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Guidelines for developing maturity scenarios on green H2 production and distribution

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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.

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- PP11 Italian German Chamber of Commerce Munich – Stuttgart (DE)

CONTENT

EXECUTIVE SUMMARY

This methodology, developed as part of the Activity A1.4 of the H2MA Interreg Alpine Space project, aims to provide support and practical guidance for the development of scenarios forecasting the maturity of green hydrogen and supply in the Alpine region.

The document is structured as follows:

Section 1 provides an introduction on the green hydrogen's potential in the long-haul transport sector, H2MA Activity A1.4 and the forecasting methodology at hand.

Section 2 explains the need for maturity scenarios forecasting green hydrogen's roll-out and summarises main scenarios developed in recent years.

Section 3 offers step by step guidance in developing forecasting scenarios and elaborates on key factor areas and the identification of drivers and trends.

An Annex concludes the document offering a methodological tool for consistent data collection for the evaluation of key factors and drivers to be used in the development of forecasting scenarios.

1. INTRODUCTION

1.1 Green hydrogen's potential in the transport sector

Despite the rapid growth of electrification, which shows promise, the transportation sector encounters numerous hurdles in its quest for carbon neutrality. Conventional fossil fuel-powered vehicles contribute substantially to carbon emissions, necessitating a transition away from these vehicles. However, this transition faces obstacles such as the range limitations of battery electric vehicles (BEVs) and the need for an extensive charging infrastructure, which poses challenges for long-haul transportation. Additionally, the aviation and marine shipping sectors, characterized by high energy intensity, struggle with limited options for carbon-neutral fuels.

In this context, hydrogen has emerged as a key component in the energy transition of the sector, especially in long haul transportation (freight, railroad, marine and aviation) in which electrification remains challenging [1]. The commitment of the EU and national governments to decarbonisation has accelerated investments and technological advancements, particularly in the areas of sustainable mobility and renewable energy sources, by providing funding for new projects and initiatives [e.g., through HORIZON Europe, European Climate Initiative (EUKI), Important Project of Common European Interest (IPCEI)]. At the same time, geopolitical factors like the war in Ukraine have created a pressing need for identifying and promoting alternatives to fossil fuels.

However, a more widespread application of green hydrogen technologies is hindered by factors such as the high production costs of green hydrogen and the current production capacity. The former is highlighted by the fact that the production costs of green hydrogen are several times more than those of grey hydrogen (i.e., hydrogen produced by natural gas or methane without capturing the greenhouses gases produced in the process)[2]. The latter is a result of the ongoing drive to phase out fossil fuels from the energy production leading to a competition for the use of RES and a reduce amount of green electricity available for water electrolysis. Additionally, social awareness and acceptance of hydrogen technologies also contribute to the delay in achieving widespread adoption. This is highlighted by several relevant studies, which have indicated a lack of awareness on the benefits of hydrogen among the general public[3]. This issue is exacerbated in the case of green hydrogen. As an example, a study in Germany[4] showed that although 85% of respondents indicate had heard of hydrogen, the same is true for only 26% in the case of green hydrogen. In particular, significant differences can be observed between different age groups and education levels.

[1] Report prepared by the IEA, 'The Future of Hydrogen', June2019.

[2] Mind the Gap—A Socio-Economic Analysis on Price Developments of Green Hydrogen, Synthetic Fuels, and Conventional Energy Carriers in Germany, 2022

[3] People's Attitude to Energy from Hydrogen—From the Point of View of Modern Energy Technologies and Social Responsibility, 2020

[4] Social acceptance of green hydrogen in Germany: building trust through responsible innovation - Energy, Sustainability and Society, 2023

Therefore, establishing a robust hydrogen production and distribution infrastructure emerges as a critical challenge, as it necessitates significant investment and coordination. Furthermore, the initial costs associated with hydrogen infrastructure and hydrogen-powered vehicles are relatively higher compared to conventional alternatives.

Existent forecasting scenarios conducted in recent years reveal a wide disagreement on the transport sector's future evolution[5]. By 2030, the highest projected energy demand regardless of the source (DNV[6] at 35 600 TWh) is already almost twice the size of the lowest (IFS[7] at 16 600 TWh). Yet, on average, demand reduction is around 15%. The downward trend continues in 2040 with an average reduction of 35% over 2019, and in 2050 the reduction is almost 40%, with the highest estimate (DNV) now three times the lowest (IFS). The differences are driven by assumptions on decarbonisation targets, societal/behavioural changes and rates of efficiency improvements,mainly electrification.

The term "electrification" refers to the process of transitioning from fossil fuel-powered technologies to electric-powered technologies in various sectors, including transportation. In the context of transportation, electrification typically involves replacing internal combustion engines with electric motors and utilizing energy storage systems, such as batteries or fuel cells, to power the vehicles. While electrification offers significant benefits in terms of reducing carbon emissions and dependence on fossil fuels, it remains challenging in certain areas of transportation, in particular, long-haul transportation. Battery electric vehicles (BEVs) have a limited driving range compared to convential vehicles, which is particularly problematic for heavy-duty vehicles that need to cover extensive distances withouth frequent rechargings. Range anxiety, the fear of running out of charge, remains a concern for both individual drivers and fleet operators. Moreover, the time required to fully charge an electric vehicle is much longer compared to refueling a conventional vehicle with liquid fuel since batteries are heavy and voluminous. The weight of the batteries depends on their capacity and the range requirements of the vehicle. Long-haul vehicles often need larger battery packs to support extended driving ranges, which further contributes to the overall weight of the vehicle.

Hydrogen Fuel Cell Electric Vehicles (FCEVs) aim to adress the above-mentionned challenges of electrification in long-haul transportation by offering specific advantages and overcoming limitations associated with range limitations and long charging times of BEVs.

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[5] CEU. JRC., *The Role of Hydrogen in Decarbonisation Energy Scenarios: Views on 2030 and 2050.* (LU: Publications Office, 2022), https://data.europa.eu/doi/10.2760/899528.

[6] DNV_Hydrogen_Forecast_2022_to_2050.Pdf.

