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Scenarios forecasting the maturity of green HYDROGEN production and distribution in the Alpine space

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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 (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.

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EXECUTIVE SUMMARY

In the context of Activity 1.4 entitled “Development of maturity scenarios on green HYDROGEN production and supply in the Alpine space, to improve transnational intelligence and coordination for green HYDROGEN mobility in the participating territories” the present report builds on the methodology proposed in D1.4.1 and develops alternative scenarios for the roll-out of renewable hydrogen in the Alpine space for 2030 and 2050.

In particular, section A provides an extended analysis and discussion of the replies that H2MA partners provided to the questionnaire presented in D1.4.1. The goal of these questionnaires was to highlight the most important factors for green HYDROGEN roll-out in the Alpine space separately for years 2030 and 2050.

Section B presents and justifies the selection of the methodological technique that was adopted in order to build the alternative scenarios.

Section C offers an analytical presentation of the scenarios for years 2030 and 2050, including a step-by-step presentation and explanation of the steps that were taken in order to build them.

Finally, Section D consists of a set of guidelines for H2MA partners on possible utilization of the outlined scenarios in future actions and policies related to H2MA’s scope.

A. Analysis of partners' feedback

This section analyses the responses of the eleven H2MA partners, i.e. their evaluations and assessments regarding factors that are deemed important for the roll-out of green hydrogen in their territories.

Essentially, all partners successfully filled two assessment forms (questionnaires), one focusing on 2030 and another on 2050, which pinpoint the key factors expected to impact the green hydrogen economy in the Alpine area over the following decades. In the first part of the questionnaire, partners were asked to assess each factor based on its expected impact on green hydrogen's future production and supply. In particular, partners were asked to choose among three values: 1 ("little impact"), 2 ("significant impact") and 3 ("very significant impact"). Based on the partners evaluations, the average score for each factor was calculated; then, based on these average scores, the overall score of each family of factors was calculated (e.g. economic factors, technical factors, etc).

As a first, broad conclusion it can be said that all factor areas are deemed rather significant from partners, i.e. their score was well above 2, with the exception of the "Public Acceptance" category regarding 2050. However, there are various points of variance between years and/or among partners which are worth presenting and focusing on. In the second part of the questionnaire, partners were asked to reflect in a more detailed fashion on major trends - in the form of drivers and barriers for the expansion of the green hydrogen mobility ecosystem - of at least one of the five factor areas in their territories. Partners' feedback and factor scores are discussed separately for 2030 and 2050 below and a brief discussion and recapitulation concludes this section.

A.1 Factors' assessment for 2030

As indicated in ANNEX I, all categories of factors received a high score by partners, with the partial exception of "Public Acceptance"; this implies that they are all considered important for the development of green hydrogen in their territories (and countries). "Technical factors" received the highest score, slightly above "Policy Support" factors, while "Economic" and "International" factors follow in level of importance.

Technical factors: The importance attributed to them on behalf of the H2MA partners aligns with a major concern of the broader public and scientific discussion regarding green (clean) hydrogen: the critical challenge of developing energy efficient, safe and affordable technologies as well as the necessary infrastructure in order to decisively boost green hydrogen's currently marginal share in the energy market. Among the five factors that compose this category, it is noteworthy that the three factors are related to the development of hydrogen infrastructure (namely, for green hydrogen production, distribution and storage) are assessed as particularly important; perhaps this denotes the existence of crucial infrastructure gaps across the Alpine region. Technological advancements in production and storage of green hydrogen are considered comparably, although slightly less, important. With regards to country variations in the answers, Italian partners (FLA, CMT, RL) tend to attribute somewhat less importance to this factor area, especially in relation to partners from Slovenia (KSSENA, BSC Kranj), France (EMS, PVF) and Austria (4ER, COD), who all assessed as "very significant" all five factors. Among the latter, five of them indicated a number of *additional* technical factors (i.e. not included in the questionnaire) that should be considered as relevant in assessing the development of green hydrogen in the Alpine region (or Europe in general): BSC Kranj highlighted the importance of "high safety standards" (score 3) and "monitoring standards) (score 2), EMS and PVF proposed the inclusion of "progress made in competing technologies, e.g. electric batteries" as a relevant technical factor (score 2), whereas 4ER and COD suggested as a relevant factor of interest the "development of infrastructure for hydrogen *imports*" (score 3).

Various trends are discussed by H2MA partners in the second part of the questionnaire, pointing out a number of drivers and barriers. Obviously, such trends are shaped by other factors (such as economic, political, international), highlighting their dynamic nature. For example, remarkably higher energy prices in most European states in combination with inadequate grid infrastructure and (current) technical limitations in producing and storing significant volumes of green hydrogen are leading a partner to report a trend for high short-term HYDROGEN prices. However, other partners (e.g. FLA) identify a positive interaction between technological innovation that increases performance and is expected to lead to more efficient use of electricity, higher conversion efficiency and (eventually) lower HYDROGEN production cost in the long-term[1]. FLA also offers in its reply a strictly technical assessment of alternative water electrolysis (WE) technologies, namely Proton Exchange Membrane (PEM-WE) and Alkaline (A-WE), discussing current drivers and barriers for their development. The partner also discusses hydrogen storage technologies, arguing that high pressure storage appears far more promising than storage within hydrides. FLA and COD also identify as a factor that may counterbalance current issues regarding the distribution of hydrogen, the existing natural gas pipelines network (whose repurposing is widely identified as a way to enhance clean hydrogen transport and distribution). Increasing investment in R&D hydrogen research in certain regions (such as Styria, Burgenland and Carinthia in

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[1] Nevertheless, FLA also underlines the current inadequacy of production and distribution infrastructures.

Austria and Baden-Württemberg in Germany) or even throughout the Alpine area and Europe in general is, moreover, identified as a driver by certain partners.

Policy support and government commitment to green hydrogen: This group of factors was evaluated by H2MA partners as practically equal in importance with technical factors. The "existence of a national/regional strategy" was one of the two individual factors from all areas that received the highest score, as it is considered as "very significant" by all eleven partners. Not only a coherent strategy, but also the existence of (fiscal) incentives for the uptake of green hydrogen on behalf of governments is assessed as an essential factor. Quite possibly, this reflects a need for considerable public funding in the initial stages of the development of green hydrogen - it is not yet "competitive" in the market, as CMT mentions in its reply - in order to address the currently high production costs, support the development of relevant technologies and infrastructure and expand green hydrogen use cases. Factors related to the setting of "specific targets" for green hydrogen in particular and RES in general, as well as the establishment of "quality and security standards", were also deemed highly important; this seems to further stress the need for a robust and target-oriented policy framework on green hydrogen. Interestingly, factors related to simplified "approval processes" and "administrative procedures" received a relatively lower score, whereas the existence of "government-backed guarantees" (e.g. in the form of long-term revenue certainty for green hydrogen producers) was still assessed as important, although it received the lowest score within this area. A number of additional "policy" factors were proposed by certain partners; KSSENA (as well as BSC Kranj) stressed the high relevance of a coherent EU policy framework that will serve to harmonise national policies and strategies[2], whereas EMS and PVF suggested a number of factors, especially policies focusing on the local aspect of green hydrogen development and on research and innovation[3].

