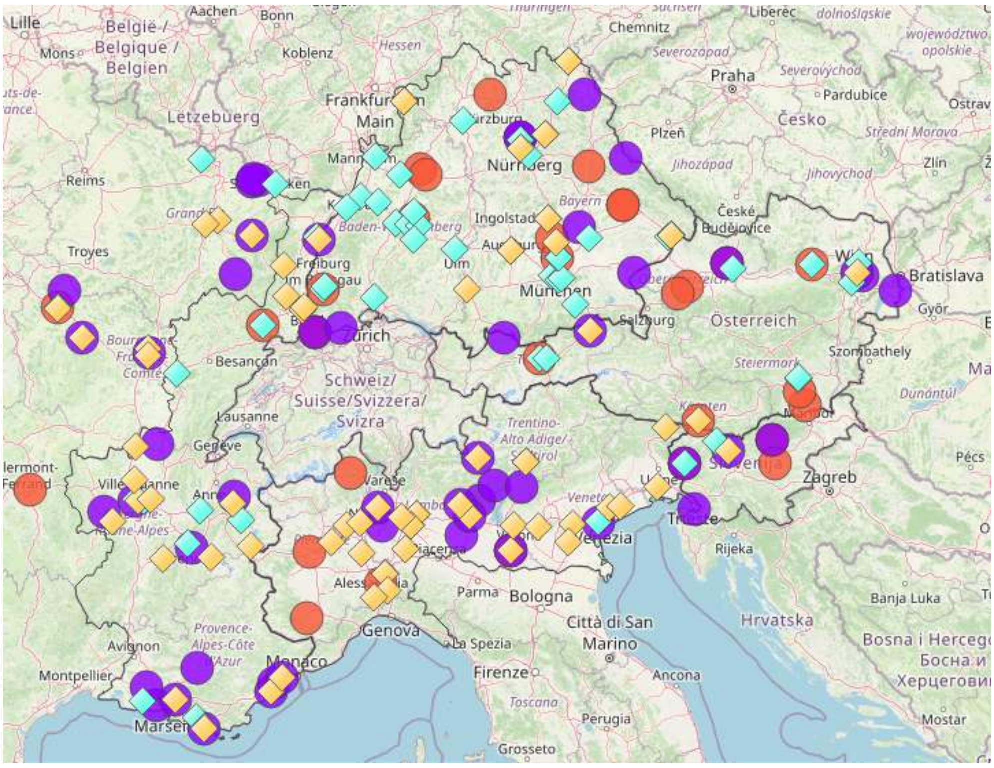


Figure 17 - *Existing and planned hydrogen infrastructures*

H2MA tool workflow

First of all the tool starts with the scenario definition of the hydrogen demand, considering the following parameters:

- FCEV penetration by vehicle category
- H2 supply options (PV+electrolysis, Wind+electrolysis, onsite at HRSs, import)
- H2 delivery modality (pipelines, compressed H2 trucks)

The input of data is done by visualization/editing of H2MA database information

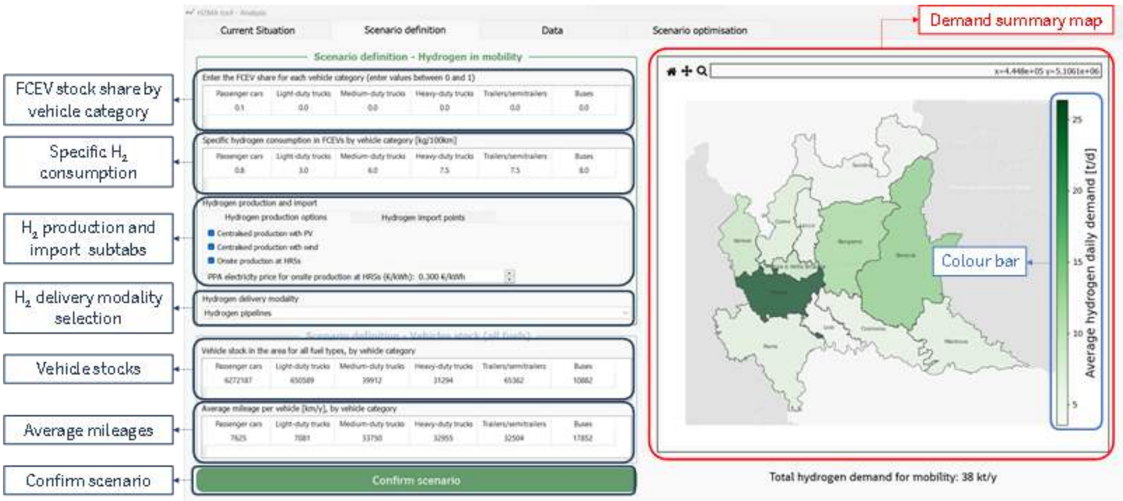


Figure 18 - Scenario definition of the hydrogen demand

Secondly the tool allows to define the shares of energy production by which carried hydrogen is generated. Table 1 resumes main classes and parameters considered by the model:

Table 2 - H2MA TOOL WORKFLOW – DEFAULT INPUT DATA

		CAPEX	OPEX	Lifetime	Performance and sizing parameters	
					Definition	Value
Photovoltaic		450 €/kW_p	2%CAPEX/y	20 y	Assigned generation profile by province (NUTS-3)	
Wind		1000 €/kW_{nom}	2%CAPEX/y	25 y	Assigned generation profile by province (NUTS-3)	
Electrolysis		600 €/$kW_{e,nom}$	2%CAPEX/y	20 y	Specific electric consumption	55 kWh_e/kg_{H2}
Hydrogen storage (pressurized metal tanks)		400 €/kg_{H2}	2%CAPEX/y	30 y	-	-
Hydrogen compressor		1500 €/$kW_{e,nom}$	4%CAPEX/y	15 y	Electric efficiency	63%
Hydrogen pipelines		6 M€/(km·m²)	4%CAPEX/y	40 y	Max section area	1.13 m²
Hydrogen delivery trucks (pressurized gaseous form)		400 €/kg_{H2}	2%CAPEX/y	20 y	Vehicle capacity	1000 kg
					Variable OPEX	1.6 €/km
Hydrogen refuelling stations		3 M€/(t_{H2}/d)	2%CAPEX/y	30 y	Maximum capacity	6 t/d
Hydrogen refuelling stations with onsite H_2 production	Station	3.5 M€/(t_{H2}/d)	2%CAPEX/y	30 y	-	-
	Electrolysis	720 €/$kW_{e,nom}$*	2%CAPEX/y	20 y	Specific electric consumption	55 kWh_e/kg_{H2}

The H2MA tool offers optimization and analysis capabilities to support hydrogen mobility planning. It uses a robust algorithm to identify the most efficient locations for hydrogen infrastructure, such as production plants, refueling stations, and delivery networks, based on current data and projected demand. By integrating spatial, economic, and demographic data, the tool conducts scenario-based analyses, evaluating different pathways for hydrogen delivery and their impact on mobility.

The optimization process considers factors like transportation costs, regional demand, and proximity to hydrogen production. It also enables sensitivity analysis to assess how changes in key parameters, such as population growth or economic conditions, affect hydrogen infrastructure needs. This comprehensive approach helps local authorities and stakeholders to make informed decisions about where to invest in hydrogen mobility solutions, ensuring both cost-efficiency and sustainability. The tool's flexibility allows for updates and adjustments as new data and regions are added, enhancing long-term planning accuracy.

The H2MA tool presents final results through interactive maps and tables, allowing users to visually explore hydrogen infrastructure scenarios and analyses. Users can navigate and filter data, such as **production sites, refueling stations, and delivery networks, with regional economic** and demographic overlays for deeper insights.

In addition to on-screen visualization, the tool enables users to save output maps and tables in various formats, including .xls for spreadsheets, .shp for geographic data, and .html for web-based presentations.

The H2MA project is co-funded by the European Union through the
Interreg Alpine Space programme

3. Description of the peer-review process

The peer-review process for the development of the transalpine green hydrogen masterplan has been implemented as a collaborative and iterative approach, in which partners assessed and optimized the local green hydrogen mobility routes developed. The objective of the process is to allow H2MA partners to

a. transfer their knowledge and perspectives from their own areas, and
b. to ensure the compatibility of the individual plans and their alignment with the overall objectives of the transalpine masterplan.

To this end, partners have provided input on key aspects of the local hydrogen plans, such as geographical coverage, environmental impact, cost efficiency, and adherence to EU and national guidelines.

3.1. Peer Review process

The peer review and assessment of the routes has been an essential step for their merging into a functional, economically viable transalpine green hydrogen masterplan since it will allow partners assess already prepared routes, iron out potential inconsistencies and inefficiencies and ensure that the Masterplan meets the foreseen quality standards and criteria (to be delineated in the following section). In particular, the peer review is expected to assess, inter alia, the following issues.

In the context of the transalpine masterplan, *green hydrogen routes* could include:

- **Production sites:** Locations where green hydrogen is produced using renewable energy.
- **Distribution networks**: Pipelines, roadways, and other transport methods for moving hydrogen from production sites to areas of demand.
- **Refueling stations**: Infrastructure for refueling hydrogen-powered vehicles, including cars, buses, trucks, and potentially trains.
- **Storage facilities:** Places where hydrogen can be safely stored for future use.
- **Integration Points:** Nodes that connect various elements of the hydrogen supply chain, ensuring efficient and continuous flow

3.1.1. Purpose

- **Quality assurance:** The peer review process will provide a second level of quality control for the separate routes developed during Activity 2.2

- **Discrepancies in the design philosophy** The green hydrogen routes, prepared in the context of A2.2, were developed individually by H2MA in cooperation with local stakeholder groups. Consequently, the approach and the network design philosophy that are adopted by the partners are expected to reflect the needs, challenges and maturity of the territorial green hydrogen ecosystems as well as broader characteristics of the respective countries (including, regulations, strategies, resources).
- **Compatibility between the hydrogen routes** Although efforts have been made by partners to ensure the efficiency and viability of the individual hydrogen routes as well as their compliance to the EU guidelines, it is possible that uncritically merging the different routes to form a transalpine Masterplan could introduce inefficiencies in the overall design.
- **Environmental risk management** All partners are expected to have taken into account environmental considerations and examined potential environmental risks when designing the territorial green hydrogen mobility plans.

3.1.2 Stages of the Peer-Review Process

The peer-review process was carried out through a structured set of questions designed to evaluate various aspects of each hydrogen mobility route. Participants assessed the local hydrogen plans with the goal of identifying strengths, weaknesses, and areas for improvement, laying the foundation for future refinement before the routes could be fully integrated into the masterplan. Although no direct changes were made during this stage, it provided crucial insights for the next steps. The process included the following stages:

- **Territorial coverage assessment**: The first stage focused on assessing the territorial reach of each proposed route. Participants evaluated whether the network provided sufficient coverage across the targeted regions, including key economic centers, industrial hubs, and major transportation corridors. They also examined the placement of hydrogen refueling stations (HRSs) to ensure minimal travel times and delays for consumers. This stage helped identify gaps in geographical coverage or areas that might require better station positioning to optimize the user experience.
- **Cost-effectiveness evaluation:** In this stage, participants assessed the economic viability of the hydrogen network. They reviewed whether the design minimized production and distribution costs, while avoiding unnecessary overlaps in infrastructure. Questions also addressed how well the network was aligned with projected future demand, ensuring that it would be both cost-efficient and

scalable. This assessment aimed to highlight areas where costs could be reduced or where infrastructure could be optimized for better efficiency.

- **Scale and alignment with future demand:** This stage examined the network's capacity to meet future hydrogen demand. Participants evaluated whether the production capacity, scale, and distribution network were adequate to support projected growth in green hydrogen use. They also assessed how strategically the infrastructure was placed to meet anticipated future demand, ensuring the network was both resilient and adaptable to changing needs.
- **Compliance with EU policies:** Participants evaluated how well the proposed routes aligned with EU hydrogen goals and guidelines. This included checking whether the distance between HRSs adhered to EU targets for heavy trucks and whether storage capacities met the required standards. The standards according to Article 6 of the Regulation include that ‘by the end of 2030, Member States must deploy at least one hydrogen refueling station **every 200km** on the TEN-T core network and at least one in every urban node (as defined by the TEN-T Regulation. Most importantly, the minimum cumulative capacity at every location must be **1 tonne per day**. Participants also reviewed whether the plan complied with local, regional, and EU regulations.’[4]
- **Environmental impact review:** This stage focused on assessing the environmental implications of the proposed hydrogen infrastructure. Participants evaluated the overall carbon footprint of the network and its potential impact on biodiversity, ecosystems, and water resources.
- **Compatibility and integration challenges:** In the final stage, participants reviewed how well the proposed routes integrated with other territorial plans, particularly in cross-border areas. They identified potential gaps in coverage and any overlaps in refueling station placement when considering the entire Alpine region. Differences in design philosophies, such as centralized versus decentralized hydrogen production or varied transportation methods, were flagged as potential challenges. This stage highlighted areas where network designs might need to be harmonized to ensure a smooth and efficient transnational system.

3.1.2. Peer-review form

The peer review process for evaluating the single routes in the H2MA project follows a structured approach using the Peer Review Form, as outlined in the D2.3.1 Peer Review Guidelines.