[7] Sven Teske, ed., *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5°C and +2°C* (Cham: Springer International Publishing, 2019), https://doi.org/10.1007/978-3-030-05843-2.

1.2 H2MA Activity A1.4

As part of Activity A1.4 within the H2MA Interreg Alpine Space project, partners will collaborate to develop maturity scenarios for green hydrogen production and supply in the Alpine space. This collaboration effort aims to enhance transnational intelligence and coordination for green H2 mobility across the participating territories.

The methodology presented in this document provides a step-by-step guide for partners to identify and prioritise trends and factors driving the roll-out of hydrogen and renewables within each territory. Subsequently, KSSENA will compile the data and develop forecasting scenarios, that encompass baseline, pessimistic and optimistic projections. These scenarios will serve as valuable tools for partners to support the utilisation of the H2MA tool and the design of the green hydrogen mobility routes.

1.3 Forecast methodology

Developing forecasting scenarios with outcome projections is one of the measures identified by the business world, national governments, and the EU to support the promotion of new technologies. Forecasting scenarios play a crucial role in strategic planning, risk management, resource allocation, stakeholder engagement, and policy development (Indicative examples have been provided later in the section). They allow for the identification of opportunities, potential challenges, and necessary actions to promote and support the adoption of new technologies. By understanding possible outcomes, decision-makers can allocate resources effectively and develop appropriate policies and strategies. Forecasting scenarios also provide a basis for evaluating potential challenges, barriers, and market dynamics. By anticipating risks, stakeholders can develop mitigation strategies and contingency plans to address potential hurdles, reducing uncertainty and increasing the chances of successful technology implementation. Moreover, accurate forecasting scenarios and outcome projections play a significant role in guiding investment decisions. Investors, both private and public, require reliable information to evaluate the potential returns and risks associated with supporting new technologies. Outcome projections provide insights into market potential, demand growth, cost reduction trajectories, and competitive dynamics. This information helps investors make informed decisions about allocating resources and supporting the development, production, and deployment of new technologies.

The present methodology builds on previous H2MA project findings to help develop forecasting scenarios on green hydrogen production and distribution in the Alpine space. It aims to establish and validate a set of factors, drivers and barriers influencing the green hydrogen production and distribution in the Alpine space through an extensive partner consultation process. The thematic background aims to help orient partners in identifying pertinent factors that are pivotal for hydrogen's roll out by 2030. Then, these factors are assembled in the form of a list, according to their estimated importance (identified during desk research). Based on this list, partners will rate them according to their weight and their believed possible impact on the **territorial** green hydrogen roll out. Once partner input is collected, KSSENA will employ these data to develop various different forecasting scenarios for the roll out of green hydrogen in the Alpine area.

2. THEMATIC BACKGROUND

This section provides an overview of key maturity scenarios that are influencing the discourse on the future of hydrogen, serving as valuable reference points to guide partners in their research.

2.1 The use of forecasting scenarios in strategic planning

Maturity forecasting scenarios serve as a foundation for strategic planning and decision-making processes, allowing the identification and assessment of risks and uncertainties inherent in predicting the development of new ecosystems and technologies (such as green hydrogen applications in mobility[8]). The complexities involve various interrelated factors such as policy changes, technological advancements, market dynamics, and social acceptance. By exploring multiple scenarios, governments and stakeholders can anticipate potential obstacles, mitigate risks, and devise contingency plans to address challenges that may arise during the green hydrogen roll-out.

Moreover, maturity scenarios aid businesses in optimizing resource allocation and investment decisions. Many of these scenarios are presented further down in detail (See Section 2.2). Since green hydrogen implementation requires significant investments in infrastructure as well as in research and market development, understanding different maturity pathways allows businesses to align their investments with the most probable scenarios, prioritize projects, and allocate resources effectively, minimising inefficiencies and maximising the impact of their investments.

[8] 'Green hydrogen applications in mobility' refer to the utilization of green hydrogen as a fuel or energy carrier in various modes of transportation, such as cars, buses, trucks, trains, ships, and even aircraft. Green hydrogen is produced through electrolysis, using renewable energy sources like wind or solar power, resulting in a zero-carbon or low-carbon fuel. Green hydrogen can be used in fuel cell electric vehicles. FCEVs use hydrogen fuel cells to produce electricity, powering the vehicle's electric motor. These vehicles emit only water vapor as a byproduct, contributing to local air quality improvements and reducing greenhouse gas emissions. FCEVs offer long driving ranges and relatively short refueling times, addressing the limitations of battery electric vehicles for long-distance travel. Green hydrogen can play a crucial role in decarbonizing heavy-duty transportation, such as trucks, buses, and freight trains. The high energy density of hydrogen makes it suitable for powering heavy-duty vehicles that require long ranges and higher power output. Hydrogen-powered heavy-duty vehicles can contribute to reducing emissions in the logistics and transportation sectors, which are significant contributors to greenhouse gas emissions.

Within the context of H2MA Interreg Alpine Space project, maturity/forecasting scenarios have an additional goal. They aim to enhance partner engagement and collaboration by establishing a shared reference point for discussions among regional administrations, policymakers, industry players, and research institutions in the Alpine space. By sharing and discussing these scenarios, H2MA partners will have the opportunity to exchange their knowledge and collectively work towards the roll-out of green hydrogen in the region.

2.2 Current scenarios for green hydrogen

Within the realm of green hydrogen, there are several established scenarios that serve as reference points for analysis and planning. This subsection presents an overview of some of these scenarios, which have been formulated to assess the prospective roll-out and integration of green hydrogen technologies in the near future. These scenarios encompass different perspectives, including the role of hydrogen in the green transition, potential pathways for hydrogen propulsion evolution, and techno-economic factors that could influence the diffusion of hydrogen technology. By leveraging these scenarios, partners can gain valuable insights into the future landscape of green hydrogen and familiarize themselves with the forecasting process. This understanding will enable them to customize their own forecasts to the Alpine space and align their strategies to potential outcomes associated with each forecasting scenario.

1. Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition by Hydrogen Europe, (2019) by Fuel Cells and Hydrogen 2 Joint Undertaking. Developed with input from 17 companies and organisations.