Overall, H2MA partners identify the existence of a strong political will to develop the sector as a key driver for accelerating the roll out of green hydrogen; this is highlighted in recent programmatic documents in several countries at both the national and regional level (e.g. Austria, Italy, Slovenia) and is exemplified in the form of higher public expenditure (direct investment, marker premiums, investment grants) earmarked for relevant policies (e.g. hydrogen valleys, refuelling stations, hydrogen-powered vehicles), which is in certain countries partly financed by the

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[2] In particular, KSSENA suggested three factors (all of which were assigned with the highest score): "Common form and concept of all national hydrogen strategies, dictated by the EU", "Development of KPI's of national hydrogen strategies by EU", "the EU should prescribe a precise procedure for developing a strategy and measuring KPIs". BSJ Kranj implied the introduction of a "European directive for standards on duties and taxes".

[3] In particular, these two partners proposed the following additional factors in this category (all scored with 3): "Developing uses with local authorities and ecosystems", "Having more visibility of the vehicle market offer", "Policy to support HYDROGEN specialist education", "Policy to support research and innovation".

introduction of new green taxes (e.g. in Austria). The recent introduction of public-private partnerships, such as the Trinational Hydrogen Initiative 3HYDROGEN that aims to enhance transnational cooperation especially in the border regions of the France-Switzerland Germany triangle are also mentioned by partners. On the other hand, lack of government commitment to a decisive and consistent development of a green hydrogen ecosystem is obviously considered as an important barrier by partners. Indicatively, BSJ Kranj notes the current lack of compliance of the Slovenian government with "its own strategic documents" and the so far limited financial assistance towards the private sector in the areas of HYDROGEN production and mobility. Complicated and/or time-consuming permitting requirements for the approval of hydrogen projects are mentioned as a barrier by Austrian partners 4ER and COD, however the recent introduction of changes in the regulatory framework in order to simplify administrative procedures is also highlighted by them.

Economic factors: This category emerged as the third most important area regarding green hydrogen development until 2030, with an overall score close to 2.5. "Government-led financial support" was the other factor that received a score of "3" by all H2MA partners[4]. "Private investments and financing opportunities)" was also judged as an especially important factor by H2MA partners; alongside their aforementioned emphasis on the need for public funding, this implies the necessity of considerable private investments and, most probably, the coordination of the efforts of these two sectors. "Cost of hydrogen production" through electrolysis was assessed as a very significant factor by partners[5]; the clear implication is that the further development of technologies related to green hydrogen production will constitute a crucial driver for the rapid expansion of green hydrogen use, whereas failure to reduce this cost will constitute a barrier for green hydrogen development. "Cost of transport and distribution" follows in significance, according to partner replies; their assessment seems to be that once cost of *production* is addressed, cost-efficiency in transport and distribution will be easier to address. "Operational costs" and "capital costs" were deemed of lesser significance. Although no high national variations are observed in the replies regarding economic factors, the utmost significance attributed to them by Austrian partners (4ER, COD) can be contrasted with relatively low scores assigned by their German counterparts (KPO, ITALCAM). Regarding the recommendation of additional factors to be included in the forecast scenarios, KSSENA indicated as very significant the familiarisation of citizens and "third parties" with hydrogen technologies through public education programs[6], whereas BSC Kranj pointed out the high relevance of the dimension "Equal opportunities and competitive markets".

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[4] This factor is closely related to the aforementioned factor "existence of incentives for the uptake of green hydrogen (e.g. fiscal incentives)" from the "policy support area".

[5] The factor "high-efficiency electrolysers (resulting in cost-effective hydrogen production)" has a similar scope with this factor.

[6] Although this factor seems of higher relevance to the "Public Acceptance" category.

Regarding the identification of economic trends, drivers and barriers, H2MA partners offer various insights and estimations in their replies, in some cases based on quantitative data; most often a mix of barriers and drivers are highlighted. The high inflation rate in almost all European states and particularly the often staggering rise of energy prices are pointed out by many partners as a current barrier for the broader green transition; this also has possible negative ramifications for securing public acceptance for the expansion of green hydrogen use. Pertinently, the currently high cost of imported hydrogen – imports will constitute a major, if not the most important, source of supply as pointed out by certain partners - and the general uncertainty regarding the pace of setting up HYDROGEN production and transport infrastructure (an issue which also has a prominent "technical" dimension) is also emphasized by partners (e.g. 4ER). Lack of adequate support of the private sector from national governments is also pointed out by some partners. On the other hand, certain partners (e.g., FLA) document an existing trend of lower electricity consumption per kg of hydrogen produced, which clearly constitutes a driver for an increase in green hydrogen production and use. Partners highlight as positive drivers the determination of the private sector to invest in HYDROGEN production and transport in certain regions (e.g. Gorenjska in Slovenia, Styria in Austria, Bavaria in Germany) or national government plans to boost public investments on HYDROGEN production. The development of synergies between all relevant sectors (i.e. production, transport and distribution), which will enable the achievement of economies of scale, is brought up as a potential driver by COD.

International factors: Although this area of factors emerges as somewhat less significant than technical, policy and economic factors, they still received a high overall score (slightly below 2.5). Among the five factors of this category the impact of "geopolitical tensions" and "disparities in standardization and certification process" were assessed as most significant. Indeed, in the second part of the questionnaires discussed below a number of partners refer to the uncertainties and disruption in the broader energy sector that have emerged as a result of the Russian invasion in Ukraine, whereas they also point out broader disparities between European states/ markets and third countries that are (expected to be) significant exporters of materials related to hydrogen production. Clearly such factors are considered as barriers for the efficient rollout of green hydrogen in the EU (and the Alpine region in particular). The other three international factors ("changes in climate change targets", "international/transnational agreements" and "trade and supply chains disruptions") received a lower score, however they are partially related to the first two factors and appear to indicate the relative importance of adherence to international conventions (e.g. the Paris Agreement or the Alpine Convention) and the corresponding targets of all state parties, as well as the supply risks associated with global/regional crises. KSENNA suggested the inclusion of an additional factor in this category, namely the current high inflation levels in the EU (and more broadly the impact of financial crises).

Regarding the diagnosis of positive and negative international trends, EU's continuing (if diminishing) dependency on Russia for natural gas, in combination with the fact that this fuel has a decisive impact on electricity cost, is identified as a current barrier for hydrogen's price as well by partners; it is worth noting however that it has only an indirect impact on green hydrogen price. This is also the case with metals that are employed in electrolysis technologies (platimum, palladium, iridium) and are primarily imported from geopolitically unstable countries such as South Africa and Russia. On the other hand, the very prospect of Europe becoming less dependent on politically unstable energy suppliers via the acceleration of decarbonisation process is identified as a driver by some partners (CMT, RL).

Public Acceptance: This category received the lowest score of all factor areas that were taken into consideration. In view of the strong public (local) opposition to other RES technologies, such as wind energy, this might appear curious at first. At a second reading, this finding seems to reflect on the one hand a generally low level of knowledge or interest on renewable hydrogen in the national public spheres across Europe at this point and, on the other hand, the generally positive connotations that "clean/green" hydrogen might produce in the public opinion. "Awareness of climate change" and "support from public" (for the development of green hydrogen) receive the higher scores among the four factors in this category, denoting that their existence is considered as a positive (yet not highly significant) driver for the rollout of green hydrogen.