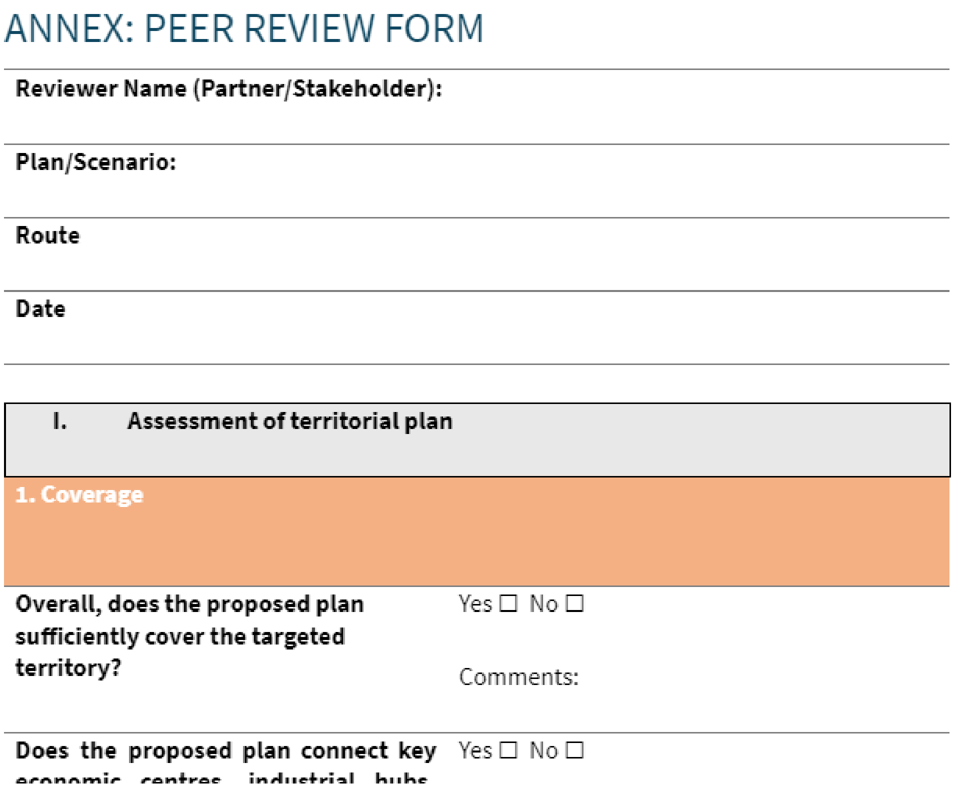
To begin, reviewers needed to connect to the link:

[4] https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf

[Peer Review Form](https://forms.gle/SrvCcbDEDKDY41Ux8).
After accessing the form, they are required to input their general information as reviewers. The evaluation process involved reviewing the single routes based on criteria specified in the D2.3.1 guidelines.
The form has been divided into sections, allowing reviewers to scroll through and assess each criterion related to the routes. At the end of the process, the review is submitted.
For each route, reviewers have access to key resources: the main folder, a presentation, and a visual map generated from the H2MA tool, which includes:

- Red dots for production sites
- Green dots for hydrogen refueling stations (HRS)
- Blue lines for transport networks
- Grey dots for imports (if applicable)

  Reviewers can modify their answers after submission and, if unsure about specific sections, can leave questions blank or skip sections entirely.

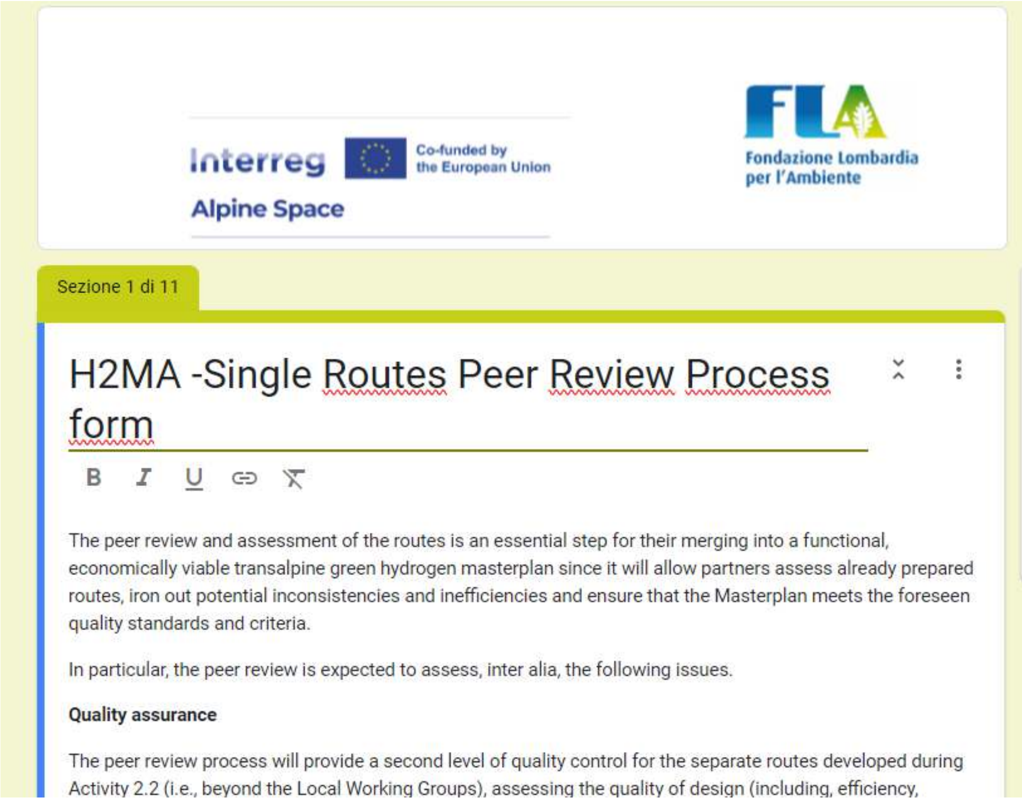


ANNEX: PEER REVIEW FORM

Reviewer Name (Partner/Stakeholder):	
Plan/Scenario:	
Route	
Date	

I. Assessment of territorial plan	
1. Coverage	
Overall, does the proposed plan sufficiently cover the targeted territory?	Yes ☐ No ☐ Comments:
Does the proposed plan connect key economic centres, industrial hubs	Yes ☐ No ☐

Figure 19 - *Peer review form*


Interreg Co-funded by the European Union
Alpine Space
FLA Fondazione Lombardia per l'Ambiente

Sezione 1 di 11

H2MA -Single Routes Peer Review Process form

The peer review and assessment of the routes is an essential step for their merging into a functional, economically viable transalpine green hydrogen masterplan since it will allow partners assess already prepared routes, iron out potential inconsistencies and inefficiencies and ensure that the Masterplan meets the foreseen quality standards and criteria.

In particular, the peer review is expected to assess, inter alia, the following issues.

Quality assurance

The peer review process will provide a second level of quality control for the separate routes developed during Activity 2.2 (i.e., beyond the Local Working Groups), assessing the quality of design (including, efficiency,

Figure 20 - *Virtual version of the Peer review form*

3.1.3 Selection of review panel participants

The panel may include, along with H2MA partners, independent specialists and representatives from various institutions, since their participation would provide valuable insights and perspectives to effectively evaluate and integrate the proposed territorial hydrogen routes into the masterplan.

3.2. Peer review results

The Transalpine green hydrogen network initiative explored various scenarios designed to address regional mobility needs and industrial hydrogen requirements. Through this analysis, a comprehensive plan for hydrogen production, distribution, and refueling infrastructure was developed, with a particular focus on heavy-duty transport within ten distinct regions.

A key outcome of these scenarios was the identification of a need for 153 hydrogen refueling stations (HRS) to meet the growing hydrogen demand in the mobility sector. Notably, 73 of these stations will be situated in close proximity to the TEN-T core networks, which are critical transportation corridors across Europe. These routes will form part of a carefully optimized distribution network, represented visually by blue lines on the scenario map, linking hydrogen production sites (marked by red dots) with the strategically placed HRS (green dots) and already existing HRS (yellow dots).

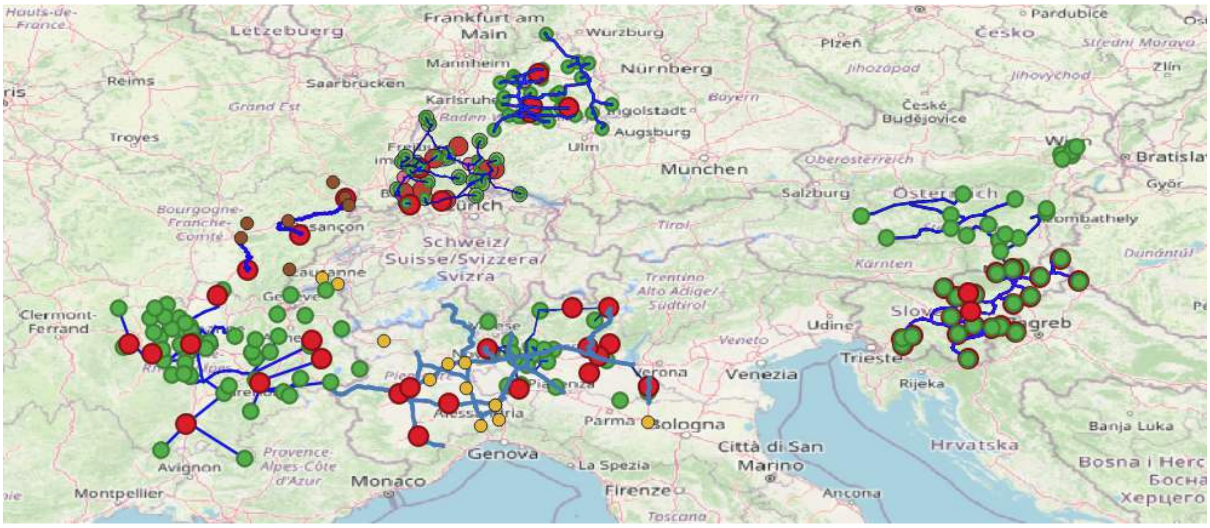


Figure 21 - Overview of all scenarios of the 10 regions (Source: H2MA D2.2.2)

The hydrogen demand in these regions is projected to surpass 100,000 tonnes per year by 2030, reflecting the significant role that hydrogen is expected to play in transforming the transportation sector.

The detailed planning conducted for each region provides a solid foundation for future implementation.

The planning, resulting from the activities of LWGs are collected into the Deliverable D.2.2.2 Compilation of territorial green H2-route designs and the detailed comments and explanations of each route are reported in the accompanying document, attached as **ANNEX I** to this current masterplan

However, while the scenarios successfully outline localized solutions, they do not fully address the broader connectivity between regions.

The strengths, challenges, and recommended next steps for each route, as identified by the partners during the peer review process, are briefly outlined below:

3.2.1 Styria (AT22) hydrogen route

The Styrian region in Austria is planning to integrate hydrogen into its transportation system by 2040. The scenario will utilize Austria's existing infrastructure, particularly the Trans Austria Gas Pipeline (TAG), which will be rededicated for hydrogen transport by 2030. The proposed routes will cover major highways and freight corridors that pass through or near Graz, reflecting the region's importance as a logistics and industrial hub.

Route 1 follows the A9 highway from the Slovenian border to Graz and extends along the A2 toward Vienna. Route 2 serves a mix of transit and domestic Austrian traffic, while Route 3 connects Graz to Lower Austria via the S35-S6 highways. Route 4 covers the A2 highway from Graz toward Carinthia, with a focus on high-volume transit leading toward Italy. Route 5 links St. Michael to the A10, with potential consideration for onsite hydrogen production where pipelines may not be viable.

The scenario proposes 16 new hydrogen refueling stations (HRS) across Styria, with nine strategically located on the TEN-T corridors. The plan also considers key freight corridors within the TEN-T network, particularly the Baltic-Adriatic Corridor and the Western Balkan-Eastern Mediterranean Corridor. However, challenges remain, such as onsite production in rural areas and cross-border connections with neighbouring Slovenia..

Strengths

The strengths of this proposed plan according to the peer review include:

i. The plan covers key transit routes, logistical hubs, and industrial areas, particularly around Vienna and Styria, making it a good starting point for hydrogen infrastructure development in Austria.
ii. The focus on industrial hydrogen demand in Austria, especially in Styria, aligns with current economic and industrial needs, addressing areas with high expected consumption.
iii. The plan generally aligns with EU hydrogen goals and guidelines, including the TEN-T core network requirements, particularly in high-demand regions like Vienna.
iv. It is recognised that environmental approvals must be completed to make sure projects take into account biodiversity, ecosystems, and water resources.

Challenges

Despite the strengths, some challenges regarding the proposed route plan have also been identified by the partners, namely:

i. The current plan only covers part of Austria's hydrogen network, focusing on Styria and Vienna while leaving significant gaps, particularly with regards to connections to Italy, Germany, and other Austrian regions.
ii. There are overlaps in the placement of refueling stations and hydrogen infrastructure, especially near the Slovenian border and Lower Austria, which may lead to redundancy.

iii. The plan does not include detailed cost comparisons between different hydrogen production and transportation methods, such as on-site production versus pipeline transportation.
iv. Although environmental authorisations are mentioned, there is no thorough assessment of potential impacts on local biodiversity, ecosystems, or water resources.

Recommendations

i. The hydrogen infrastructure plan should be expanded to cover all of Austria and other key regions, ensuring full alignment with the TEN-T network. This includes establishing connections with neighbouring countries, such as Italy, Germany, and Slovenia, while avoiding redundant infrastructure at critical border points.
ii. Conduct detailed cost comparisons between on-site hydrogen production and pipeline transportation to identify the most cost-effective solution for each region. In rural areas where pipelines likely won't be economically viable in the near future, alternative distribution methods should be explored to ensure comprehensive network coverage.
iii. More precise long-term projections for hydrogen demand, particularly for freight and transport beyond 2030, should be developed to ensure the infrastructure is scalable and able to meet increasing demand.
iv. The plan should address gaps in coverage and infrastructure placement to fully align with EU hydrogen goals and regulations. This includes meeting the EU's distance requirements for refueling stations and conducting thorough environmental assessments to mitigate impacts on biodiversity, ecosystems, and water resources.
v. It is recommended to improve coordination between regions, especially at key connection points, to create a smooth hydrogen infrastructure across borders. A unified plan for transalpine hydrogen transport should be developed, using data from logistics companies and regional inputs to address gaps and overlaps in the network.

3.2.2 Vienna hydrogen route

The scenario for the Vienna (AT13) region focuses on establishing a strategic hydrogen infrastructure along key transit routes and logistical hubs.

In Vienna, the primary hydrogen route follows the A21 motorway, part of the Baltic-Adriatic and Rhine-Danube corridors. Four new HRSs are proposed, all exceeding one tonne per day in capacity, with two featuring onsite production. One station is near the Danube River to facilitate inland transport, while there is a significant gap in hydrogen infrastructure near Vienna Airport, a crucial logistics hub.

Below is an overview of the strengths and key challenges identified in the peer review process.