This report provides a comprehensive analysis of the potential and challenges associated with green hydrogen deployment in Europe. It outlines different scenarios and pathways for the roll-out of hydrogen technologies, considering factors such as policy frameworks, infrastructure development, and market dynamics. It uses **a three-step process** built atop a baseline established from multiple EU-specific sources, combined with adoption rates provided by the coalition consisting of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and multiple industry players.

The **first step** involves modeling the general EU energy system of the future based on multiple sources. These include using the “2-degree Celsius scenario” energy system from the International Energy Agency as a main baseline for all segments. The EU Commission’s PRIMES model, which offers a reference scenario and detailed forecasts per country until 2050 is used as a comparison model. To model granular developments within sectors, the scenario uses various complementary insights including socioeconomic factors, industry perspectives, and external studies for sector, country, and regional level analyses. The **second step** estimates the market potential for hydrogen, defined sector-specific adoption rates and modeled fleets, and energy demand. Hydrogen adoption is then modeled according to two different scenarios: a) an ambitious scenario based on an accelerated expansion of green hydrogen use cases in a 2-degree Celsius world and with a coordinated effort of industry, investors, and policymakers, and b) a business-as-usual (BAU) scenario in which current policies continue, but no step-up of activities takes place. In this second scenario, the EU fails to reach the 2-degree target in 2050.

To simulate the supply of the required hydrogen for these adoption rates, two additional scenarios were modeled with similar CO2 abatement potential : a) The “water-electrolysis-dominant scenario” and b) the steam methane reforming/autothermal reforming (SMR/ATR) dominant scenario. In the “water-electrolysis-dominant scenario”, new hydrogen demand is met to a large degree through water electrolysis, with natural gas-based production methods as a bridge until 2030. Existing hydrogen demand (i.e., hydrogen that is already in use today) is converted, where feasible, to electrolysis in the long term. The “SMR-/ATR-dominant scenario” describes a world in which new hydrogen demand is met partially from decentral electrolysis, with the majority of demand coming from natural gas reforming. In this world, SMR/ATR remains the lowest cost option and dominates the production mix and will be utilized in combination with carbon capture and storage technologies to produce decarbonized hydrogen. Both scenarios achieve similar carbon abatement by 2030 and almost complete decarbonization of hydrogen production by 2050.

Finally, the **third step** combines baseline and adoption scenarios and performs multiple quality and feasibility tests on the developed scenarios. Then, results are compared against other published studies, and bottlenecks to hydrogen deployment are identified and analysed.

2. The role of hydrogen in decarbonization energy scenarios: Views on 2030 and 2050, by European Commission, (2022) Joint Research Centre (JRC), Author: Tarvydas, D., Publications Office of the European Union. https://data.europa.eu/doi/10.2760/899528

This report examines the future role of hydrogen in global and EU energy systems. It investigates the commonalities and differences of the decarbonisation pathways presented in selected energy scenarios, along with calculating the necessary infrastructure expansion efforts. It thus assesses the magnitude of the challenge ahead, as meeting hydrogen demand requires substantial increases in the installed capacity not only of electrolysers but also of solar and wind generation. More specifically, the report analyses current hydrogen consumption and then delves into the perspectives presented in scenario studies regarding how and where hydrogen will be utilized in the medium and long terms. Lastly, hydrogen production capacities are thoroughly discussed, drawing insights from scenario studies and the author’s estimates.

All scenarios analysed in the report (both global and EU) see electricity as the main contributor to the energy sector's transition towards carbon neutrality. By 2050, all end-use sectors will benefit from higher direct use of electricity. Yet, not all scenarios agree on the role that hydrogen will play in this hard-to-abate sector.

Globally, all the scenarios analysed expect hydrogen deployment to be slow in the coming years. In 2030, hydrogen and its derivatives could provide only 2% of final energy demand. Industrial feedstock will still be a main user of hydrogen. In 2040, all studies agree on the increasing importance of hydrogen, but due to differing assumptions, hydrogen demand varies. By 2050, hydrogen could provide more than 25% of final energy, if a full transition to a hydrogen economy is assumed.

Compared to global trends, some of the EU scenario studies see a faster adoption of hydrogen. According to some of them, hydrogen and its derivatives could already cover over 6% of final energy demand and reach 15 Mt by 2030 (almost doubling current hydrogen demand as a feedstock in industry). Other scenarios expect growth to be slower, ranging from almost non-existent to 3% (6 Mt). In the Fit-for-55 Mix H2 variant, hydrogen demand in end use sectors amounts to 3 Mt and provides slightly above 1% of demand. In REPowerEU, hydrogen adoption happens faster: 14 Mt is used in final demand. By 2040, the importance of hydrogen in final energy demand grows much faster in the EU than globally, reaching 17% of final demand (27 Mt). The energy studies disagree on the role of hydrogen in the EU transport sector in 2030. While the majority see hydrogen and e-fuel consumption at or below 1% of total demand in the sector, others anticipate a fast transition, with 13% (10 Mt) covered by hydrogen-based fuels. In EC Fit-for-55, 1.4 Mt used in the transport sector, providing 2% of final demand in the transport sector in 2030. By 2040, more studies see hydrogen increasing in importance. In EC Fit-for-55, 10.5 Mt is used in transport. In another scenario, despite a high hydrogen penetration rate of 23%, this accounts for only 6.5 Mt due to low energy consumption in the transport sector. By 2050, hydrogen and its derivatives provide from 11% (EUCalc) up to 43% (EC Fit-for-55 MIX H2 variant) of final energy in transport. The report notes that the highest hydrogen demand is to be found in the transport sector, but due to different demand projections, hydrogen provides only 36% of final demand in transport in 2050.

3. European Hydrogen Backbone: A European hydrogen infrastructure vision covering 28 countries (2022) by Gas for Climate.