Regarding trends in this area, one partner (FLA) recognizes a certain skepticism that a segment of the public adopts *vis à vis* renewable energy at large, however its assessment is that gradually the positive aspects related to clean hydrogen will be appreciated by a majority of citizens.

A.2 Factors' assessment for 2050

A first remark that can be made regarding the assessment of factors for 2050 is that three out of five categories (areas) receive a slightly lower score in relation to 2030. The most notable change regarding the relevant significance of categories is the shift of policy support factors from the second to the fourth rank. Similarly with above, all partners' replies and average scores and included in ANNEX II.

Technical factors retain their primary significance, as evaluated by the H2MA partners. Production and distribution infrastructure are deemed as slightly less important in relation to 2030, although the factor of storage infrastructure receives an identical score (the highest in this category and one of the two highest across all categories). This probably reflects an assessment on behalf of the partners that by 2050 advancements in production (and, also, distribution) technologies would have increased the cost-efficiency of green hydrogen production, mainstreaming green hydrogen use cases; thus the storage of increased quantities of green hydrogen would be the central stake at that stage. Related to the above, technological advancements in green hydrogen production and storage retain their high significance, although slightly truncated, possible due to the anticipation that such technologies would have attained a significant level of maturity by then. Regarding regional variations, the attribution of a rather low level of significance (below 2) on behalf of the German H2MA partners stands out. Of more interest are the additional technical factors on behalf of certain partners: Austrian partners 4ER and COD, one the one hand, as well as French partners EMS and PVF, on the other hand, reiterate the suggestions they made for 2030 (infrastructure for hydrogen imports and progress made in competing technologies, respectively); KSSENA proposes that "state regulation of the price of alternative fuels" and the insurance of "lower prices for locally produced hydrogen" are considered as highly significant factors (in this case, drivers) for clean hydrogen uptake in 2050[7].

Trends in technical factors are closely associated with economic aspects in partners' replies, something also noted in 2030 assessments. For example, FLA highlights as a barrier for hydrogen technological developments the potential continuation of electricity price being tied to natural gas price. On the other hand, FLA identifies, based on recent reports, foreseen technological developments in electrolysis processes, such as the increase in the performance of various electrolysis technologies, the increase in electrolysers' lifetime and the decrease in their operation cost, as drivers; in general, this partner in its detailed reply assesses in a positive manner technological developments in production, storage and distribution of hydrogen. The introduction and expansion of hydrogen production technologies other than electrolysis, e.g. those based on other RES such as biomass as indicated by ITALCAM, is also mentioned as a technical driver. Such developments will lead to the replacement of fossil fuels by green hydrogen, especially in "heavy-duty transportation" - trains, trucks, buses, perhaps aviation – but also in steel industry, according to certain partners (CMT, 4ER).

Economic factors: In contrast to other top categories, this area has retained their level of significance between 2030 and 2050, as reflected in the partners' replies. Cost of hydrogen production (electrolysis) – as well as the closely related factor "high-efficiency electrolysers" - are considered as even more important factors, denoting that too high a cost will be a barrier for green hydrogen to achieve the envisaged share in the energy market. Closely related to production cost and of similar significance is "cost of transport and distribution". "Operational costs" are regarded more important for 2050, which is probably related to the expectation that an extensive transport and distribution network will be in place and in need for maintenance. "Private investments" continue to be regarded as highly significant for

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[7] It may be pointed out that such factors fit better in the "policy support" or "economic" categories.

the hydrogen uptake; however, in contrast to the 2030 scenario, it is noticeable that government-led financial support “loses” a whole point, a change which could indicate an expectation on behalf of partners (e.g. BSJ Kranj, FLA) for a downward trend of (the need for) government spending on a mid-term basis.

Some partners (e.g. BSC Kranj) predict the share of clean hydrogen in transport will not be “significant” in their countries, due to delays in the implementation of strategic plans or even due to the rather limited target envisaged by the EU (around 25% share of hydrogen in the transport sector). The projected fall of green HYDROGEN price is treated as a driver, however the possibility that other alternative fuel solutions become more affordable is mentioned as a potentiality that will hamper clean hydrogen expansion.

International factors: This constitutes the second category that received a (slightly) higher score for 2050. This change is mostly attributed to the noticeable increase in the significance of one of five factors of this category: “trade and supply chains disruptions” appear to be considered a factor that may represent a considerable barrier for the import and transportation of green hydrogen (or crucial materials for its production).

Thus, geostrategic fluidity and instability continue to be evaluated as a possible barrier by some partners. At the same time, this is expected to be (at least partially) offset by the realization of the EU strategic goals for energy independence.

Policy factors: The relative reduction in the significance that H2MA partners attribute to this category constitutes another visible change from 2020 assessments. This decline is reflected in the score of six out of eight factors, most noticeably in “government-backed guarantees”, which is consistent with the aforementioned blunted emphasis in government-led financial support. Despite this overall trend, the existence of national and/or regional hydrogen strategies, which would set specific targets for this renewable fuel, are still considered very significant[8].

A trend related to this category as identified by partners (e.g. FLA, BSC Kranj) is that by 2050 gaps and inconsistencies in national HYDROGEN strategies will have been largely overcome; at the same time, a need for systematic updates and revisions is pointed out.

Finally, **public acceptance** factors remain the least significant of all categories. This is in part, or even mainly, related to an assessment on behalf of partners that green hydrogen benefits will be obvious to most by 2050.

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[8] The two first factors proposed by KSSENA, as well as all four factors proposed by EMS and PVF for 2030 are reiterated in these partners’ replies for 2050.

A.3 Brief discussion of partner replies

Some changes in partners' assessment of the various factors have already been mentioned above. Taking also into consideration the trends, barriers and drivers, identified by the H2MA partners, one line of general assessment could be that, despite the identified changes in the factor significance between 2030 and 2050, all categories of factors – except for public acceptance – seem to be closely interwoven in a relatively balanced way. For example, production and distribution costs of green hydrogen and technological advancements in those areas seem to be almost inextricably linked; at the same time, a policy environment (at all levels, but especially the national one) that creates comprehensive strategic and regulatory frameworks, on the one hand, and makes available considerable public funds, on the other hand, seems to constitute a necessary condition for the activation of techno-economic positive feedback loops. In turn, this complex ecosystem appears to be dependent on international developments, as energy transition and geopolitics become more and more entangled in academic and policy discussions[9]; in this vain, lack of major geopolitical crises such as that in Ukraine, or the achievement of "strategic (energy) autonomy" on behalf of the EU emerge as another prerequisite for an effective rollout of green hydrogen in the Alpine region. In fact, although regional and national particularities are discussed by partners in their replies, major dependent variables and trends that are identified have a European or even global scope (e.g. production and import costs, inflation rate and energy prices, advancement of HYDROGEN technologies), something that perhaps renders "international factors" reverberations more consequential that the individual score of this category implies at face value.