Strengths

The strengths of this proposed plan include:

i. Partners highlighted that the proposed route for the Vienna region effectively covers the primary economic centers, including Vienna Airport, the Danube River, and critical logistics hubs. In particular, the network connects essential transportation corridors, particularly the TEN-T corridors, ensuring that major logistics nodes are well integrated into the plan.
ii. The placement of hydrogen refueling stations (HRSs) is considered well thought out, minimizing consumer travel time and strategically aligning with the key logistics corridors. The overall distribution of the stations is in line with EU targets of 200 km between each HRS, ensuring coverage for long-distance travel, especially for freight transport.
iii. The proposed route follows EU guidelines for hydrogen infrastructure development by 2030. The plan is well-suited to meet the hydrogen demand of heavy-duty vehicles (HDVs) and aligns with the EU's goal of supporting the energy transition through sustainable mobility solutions.
iv. The environmental impact of the plan is considered to be moderate, due to the low anticipated hydrogen demand levels for 2030.

Challenges

i. The Vienna region and immediate surroundings are adequately covered, however significant gaps exist in the hydrogen infrastructure, particularly when considering connections to neighbouring regions like Northern Italy and Slovenia. This underdeveloped infrastructure raises concerns about the overall efficiency of transalpine hydrogen transport routes.
ii. There is a lack of detailed cost comparisons, especially between on-site hydrogen production and transportation via pipelines.
iii. There are concerns regarding the logistical challenges of setting up hydrogen pipelines in densely populated areas like Vienna. Additionally, overlaps in refueling stations in the northern parts of the city could lead to inefficiencies, particularly with the existing stations serving primarily public transport rather than freight.
iv. There are questions about how the network will scale to meet the rising demand in future decades, especially by 2050, when hydrogen demand could rise significantly.

v. There are uncertainties surrounding the plan's compliance with local and EU safety standards, particularly regarding hydrogen storage and blending with ammonia, which could present environmental risks. Furthermore, the plan lacks a detailed assessment of social, economic, and environmental impacts, which are critical for future regulatory approvals.

Recommendations

i. Greater coordination is necessary between regions, especially at the critical connection points, to ensure a seamless hydrogen infrastructure across borders. It is recommended to develop an overarching scenario for transalpine hydrogen transport, integrating data from logistics companies and various regions to address gaps and overlaps in the infrastructure.
ii. More robust forecasting for hydrogen demand beyond 2030 is essential, particularly for industries and sectors other than freight transport, such as aviation and heavy industry. This will help ensure the infrastructure is future-proof and scalable to meet long-term hydrogen demands.
iii. Ensuring compliance with evolving EU safety standards and environmental regulations is crucial for the success of the plan.
iv. Conducting detailed cost comparisons to evaluate the feasibility of on-site production versus pipeline distribution, especially considering the complexities of establishing hydrogen infrastructure in urban areas, is recommended. Efforts should be made to minimize overlaps in the placement of refueling stations, particularly where public and freight transport stations could be better integrated.

3.2.2. Zahodna Slovenija (SI04; Western) hydrogen route

The scenario for Slovenia's Western region focuses on hydrogen distribution along two TEN-T corridors: the Baltic to Adriatic (A1, E61) and the Western Balkans to Eastern Mediterranean (A2, E61). The scenario proposes 10 new hydrogen refueling stations (HRS), with two distribution models—pipelines and trucks. In the Gorenjska region, an onsite green hydrogen production facility is under construction, with one HRS located in Lesce. The Goriška region also hosts a hydrogen production site in Deskle. The proposed HRS are strategically located within 200 km of each other, but current minimum cumulative capacities fall short of the EU directive minimum of 1 tonne per day per station. Key HRS locations include the Austrian-Slovenian border, the main national airport, and Koper, with additional stations near the A2 highway toward Croatia.

Demand for hydrogen is highest in Central Slovenia and lowest in Goriška, while the Obalno-Kraška region is expected to have the highest production capacity. The scenario acknowledges the potential for alternative energy sources, such as wind and nuclear power, to support hydrogen production. Transport of hydrogen to HRS will primarily be done via trucks, with existing grey hydrogen facilities transitioning to green production. Notably, a proposed 252 km pipeline from Spielfeld/Šentilj to Vrtojba/Nova Gorica could enhance hydrogen distribution across Slovenia, emphasizing the need for a holistic approach to hydrogen supply and infrastructure development.

Below is an overview of the strengths and key challenges identified in the peer review process.

Strengths

The strengths of this proposed plan include:

i. The proposed plan effectively addresses the targeted hydrogen demand for 2030, ensuring comprehensive coverage of the region. Hydrogen refueling stations (HRS) are strategically placed along major transportation corridors and logistics hubs, including key locations like the port of Koper. This distribution supports strong connectivity for both local traffic and cross-border routes with Italy and Austria, facilitating seamless hydrogen infrastructure integration across the region.

ii. HRS are placed on main roads where heavy-duty truck traffic is expected, making the network well-positioned to serve key economic centers, industrial hubs, and transportation corridors of Slovenia. Furthermore, the HRS stations align well with the EU targets, especially for 2030, in which HRS should be placed every 200 km along the TEN-T core network.

iii. The centralized production of green hydrogen at the Thermal Power Plant Šoštanj offers a scalable supply, starting from a few tonnes of green hydrogen per year and gradually increasing to 5,000–8,000 tonnes annually. This centralized model also supports the transportation of hydrogen using trucks to remote HRS locations equipped with on-site electrolysers.

iv. The expected production of green hydrogen implies minimal carbon footprint, as the plan anticipates using renewable energy sources.

Key challenges

Despite the strengths, some challenges regarding the proposed route plan have also been identified by the partners, namely:

i. The plan covers the needs for 2030, however there are doubts regarding the adequacy of the infrastructure for 2050. The expected market demand for green hydrogen could significantly increase, leading to much higher hydrogen demands that require new HRS installations in key urban areas. The current predictions may not sufficiently address the larger scale of demand beyond 2030.

ii. The number of planned HRS stations may be too high, given the predicted demand for hydrogen, particularly for the initial phase. Due to almost zero demand in the pilot phase, it may not be profitable to establish many HRS with low capacity, especially considering the high OPEX and CAPEX.

iii. The plan does not fully meet EU guidelines for storage capacity per HRS. According to the scenario some HRS have less than 1 tonne of daily storage capacity of hydrogen, which is below the EU's directive of a minimum of 1 tonne per day[5]. This discrepancy could lead to inefficiencies in meeting the growing demand in the future.

iv. Although the Slovenian network is well-structured for local logistics and strategic locations, it lacks connectivity with neighbouring countries, such as Italy and Austria. This gap could hinder the integration of the network into the broader Alpine hydrogen mobility strategy.

Recommendations

i. The high number of HRS may not be justified based on the current demand projections. A phased approach should be considered, starting with fewer stations, and expanding as demand grows. Furthermore, the HRS minimum cumulative capacities should be increased to at least 1 tonne per day to meet EU regulations.

ii. The network should be better linked with surrounding regions, particularly in Italy and Austria, to facilitate cross-border hydrogen mobility.

iii. Additional planning is needed to accommodate the expected increase in hydrogen demand by 2050, which could include installing additional HRS in important urban areas and making adjustments for a possible increase in transportation demand.

iv. Although the centralized model at Šoštanj is a strong point, truck delivery of hydrogen might not be cost-effective in the long run. The feasibility of a pipeline network should be explored more thoroughly, even though this may not be achievable by 2030.

v. Given the potential environmental risks associated with hydrogen production, transportation, and storage, more detailed studies on biodiversity, ecosystems, and water resources should be conducted. The safety of hydrogen storage, particularly blending with other chemicals or gasses, should be assessed further.

[5] One Hydrogen Refuelling Station (HRS) every 200km on the TEN-T Core network by the end of 2030. HRS along the network must be designed for a cumulative daily capacity of one tonne, with at least a 700 bar dispenser.

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3.2.3. Vzhodna Slovenija (SI03; Eastern) hydrogen route

The scenario for Eastern Slovenia focuses on establishing a hydrogen refueling network along key Slovenian highways (A1, A2, A4, and A5) that are part of the Baltic Sea - Adriatic Sea TEN-T corridor. The primary H2-route connects Slovenia's three largest cities—Ljubljana, Maribor, and Celje—and extends into Croatia, Hungary, and Austria. 21 new hydrogen refueling stations (HRSs), with 15 near key highways or cities and 7 immediately on the TEN-T core network have been proposed. A further 11 HRSs are planned for rural areas with minimal traffic and demand.

Pipelines and on-site production were chosen as delivery methods, with experts advising that the hydrogen pipeline should be constructed alongside the existing natural gas infrastructure. However, because of the high construction and operating expenses (CAPEX and OPEX) of H2 pipes, truck distribution is viewed as a more realistic short-term option. The current gas distribution network in Slovenia can only accept 5-7% hydrogen, however EU laws limit mixing to 2%. The majority of HRSs in the early stages will most likely rely on onsite or centralized hydrogen production. Overall, this scenario appears possible, but it requires further investigation with possible investors and current fuel station operators.

Below is an overview of the strengths and key challenges identified in the peer review process.

Strengths

The following strengths of the project have been identified:

i. The proposed plan provides broad coverage of the targeted territory of Eastern Slovenia, particularly for the 2030 scenario, and the HRS locations are well-aligned with key economic centers and transportation corridors.
ii. Many of the hydrogen refueling stations (HRS) are placed near main roads, key transportation corridors (TEN-T), and urban areas, which helps minimize travel time for users and ensures optimal accessibility for heavy-duty trucks.
iii. The proposal meets EU hydrogen infrastructure targets for 2030, aiming for HRS availability every 200 km along high-traffic corridors. The centralized hydrogen production at the Thermal Power Plant Šoštanj is planned to produce thousands of tonnes of green hydrogen annually, offering a significant supply to meet the expected demand for the 2030 scenario. This further strengthens the plan's alignment with EU goals, positioning Slovenia as a key player in green hydrogen production and distribution.

iv. The plan incorporates both centralized and on-site production, which helps reduce transportation costs and energy losses in the long term, particularly for rural areas with low demand.
v. By emphasizing green hydrogen production, the plan aims to reduce carbon emissions and aligns with Slovenia's decarbonisation goals. The plan also ensures minimal environmental disruption, although further assessments are recommended for biodiversity impact.

Key challenges

The following are the main weaknesses of the plan as identified during the peer-review process:

i. A high number of HRS are planned in areas with low expected demand, such as the Notranjsko kraška region, which could lead to inefficiencies and high operational costs. In some cases, three stations are located very close together where one might suffice.
ii. The plan is based on demand projections for 2030, but doubts exist about its adequacy for 2050, when demand is expected to rise significantly. There is a risk that the infrastructure may not be able to handle the future demand spikes, especially in urban nodes.
iii. Currently, there are only two planned hydrogen production plants in Slovenia, which may be insufficient to support the network of 20 HRS, leading to high transportation costs and inefficiencies.
iv. There has been insufficient analysis of the impact on local biodiversity, ecosystems, and water resources. The recommendation to place hydrogen production near consumption sites and avoid storing large quantities has not been fully addressed.

Recommendations

i. Reduce the number of HRS in rural or low-demand areas to avoid unnecessary overlaps and inefficiencies. Focus more on urban centers and high-demand corridors for more cost-effective coverage.
ii. Increase production capacity by adding more hydrogen production facilities or expanding the current capacity to support the anticipated increase in hydrogen demand for the 2050 scenario. This will help reduce transportation costs and energy losses.

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iii. Align key performance indicators (KPIs) with long-term projections, particularly focusing on hydrogen demand for heavy-duty trucks and industrial applications by 2050.
iv. Implement cost-saving strategies by using on-site hydrogen production for low-demand areas and streamlining the number of HRS where feasible. This could significantly reduce OPEX and CAPEX costs, particularly in regions with minimal hydrogen consumption.

3.2.4. Lombardy (ITC4) hydrogen route

The scenario for the Lombardy region, focusing on hydrogen demand in the mobility sector, estimates an annual need of 21,000 tonnes, with the highest daily demand of 13 tonnes in the Milan area. It proposes 16 new hydrogen refueling stations (HRS), with key routes following major highways such as the A1, A7, A8, and A9, which are part of the North Sea-Rhine-Mediterranean and Mediterranean TEN-T corridors. Key connections include Milan to Switzerland, Bologna, Genoa, Venice, and Malpensa airport. Additionally, a hydrogen valley is planned near Mantova, and the H2-Iseo project will connect Brescia to Edolo with hydrogen trains and bus refueling stations. Some HRSs proposed outside these routes are considered less critical.

The proposed hydrogen route in Lombardy according to the partners demonstrates several key strengths but also faces significant challenges:

Strengths

i. The proposed hydrogen network effectively connects key economic centers, industrial hubs, and transportation corridors. This ensures that the network supports major economic zones and facilitates cross-border mobility, particularly for heavy-duty trucks.
ii. The plan considers future green hydrogen demand, with hydrogen production sites close to renewable energy sources. Hydrogen refueling stations (HRS) are well-distributed across the region, especially along major roads, ensuring availability for logistics operations. The distance between HRS meets or exceeds EU targets for the TEN-T core network by 2030 (with a minimum of one station every 200 km).
iii. The network supports potential collaboration with bordering regions, promoting knowledge exchange between Italy, Switzerland, and other Alpine countries for enhanced hydrogen infrastructure planning.

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Key challenges

i. The route doesn't address the hydrogen needs of the industrial sector. This gap could hinder the plan's ability to cater to sectors beyond transport, such as heavy industry, which is crucial for scaling hydrogen use. Additionally, leaving certain regions underserved could become a bottleneck for a truly comprehensive regional network.
ii. There are concerns about overlaps in hydrogen infrastructure, particularly with refueling stations placed too close to existing ones. Expanding existing stations, rather than building new ones, might optimize costs and resources.
iii. The reliance on hydrogen delivery via trucks, rather than pipelines, could increase transportation costs and carbon footprint. Although justified by the lower development stage in some regions, the network could benefit from diversifying transportation methods, especially in anticipation of growing demand.
iv. The exclusion of regions like Emilia Romagna and incomplete alignment with bordering regions like Piedmont highlights the need for better regional coordination to ensure seamless hydrogen infrastructure.

Recommendations

i. Integrate hydrogen infrastructure planning with industrial hubs to ensure the future hydrogen demand from the industrial sector is met. This can help the plan extend its scope beyond transportation.
ii. Consider expanding existing refueling stations rather than constructing new ones in close proximity, minimizing costs and operational challenges. Additionally, re-evaluate station locations in less-covered areas, to ensure better regional balance.
iii. Explore alternatives to truck-based hydrogen transportation, such as building onsite production facilities at key refueling stations or planning for future pipeline infrastructure, to lower costs and energy losses over time.
iv. Strengthen partnerships with regions that are not part of the Alpine space, such as Emilia Romagna and Switzerland, to ensure seamless coverage across borders and prevent gaps in the network.