This study focuses on the development of a European hydrogen infrastructure, examining the requirements and potential investment needs for a widespread deployment of green hydrogen. It provides an outlook for different maturity scenarios, taking into account regional developments and cooperation. More specifically, the 2022 report presents an updated, extended, and accelerated EHB vision. The updated hydrogen infrastructure network maps as presented in this report build on the EHB initiative's prior body of work. The accelerated vision shows that by 2030, five pan-European hydrogen supply and import corridors could emerge, connecting industrial clusters, ports, and hydrogen valleys to regions of abundant hydrogen supply – and supporting the EC's ambition to promote the development of a 20.6 Mt renewable and low-carbon hydrogen market in Europe. The hydrogen infrastructure can then grow to become a pan-European network, with a length of almost 53,000 km by 2040, largely based on repurposed existing natural gas infrastructure. Moreover, the study indicates possible additional routes that could emerge, including potential offshore interconnectors and pipelines in regions outside the area where the EHB members are active. A 'live' version of the maps presented in this report can also be found in digital format on the EHB initiative's website.

The European Hydrogen Backbone for 2040 as proposed in this report requires an estimated total investment of €80-143 billion. This investment cost estimate, which is relatively limited in the overall context of the European energy transition, includes subsea pipelines and interconnectors linking countries to offshore energy hubs and potential export regions. Transporting hydrogen over 1,000 km along the proposed onshore backbone would on average cost €0.11-0.21 per kg of hydrogen, making the EHB the most cost-effective option for large-scale, long-distance hydrogen transport. In case hydrogen is transported exclusively via subsea pipelines, the cost would be €0.17-0.32 per kg of hydrogen per 1,000 km transported.

4. Green Hydrogen Deployment in the Europe-MENA Region from 2030 to 2050: A Technical and Socio-Economic Assessment" (April 2023), by Jan Frederik Braun, Felix Frischmuth, Norman Gerhardt, Maximilian Pfennig, Richard Schmitz, and Martin Wietschel (Fraunhofer CINES), Benjamin Carlier, Arnaud Réveillère, Gilles Warluzel, and Didier Wesoly (Geostock).

This paper provides a technical and socio-economic assessment of the EU's strategic REPowerEU target of 20 Mt hydrogen production and import target by 2030. Due to their geographical proximity, low-cost production potential, and existing gas infrastructure, six MENA ('Middle East and North Africa') countries are regarded as crucial players for realizing the REPowerEU 10 Mt import target (i.e., 6 Mt of hydrogen by pipeline and 4 Mt of ammonia): Morocco, Algeria, Tunisia, Libya, Egypt, and Saudi Arabia.

The technical assessment conducted in this report, by linking the pan-European cross-sectoral capacity expansion planning framework SCOPE Scenario Development (SCOPE SD) with the new gas market-based expansion planning framework IMAGINE (Infrastructure and Market transformations for Gas In Europe), does not see a domestic (European) hydrogen production capacity of 10 Mt p/yr. materialise until sometime between 2035 and 2040. Regarding sectoral demand, the analysis shows that 376 TWh (11.4 Mt) constitutes a very ambitious, maximum hydrogen demand that can be covered by domestic European production by 2030.

In terms of infrastructure, this report argues that integrating larger quantities of hydrogen by repurposing existing natural gas-based infrastructure in Europe is possible and could be a building block in the continent's transition towards a climate-neutral energy system. Imports by pipeline from the selected MENA countries could contribute to diversifying Europe's transport and supply options in the medium term. These pipeline imports are essential in the case of high hydrogen demand in the long term, i.e., up to 2050 and beyond. Sufficient hydrogen storage capacity in salt caverns in Europe is also available in the short to medium-term. From 2045 onwards, however, there will be an increasing need for new hydrogen storage capacity. Although a massive endeavor, the 216 TWh of new and repurposed hydrogen storage potential in salt caverns by 2050 does not consider other storage options and strategic possibilities like the reserve required to achieve the REPowerEU target by 2030.

The report also points out that the technical analysis conducted here focuses on cost optimization, and that the war in Ukraine, and the EU's response in the form of REPowerEU, have made it very clear that strategic considerations are becoming increasingly important for Europe's ambitions regarding hydrogen. The report touches upon possibly repurposing the proposed EastMed pipeline for clean hydrogen as an example of geopolitical concerns in a 'post-Ukraine war' Europe.

The selected MENA countries have a huge technical potential to export clean hydrogen. Under the right conditions, including production capacities, policies, infrastructure, financing, certification and human capital development, this potential could meet Europe's demand for hydrogen. However, there are major hurdles to be overcome when turning this technical potential into a realizable one. The initial remarks on the theoretical storage potential of hydrogen in salt caverns require more extensive and in-depth analysis, including of depleted oil and gas fields.

Even though this report goes beyond the EU territory, it is interesting since it considers political and institutional aspects that other methodologies tend to neglect. It uses five composite indicators, as used by the World Bank (2022) to account for a more systemic approach, including, political stability, government effectiveness, Voice and accountability, regulatory quality, the rule of Law and control of corruption.

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All four of the above report scenarios and their respective methodologies illustrate the intricacy and challenges involved in the forecasting process. Moreover, they underscore the critical importance of defining the elements to be forecasted beforehand. In addition to the valuable thematic information they offer, these scenarios can serve as tools to guide the H2MA consortium partners in considering and evaluating the essential parameters required for developing accurate forecasting scenarios pertaining to green hydrogen production and supply in the Alpine space.

3. METHODOLOGY

This methodology is designed to assist partners in the identification and assessment of factors, trends, and barriers that impact the development of maturity scenarios for green hydrogen production and supply in the Alpine region. The first subsection presents a clear outline of the methodological steps to be followed and the subsequent ones offer practical guidance in recognizing key factors, drivers, and trends that influence the rollout of green hydrogen initiatives.

3.1 Methodological steps

Developing maturity scenarios for green hydrogen production involves a series of steps that need to be followed. These are further explained below.

3.1.1 Defining scope, focus and timeframe

The initial step in developing maturity scenarios involves determining the precise scope, focus, and timeframe for these scenarios. Given that the regional scope (EUSALP) and thematic focus (green hydrogen production and supply) are already established by the project's objectives, partners only need to deliberate on the specific period or target years to be covered. More specifically, the European Union has set ambitious climate and energy targets to be achieved by 2030 and 2050. These targets include reducing greenhouse gas emissions, increasing the share of renewable energy, and promoting clean and sustainable transportation. By choosing the short-term (2030) and/or the long-term (2050) horizon, the forecasting scenarios align with these targets and provide insights into the progress of green hydrogen adoption in the Alps towards meeting these goals. Alternatively, partners may also choose to cover both horizons, facilitating the development of both short-term and long-term scenarios for green hydrogen development.