A second general remark is that certain regional and national differentiations and inequalities appear to exist within the Alpine area regarding the prospects of green hydrogen expansion. For example, Austrian regions appear (based on partners' replies) to be in better position than other regions to participate in the uptake of green hydrogen, in policy, economic and technological terms. In any case, it appears that the need to promote policy coordination and avoid economic and technological rifts within the Alpine area could be even more actively addressed by all stakeholders and actors of the region, especially by governments.

A third point to be made stems from the finding that H2MA partners' replies regarding trends are more detailed for 2030 than 2050. This should not be surprising, given that the majority of strategies, policies, economic and technological initiatives brought up by the partners are very recent or in the process of being materialized; thus, longer-term predictions or even assessments cannot be very detailed at this point, at least until the "first wave" of developments unfolds (e.g. by 2030). In other

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[9] For example see IRENA, 2023, *Geopolitics of the Energy Transition: Critical Materials*, https://www.irena.org/Publications/2023/Jul/Geopolitics-of-the-Energy-Transition-Critical-Materials.

words, the whole green hydrogen rollout endeavour is in its infancy, something that justifies mixed assessments of ambition, hope, reservation and uncertainty in partners' replies.

B. Presentation of the methodology used for the analysis of the scenarios

The academic literature on climate change mitigation is replete with studies and reports that employ some form of scenarios or forecasting regarding its pace and manifestation over the following years and decades. Given that it is becoming more and more important to define an appropriate set of actions and/or policies for governance institutions and various stakeholders, it not surprising that forecasting on various sectors and themes related to climate change mitigation has been included in various policy and project reports. The selection of one scenario building methodology over the others depends on a variety of factors, including the concrete goal and focus of each study, the characteristics of audience to which it is addressed, the availability of data, the adequacy of a quantitative or qualitative approach (or a combination of them), etc.

In any case, a common goal of forecasting and scenario-based methods is to offer to actors and stakeholders a way not only ways to navigate, adapt and formulate efficient strategies, but also to offer a better understanding of current trends. Hence, constructing scenarios for green hydrogen roll-out falls into this logic.

This section aims at presenting and justifying the selection of the methodology used for the analysis of scenarios regarding the clean hydrogen rollout in the Alpine space. Firstly, a number of alternative scenario-building techniques that are relevant to the broader scientific and policy literature on (clean) hydrogen are reviewed and briefly discussed. The second subsection presents and justifies the adequacy of the - qualitative in nature – scenario-building methodology that is adopted here.

B.1 A brief review and discussion of alternative scenario-building techniques

B.1.i Forecasting

Various studies that focus on, or include in their broader assessments, the use of hydrogen until 2050 unavoidably contain forecasts and scenarios. The European Hydrogen Observatory (an online platform of the Clean Hydrogen Partnership) has concentrated all relevant studies and their forecasts on the future demand of hydrogen (per sector, e.g. transport, industry, etc)[10]. Typically, these forecasts are based on specified assumptions; based on available data and taking into consideration policy targets and the relevant literature, they move on to specify concrete forecasts for a given timeframe.

For example, in trying to forecast the share of various technologies (hydrogen, diesel, electricity, LNG) a report for the European Hydrogen Backbone firstly specifies a number of assumptions (e.g. “2% energy consumption improvements every 5 years” or “Hydrogen fuel cell vehicles are assumed to have a 40% reduction in energy consumption relative to diesel trucks”); then, data sources (e.g. “Historical total road transport energy demand values from the European Environmental Agency”) and subsequently methodological steps are specified (e.g. “Technology share penetrations are modelled using S-curve technology adoption curves”); then, a concrete value is calculated (e.g. hydrogen s expected to be used in 5% of freight vehicles in 2030 and in 55% in 2050)[11]. Vey often such studies do not specify a single scenario, but a number of alternative scenarios. For example, a 2023 Clean Hydrogen Study includes the values of the aforementioned example in its “ambitious” scenario; however, in the “moderate” scenario 40% of heavy-duty vehicles will be hydrogen-powered by 2050 and “only” 25% of them in the “conservative” scenario[12].

Such forecasts are certainly useful in various endeavours, e.g. in trying to specify policies that governments need to adopt or to identify possible trends; elements of such scenarios are indeed employed in out attempt to specify maturity scenarios in section C. Developing alternative scenarios for clean hydrogen demand specifically in the Alpine area could certainly be a valuable addition in the existing literature. However, one impediment for this is the lack of data specifically for the Alpine space. A further problem refers to the inherent uncertainty related to the deployment of new technologies, manifested also in probabilistic approaches (such as those reviewed here): whereas divergences in the estimation of a given factor among different scenarios or individual studies is certainly explicable and to a certain extent reflects pragmatically the level of uncertainty that characterises such forecasts, the often wide scope among the different projected values weakens the very usefulness of the forecasts. Thus, an accepted and widely used qualitative technique, such as

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[10] See European Hydrogen Observatory website, “Scenarios for future hydrogen demand”, https://observatory.clean-hydrogen.europa.eu/tools-reports/scenarios-future-hydrogen-demand.

[11] Guidehouse, 2021, https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021.pdf , p.88-9.

[12] https://www.clean-hydrogen.europa.eu/media/news/press-release-study-hydrogen-ports-and-industrial-coastal-areas-2023-03-30_en#:~:text=Overall%2C%20by%202050%2C%20in%20the,demand%20being%20in%20port%20areas., p.64.

the one adopted here, constitutes a more desirable option for the purposes of this study.

B.1.ii Monte Carlo simulation

A quantitative methodological technique that has been employed in order to build alternative scenario is Monte Carlo simulation. As specified in H2MA report for the current activity (“Guidelines for developing maturity scenarios on green HYDROGEN production and distribution”), it is a stochastic modeling technique used to generate a large number of scenarios by selecting values from specified probability distributions for various input parameters. For example, Lane et al (2021) perform 100 Monte Carlo experiments with 10,000 trials with the goal to forecast market share of competing green hydrogen production technologies (PEMEC, gasifier); this large number of experiments, in combination with various methodological assumptions (e.g. projected hydrogen feedstock cost), leads to the calculation of market shares for each technology for every five years between 2025 and 2050[13]. Another example of a study that applies this methodology to construct alternative scenarios with a focus on the growth of electrolyser capacity in the EU by 2050[14]. Such studies present similar weaknesses with forecasting techniques; nonetheless, as with the previous methodology presented, their findings (i.e. the alternative scenarios or forecasts they present) can be taken into consideration in discussing clean hydrogen mobility in the Alpine space for 2030 and 2050.

B.1.iii Decision Trees

This methodology has been also identified in the aforementioned report. Decision trees are used in decision analysis to represent decisions and potential outcomes in a tree-like structure. They are a visual representation of decision-making processes, showing the decision points, possible alternatives, and the consequences of each choice. In a stochastic modeling context, i.e. similarly to Monte Carlo simulation, it is critical to assign probabilities to different branches of the decision tree to reflect uncertain events and their likelihoods.