3.2.5 Piemonte region (ITC1) hydrogen route

The scenario for the Piemonte region (ITC1) outlines a strategic approach to developing hydrogen refueling infrastructure in response to projected demand. By 2030, hydrogen demand in Piemonte is expected to reach 2,000 tonnes per year, with the highest daily demand of around 2 tonnes concentrated in the Turin area. The proposed plan includes the establishment of **4** new hydrogen refueling stations (HRSs) strategically positioned based on extensive analysis made under H2MA, taking the total number of expected stations to 11 by 2030.

Key investments are required to establish an HRS inside the logistics platform of Turin, completing the Mediterranean TEN-T corridor and ensuring compliance with the Alternative Fuels Infrastructure Regulation (AFIR). Proposed routes for new HRSs include the E70 from Turin to Bologna, E25 from T1 Mont Blanc to Turin, and E717 from Turin to Vado, a major container ship port and logistic platform . The density of HRSs along these routes aims to enhance hydrogen availability, supporting both light and heavy-duty vehicles. Additionally, a redundancy approach will introduce a second HRS in the Turin urban area to ensure reliable fuel availability under all conditions. Collaborations with ongoing projects like HYMPULSION in France and HYDROSPIDER in Switzerland further support the region's hydrogen mobility infrastructure.

The Turin plan is strategically designed to support regional and cross-border mobility, aligning with EU hydrogen goals. Below is an overview of the strengths and key challenges identified in the peer review process.

Strengths

i. The proposed hydrogen refueling station (HRS) network effectively connects major economic centers and industrial hubs across Turin, extending to France, Switzerland, Lombardy, and the Mediterranean ports. The plan effectively integrates with neighbouring regions, particularly the Rhône-Alpes region in France and Lombardy.
ii. The HRS placement minimizes travel time for consumers and provides strong connections from north to south and west to east. It is aligned with regional and EU hydrogen goals, meeting the TEN-T core network requirements for HRS availability.
iii. The plan embraces a decentralized approach with local hydrogen production at select HRS and distribution via tube trailers, avoiding the complexities of immediate pipeline construction. This strategy optimizes short-term investments and allows for rapid deployment of infrastructure.

Key challenges

i. While the eastern region is well-served, the western part, particularly along routes toward France, lacks sufficient HRS coverage. The overtaking of those limits of accessibility for users in these areas is the core of H2MA HRS's deployment plan.
ii. The reliance on tube trailers for hydrogen distribution is a mandatory choice considering that italian national plan for H2 pipelines doesn't expect to invest in such infrastructure in the region. Nevertheless, H2 production sites in the region lay in a range of less than 100 km form HRS's, distance currently considered as optimal to

ensure fuel supply both by tech and economic points of views. Moreover, two stations will have on-site electrolysers yet, and is expected that in the near future, in line with demand growth, further stations will be equipped this way too.

iii. The absence of a pipeline network for hydrogen distribution increases dependence on tube trailers. Over time, this could result in higher transportation costs and logistical inefficiencies compared to centralized production and pipeline delivery systems.

iv. The plan's decentralized production model contrasts with centralized approaches used in other territorial routes, potentially creating coordination issues when integrating networks across regions, such as those in Lombardy and Rhône-Alpes. A decentralized (meaning production of H2 at HRS site) production model is not under consideration in Piedmont by 2030.

Recommendations

i. To ensure balanced coverage across the territory, additional 4 HRS should be considered for the western parts of the region and along less-served corridors towards AURA (FRA), Bologna (ITA) and western Liguria (ITA) regions.

ii. in a long term scenario (beyond 2030), evaluate if an increase of HRS with on-site hydrogen production may ensure and meet future fuel demand and reduce reliance on tube trailer transport.

iii. While tube trailers are suitable for early deployment, the long-term feasibility of pipelines should be re-evaluated and included in future planning, in line with national and EU “H2 backbone” development plans.

iv. Coordinate the decentralized Turin network design with neighbouring regions that favor centralized production. Develop a unified strategy to ensure seamless integration and hydrogen supply management across different territorial routes.

3.2.6. Strasbourg hydrogen route (Franche-Comté (FRC2) + Alsace (FRF1))

The Strasbourg hydrogen route plan in Eastern France includes the combined scenarios for the Franche-Comté (FRC2) and Alsace (FRF1) regions and focuses on hydrogen infrastructure development along key transportation routes, with an emphasis on truck delivery for hydrogen in the short term due to the limited pipeline infrastructure. The Franche-Comté region currently has no immediate plans for pipelines, except for the Hy-FEN project that would cross the region without local use. Instead, hydrogen delivery by trucks has been chosen, with five new hydrogen refueling stations (HRSs) proposed. Three of these are located near the main hubs of Besançon, Belfort, and along the A36 highway, a part of the North Sea-Rhine-Mediterranean TEN-T corridor. The remaining two stations are further from the main routes, requiring further feasibility evaluation.

Currently, there are two existing HRSs in the region (Dole and Belfort) and nearby stations in Alsace and Switzerland. Similarly, the Alsace region plans to meet its hydrogen demand of 12,000 tonnes per year, with the highest daily demand of 14 tonnes in the northern areas. Compressed hydrogen trucks are also the preferred delivery method. The main H2 routes include the A5 highway, following the River Rhine, which is critical for cross-border transport. Seven new HRSs are proposed, with three located near major routes connecting Alsace with Switzerland and Franche-Comté, and four positioned in rural areas, which will require more detailed planning.

Both regions are strategically aligned along the North Sea-Rhine-Mediterranean TEN-T corridor, emphasizing cross-border connectivity with Switzerland and other French regions, but further planning is needed for HRS placement in rural areas and neighbouring regions.

Below is an overview of the strengths and key challenges identified in the peer review process.

Strengths

i. The Strasbourg hydrogen route strategically places hydrogen production sites near renewable energy sources, particularly hydroelectric power, which helps minimize energy transportation losses and supports environmental goals.
ii. The HRS are well-distributed along major transportation corridors every 100 km, improving accessibility for cross-border trade and long-distance travel, especially with Germany and Switzerland.
iii. The plan emphasizes on-site hydrogen production in Alsace, reducing the need for costly transport infrastructure and enhancing short-term cost efficiency.
iv. The route effectively connects key regional hubs such as Strasbourg, supporting economic activities by ensuring HRS availability along major trade routes.

Key challenges

i. The plan lacks adequate connections with key neighbouring regions like Italy (via the T4 Tunnel Frejus) and southern France. The weak integration limits the route's effectiveness as part of a broader European hydrogen network.
ii. HRS storage capacities are below the EU's recommended minimum for HDVs (6 t/d), and there is no plan to develop infrastructure to serve the anticipated growth of hydrogen trucks.
iii. While Alsace benefits from on-site production, Bas-Rhin has potential redundancies due to multiple production sites, while Haut-Rhin lacks sufficient infrastructure, creating regional imbalances in hydrogen supply.

iv. While linked to renewable sources, the plan has not fully assessed the environmental impact, particularly on water usage, biodiversity, and waste management related to hydrogen production and infrastructure.
v. The current network prioritizes personal vehicles over heavy-duty hydrogen vehicles, which could limit long-term growth and scalability in freight transport.

Recommendations

i. Prioritize the development of infrastructure for HDVs, including increasing HRS storage capacity to align with EU targets for 2030.
ii. Improve connectivity to Italy and southern France, particularly focusing on the Lyon-Turin corridor and the T4 Tunnel Frejus.
iii. Extend the pipeline planned for the RhyN region to serve additional areas such as the industrial zones of Dessenheim and Chalampé-Ottmarsheim, as well as Mulhouse, to meet local demand.
iv. Consider centralising production in certain areas to avoid redundancy, particularly in Bas-Rhin, and optimize infrastructure placement to ensure balanced coverage across the region.

3.6.7. Stuttgart (DE11) hydrogen route

The proposed hydrogen network route for Germany, specifically in the Stuttgart region is projected to have a total hydrogen demand of 27,000 tonnes per year for mobility, with the highest usage centered around Stuttgart. The main hydrogen route is H2-route 1, which follows the A8 highway, part of the Rhine-Danube TEN-T corridor. The scenario assumes 0.5% of passenger cars and 1% of heavy vehicles will use hydrogen. However, key factors like pipeline infrastructure and transit vehicle demand are not fully accounted for.

The partners identified the following strengths, challenges, and recommendations:

Strengths

i. The proposed plan sufficiently covers the Stuttgart region, including essential economic and industrial hubs. The location of HRS along the main roadways ensures accessibility for heavy traffic. Furthermore, the plan ensures solid connectivity with France, particularly with regions like Strasbourg, facilitating cross-border hydrogen trade and mobility.
ii. A significant number of hydrogen production sites are planned, placing Germany in a strong position for future hydrogen demands, particularly in the Stuttgart area.

iii. The plan emphasizes pipeline delivery as a preferred mode of hydrogen transportation. Pipelines offer long-term cost efficiency and scalability, reducing transportation costs and energy losses compared to trucks. This strategic focus aligns with the vision of developing a hydrogen economy.
iv. The proposal is well-aligned with EU hydrogen policies, including targets for HRS distance, storage capacity, and overall infrastructure deployment by 2030.
v. The hydrogen production capacity and infrastructure network consider key European and German regulations for safe and sustainable development.

Key challenges

i. A critical gap is the exclusion of high-demand industries, such as steel, cement, and chemicals, from the planning process. These industries are expected to generate a significantly higher demand for hydrogen compared to the mobility sector, and their absence from the planning framework could limit the network's potential.
ii. The plan does not adequately address connections with Austria and Switzerland, which could create significant gaps in the broader Alpine hydrogen mobility network. While the design connects well with France, these missing links might limit Germany’s integration into a fully cohesive trans-European hydrogen corridor.
iii. While pipelines are efficient for long-distance hydrogen transport, the construction of new hydrogen pipelines is time-consuming and costly. Given the short timeframe until 2030, it may be unrealistic to fully implement this approach in the absence of concrete pipeline construction plans, such as the European Hydrogen Backbone. Meanwhile, other regions may prioritize truck-based delivery, leading to potential inconsistencies when merging network designs.
iv. The plan primarily focuses on regional mobility, overlooking supra-regional and international long-distance transport. This narrow scope may hinder Germany’s potential role as a leader in transnational hydrogen trade and infrastructure.
v. The plan does not fully address potential impacts on local biodiversity, ecosystems, and water resources.

Recommendations

i. Enhance cross-border connectivity by establishing links to Austria and Switzerland to facilitate broader hydrogen distribution and integration into the European hydrogen market.
ii. Incorporate the hydrogen needs of regional industries into the planning process to ensure the infrastructure supports the overall demand for hydrogen, not just from the mobility sector.

iii. Evaluate the feasibility of developing a hydrogen pipeline network to complement truck transportation, as pipelines can reduce long-term transportation costs and energy losses, thus improving overall efficiency.
iv. Regularly reassess the network design to account for evolving hydrogen market conditions, technological advancements, and regulatory changes to ensure it remains aligned with EU hydrogen goals and guidelines.

3.6.8. Freiburg (DE13) hydrogen route

The Freiburg region scenario outlines a hydrogen infrastructure plan to meet a projected mobility demand of 18,000 tonnes per year, with the highest daily consumption of 9 tonnes in Ortenaukreis. Pipelines are the preferred delivery method, though it might not be a cost-effective solution. The approved RhynInterco pipeline will extend from Freiburg to Offenburg, with potential expansion to Kehl. However, additional rural pipelines will require strong business cases to justify their development. Regional solutions, such as the H2-trailer Hub[6] in Villingen-Schwenningen, are also being considered for hydrogen distribution in rural areas.

Key hydrogen routes include H2-route 1 along the Rhine River and A5 highway (part of the North Sea-Rhine-Mediterranean TEN-T corridor), H2-route 2 as a vital west-east connection, and H2-route 3 linking Stuttgart with Lake Constance and Switzerland. A total of 26 new hydrogen refueling stations (HRSs) are proposed, with 16 near main routes and 8 in rural areas needing further planning.

The partners identified the following strengths, challenges, and recommendations:

Strengths

i. The plan effectively covers key regions within Regierungsbezirk Freiburg, strategically connecting important economic hubs such as Strasbourg/Kehl, Freiburg, and Basel. It also links to key industrial centers along the Rhine and important transport corridors like the Autobahn A5 and A81.
ii. The plan aligns well with EU hydrogen infrastructure goals, particularly the requirement for hydrogen refueling stations (HRS) every 200 km along the TEN-T core network by 2030. It ensures strategic placement of infrastructure in line with EU recommendations for hydrogen distribution.

[6] https://www.infener.com/blogs/newsroom/infener-launches-20-mw-hydrogen-hub-in-villingen-schwenningen

iii. By focusing on minimizing transportation costs and placing hydrogen production infrastructure strategically, the plan attempts to balance cost efficiency with hydrogen production. The design seeks to reduce reliance on longer-distance transportation to minimize energy losses.
iv. The network is aligned with broader EU goals of reducing emissions and promoting renewable energy. This includes the incorporation of renewable electricity sources for electrolysis, aiming for a sustainable and environmentally conscious hydrogen network.

Key challenges

i. While the plan covers major economic hubs, there are significant gaps, especially towards Stuttgart, Karlsruhe, and Italy. These coverage gaps could reduce the network's effectiveness in connecting key regions across borders.
ii. Some refueling stations are planned in high-altitude areas like the Black Forest, where pipeline installation may not be economically feasible, raising concerns about the practicality of HRS placement in these remote locations.
iii. The plan relies on truck delivery of hydrogen over long distances, which can result in energy losses up to 35%. While pipelines would be more efficient, the economic justification for building them in rural or high-altitude areas remains uncertain. The high electricity costs for hydrogen production via electrolysis also pose an economic challenge.
iv. There is insufficient focus on cross-border hydrogen infrastructure connections, particularly with France, Switzerland, and Italy. The lack of a cohesive transnational strategy could hinder the development of an integrated hydrogen network across Europe.
v. The plan primarily focuses on hydrogen demand in the mobility sector but neglects the significant demand from regional industries such as steel, cement, chemical, and aluminum. These industries will drive a large portion of future hydrogen consumption, which the plan does not adequately address.
vi. The projected number of HRSs and hydrogen production capacities are conservative and may not be enough to meet the growing demand, especially for heavy-duty vehicles (HDVs). This raises concerns about overinvestment given the small market share of hydrogen-powered HDVs by 2030.