3.1.2 Identifying and rating key factor areas

The next step involves the identification of factors or factor areas that are believed to significantly impact the maturity of green hydrogen production and supply. These include RES capacity, electrolyzer technology and capacity, technological advancement, infrastructure development, policy support, market demand, cost competitiveness, public acceptance and others. The following subsection provides further elaboration on these key factors to be considered. After identifying the key factors, it is necessary to assign them values that indicate their respective levels of influence on the production and supply of hydrogen. These values will help in assessing the relative importance of each factor and its potential impact on the overall development of green hydrogen. For the purpose of this methodology, a rating from 1 to 3 is recommended as seen in the methodological tool annexed at the end of this document.

3.1.3 Data collection and research on drivers and barriers within each factor area

Once the key factor areas have been identified, which are the specific domains of interest impacting the subject, a survey should be conducted to identify individual elements related to each of these factor areas, specifically individual drivers, and barriers. Drivers represent positive or beneficial factors that promote progress, while barriers are factors that impede, hinder, or slow down the progress of the matter at hand. For instance, in the context of green hydrogen production, a key factor area could be "policy support." Research may reveal the presence of supportive government policies (driver) or, conversely, regulatory uncertainties (barrier). Depending on the findings, the presence of a driver may support a more optimistic scenario, while the existence of a barrier may indicate a more pessimistic one, highlighting a series of challenges and limitations requiring resolution.

The research to identify drivers and barriers for green hydrogen adoption in the Alps should be conducted by partners on a regional level within the Alpine space, exploring sources such as press releases and academic literature, regulatory frameworks, and targets, and reviewing social surveys in various fields (e.g., social acceptance and attitudes towards green technologies). This approach is essential to gather region-specific data and insights, ensuring that the forecasting scenarios accurately reflect the local context. By involving regional stakeholders, including policymakers, industry experts, and local communities, the research can capture the unique characteristics, challenges, and opportunities within the Alpine region. This regional perspective will enhance the accuracy and relevance of the forecasting scenarios and provide valuable insights for policymaking, investment planning, and the successful implementation of green hydrogen initiatives in the Alps.

This comprehensive approach will enable the prioritization of the development of optimistic or pessimistic scenarios based on the real-world factors influencing green hydrogen production and supply.

3.1.4 Identifying trends

Another crucial aspect in developing maturity scenarios and forecasting future outcomes involves identifying and analysing trends. These trends encompass patterns, directions, or tendencies that illustrate the historical or current trajectory of specific aspects or factors relevant to the subject under analysis. The following subsection provides further elaboration and indicative examples of trends to help partners comprehend what to look for. It is essential not to conflate trends with drivers and barriers. While drivers and barriers represent specific elements that contribute to or hinder the subject's development, trends offer a broader context by showcasing the evolution and interaction of key factors over time. For example, within the key factor area of "policy support" mentioned above, a trend can be observed where successive national and regional governments adopt hydrogen strategies and set specific targets. This trend indicates a growing policy support expected to continue in the future. In order to identify trends related to green hydrogen production and supply in the Alpine space, partners can explore reports and analyses from industry experts and research organizations, track policy developments, and examine market trends and forecasts for green hydrogen in the mobility sector.

3.1.5 Scenario development using stochastic methods

This step involves the practical development of maturity scenarios. These scenarios should cover a spectrum of possibilities considering various combinations of the identified key factors and trends. When developing maturity scenarios, stochastic methods are commonly deployed. A stochastic method refers to an approach that incorporates randomness or uncertainty into the scenario analysis. Unlike deterministic methods that rely on fixed input values to generate specific outcomes, stochastic methods introduce probability distributions for key variables, allowing for a range of possible outcomes based on different scenarios. The main idea behind using stochastic methods is to account for the inherent uncertainty and variability in real-world situations. In complex systems like green hydrogen production and supply, numerous factors and variables interact in unpredictable ways. Stochastic methods can thus enable the development of a wide range of potential scenarios by considering multiple possible values for uncertain parameters.

One common technique used in stochastic modeling is Monte Carlo simulation. In this approach, random sampling is used to generate a large number of scenarios by selecting values from specified probability distributions for various input parameters. Each simulation run produces a different outcome, and by repeating the process multiple times, analysts can obtain a distribution of possible results, allowing them to assess the likelihood and potential impact of different scenarios. In the context of scenario development for green hydrogen, Monte Carlo simulation can capture the uncertainty and variability associated with various factors, such as input parameters, market conditions, technology costs, and policy outcomes. It does so through considering uncertain variables and through assigning probability distributions to represent their possible values. These distributions can reflect the inherent uncertainties in parameters like renewable energy availability, hydrogen production costs, infrastructure development, and demand patterns. By running numerous simulations with different values sampled from these distributions, the method provides a probabilistic range of possible outcomes, enabling a comprehensive assessment of the system's behavior.

In that way, Monte Carlo simulation considers not only uncertainty but also variability in the system. It takes into account the potential interactions and dependencies among different variables and factors. By incorporating correlations and dependencies in the random sampling process, the simulation can capture the complex interplay between various elements of the green hydrogen production and supply system. This allows for a more realistic representation of the variability and potential outcomes of the system under different scenarios.

Another, simpler, stochastic method, that can be used on its own or in combination with the Monte Carlo simulation, is Decision Trees regressor. Decision trees are graphical models that represent decision-making processes by mapping out a sequence of events, choices, and possible outcomes. Decision trees are particularly useful for analyzing complex systems with multiple decision points, uncertainties, and alternative paths.