Decision trees[15] have been used in studies that attempt to formulate and assess alternative scenarios on the viability of alternative energy projects[16], the profitability

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[13] https://www.sciencedirect.com/science/article/abs/pii/S0360319921021558

[14] https://www.nature.com/articles/s41560-022-01097-4#Fig7

[15] https://www.researchgate.net/publication/40499015_Project_risk_management_A_combined_analytic_hierarchy_process_and_decision_tree_approach

[16] https://onlinelibrary.wiley.com/doi/abs/10.1002/sdr.433

of a combination of power-plant and hydrogen storages[17] or the efficiency of biomass-based hydrogen production units[18]. Decision-trees regressions share the probabilistic nature of aforementioned methodologies that render them inadequate for the present goals; among its other limitations (e.g. "it is only applicable to the forecasting of exponentially growing data"), this methodology is usually employed on a case-specific basis (i.e. not in assessing alternative scenarios such as clean hydrogen roll-out in the Alpine region)[19].

However, the decision-tree format can be less-strictly employed in a qualitative fashion, i.e. in a way that depicts alternative routes or decision based on certain assumption. In effect, the qualitative scenario-building technique that is used in the present report and is presented subsequently shares a similar logic with the non-probabilistic tree-decision version.

B.2 A presentation of the adopted scenario-building methodology

The scenario-building technique that this report adopts builds on the "intuitive logics" method, originating from the business sector but nowadays widely used in various disciplines and for various purposes (including policy-related ones). A core feature of this method is its qualitative character, something related to its flexible character[20]. Crucially, it is not a probabilistic method, as the ones presented above, i.e. does not entail the calculation of probabilities of future events; rather it has been described as a "plausibility-based" method. This implies that the proposed alternative scenarios are equally probable[21]. In this methodological tradition, dealing with uncertainty and complexity of future trajectories - a common feature of scenario-based approaches - is not dependent on data-driven analysis; rather it is centered on testing pragmatic assumptions and expectations about the future. The goal is not to forecast the future in the strict sense or to offer a precise prediction (in fact, concrete estimations are deemed difficult in situations of low predictability[22]), but rather to offer interpretative frames in order to grasp and handle alternative *plausible* versions of the future[23].

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[17] https://www.researchgate.net/publication/317551815_Valuation_of_Combined_Wind_Power_Plant_and_Hydrogen_Storage_A_Decision_Tree_Approach

[18] https://www.sciencedirect.com/science/article/abs/pii/S0360319922014926

[19] https://www.sciencedirect.com/science/article/abs/pii/S0360319922014926

[20] R. Bradfield et al, 2005, https://www.sciencedirect.com/science/article/abs/pii/S0016328705000042, p.806.

[21] R. Bradfield et al, 2005, https://www.sciencedirect.com/science/article/abs/pii/S0016328705000042, p.809.

[22] G. Wright & P. Goodwin, 2009, https://www.sciencedirect.com/science/article/abs/pii/S0169207009000910, p.816.

[23] https://www.sciencedirect.com/science/article/abs/pii/S0040162512002971, p.700-703.

In this context, a scenario is treated as a "description of a 'possible future' based on a set of mutually consistent elements, within a framework of specified assumptions"[24]. Scenarios do not constitute predictions, as aforementioned, but rather "*purposeful stories* about how the contextual environment could unfold over time", consisting of three basic elements: "a description of a future end state in a horizon year" (e.g. 2030 or 2050), "an interpretation of current events and their propagation in the future" (e.g. the development of clean hydrogen technology and infrastructure) and "an internally consistent account of how a future world unfolds", i.e. an explanation that by taking into consideration past events and current developments one can attempt to account for (or "resolve") uncertainties about the future (e.g. what will be the share of clean hydrogen technologies in the transport sector in the Alpine space in 2050?)[25].

Based on the above, scenarios developed through the "intuitive logics" method are the end result of a process of "disciplined intuition", rather than on the distribution of probabilities (often through computer-based analysis and mathematical modeling, as seen above). Various factors – economic, technological, political (e.g. in the form of STEEP analysis) – are taken into consideration in this process; this does not preclude however the use of quantitative data as a source of input. Despite the concrete methodology followed (dependent also on particularities of the issue or the context at hand), scenarios are evaluated base on factors such as their plausibility, internal consistency and logical underpinning[26].

Various studies in the broader climate change literature have employed an "intuitive logics" method. For example, a recent study uses this technique in order to map the key factors influencing the developments of the blue and green hydrogen export industry in Norway and define the content of relevant alternative scenarios by 2050[27]. These studies, as well as other more "theoretical" or "methodological" in orientation, follow and describe a number of steps that lead to the building of alternative scenarios. Typically, these steps focus on a limited number of significant factors and the identification of – usually two - key drivers, something that enables the development of (usually four) alternative scenarios. The present document most closely follows the "intuitive logics" scenario-building process as applied by A. Symstad et al. (2014) in their analysis of the effect of climate change on natural resource management planning[28].

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[24] https://www.sciencedirect.com/science/article/abs/pii/002463019390240G, p.124.

[25] G. Wright & P. Goodwin, 2009, https://www.sciencedirect.com/science/article/abs/pii/S0169207009000910, p.817.

[26] R. Bradfield et al, 2005,p.809.

[27] C. Siew Wan Cheng, 2023, https://www.sciencedirect.com/science/article/pii/S2214629623001299#bb0025.

[28] A. Symstad et al., 2014, https://pubs.usgs.gov/publication/70160601; see also A. Symstaad et al, 2017, https://www.sciencedirect.com/science/article/pii/S2212096316300663.

Using this study as a basis and taking into account other applications of this method[29], a delineation of the steps followed for the building of the scenarios is offered below. The concrete way according to which these steps were performed and the associated methodological choices were made is fleshed out in section C1. Crucial steps for scenario-building are:

- *The identification of the relevant factors*; in this case, H2MA partners replies (as presented and discussed in section A) were used as a basis for identifying factors relevant of green hydrogen roll-out.
- *The ranking of those factors according to their significance;* average scores of factors (as presented in section A) were again critical for carrying out this step.
- *The further delimitation of most important factors*, e.g. through merging and clustering of similar factors, and the identification of the various relationships between the factors (e.g., improved financial support schemes can accelerate the rate of technological improvements).
- *The identification of two central drivers (and the justification of this particular selection).* These drivers are considered as the most crucial and determining forces (among other important or even essential ones) for the unfolding of events at a given timeframe (e.g. 2030).
- *The determination of two basic alternative "outcomes" for each one of the selected drivers*. These outcomes correspond to the two most plausible future realities.
- *The synthesis of the different envisaged outcomes for the construction of four alternative scenarios.* By combining the two alternative "outcomes" of each driver, four distinct scenarios are produced. Factors that were examined in previous steps, as well elements of and insights from other (explicitly presented) sources, are employed in order to build internally consistent "purposeful stories.
- *Specifying implications of the alternative scenarios.* This step that is often-included in relevant studies and follows the actual building of the scenarios basically refers to section D of the present report, i.e. guidelines for H2MA partners on how to employ the proposed scenarios (their particular insights and broader logics).