Recommendations

i. Enhance the proposed HRS network to address gaps toward Stuttgart, Karlsruhe, and Italy, ensuring a more comprehensive hydrogen infrastructure that facilitates regional and international transport.

ii. Conduct detailed feasibility studies on the HRS placement in high-altitude areas and explore alternative methods (e.g., decentralized production) for hydrogen distribution in these regions.
iii. Foster better communication and collaboration between different regions to create a unified strategy for hydrogen infrastructure development that includes both centralized and decentralized production methods.
iv. Continuously update the hydrogen scenario based on ongoing developments in hydrogen technology and infrastructure to remain aligned with evolving market demands and technological advancements.

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4. Green H2 Masterplan design

1.2 Goal and Objective of the Masterplan

The Green Hydrogen Mobility Masterplan for Alpine Space, developed under the H2MA (Hydrogen Mobility Alpine Space) project, aims to foster the adoption of green hydrogen (H2) technologies to decarbonize the transalpine transportation sector. The plan leverages on the unique geographical and environmental context of the Alpine region, with a focus on sustainable mobility and renewable energy integration. Key goals and objectives of this masterplan, shaped by insights from collaborative workshops, are outlined below.

Goal 1: Decarbonization of Alpine Transportation through Green Hydrogen
Objective: Facilitate the large-scale deployment of green hydrogen technologies to significantly reduce carbon emissions across all modes of transport in the Alpine Space, including road, and freight.

Goal 2: Promote Cross-Border Collaboration in Hydrogen Infrastructure
Objective: Develop a coordinated, transnational network of hydrogen refueling stations (HRS) and infrastructure that ensures seamless cross-border mobility for hydrogen-powered vehicles. This includes optimizing H2 production, storage, and distribution across Alpine countries (Austria, Switzerland, Italy, Germany, France, and Slovenia).

Goal 3: Enhance Renewable Energy Synergies in Hydrogen Production
Objective: Support the development of green hydrogen production facilities using renewable energy sources, such as hydropower, wind, and solar, which are abundant in the Alpine region.

Goal 4: Strengthen the Economic Viability of Hydrogen Mobility
Objective: Create a sustainable hydrogen economy that supports local industries, job creation, and regional economic growth, while driving down the costs of hydrogen production and distribution.

Goal 5: Public Awareness and Policy Support for Hydrogen Adoption
-Objective: Engage policymakers, industry leaders, and the public to build broad support for hydrogen as a sustainable mobility solution.

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4.1. Stage of the design process

The primary objective of the Masterplan has been to design a comprehensive and cohesive Alpine hydrogen mobility network that will integrate the individual territorial plans developed by project partners.
The process of design of the masterplan from the single regional routes has consisted in 4 main steps.

STEP 1: Merging territorial route designs: single regional routes have been merged considering 3 main scenarios on the bases of the assumptions.

STEP 2: Fine tuning individual routes: following the identification of areas of improvement by the recommendations in the individual route designs, partners are expected to further fine-tune the routes (if necessary) and address any compatibility issues as a prerequisite to the merging of the routes.

STEP 3: Addressing compatibility issues: compatibility between individual routes (particularly in neighbouring territories) has been considered during the preparation of the transalpine masterplan especially in the following elements.

- Gaps and overlaps in refueling station network coverage
- Differences in the design philosophy
- Inefficiencies in the production and distribution infrastructure
- Environmental impact

4.2. Assumptions to the design process

The full design of the masterplan has been based on basic overall fundamental assumptions that has basegrounded all the outcomes of the process.
These basic assumptions have been agreed among all the beneficiaries of H2MA as foundational of the proposal of the masterplan.

Mobility Targets

The routes represented in the masterplan for the Alpine Space are thought to be addressed and used by mainly freight transport, heavy duty vehicles and long distance buses.

Additionality principle and Temporal and Geographical Correlation for green H2 route in the Alpine Space

In order to define what is a "*green H2 route*" we refer the additionality principle and Temporal and Geographical Correlation

In the REPowerEU plan, two key principles are emphasized for hydrogen production:

1. **Additionality**: This principle ensures that renewable hydrogen production is supported by new renewable energy capacity. This means the renewable electricity used to produce hydrogen must come from newly built renewable sources, not existing ones, to avoid diverting renewable energy from other sectors.
2. **Temporal and Geographical Correlation**: the second principle mandates that the production of hydrogen must be aligned with the time and location of renewable energy generation. This ensures that hydrogen is produced when and where renewable electricity is available, further supporting the goal of ensuring the sustainability of hydrogen production.

These principles are part of the EU's effort to promote green hydrogen, ensuring that it is produced in a manner that contributes meaningfully to the overall energy transition.

The new EU definition of Green Hydrogen emphasizes the Additionality Principle: planned renewable energy for national demand (e.g., 2024's 5 KW) cannot be diverted to hydrogen. Future transformation towards green energy is prioritized, with refilling based on demand for mobility, including storage, transport, and distribution.

Scenario definition

Most viable scenario: in providing the single regional routes, all partners have been asked to select the scenario which they rate as **the most viable scenario**, i.e. the scenario with the most reliable data input for the H2MA tool, considering their national and regional H2 circumstances, strategies and predictions. The resulting H2-infrastructure suggested by the H2MA tool was used for developing H2 routes that consider factors such as the TEN-T corridors in the region and existing infrastructure-In the description of the scenario, the partners were asked to rate the confidence level of their scenario on a scale from 1 to 10, where a value of 1 indicates confidence related to uncertain boundary conditions, and a value of 10 resembles very reliable boundary conditions and results with a high likelihood of realization

Alpine Space 2030 and 2050 scenarios: with the support of the H2MA tool, the masterplan is also providing two alternative scenarios that are

- *Alpine Space 2030_medium:* an alternative of the most viable scenario considering a medium penetration of hydrogen into the market of transportation, and with concurrent investment in facilities. The scenarios refers to the time horizon of 2030, in agreement with the EU Hydrogen Strategy [LOW CONFIDENCE]

- *Alpine Space 2050_low* : a projection to 2050 considering a low penetration of hydrogen into the market transportation [HIGH CONFIDENCE}

4.3. Merging territorial route designs

4.3.1. Most viable scenario

All partners were asked to select the scenario which they rate as the most viable scenario, i.e. the scenario with the most reliable data input for the H2MA tool, considering their national and regional H2 circumstances, strategies and predictions. The resulting H2-infrastructure suggested by the H2MA tool was used for developing H2 routes that consider factors such as the TEN-T corridors in the region and existing infrastructure.

In the description of the scenario, the partners were asked to rate the confidence level of their scenario on a scale from 1 to 10, where a value of 1 indicates confidence related to uncertain boundary conditions, and a value of 10 resembles very reliable boundary conditions and results with a high likelihood of realization.

The timeframe of the scenario was a free choice for each partner, as H2-demand and speed of infrastructure development may differ between regions.

To give an overview of the H2-scenarios, the following table shows the inputs used by each region and key results.

Table 3. Overview table of H2-mobility parameters for scenario optimization in the H2MA tool

Partner	Region	Year	FCEV vehicle share	regional H2 demand	Delivery method	Number of planned HRSs	TEN-T corr. respected	Confidence rating (1-10)
1 KSSENA	SI03	2030	0,0047-0,0082	1 kt/y	pipelines	21	Yes	3
2 BSC	SI04	2030-2050	0,0047-0,0082	2 kt/y	pipelines	10	Yes	6
4 FLA & 9 RL	ITC4	2030	0,002-0,02	21 kt/y	trucks	16	Yes	5-7
5 PVF & 3 EMS	FRC2/ FRF1	2030	0,005-0,1	1,4 kt/y	trucks	7	Yes	7
6 CMT	ITC1	2030	0-0,0025	2 kt/y	trucks	18 □ 4	Yes	3
7 KPO	DE13	2030	0,005-0,01	18 kt/y	pipelines	26	Yes	3
8 4ER	AT22	2040	0,01-0,25	17 kt/y	pipelines	16	Yes	2
10 COD	AT13	2030	0-0,2	7 kt/y	pipelines	4	Yes	7
11 ITALCAM	DE11	2030	0,005-0,01	27 kt/y	pipelines	30	Yes	3

The maps created by the H2MA tool with existing and future hydrogen refueling stations (HRS), hydrogen production sites and H2 delivery pipelines has been used as a base to mark the H2-routes, with a focus on TEN-T corridors and neighboring H2 infrastructure.

Figure 21 renders the integration of all the routes indicated *as most viable* into a unique map of the alpine space done with the software QGIS.

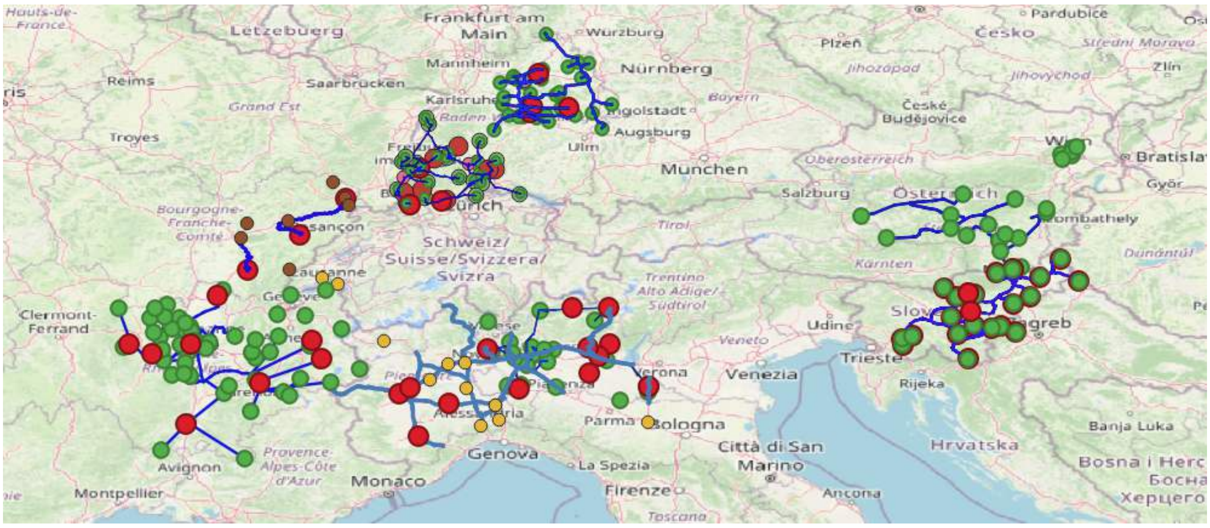

Figure 22 - integration of all the most viable routes of the 10 regions calculated with H2MA tools during the LWGs

Legend : (red dots)-production sites, (green-dots)-HRS, (yellow-dots)-existing HRS (blue lines)-network pipelines, (violet dots/lines)- imports

In order to explore the connection and intersection with EHB and TEN-T: Figure 22 reports indeed the superposition of the maps of the TEN-T networks in the region involved into H2MA.

On the map routes are represented visually by blue lines on the scenario map, linking hydrogen production sites (marked by red dots) with the strategically placed HRS (green dots).

The maps in Figure 21 and Figure 22 are available also in digital form as ANNEX II of the masterplan

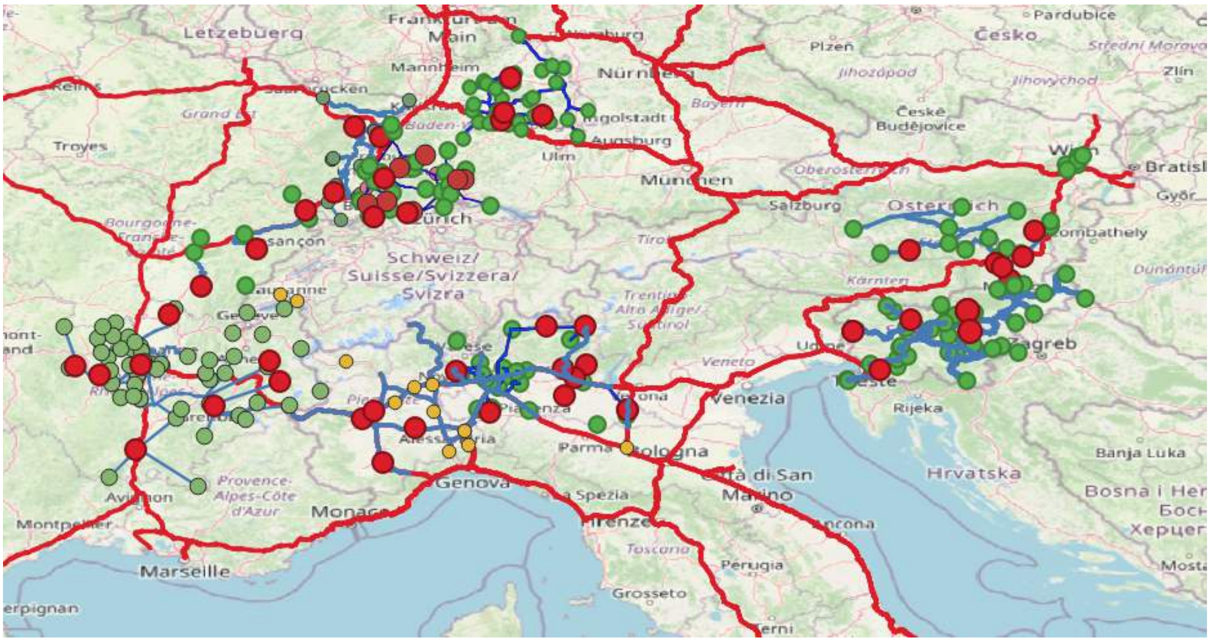

Figure 23 - Most viable routes + TEN-T corridors
Legend : (red dots)-production sites, (green-dots)-new HRS, (yellow-dots)-existing HRS
(blue lines)-network pipelines, (violet dots/lines)- imports
(red lines) - TEN-T corridors

Main points to note:

- Most partners chose the year 2030 for developing their scenarios
- Expected share of fuel cell electric vehicles (truck and buses) varies significantly. This factor is decisive for demand calculation, but many partners state uncertainties in future market acceptance and predictions of H2-based mobility.
- Demand per region and thus requirements for the number of HRSs and H2-production facilities varies greatly between regions. An extreme example is the scenario of KSSENA in Slovenia with an annual demand of 1 kt/y distributed over 21 suggested HRSs, meaning an equivalent of ca. 47 kg H2 as average consumption per HRS. Such a result of the H2MA tool is unrealistic, as a long distance truck is equipped with an 80 kg H2-tank (e.g. Mercedes Truck - Link) and half a tank filling per year will not create a business model for a refueling station
- Most regions chose pipelines as preferred delivery method, however, all partners explain that rural regions will benefit from truck delivery.
- All partners succeed in including the TEN-T corridors in their H2-routes. Overall the confidence rating in the described scenarios relying on the H2MA tool are, in general, low. The confidence rating is only set to reasonably reliable, if partners did extensive rework on the scenario with their local working groups (LWG)-

4.3.2. Alternative scenarios.

The alternative scenarios have been defined primarily in relation to the different degree of penetration of hydrogen in the different categories of vehicles; in particular, 6 scenarios were created: 3 scenarios in 2030 and 3 in 2050, with low, medium or high hydrogen penetration. The tables below show the degree of penetration of hydrogen in different scenarios.