As such, they can handle both deterministic and probabilistic information, making them compatible with the stochastic method. In a stochastic context, probabilities can be assigned to different branches of the decision tree to reflect uncertain events and their likelihoods. When combined with Monte Carlo simulation, decision trees can be used to explore various decision paths and their corresponding outcomes under uncertainty. Moreover, decision trees allow for the evaluation of different decision paths and their potential outcomes, considering both uncertainties and the decision-maker's preferences. This enables the analysis of trade-offs and the comparison of alternative strategies or scenarios. Decision trees can quantify the expected values of different decision paths, providing insights into the risks and benefits associated with different choices and helping decision-makers select the most favorable options.

In the context of green hydrogen production and supply, a stochastic method is recommended. A decision tree or the Monte Carlo stimulation could help assess the likelihood of different technology adoption rates, cost variations, policy developments, and other key factors that influence the future of the green hydrogen’s roll-out. As a result, one could identify both optimistic and pessimistic scenarios and several combinations in between. More specifically, a decision tree could include decision points such as infrastructure investment (e.g., building hydrogen refueling stations), fleet conversion costs, and operational considerations (e.g., refueling time, range, and hydrogen availability). Each decision point would have associated uncertainties, such as the adoption rate of green hydrogen technology, the cost of hydrogen infrastructure, and the future demand for public transportation.

Stochastic methods are valuable in scenario development because they provide a more comprehensive and robust analysis of the uncertainties and risks associated with different pathways. By exploring a wide range of possible outcomes, decision-makers can make more informed choices and develop strategies that are resilient to various potential future conditions.

3.1.6 Results analysis and recommendations

The last step of the process entails the analysis of the outputs from the model simulations for each scenario. Different outcomes need to be examined and compared. Combining quantitative and qualitative analysis is essential for providing a more comprehensive understanding of the feasibility and potential risks associated with each scenario in the context of green hydrogen production and supply. Numerical data, such as hydrogen production capacity, energy demand, investment requirements and market size help understand the potential scale and magnitude of each scenario's impact. Then, a qualitative analysis can provide a more holistic understanding of each scenario's feasibility, taking into account factors that are difficult to be quantified, such as technological readiness, social acceptance and stakeholder engagement. Quantitative analysis thus provides the numerical basis for evaluating the technical and economic feasibility of scenarios. It offers data-driven insights into costs, performance metrics, and potential benefits. However, it may not capture the full complexity of the real-world context and the various uncertainties that exist. Qualitative analysis comes to supplement the quantitative assessment by considering the broader landscape and qualitative factors. It helps identify potential risks, social acceptance issues, regulatory challenges, and stakeholder engagement requirements that can influence the outcomes of the scenarios. It provides valuable insights into the non-quantifiable factors that are critical for successful implementation and adoption.

The final analysis should be consistent and aligned with the identified trends in the pre-development stage. Unrealistic or highly unlikely scenarios should be refined or excluded from further consideration. In a more complex analytical process, like in Monte Carlo simulation, key assumptions and drivers are usually tested through sensitivity analysis to examine how smaller or bigger changes in each of the identified factors affect the outcomes of each scenario.

Here's how a sensitivity analysis is typically conducted: The first step in a sensitivity analysis is to identify the key assumptions or drivers that have a significant impact on the outcomes or results of interest. These could be variables such as input parameters, market conditions, technology costs, policy outcomes, or other factors relevant to the analysis. Once the key assumptions or drivers are identified, they are systematically varied within a specified range or set of scenarios. Each assumption or driver is tested by assigning different values to it, such as increasing or decreasing the value by a certain percentage or using different scenarios or data sources. The variations can be done individually or in combination, depending on the analysis objectives. The next step is to evaluate the impact of varying the key assumptions and drivers on the outcomes or results of interest. This involves running the model or analysis multiple times, each time with a different set of assumptions or drivers. The outcomes are then compared to determine how sensitive they are to the changes in the key factors. The sensitivity analysis results help in interpreting the robustness and reliability of the outcomes. It helps identify which assumptions or drivers have the most significant influence on the results and which factors are more uncertain or critical in the analysis. Sensitivity analysis can reveal potential risks, vulnerabilities, or opportunities associated with specific assumptions or drivers.

Once the analysis is concluded, conclusions can be drawn regarding possible risks associated with each scenario in a separate risk assessment process (e.g., market volatility, technology disruptions, or even geopolitical factors). Last but not least, the analysis can incorporate policy or investment recommendations and, in that way, assist stakeholders in well-informed decision-making and strategic planning.

3.2 Factors influencing the green hydrogen's roll-out

The identification of factors is the second step of the maturity scenarios development process. As stated before, factors are those variables that directly or indirectly influence the subject under consideration. In the context of green hydrogen production and supply, a set of factors has been systematically identified. These include renewable energy capacity, electrolyser technology and capacity, policy support, market readiness, demand, infrastructure development, cost competitiveness, public acceptance, and even international collaborations. These factors play a significant role in shaping the development and maturity of green hydrogen initiatives.

Withing Activity A1.4 of H2MA Interreg Alpine Space project, partners are asked to identify and rate factors to be used as inputs in forecasting scenarios and assess their potential impact on green hydrogen's future production and supply. A list of five factor areas is included in the methodological tool annexed at the end of this document. Hereafter, these factor areas are briefly outlined to help partners evaluate them and rate their importance.

3.2.1 Policy support: Government-led commitment to green hydrogen

Policy support is considered an essential factor when developing maturity scenarios, since it is believed to provide a stable and predictable environment for green hydrogen development, encouraging private sector participation and driving technological advancements. This factor encompasses a range of elements (i.e., drivers) related to energy policies and incentives crucial for promoting the attractiveness and development of green hydrogen production. These elements can take the form of policies or incentives and should be carefully identified as drivers (or in case of their absence as barriers) when developing maturity scenarios.

First and foremost, the existence of dedicated national or regional policies (e.g., National Hydrogen Strategy, Bavarian Hydrogen Roadmap etc.) can play a significant role in driving the technology's growth and should be considered a major driver. However, policies should be geared towards concrete decarbonization targets to make hydrogen viable from a systems perspective. A general declaration of support to hydrogen technology does not have the same weight as the adoption of ambitious targets for example. Another element that can be considered as a driver is the existence of a substantial share of renewables in the electricity mix. If there is little or no decarbonization targets and little or no renewables in the electricity mix of a country or region, then this reality should be considered as a barrier.