It should be noted here that in many versions of the "intuitive logics" method (including the one that is mostly adopted here), the whole scenario-building process

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[29] S. Phadnis et al, 2014, https://www.sciencedirect.com/science/article/abs/pii/S0040162514002194 ; Foster 1993; Wright & Goodwin 2009.

is not driven by a single or a handful number of persons, but rather by the workings of a dedicated workshop. Workshop participants can be considered as stakeholders who discuss and reflect on the issue at hand; through deliberations and brainstorming, factors are prioritised, drivers defined and scenarios constructed[30]. Clearly, this method could not be implemented for the construction of the scenarios proposed in this report; *however,* H2MA partners' replies can be considered as a valid alternative of this method. Thus, using the average of impact scores assigned by H2MA partners as a basis for the proposed scenarios (and also taking into account their assessment of trends, drivers and barriers) is a methodologically plausible choice.

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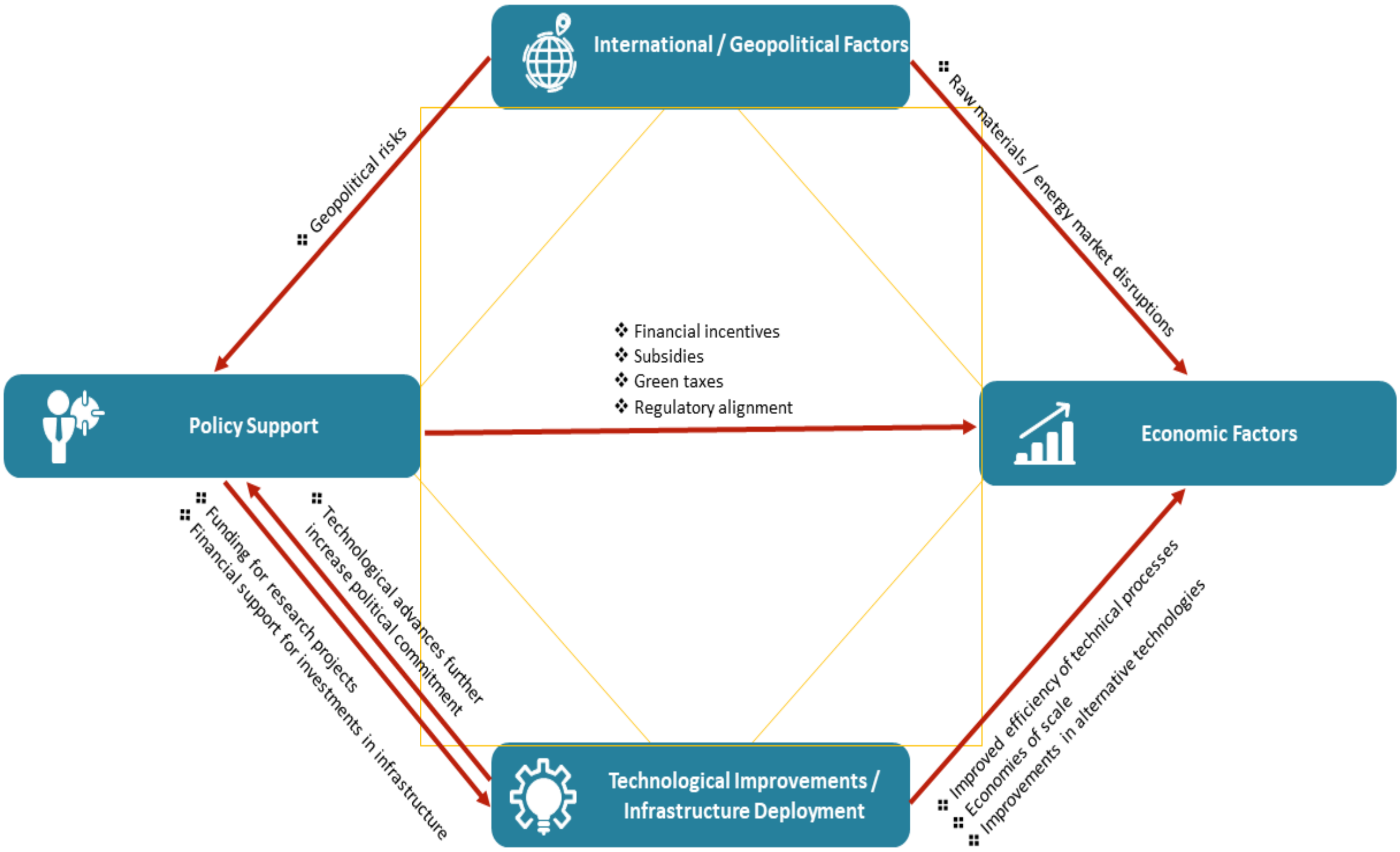
[30] A. Symstad et al., 2014, https://pubs.usgs.gov/publication/70160601; [30] G. Wright & P. Goodwin, 2009, https://www.sciencedirect.com/science/article/abs/pii/S0169207009000910

C. Forecasting scenarios

Having outlined the methodology used, the scenarios and their implications for H2MA partners are presented in this section. Following the broader logic of Activity 1.4 and the structure of section A, scenarios for 2030 and 2050 are presented separately, although developments and factors discussed regarding the two timeframes have multiple commonalities and other close interconnections (as it will be shown). As will be mentioned in the following sections, to facilitate the purposes of this report the various factors proposed by partners have been categorised in different thematically relevant clusters, namely policy factors, technical/technological factors, economic factors and international/geopolitical factors. Identifying the key relations and interdependencies between these clusters (as well as the factors comprising each cluster) is essential in order to identify the key drivers and construct the various scenarios. These are schematically shown in Figure 1.

Fig 1 Thematic clusters and their interdependencies



As will be discussed in the next section, two main drivers were identified for each target year. In brief, policy support and technical/technological improvements (including infrastructure) were determined as the most impactful factors for the period up to 2030 (a more in-depth discussion on this is included in the following section). This reflects the high importance of support policies and technological progress in supporting early initiatives in green hydrogen and increasing its cost-competitiveness vis-à-vis other alternative technologies respectively. For the 2030-2050 period, economic factors were deemed more crucial than policy support, since at that point policy support is expected to have an increasingly smaller role in supporting the expansion of the green hydrogen ecosystem. Instead, the growth of the ecosystem is expected to become market driven at some point within this period. The selection of economic factors as the second main driver (instead of policy support) for this period reflects exactly this expectation.

C.1 Alternative scenarios for 2030

As discussed in section B, in order to determine key drivers it is necessary to focus on those factors that are expected to have the most critical impact on the issue at hand, in this case green hydrogen roll-out in the Alpine region. The whole process is driven by an attempt to moderate the inherent complexity of such matters by focusing on the most pivotal dimensions and dynamics. The assumption here is that by examining the most salient parameters one may still capture the overall dynamics of the system.

In order to filter the most important dimensions, the factor assessment on behalf of H2MA partners that was presented and discussed in section A was used as a basis. The first step taken was the ordering of the list of factors according to the average score of each factor; this list, from the highest to the lowest, is depicted in table 1.