Table 4 - Different degree of penetration of H2 considered in the scenarios evaluated with the H2MA tool

Scenario 2030

	% FCEVs on regional stock			
Scenario	**Passenger Cars [%]**	**LDVs [%]**	**HDVs [%]**	**Buses [%]**
LOW penetration	0.0%	0.0%	0.5%	0.5%
MEDIUM penetration	0.5%	0.5%	1.7%	2.0%
HIGH penetration	1.0%	1.0%	4.0%	5.0%

Scenario 2050

	% FCEVs on regional stock			
Scenario	**Passenger Cars [%]**	**LDVs [%]**	**HDVs [%]**	**Buses [%]**
LOW penetration	10%	10%	40%	15%
MEDIUM penetration	15%	20%	65%	25%

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HIGH penetration	20%	50%	85%	35%

LDVs = Light-Duty Vehicles, HDVs = Heavy-Duty Vehicles, FCEVs = Fuel Cell Electric Vehicles

The maps of the simulation of the alternative scenarios *Alpine Space 2030_medium and Alpine Space 2050_low* done with the support of the H2MA runned for the overall alpine space in the region considered, are reported respectively in Figure 23 and Figure 24.On the map routes, are represented visually by blue lines on the scenario map, linking hydrogen production sites (marked by red dots) with the strategically placed HRS (green dots).

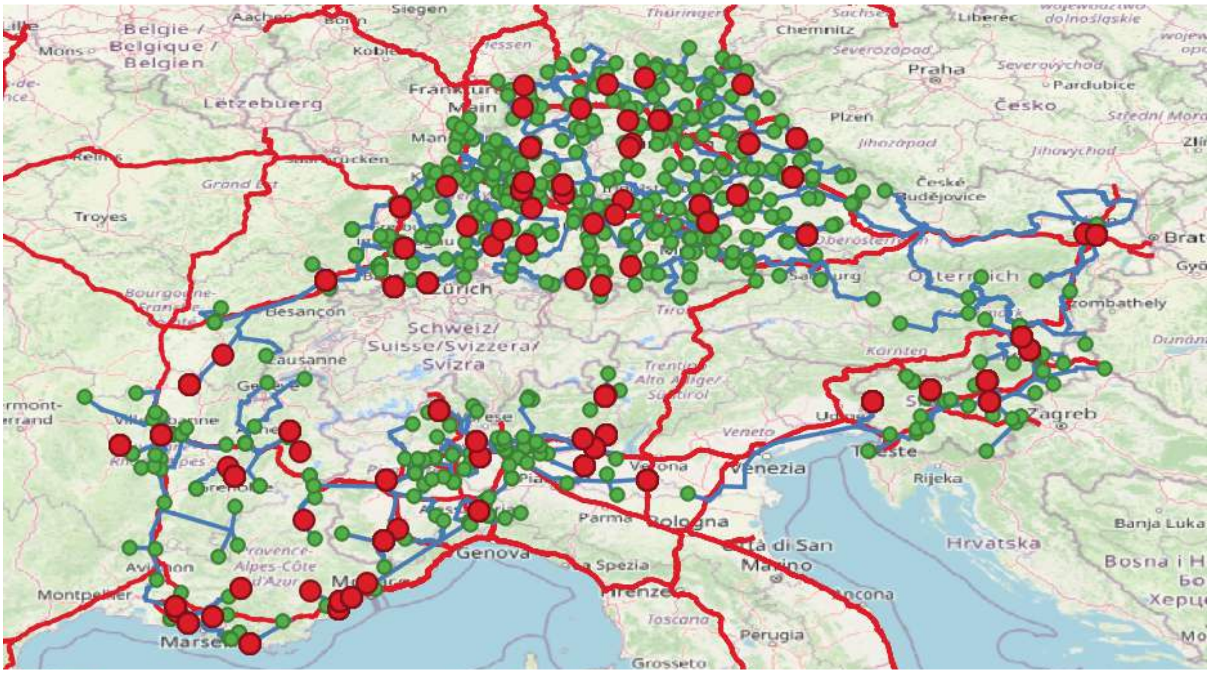


Figure 24 - Alpine Space 2030_medium by H2MA tool of all the Alpine Space in the regions of the project

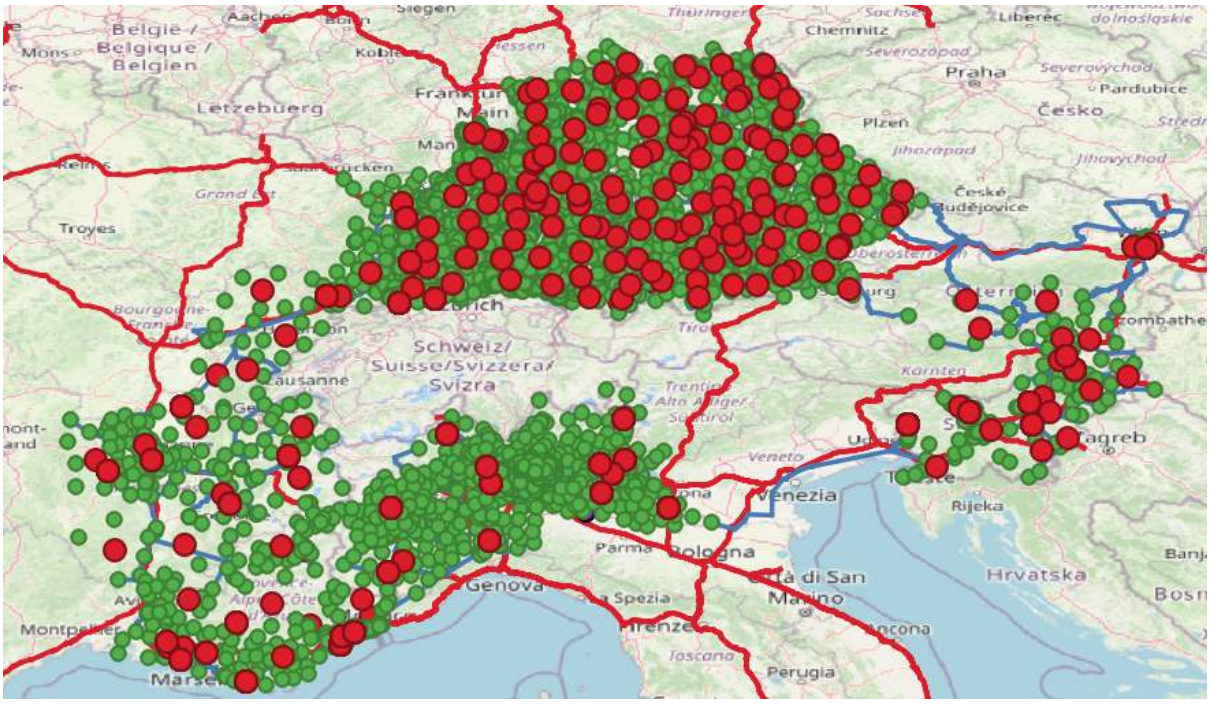


Figure 25 - Alpine Space 2050_low by H2MA tool of all the Alpine Space in the regions of the project

The maps in Figure 23 and Figure 24 are let available also in digital form as ANNEX II of the masterplan

4.3 Limitations of the GreenH2 Masterplan Design

The Green Hydrogen (GreenH2) Masterplan faces several challenges, particularly due to a lack of comprehensive data and inconsistencies in critical infrastructure networks.
One major limitation stems from the fragmented and inconsistent development of the Trans-European Transport Network (TEN-T), which hampers the efficient integration of hydrogen supply and distribution across member states.

The lack of coherence in road distribution networks, further complicates logistical planning, making it difficult to ensure smooth transportation and accessibility to hydrogen refueling stations. Additionally, the pipeline distribution network, crucial for hydrogen transmission, at the moment, is underdeveloped and lacks alignment with existing energy grids, creating bottlenecks in supply and raising costs.

These infrastructure gaps limit the scalability of hydrogen technologies and the overall feasibility of the GreenH2 Masterplan, requiring coordinated improvements to ensure sustainability and efficiency in hydrogen distribution across Europe.
Here are listed some of the limitations the consortium has identified to proper address a Green H2 plan.

Such limitations regard aspects of the design that are out the potentials of the process as it has been designed.
The list also indicates possible suggestions to address these limitations.

4.1.1 Lack of data

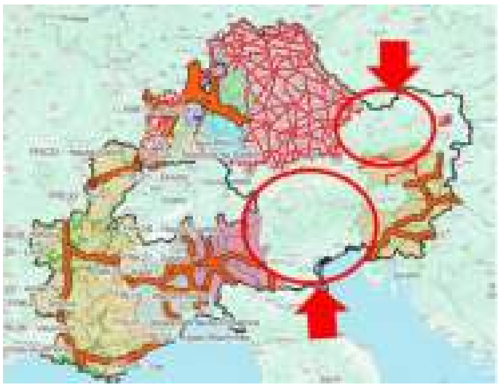
As shown in the image, large Alpine areas lack data, making coherent hydrogen route design highly affected.	

Figure 26 - *Main evidence of lack of data*

Suggestions to address the limitation

- Reference data for the entire Alpine region should be integrated.

4.1.2 Inconsistencies in TEN-T networks

In some sectors, the partners have integrated the road TEN-T networks only into the H2MA tool, while in other sectors, the river and rail TEN-T networks have been taken into account.

TEN-T networks on the Franco-German border integrated into the H2MA tool by the partners

TEN-T networks in the same area imported into the Alpine region as a whole.

Figure 27 - *TEN-T network connection*

Suggestions to address the limitation

- The TEN-T networks to be included and their version should be agreed and data updated accordingly before the analysis is relaunched.

4.1.3. Lack of coherence in road distribution networks

In some sectors, such as Italy, the road distribution network is very detailed and includes the smaller routes. On the other hand, in other sectors such as Germany and Austria, only the very major roads are included in the tool. In the latter case, the results of the scenarios cannot be consistent. On the map below, there is a compilation of the data available in the tool into a single map. Road distribution networks are shown in red.

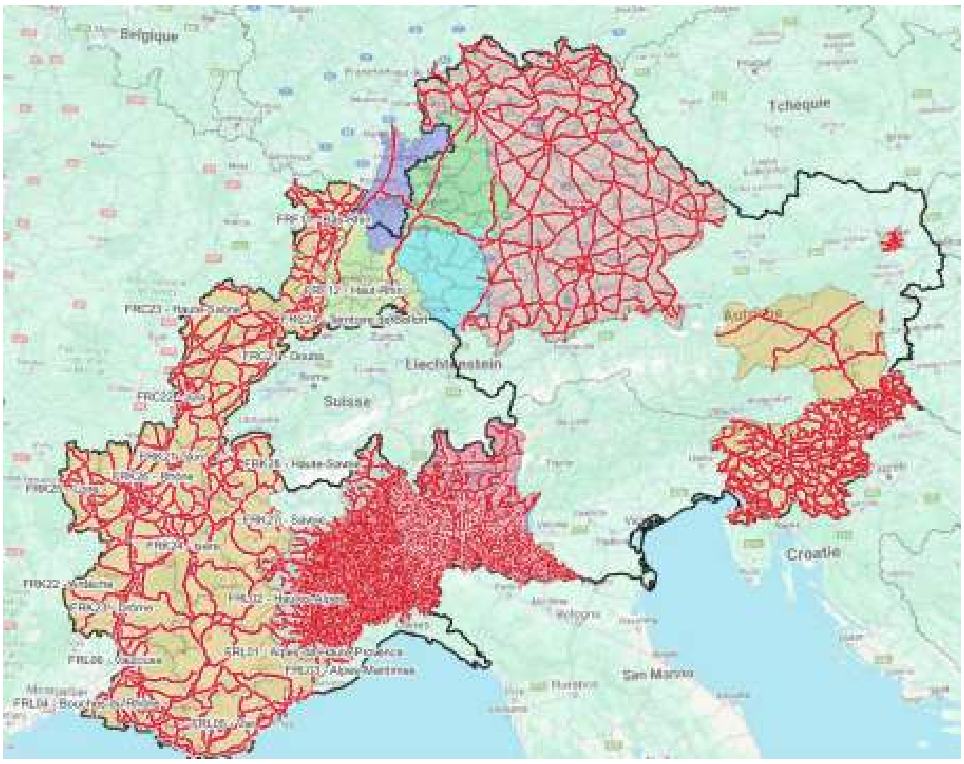


Figure 28 - Insufficiently detailed road network

4.1.4. Pipeline distribution network (Parameter 5)

The partners were asked to provide existing gas networks that could be used to distribute hydrogen. However, it has been established that using pipelines distributing methane for example to transport hydrogen requires adaptation and testing. The existing network cannot and will not be fully converted to hydrogen by 2030. This raises the question of whether it makes sense to include the entire existing gas network in the tool.