Another type of policy support is the existence of incentives for market creation, which are considered vital in overcoming the current limitations in hydrogen trading. These incentives may take the form of quotas for various end uses, public procurement, or capacity targets (e.g., for electrolysis) to encourage competition and cost reduction. Moreover, addressing the higher production and transport costs of hydrogen compared to fossil fuels also requires policy-let support. Grants, fiscal incentives, or carbon contracts for difference (CCfD) can help offset these costs and make hydrogen more economically competitive. Government-backed guarantees can also provide long-term revenue certainty and reduce project risk, serving as an additional incentive.

Additionally, regulation of infrastructure also plays a crucial role in creating a conducive environment for hydrogen development. This includes establishing quality and security standards, a clear tariff structure, and appropriate financing mechanisms to foster free and fair competition among suppliers. Lastly, streamlining permitting and approval processes is essential to facilitate project execution and avoid unnecessary delays. Simplifying administrative procedures and integrating them with existing processes for renewable power can accelerate the implementation of green hydrogen projects and should therefore considered an important driver.

3.2.2 Economic factors

Economic factors play a pivotal role in shaping maturity scenarios for green hydrogen production and supply since they have a significant impact on the feasibility, competitiveness, and overall proliferation of green hydrogen use cases. These factors include the cost of hydrogen production (including cost of electrolysis from RES), the cost of transport and distribution, the share of investments and financing opportunities, the market demand, but also supply-chain resilience and long-term viability and return of investment. When assessing drivers within this key factor area, several elements should be looked upon.

The primary driver of the cost of green hydrogen production is the price of renewable electricity used in the electrolysis process. The cheaper and more abundant the renewable energy sources (e.g., wind and solar), the lower the production cost of green hydrogen. Also, the efficiency of the electrolyser directly impacts the cost. High-efficiency electrolysers are more cost-effective as they require less electricity for the same hydrogen output. A thorough research must be conducted to assess capital and operating costs of hydrogen projects. The initial investment in setting up the electrolysis plant and related infrastructure plays a significant role in the overall cost of production. Capital costs include the price of electrolyser units, power conversion systems, storage facilities, and other plant components. But also, ongoing operational expenses, maintenance work, and servicing of the electrolysis plants are additional factors influencing the cost of hydrogen production.

Other economic aspects to be considered relate to transport and distribution costs. Green hydrogen, being a gas, requires appropriate infrastructure and a logistical system to transport and distribute it efficiently. The distance between the hydrogen production site and end-users or export facilities directly impacts transport costs. Longer distances typically incur higher expenses, especially if the hydrogen needs to be transported overland. The geographical location and accessibility of production units and consumption centres play a crucial role in determining the feasibility and cost-effectiveness of hydrogen transport. Pipelines is the most cost-efficient option for large-scale and long-distance transportation, while trucks and ships are more suitable for smaller-scale or niche applications, especially at the early stages of the ecosystem development. Government-led financial support is also to be considered under this key factor category since state subsidies can significantly reduce the financial burden on project developers and incentivise private investments. Previous experience of financial institutions in renewable energy projects, attractive funding opportunities and low interest rates can also be considered as major drivers. Finally, a collaborative public-private environment also plays a pivotal role in scaling up green hydrogen projects and dictates a rather optimistic maturity scenario.

3.2.3 Technical factors

This key factor area encompasses various technical aspects that significantly influence the development and supply of green hydrogen. Firstly, it considers the presence and scale of an existing hydrogen industry in the territory, as well as the level of experience with renewable hydrogen. Moreover, the size and nature of ongoing hydrogen projects play a pivotal role in shaping the maturity scenarios. Another critical consideration is the state of the hydrogen infrastructure, including the availability of a pre-existing gas network that can be repurposed, thereby reducing local transport costs. Additionally, the proximity of suitable underground formations for hydrogen storage near production sites, experience with gas liquefaction, and well-connected ports with ample capacity and adequate facilities for hydrogen are all crucial factors to examine. A separate dimension that can however be examined under the technical factors area revolves around the presence of a national alliance or organization that fosters effective coordination of project execution and facilitates partnerships among companies. Such collaboration is indispensable as hydrogen value chains typically involve multiple actors and require a collective effort for successful implementation.

3.2.4 International and geopolitical factors

Geopolitical factors relate to the interactions between different countries and regions and can either support or hinder the development of the green hydrogen economies. This became entirely evident during the recent war in Ukraine. European embargo to Russia's energy sources created an uncertainty in energy markets and raised concerns about energy security. To ensure a stable energy supply, national governments prioritized regional autonomous energy solutions, like energy generation from RES. This could result in larger electolyser capacity and should be considered a driver for green hydrogen production in the long term. However, geopolitical tensions are known to disrupt trade and supply chains and to negatively impact the import and export of hydrogen-related equipment, materials, and technologies, delaying projects and increasing costs. Interruptions in supply chains should therefore be considered as major barriers.

Geopolitical factors can shape the regulatory environment for green hydrogen production and supply. Supportive policies and incentives from governments can accelerate the deployment of green hydrogen projects, while conflicting regulations or policy uncertainties may hinder investments. Shared concerns about climate change and commitment to drastically cut greenhouse gas emissions led European governments to accelerate RES adoption and search for zero-emissions technologies, like green hydrogen. Such a shared geopolitical commitment can greatly affect crucial components of international cooperation across the green hydrogen value chain such as the standardization and certification processes for the facilitation of international trade and hydrogen infrastructure interoperability.