Table 1 Factors assessed by partners for 2030 from highest to lowest score

1	Existence of national/regional strategy	3,00
2	Government-led financial support	3,00
3	Existence of incentives for the uptake of green hydrogen (e.g. fiscal incentives)	2,91
4	Development of hydrogen production infrastructure	2,91
5	Development of hydrogen distribution infrastructure	2,91
6	Development of hydrogen storage infrastructure	2,91
7	Existence of specific targets for green hydrogen at a set timeframe	2,82

8	Existence of specific targets for Renewable Energy Sources (RES) in the energy mix	2,82
9	Establishment of quality and security standards	2,82
10	Private investments and financing opportunities	2,82
11	Streamlined permitting and approval processes	2,73
12	Simplified administrative procedures	2,73
13	Cost of hydrogen production (electrolysis from RES)	2,73
14	Technological advancements in green hydrogen production	2,73
15	Technological advancements in hydrogen storage technologies	2,64
16	Government-backed guarantees (e.g., long-term revenue certainty)	2,55
17	High-efficiency electrolysers (resulting in cost-effective hydrogen production)	2,55
18	Cost of transport and distribution	2,45
19	Geopolitical tensions (e.g. Russia's invasion in Ukraine)	2,45
20	Disparities in standardisation and certification process	2,45
21	Changes in Climate change targets	2,36
22	International/transnational agreements	2,36
23	Awareness on climate change	2,36
24	Capital costs	2,18
25	Operational costs (incl. maintenance)	2,18
26	Trade and supply chains disruptions	2,18
27	Support from public (incl. civil society)	2,18
28	Customer demand for climate friendly products	2,00
29	Gaining a social license for operation	1,73

As a subsequent step, factors that refer to nearly identical dimensions or items were merged; this is indicated in the table by cells that have the same color. E.g. "government-led financial support", "government-backed guarantees" and "existence of incentives" all refer to government economic/financial incentives aimed at assisting various actors, mostly from the private sector, to invest in green hydrogen processes (R & D, production and storage facilities, etc). The third step was to delimit the range of factors by selecting those that were evaluated as the most impactful. It was decided to take into consideration those factors that received the 10 highest scores (out of an initial total of 29 factors). After conducting the aforementioned "merging" of coterminous factors and taking into account score equalities, factors until rank 14 were selected (as indicated by the red line).

The fourth step was an attempt to move from individual factors to discerning relevant “clusters” of factors, wherever possible. Four such clusters were identified: the first one contains policy-related factors, i.e. existence of national hydrogen strategy, government-led financial support (and the aforementioned similar factors), existence of specific targets for green hydrogen and RES, establishment of quality and security standards and streamlined administrative / permitting procedures. The second cluster contains factors that fall under technology-related dimension: development of production, distribution and storage infrastructure (identified as three distinct factors in the questionnaire) and technological advancements in green hydrogen production. Two factors among those receiving the highest scores could not be meaningfully included in previous clusters or grouped under another distinct cluster (although both have an economic character): “cost of hydrogen production”, which also contains the highlighted merged factor “high-efficiency electrolysers (resulting in cost-effective hydrogen production)”) and “private investments and financing opportunities”.

The aforementioned steps facilitated the determination of key drivers that affect the green hydrogen rollout in the Alpine region until 2030. The two drivers that were identified are 1) “political commitment” and 2) “technological advancements”. These two drives represent the two largest clusters of factors identified above, in other words they represent the two main “families” of factors among those with the highest scores; pertinently, this selection of drivers broadly corresponds to the two areas of factors that emerged as almost equally important from the H2MA partners’ replies. The remaining top factors (i.e. cost of HYDROGEN production and private investments, as aforementioned) are integrated in these drivers, as it will be shown below; a number of other factors included in the questionnaire will be also considered as components of those drivers. Moreover, the various trends that were brought up by partners in their replies (please see section A) inform the description of the two selected drivers; in any case, these drivers are considered broad enough in order to accommodate other factors or trends that appear of particular relevance to the region or country of H2MA partners. The following discussion offers further justification for the selection of the two drivers.

The following, sixth, step according to the qualitative scenario building technique that is followed, is the description of two alternative future “outcomes” for each driver, i.e. alternative ways that each driver unfolds until 2030; table 2 summarises this description. Essentially these two outcomes refer to “positive” and “negative” scenarios (in the latter case, “drivers” turn into “barriers”). It may be noted that in the delineation of these two outcomes effort has been made to take into account realistic, rather than extreme, possibilities; for example, the renewed EU targets for 10 Mt green hydrogen production (in addition to another 10 Mt of imports) is treated as the “positive” or optimistic scenario.

Table 2 Alternative outcomes for two drivers of green hydrogen rollout until 2030

Driver	Outcome 1	Outcome 2
Policy environment	A comprehensive national green HYDROGEN strategy (containing concrete targets and financial tools) that is consistently applied by all levels of government.	A national strategy that is fragmentary or contains unrealistic goals or is not supported by adequate public funds or is tepidly implemented.
Technological advancements	Technological improvements in green hydrogen production and storage along with rapidly expanding infrastructure make green hydrogen competitive to fossil fuels by 2030	Technological advancements are moderate, undermining the overall competitiveness of green hydrogen and slowing down the establishment of the necessary infrastructure

C.1.i First driver: “Supportive policy environment”

It is widely accepted that in the “formative” period of innovative energy technologies – as the period decade 2020-2030 is for clean hydrogen – demand is policy—backed and driven by regulatory certainty[31]. As stressed in a recent report, in this early period for green hydrogen “financiers are unlikely to accept such risk without significant government support in terms of creating certainty and providing more direct support through subsidies”[32]. In other words, a supportive policy environment (exemplified in the establishment of a comprehensive regulatory framework and the commitment of adequate public funds) will serve as the locomotive for the growth of the green hydrogen ecosystem. This logic is also adopted by the EU Hydrogen Strategy[33]: in the first phase (2020-2024) the policy focus is on “laying down the regulatory framework for a liquid and well-functioning hydrogen market and on incentivising both supply and demand in lead markets”; similarly, during the second phase (2025-2030) it is specified that the goal of achieving a “sustained scale up” of hydrogen production and supply will necessitate “dedicated demand side policies” and “will require gearing up EU’s support and stimulate investments to build a fully-fledged hydrogen ecosystem”. To be sure, technological advancements (e.g. in the

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[31] https://www.nature.com/articles/s41560-022-01097-4

[32] DNV, 2022, https://www.dnv.com/news/hydrogen-at-risk-of-being-the-great-missed-opportunity-of-the-energy-transition-226628, p.27.