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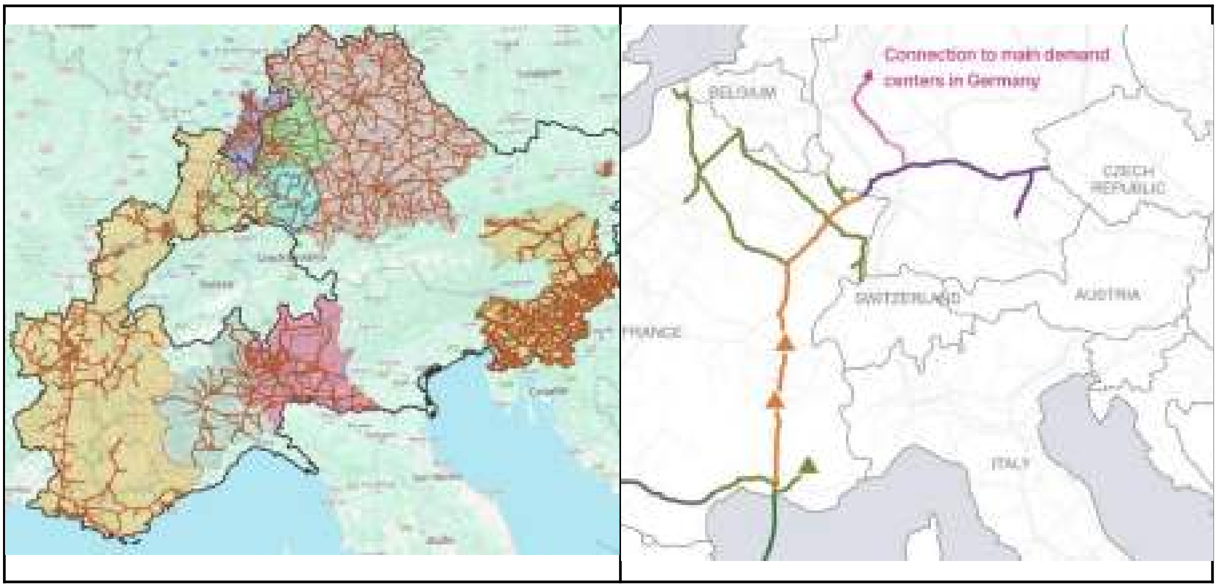

Figure 29 - Pipeline distribution network error

Suggestions to address the limitation

Gas network in the H2MA Vs H2Med project

- Only networks where there are plans to convert to hydrogen should be included.

The H2MA project is co-funded by the European Union through the Interreg Alpine Space programme

5. Recommendations

5.1. Overall conclusions and lessons learnt from peer-review process

The peer review revealed an **inconsistency** in hydrogen network design and delivery methods across different regions. For instance, the Strasbourg hydrogen route emphasized on-site hydrogen production near renewable sources, aligning with environmental goals of minimizing energy transport losses. In contrast, the KPO route in Germany primarily relied on truck transport for hydrogen delivery, which may lead to significant energy losses and raise economic concerns. This divergence in transportation methods suggests a need for greater coherence in approach, as reliance on varied delivery systems could complicate the integration of these hydrogen networks. Additionally, the Vienna route and the Lombardy route adopted a more centralized hydrogen production strategy, focusing on utilizing existing infrastructure and industrial sites to streamline the process. This approach contrasts with the decentralized production favored by the Slovenia BSC route, which emphasizes local production and distribution. The Styrian route in Austria focuses on using pipelines, taking advantage of the Trans Austria Gas Pipeline (TAG), which will be converted for hydrogen transport by 2030. While this pipeline Styrian strategy is feasible along major transit routes like highways A9 and A2, rural areas require alternative solutions, such as on-site production. The differences in production strategies across these regions reveal a potential challenge in integrating networks into a cohesive system. The lesson learnt is that more **standardization** or better coordination is required across all routes to harmonize design principles. A transalpine masterplan should account for these disparities while promoting long-term solutions, such as centralized production hubs when viable.

The peer review also revealed significant **gaps in HRS coverage**, especially in rural areas and near borders. The Strasbourg route demonstrated decent coverage along major corridors, but it lacked adequate connections to southern France and Italy, potentially limiting cross-border mobility. Similarly, the KPO route in Germany highlighted significant gaps toward Stuttgart and Karlsruhe, particularly for heavy-duty vehicles (HDVs). In Lombardy, insufficient HRS in key industrial zones hampers the network's efficiency, while the Vienna route struggles with rural coverage, making hydrogen less accessible. The Slovenia BSC and KSSENA, and Styrian routes also exhibited deficiencies in HRS placement, particularly concerning connectivity to neighbouring regions. The Styrian route, for example, placed nine out of 16 proposed HRSs along TEN-T corridors but requires more careful planning in rural areas where hydrogen pipelines may not be available until 2040. These coverage gaps pose a risk to the overall effectiveness of the transnational hydrogen network, particularly for long-distance transport and regional commerce. The analysis emphasizes the need to prioritize these underserved areas to ensure seamless connectivity across all regions and promote the adoption of hydrogen as a sustainable transport solution.

Another important finding concerned the future **scalability** of hydrogen infrastructure. While the German ITALCAM route incorporated future hydrogen demand from industries like steel and cement, other routes—such as KSSENA in Slovenia and the KPO route—primarily focused on personal vehicle refueling. This oversight could limit infrastructure growth as the market for HDVs expands. Similarly, the Styrian route anticipates a hydrogen demand of 17,000 tons annually by 2040, particularly for freight and heavy-duty transport, emphasizing the need for scalable infrastructure that can accommodate future demand. A more balanced approach is required across all routes to ensure that infrastructure supports both individual and commercial hydrogen needs.

The peer review identified significant **overlaps** in HRS placement across several routes, particularly in the Strasbourg and Freiburg areas, where refueling stations are situated too close to one another. This clustering, especially along the border regions, could lead to inefficiencies and wasted resources, undermining the overall effectiveness of the hydrogen network. Additionally, overlaps were noted in the Stuttgart region, where HRS are concentrated without sufficient consideration for distribution across wider areas, risking redundancy in service. The Lombardy and Turin routes also displayed similar issues, with HRS located in proximity to existing stations, which may hinder the expansion of hydrogen infrastructure. Additionally, the **Styrian route** showed overlaps at the Slovenian border and on the border to Lower Austria (connection to Vienna). The lesson learned is that **enhanced coordination** among neighboring regions is essential to prevent such overlaps. Cross-border consultation and collaboration can facilitate strategic HRS placement, ensuring that resources are utilized efficiently while maintaining adequate coverage for all areas. This approach will help create a more integrated and effective hydrogen network across Europe.

Regional imbalances in hydrogen **production** capabilities were evident, with some areas—such as Alsace in the Strasbourg route—benefiting from multiple production sites, while others, like Haut-Rhin, faced infrastructural deficiencies. Similarly, the Slovenia BSC route highlighted the potential for growth, yet lacked the same level of integration as neighbouring routes, while the Styrian route had the advantage of using existing natural gas infrastructure (such as the TAG pipeline), which could enhance distribution efficiency. These disparities raise concerns about equitable access to hydrogen across regions. A central takeaway is that a more **centralized production** strategy might mitigate these disparities, allowing for optimized distribution networks that ensure balanced coverage and support regional economic activities.

The review revealed that some regions, like Italy's Lombardy and Austria, did not fully account for **cross-border environmental impacts.**
The takeaway message is that environmental assessments should be extended to examine these impacts, especially in Alpine ecosystems, and a coordinated approach to risk management would help mitigate adverse effects on biodiversity and natural habitats.

The German and Strasbourg routes may face significant challenges regarding **cost efficiency** due to their reliance on dispersed hydrogen production methods. In these areas, the transportation of hydrogen from multiple, smaller production sites over longer distances has escalated costs, making green hydrogen less competitive compared to other energy sources. This situation contrasts with the Styrian route and other centralized approaches in Austria, where hydrogen production facilities are strategically located near key demand centers, thereby minimizing distribution costs. The review underscored the need for regions such as Germany and France to evaluate their hydrogen strategies to achieve greater cost efficiency. By exploring options for centralized production or shared cross-border infrastructure, these regions could effectively reduce transportation expenses and enhance the overall competitiveness of green hydrogen. Future planning should focus on creating **economies of scale** by clustering hydrogen production facilities near major consumption areas, such as Stuttgart and Strasbourg, which would optimize both cost and resource allocation while supporting the broader hydrogen economy.

While the Strasbourg and German routes align closely with **EU regulations** such as the TEN-T framework, the Italian and Slovenian routes exhibit notable gaps in compliance. Specifically, the Lombardy region's hydrogen infrastructure lacks integration with broader EU hydrogen deployment strategies, while Slovenia has not fully embraced EU standards, risking fragmentation of its hydrogen network. This discrepancy poses a threat to the overall effectiveness of the EU's hydrogen strategy and could isolate these regions from more integrated European infrastructure. The review emphasized that Italy and Slovenia must enhance their alignment with EU regulations to secure their position within the continental hydrogen framework. Strengthening cross-border collaboration and communication is essential for addressing these regulatory gaps, especially for Slovenia, which could benefit from closer ties with neighboring EU countries to ensure compliance and foster a cohesive hydrogen market across the region.

5.1.1. Areas for enhancement and ways to address the inefficiencies

The peer review process highlighted both the advantages and disadvantages of the various hydrogen transportation routes, with a particular emphasis on regional differences and potential inefficiencies. Lessons learnt highlight the importance of standardizing design concepts, strategically placing hydrogen refuelling infrastructure, improving cost-efficiency, and ensuring environmental and regulatory compliance. Addressing these difficulties it is important to successfully integrate the separate routes into a cohesive and sustainable transalpine green hydrogen network. Through tight regional cooperation, particularly cross-border collaborations, the project can create a more efficient, cost-effective, and ecologically friendly hydrogen mobility infrastructure that aligns with EU policies and matches future demand across the Alpine area.

More specifically:

1. A more standardized methodology is required to connect the various design processes across routes. The Slovenia BSC route favours decentralized production, which contrasts with the Austrian and Lombardy routes' centralized production techniques. Italy and Slovenia should look at options for centralized hydrogen production where possible, potentially collaborating with neighbouring countries to build joint production hubs. This move could lower transportation costs and increase the scalability of hydrogen production by harmonizing design concepts across networks..
2. The peer review emphasized the necessity of a balanced approach to accommodate hydrogen demand across various sectors, particularly for heavy-duty vehicles (HDVs). There are significant gaps in HRS coverage, especially in rural areas and near borders. Addressing these gaps is essential for enhancing connectivity. For example, the lack of adequate HRS connections to southern France and Italy limits cross-border mobility, while the KPO route in Germany exhibits significant deficiencies toward Stuttgart and Karlsruhe. To enhance accessibility, additional HRS should be strategically placed in underserved regions like the Aosta Valley and Lombardy, ensuring seamless hydrogen accessibility. Additionally, minimizing overlap in HRS placement, particularly in border areas like Munich and Salzburg, will help optimize resource use and improve overall network efficiency.
3. on personal vehicle refueling, while neglecting the needs of HDVs, highlights a significant gap. Future planning must prioritize infrastructure requirements for both personal and commercial hydrogen refueling to ensure scalability and

effectiveness as the market for HDVs expands. The review underscored the necessity of comprehensive environmental assessments, especially in regions with protected natural landscapes, such as Lombardy and Tyrol. These regions should collaborate on environmental risk management strategies to mitigate adverse effects on biodiversity. Additionally, enhancing alignment with EU regulations, particularly for Italy and Slovenia, is critical for integrating these regions into a broader continental hydrogen framework. Strengthening cross-border collaboration can facilitate compliance with EU standards, fostering a cohesive hydrogen market.

4. The identified overlaps in HRS placement across routes, particularly in Strasbourg and Freiburg, underscore the need for enhanced coordination. Collaborative efforts among neighbouring regions can facilitate strategic HRS placement, ensuring efficient resource utilization while maintaining adequate coverage. Cross-border consultation will be essential for developing an integrated hydrogen network across Europe, maximizing the effectiveness of the overall infrastructure.

5.1.2. Recommendations for the H2 mobility Masterplan

The H2 Mobility Masterplan for the Alpine region should be built around key design principles that promote the creation of a cohesive, efficient, and sustainable hydrogen network. This plan aims to integrate routes developed by various regional partners into a unified framework, addressing inefficiencies, overlaps, and redundancies. These principles will help achieve a transnational hydrogen infrastructure that supports long-range transportation and reduces emissions across the Alpine corridor.

5.1.3. Harmonization of route design philosophies

A central principle of the Masterplan is harmonizing the diverse design philosophies originally employed by different regions. Various regions developed routes reflecting local priorities—some, like Austria, adopted centralized hydrogen production with pipelines, while others, like Italy, opted for decentralized production with road-based transport.

To resolve these disparities, the Masterplan should propose a unified framework that:

- Balances centralized and decentralized models: By introducing a hybrid approach, the Masterplan allows regions to adopt centralized production in areas where high demand justifies it (such as near large population centers like Milan or Vienna), while maintaining decentralized production in more remote or less populated areas like Carinthia or Burgenland.
- Standardized transportation methods: encouraging pipeline use where infrastructure exists, as for instance Styrian region's approach, leveraging the Trans Austria Gas Pipeline (TAG), ensuring efficient hydrogen transport along key corridors like the A9 and A2 highways, extending to Vienna and beyond. On the contrary, supporting road transport in areas where pipelines are less feasible.

5.1.4. Optimisation of Hydrogen Refuelling Station (HRS) placement

Another core design principle is optimizing the placement of Hydrogen Refuelling Stations (HRS) to ensure both comprehensive coverage and cost-efficiency, while avoiding unnecessary redundancies. The initial design phase identified significant gaps in some regions, such as Italy, and overlaps in others, particularly near borders like the Austria-Germany frontier.

To address these issues, the Masterplan should focus on:

- Eliminating gaps: New HRS locations can be proposed to fill critical coverage gaps, particularly in under-served areas such as northern Italy and eastern Austria, ensuring reliable coverage for long-haul transport and cross-border traffic.
- Reducing redundancy: The plan also should reallocate HRS locations near border regions, such as the over-dense network between Munich and Salzburg, where unnecessary overlaps were identified. By better distributing refueling stations across neighbouring regions, the Masterplan maximizes both efficiency and coverage.