3.2.5 Public acceptance

Public acceptance is finally another crucial factor for the successful roll-out of green hydrogen production and supply. It refers to the willingness and support of the public, communities, and stakeholders to embrace and actively participate in the adoption of green hydrogen technologies. More specifically, for any large-scale energy infrastructure project, including green hydrogen facilities, gaining a social license to operate is essential. This means obtaining approval and support from local communities and the broader public. Without public acceptance, projects may face opposition, protests, and legal challenges, leading to delays or even project cancellations. Also, investors and financiers tend to consider public acceptance as a risk factor. A lack of support from the public may make it difficult to secure funding for green hydrogen projects, as investors may view them as financially risky due to potential delays and uncertainties. Lastly, since green hydrogen's success depends largely on end-user adoption, especially in sectors such as long-haul and freight transportation, public acceptance is key. For instance, demand for environmentally friendly products and services may lead consumers to choose a logistics company that operates a hydrogen fleet for their parcels, while lack of transparent communication on hydrogen trains operation may lead to safety concerns and reluctancy to passengers. On the contrary, public confidence is bolstered when it is communicated that the technology has undergone rigorous safety testing and meets required safety criteria.

3.3 Examples of current trends

Trends refer to the prevailing patterns or directions of development and change in relevant factors that may influence the maturity of green hydrogen technologies. These trends can be located in all of the above-mentioned key factor areas. Considering trends in forecasting maturity scenarios involves examining past and current developments and identifying consistent patterns or trajectories that may continue. These trends can offer even more informed assumptions on how green hydrogen’s roll out might evolve over time.

This subsection aims to help partners identify trends and patterns in relation to green hydrogen from their respective territories.

Example 1: Trend in growing policy support

Between late 2019 and January 2022, 15 countries and the European Commission published hydrogen strategies. One of the most common dimensions covered has been international collaboration, from the perspective of knowledge exchange and lessons learned, but also for potential future trade. Many of these strategies have translated into actual agreements, feasibility studies, and memoranda of co-operation. Announcements fall broadly in two categories: general technology collaboration for knowledge exchange, and specific pilot projects or studies for hydrogen trade across borders. This indicates that there is a noticeable pattern or tendency of increasing policy support over time.

Example 2: Trend in scaling up green hydrogen production

Increasing stack production with automated processes in gigawatt-scale manufacturing facilities can achieve a step-change cost reduction. Increasing plant size from 1 MW (typical in 2020) to 20 MW could reduce costs by over a third. Recent announcements of plans for new green hydrogen projects (both production plants and HRS) concern units with significantly bigger production capacity than existent one. Based on historic cost declines for solar photovoltaics (PV), whereby costs fall as capacity expands, the scaling up of green hydrogen production capacity is expected to drop costs significantly. A trend in increasing green hydrogen production is expected to be observed in many European countries of the Alpine space, in particular, Germany, France and Italy. This trend is expected to continue in the future and lead to important cost reductions in green hydrogen production.

ANNEX: METHODOLOGICAL TOOL

INPUT FORM

Name:	
Partner organisation:	
I. TIMEFRAME	
Please chose the expected timeframe for the development of maturity scenarios	
2030 HORIZON	☐
2050 HORIZON	☐
II. KEY FACTOR AREAS / DRIVERS **Rating** ***Please evaluate parameters in each key factor area by rating on a 1 to 3 scale*** **1: Little impact** **2: Significant impact** **3: Very significant impact**	
II.1 POLICY SUPPORT: GOVERNMENT-LED COMMITTMENT TO GREEN HYDROGEN	
Existence of national/regional strategy	1 ☐ 2 ☐ 3 ☐
Existence of specific targets for green hydrogen at a set timeframe	1 ☐ 2 ☐ 3 ☐
Existence of specific targets for Renewable Energy Sources (RES) in the energy mix	1 ☐ 2 ☐ 3 ☐
Existence of incentives for the uptake of green hydrogen (e.g. fiscal incentives)	1 ☐ 2 ☐ 3 ☐
Government-backed guarantees (e.g., long-term revenue certainty)	1 ☐ 2 ☐ 3 ☐
Establishment of quality and security standards	1 ☐ 2 ☐ 3 ☐
Streamlined permitting and approval processes	1 ☐ 2 ☐ 3 ☐

Simplified administrative procedures	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
II.2 ECONOMIC FACTORS	
Cost of hydrogen production (electrolysis from RES)	1 ☐ 2 ☐ 3 ☐
High-efficiency electrolysers (resulting in cost-effective hydrogen production)	1 ☐ 2 ☐ 3 ☐
Cost of transport and distribution	1 ☐ 2 ☐ 3 ☐
Capital costs	1 ☐ 2 ☐ 3 ☐
Operational costs (incl. maintenance)	1 ☐ 2 ☐ 3 ☐
Government-led financial support	1 ☐ 2 ☐ 3 ☐
Private investments and financing opportunities	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
II.3 TECHNICAL FACTORS	
Technological advancements in green hydrogen production	1 ☐ 2 ☐ 3 ☐
Technological advancements in hydrogen storage technologies	1 ☐ 2 ☐ 3 ☐
Development of hydrogen production infrastructure	1 ☐ 2 ☐ 3 ☐
Development of hydrogen distribution infrastructure	1 ☐ 2 ☐ 3 ☐
Development of hydrogen storage infrastructure	1 ☐ 2 ☐ 3 ☐

Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
II.4 INTERNATIONAL FACTORS	
Geopolitical tensions (e.g. Russia's invasion in Ukraine)	1 ☐ 2 ☐ 3 ☐
Trade and supply chains disruptions	1 ☐ 2 ☐ 3 ☐
Disparities in standardisation and certification process	1 ☐ 2 ☐ 3 ☐
Changes in Climate change targets	1 ☐ 2 ☐ 3 ☐
International/transnational agreements	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
II.5 PUBLIC ACCEPTANCE	
Awareness on climate change	1 ☐ 2 ☐ 3 ☐
Customer demand for climate friendly products	1 ☐ 2 ☐ 3 ☐
Gaining a social license for operation	1 ☐ 2 ☐ 3 ☐
Support from public (incl. civil society)	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
Other	1 ☐ 2 ☐ 3 ☐
III. CURRENT TRENDS, PATTERNS AND TENDANCIES	

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

Could you please identify one or more trends that you could observe in your territory regarding one or more of the 5 key factor categories rated above?
TREND 1 *(Please also state which key factor area it regards)*
TREND 2 *(Please also state which key factor area it regards)*
TREND 3 *(Please also state which key factor area it regards)*
Extend inputs if necessary