5.1.5. Integration of cross-border infrastructure

Given the transnational nature of the Alpine corridor, another essential design principle is the seamless integration of cross-border infrastructure. The peer review process revealed that some regions had initially focused on their own national priorities without sufficient consideration of neighbouring networks. For example, the Italian route exhibited low levels of cross-border collaboration, while France and Austria had better-aligned networks.

To foster a truly integrated system, the Masterplan should:

- Facilitate cross-border collaboration: A coordinated effort is central to the Masterplan, ensuring that production and distribution capacities across borders are mutually supportive. For example, hydrogen produced in Austria could be supplied to Northern Italy, while Italian production sites could support southern Austria. The TAG pipeline could also serve as a backbone for cross-border hydrogen distribution, potentially supplying hydrogen to neighbouring countries such as Italy and Slovenia.
- Prioritize border-area connectivity: By ensuring that HRS locations in border regions complement rather than duplicate one another, the Masterplan enables seamless hydrogen mobility across national borders. This will reduce inefficiencies and ensure continuous refueling options for long-range transportation across the Alpine region.

5.1.6. Ensuring environmental and regulatory compliance

A cornerstone of the Masterplan is ensuring that the hydrogen network adheres to stringent environmental and regulatory requirements, as outlined by both national and EU guidelines. Initially, certain routes—particularly in Italy—were not fully aligned with EU standards, creating potential barriers to integration.

The Masterplan can address these issues by:

- Aligning with EU guidelines: Even for non-EU members like the bordering Switzerland, the Masterplan incorporates EU regulatory frameworks (such as the TEN-T regulations), ensuring that all routes comply with safety, environmental, and technical standards. This includes adhering to environmental protection protocols, especially in sensitive areas like the Tyrol region and Italy's Lombardy, to minimize the impact on ecosystems.
- Mitigating environmental impacts: To protect biodiversity and reduce the carbon footprint of the hydrogen supply chain, the Masterplan could emphasize minimizing land use in sensitive Alpine areas and prioritizing pipeline infrastructure, which has a lower environmental impact compared to road transportation. Additionally, production sites will be located away from protected areas, limiting disruptions to natural habitats.

5.1.7. Focus on cost-efficiency and scalability

A critical design principle underpinning the Masterplan is ensuring that the hydrogen network is not only functional but also cost-efficient and scalable. Initially, cost discrepancies arose due to decentralized production models such as in Austria and Italy, which can increase the expense of hydrogen transportation.

To address these cost inefficiencies, the Masterplan can:

- Use economies of scale: By promoting centralized production hubs in regions with high demand and supporting shared production facilities across borders, the plan reduces overall costs. For example, centralized production hubs serving both Italy and Austria could optimize supply chains, lowering hydrogen prices and improving the network's economic viability.
- Ensure scalability: The Masterplan should be designed to be flexible, enabling future expansion as hydrogen demand increases across the Alpine region. Scalability is built into the infrastructure, allowing for the addition of new HRS or production facilities as the network grows to meet rising demand.

5.1.8. Achieving network efficiency through smart integration

Finally, the principle of network efficiency should be embedded in the Masterplan. The initial peer review revealed inefficiencies in the simple merging of regional designs, such as redundancies in HRS placement and an uncoordinated supply chain between regions.

To rectify these inefficiencies, the Masterplan should promote a smart, data-driven approach that considers hydrogen production, distribution, and consumption as an interconnected system.

The Masterplan can achieve efficiency by:

- Optimizing supply chains: Hydrogen supply chains to be designed with minimal transportation distances between production and consumption sites, particularly for high-demand areas like Milan, Vienna and Munich. This reduces transportation costs and energy use while ensuring a reliable hydrogen supply across regions.
- Real-time monitoring: The integration of smart technologies will allow real-time monitoring of hydrogen levels at refueling stations and production facilities. This will ensure that hydrogen supply is continuously optimized, with automatic adjustments to meet demand fluctuations, particularly in border areas where multiple regions share infrastructure.

5.2. Feedbacks and recommendations from LWGs

The Local Working Groups (LWGs) provided key insights and recommendations beyond the hydrogen mobility scenarios covered by the H2MA planning tool. Their discussions emphasized several additional factors that future policies and planning must consider to foster a robust hydrogen infrastructure across the Alpine Space.
LWGs offered valuable insights into the broader context of hydrogen infrastructure development in the Alpine Space. They suggested the integration of hydrogen into both mobility and industrial applications, alongside robust cross-border cooperation and clear regulatory frameworks, to be crucial for developing sustainable hydrogen ecosystems. These discussions laid the groundwork for establishing transnational hydrogen routes and optimized locations for infrastructure

5.2.1 Additional Factors Beyond H2MA Tool Scenarios

Stakeholders stressed the need to consider hydrogen requirements in industries beyond transalpine mobility, such as local industrial sectors. Future policies must account for on-site hydrogen production, waste heat usage, and existing gas networks or planned hydrogen pipelines. They also highlighted the importance of balancing regional disparities in renewable energy potentials and promoting incentives to stimulate green hydrogen demand.

Key regulatory standards, such as France's ICPE and CVESO, which govern industrial activities, must be taken into account. These regulations aim to mitigate environmental risks, with some areas prohibiting renewable energy projects like wind and solar to preserve biodiversity, landscapes, and cultural heritage. Additionally, the availability of water resources is critical for electrolysis, making water resource management essential to ensure efficient and sustainable hydrogen production.

Stakeholders also emphasized the significance of cross-border hydrogen refueling infrastructure, trade agreements, and different hydrogen production types—green, grey, and pink. These must be aligned with national energy and climate plans to support a comprehensive hydrogen ecosystem. Accurate demand estimates for mobility infrastructure, especially for long-distance transit, are also crucial for planning.

5.2.2. Hydrogen Demand in Nearby Industries

Besides the mobility sector, there is substantial hydrogen demand across several industries in Alpine Space countries. In Austria, green hydrogen is poised to support the iron, steel, pulp, paper, and chemical industries, which face fewer localization challenges but struggle with technological readiness. In Italy, hydrogen is integral to chemical processes like ammonia and methanol production. Regional planning should focus on meeting the hydrogen needs of these industries and promoting hydrogen-based processes.

Germany's industrial hydrogen demand is projected to exceed 22 TWh annually by 2030 and 73.5 TWh by 2035, particularly in Baden-Württemberg. Slovenia, meanwhile, is working to integrate hydrogen production into military and thermal power plants.

The Piedmont region has shown growing interest in aviation hydrogen applications. Overall, hydrogen demand extends well beyond mobility and will be critical in industries such as steel, chemicals, and aviation.

5.2.3. Strategies for Awareness and Adoption of Hydrogen Technology

Raising awareness of hydrogen technologies is crucial. Stakeholders recommended promoting success stories, showcasing infrastructure, and fostering public-private collaborations to influence policy. Cross-border networks and triple-helix discussions involving academia, industry, and government can help advance hydrogen technology awareness and green transition planning.

The electrification of industries using hydrogen is another priority. Hydrogen's application in sectors like steel, chemical industries, and high-energy metallurgy, where direct electrification is challenging, should be considered. Stakeholders noted the importance of ensuring sufficient hydrogen supply and availability.

Engaging major industries in adopting hydrogen infrastructure requires broad regional approaches, allowing diverse stakeholders to benefit from technological advancements.

6. Conclusions and Final Remarks

Regarding the Green Hydrogen Distribution routes, limitations are present in the overall alpine region. In particular, some connecting regions in the alpine space are missing and this is a crucial limitation to pursue a complete HRSs and hydrogen production network. In fact, some regions are not covered within the H2MA Consortium, and this is limiting the overall view of the entire region. Particularly, a good example is represented, for example, between Region Piedmont and Region Lombardy, in the northern part of Italy, where, despite being different regions, covered from different partners, show continuity in both hydrogen production and hydrogen refueling stations, covering the major arteries that are intended to be used for heavy duty trucks and buses. the overall alpine region, the northern east of Italy is currently not covered by any partner within the H2MA partners. This part is crucial to connect:

- Lombardy region with Austria through the highway Milan-Verona-Brennero;
- Lombardy Region with Slovenia through the highway Milano-Verona-Venice-Trieste;
- Lombardy Region with Austria through the highway Milano-Verona-Venezia-Udine-Tarvisio.
- Piedmont Region with Strasbourg area (Grand Est Region) through the various highways.
- South of Germany (Region Baden Württemberg) that connects with Austria through several highways.

The regions of the alpine space missing not covered from the existing partners that belong to the H2MA project are:

- Veneto, Trentino-Alto Adige and Friuli-Venezia Giulia for Italy;
- Baden Wurttemberg for Germany;
- Auvergne-Rhône-Alpes,, Provence-Alpes-Côte d'Azur for France.

Switzerland is not considered nor included as it is not within the EU, however, it should be integrated to give continuity to the entire alpine region as some main connection roads cross Switzerland. It is of critical importance to cover the overall parts including the one missing and not covered from the existing partnership. Continuity needs to be guaranteed otherwise the overall map will not be helpful during the decision project.

Critical for the success of the project H2MA is the connectivity among different regions and countries. However, limitations can be seen when different countries and within the same countries, different regions, are adopting different refueling strategies, centralized or not. European strategies are not defined strictly, and different options can be found but it is critical the communication between different areas to guarantee sufficient coverage of HRS. Common ground must be found and local, regional, national and European strategies need to overlap reducing the selection of different options.

Despite the project being concentrated mainly on the Alpine Region, connectivity and continuity with the entire Europe is also envisioned but not considered within the H2MA project.

Another limitation is seen in the fact that certain regions have selected capillary distribution of HRSs composed of multiple HRSs but a unique hydrogen production site. Redundancy in production sites is strongly suggested to avoid eventual possible failure or break down ("out of service" or simply maintenance) of the hydrogen production that might jeopardize the hydrogen distribution and HRSs operations. On this note, also the HRSs might be a shorter distance than the 200 km envisioned by the EU. Redundancy in HRSs is also critical to guarantee the need of refueling of heavy duty track and buses. This is an important drawback that needs to be learned from the experience currently occurring in California, USA. Lessons learned from other experiences are also critical to be exported here in the Alpine region. In general, HRSs are new systems, especially at the beginning of life, as expected, HRSs might undergo frequent maintenance or be "out of service", therefore redundancy in HRSs placement needs to be envisioned to guarantee full coverage.

In the general audience's common perspective, hydrogen is seen as dangerous, explosive and in general with a negative perspective. As initial deployment of HRSs, these refueling stations need to be built on highways and routes where there is the presence of heavy duty tracks and buses, outside of cities and urban areas. It is crucial to increase awareness highlighting the positive sides of hydrogen for the decarbonization of the transportation sector.

One main limitation related to green hydrogen is the definition of green hydrogen itself that has changed within the duration of the project. Green hydrogen can be produced through water electrolysis connected to renewable energy or through steam reforming of biomethane or through biochemical conversion of biomass.

Moreover, in February 2023, the EU has approved the Delegated Act on a methodology for renewable fuels of non-biological origin, that defines the conditions in which hydrogen, hydrogen-based fuels, or other energy carriers can be considered as renewable fuels of non-biological origin (RFNBO).
(https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.157.01.0011.01.ENG&toc=OJ%3AL%3A2023%3A157%3ATOC).

The additionality delegated act includes 2 types of criteria making ensure that hydrogen is renewable:

The additionality requirement, to ensure that increased hydrogen production and new renewable electricity generation capacities grow in parallel. This means that additional renewable energy needs to be installed to produce hydrogen to be considered green.

The criteria on temporal and geographic correlation, to ensure that hydrogen is produced when and where renewable electricity is available. These criteria want to avoid that renewable electricity is used for hydrogen production and it is subtracted to the electricity generation that in turn is substituted with fossil fuel leading to greenhouse emissions.

This new rule, despite going into the desired direction to fully decarbonize the energy system, increases the issue related to the penetration of hydrogen into the energy system and large-scale implementation. Often deployment of renewable energy is slowed down by lengthy bureaucracy therefore this might be an important bottleneck for reaching the intermediate goals. In fact, if renewable deployment is slowed down, green hydrogen production considering additional parameters can be delayed.

A typical example can be done for Switzerland, which is not included into the H2MA, however geographically is within the Alpine Region. Some adjacent regions of the H2MA project are envisioned to receive hydrogen from Switzerland for fulfilling their needs. Switzerland produces its electricity mainly through hydropower plants that cover up to 62% of the overall annual needs (https://www.eda.admin.ch/aboutswitzerland/en/home/wirtschaft/energie/energie---fakten-und-zahlen.html) To produce and export green hydrogen, Switzerland should increase its renewable energy sources that is happening with enhanced solar production to respect the principle of additionality.

Another point to underline is related to the integration of the hydrogen production and distribution system dedicated to the transportation decarbonization with the one envisioned by the hard to abate industrial sector which will be also very energy demanding to fulfill the hydrogen request to decarbonize their sector.

Therefore, renewable energy dedicated to hydrogen production needs to be built to consider hydrogen green and this is the first step. In parallel, electrolysers need to be built to and be operational achieving the standards of safety and durability. In the meantime, a large number of heavy-duty trucks need to be produced and be operational. A great limitation might be related to the short time available till 2030 to be able to produce large amounts of hydrogen (tens of tons) necessary to partially reduce the emissions related to transportation. A solution might be envisioned through the gradual decarbonization of the hydrogen production by the usage of gray hydrogen first, then blue and finally the desired green. The additionality strategy might slow down significantly all the other steps such as building, deploying and maintaining HRSs, building renewable energy sources, deploying fuel cells, heavy duty trucks and buses.

As mentioned in the document, a capillary natural gas distribution system exists, but it is not yet proven the possibility of transporting large quantities of hydrogen through existing distribution systems at high percentages (if it is expected to be done mixed with natural gas) and pressure (when only hydrogen is transported). Certainly, a capillary distribution system via dedicated and robust pipelines will not be available along the entire alpine region by 2030. Therefore, the most logical and immediate solution stands in the production of hydrogen in-situ with transportation of electricity through the existing grid. This seems reasonable and feasible because the energy grid exists, and it is already capillary within the alpine region.

As previously mentioned, from an energy system perspective, hydrogen can play a major role in alleviating the burden of additional electricity load on the grid, especially in regions where grid development is an expensive or difficult-to-implement option. This situation raises new questions regarding the topology of the electricity grid, along with the existing natural gas grid and future hydrogen pipelines. These extensive energy infrastructures must work in synergy to enable system decarbonization at a lower cost and a faster pace.

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