[33] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301

efficiency of electrolysers) and private investments (e.g. in the steel industry) are specified as important in the document for the period up to 2030; however, it is in the third phase (2030-2050) that green HYDROGEN technologies are expected to reach "maturity and be deployed at a large scale"[34]. Moreover, EU recent hydrogen initiatives clearly demonstrate the key significance attributed to public policies for the rapid expansion of green hydrogen. The "Hydrogen Bank" has as an explicit aim to "to unlock private investments in hydrogen value chains in the EU and in third countries"; although it is recognised that it is the private sector that will assume the greatest part of the total amount of necessary investments (close to 1 trillion euros), the Hydrogen Bank aims to cover a significant share of the "cost gap" that currently exists between green and fossil (grey) hydrogen[35]. Furthermore, the European Commission recently approved two Important Projects of Common European Interest (IPCEI) that focus on the development of the green hydrogen sector; a combined total of more than 10 billion euros of public funding is expected to be pivotal for the investment of even larger private capitals[36]. Some indicative policy aspects that will promote the growth of the green hydrogen ecosystem are the following:

Schemes to support the operation of green hydrogen production facilities

Currently, incentives in most countries place particular emphasis on clean hydrogen infrastructure and related equipment (e.g. electrolysers). This is a standard practice to support the mainstreaming of innovative technologies, however some subsidization of the operation of green hydrogen initiatives will also be required to ensure the longevity of these initiatives and ultimately achieve the necessary economies of scale.

In this context, the adoption of more effective financial incentives to prospective clean hydrogen producers (such as tax exemptions in cases of fossil fuel replacement by hydrogen, regulated returns for hydrogen producers, contractual payments that cover the difference between clean hydrogen and fossil fuel) is expected to have a strongly positive impact on current and future green hydrogen initiatives, since it directly addresses (to various degrees) one of the primary barriers for the uptake of green hydrogen technologies, namely the still high production costs for green hydrogen.

As a result, a key policy factor to be examined is whether there will be a partial reorientation of public funding to support the operation of green hydrogen initiatives (potentially, within the context of an overall increase in the available

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[34] Although political commitment is expected to continue to be important in the long term, it is indicative of the emphasis put in the first period that no "policy focus" is specified for the period after 2030.

[35] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0156&qid=1689756932873

[36] https://hal.science/hal-04158824/document

funding, which will ensure that financial support for the roll out of clean hydrogen infrastructure will not be diminished).

Removal of regulatory barriers

Another component of “effective and supportive policy environment” of Alpine countries would be the removal by 2030 of a number of regulatory barriers regarding the production and use of green hydrogen. Such barriers include the mandatory connection of electrolyser operators to the national grid, which implies a certain amount spent on grid fees; this constitutes an additional burden to the currently non-competitive clean HYDROGEN cost. The introduction of regulations that would allow direct connection between renewable energy sources and electrolysers (thus avoiding grid fees, at least for a specified period of time) would be an alternative solution that would reduce the operational costs of green hydrogen production facilities.

Systematic data collection

Collecting data on clean hydrogen would also be a factor that could contribute to the establishment of a more effective and supportive policy framework and the development of more targeted policy initiatives. This could include, inter alia, the systematic collection of data on hydrogen supply and demand as a separate category in national energy balances, as well as creation of an online repository on hydrogen rollout and related initiatives.

Policy harmonisation

International cooperation (both at the Alpine and the EU levels) remains essential in order to coordinate the different policy initiatives, thereby maximizing their overall impact, and ensure the development of an integrated green hydrogen ecosystem. In this context, a further set of policy actions refers to strengthening and harmonizing clean hydrogen policies a transnational level. Indicatively, the Climate Action Plan 2.0 of the Alpine Convention[37] contains a separate category for the Transport sector, with concrete implementation steps and timeframes; targets include the decarbonization of freight transport and public transport in the Alpine area, however the role of hydrogen in those areas could be further specified and upgraded. Similarly, Alpine countries could pursue the establishment of a set of common criteria for the certification of clean hydrogen, as well as safety standards and other regulatory mechanisms.

Subsidising end users

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[37] https://alpineclimate2050.org/climate-action-plan-2-0/#:~:text=The%20Climate%20Action%20Plan%202.0%20was%20adopted%20by%20the%20XVI,pressing%20challenges%20in%20the%20Alps.

A final set of (indicative) policies includes the introduction of actions targeting the demand-side of clean hydrogen, primarily in the form subsidies to the end-users, i.e. once green hydrogen has been delivered. However, given the consensus that clean hydrogen demand (in all sectors and transport in particular) will most probably start to take off after 2030[38], this is a policy that most probably will be meaningful towards the end of the current decade.

In this context, the following outcomes, representing diverging yet realistic developments, of this driver have been considered:

Outcome 1 of the "policy environment" driver refers to a condition that by 2030 each country of the Alpine region not only has in place a comprehensive green hydrogen strategy – in the sense of a detailed, target-oriented policy document – but also that this strategy has led to the enactment of hydrogen-specific legislation which, in turn, is consistently implemented by the national and regional/local authorities, leading to high levels of achievement of concrete clean HYDROGEN targets.

Generally speaking, it may be argued that the formation of national strategies and laws specifically for (green) hydrogen production and its expansion is a project only in its initials steps, as only in recent years it was initiated in EU countries. Most (if not all, by now) EU countries have included in their National Energy and Climate Plans (NECP) provisions related to clean HYDROGEN roll-out until 2030; however, not all of them have published (until recently) a specific national hydrogen strategy[39] and only few of them have developed a dedicated legal and regulatory framework for the governance of green HYDROGEN production and use[40]. It is expected that such national strategies will be soon concluded in all states; however, in itself such a document does not demonstrate "political commitment" on behalf of national governments.

A first parameter (of assessing whether a country's policy environment corresponds to Outcome 1) is whether national and territorial strategies set specific targets regarding the green HYDROGEN production capacity for 2030; preferably they should also set intermediate targets (e.g. for 2025). A further parameter is whether national hydrogen strategies contain targets on the use of green hydrogen (e.g. regarding its share in energy consumption). Such provisions should directly tackle with the use of green HYDROGEN in transport and mobility and should define transport modes in

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[38] E.g Deloitte, 2023, https://www.clean-hydrogen.europa.eu/system/files/2023-04/Study%20on%20hydrogen%20in%20ports%20and%20industrial%20coastal%20areas.pdf, p.71-5.

[39] Sixteen EU countries have adopted national hydrogen strategies by March 2023 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0156&qid=1689756932873).

[40] https://fleishmanhillard.eu/wp-content/uploads/sites/7/2022/02/FH-National-Hydrogen-Strategies-Report-2022.pdf; https://www.intereconomics.eu/contents/year/2021/number/6/article/green-hydrogen-in-europe-do-strategies-meet-expectations.html

which hydrogen technologies will be suitable/available in 2030; ideally, related targets (e.g. number of fuel cell vehicles, number of refueling stations) should include all relevant transport segments, i.e. should not be confined to Heavy-Duty Vehicles that currently appears as a priority sector, but also make concrete projections for the use of green hydrogen in rail, shipping and aviation[41]. A third parameter is whether national hydrogen strategies are adequately integrated within broader green transition regulatory frameworks (usually in the form of a NECP) and whether they lead rather soon to the adoption of hydrogen-specific legislation. As mentioned above, in the majority of EU states the various dimensions of hydrogen deployment (production, transportation, utilization, storage) are regulated within the framework of disparate existing regulatory frameworks (e.g. energy laws, regulations on natural gas and alternative fuels, etc)[42]. The achievement of ambitious goals, such as those set by the EU, necessitate national regulatory frameworks that will deal with the specificities of hydrogen production, storage and distribution; the enactment of such laws and regulations will be an indicator that government officials and political leaders in a country are committed to the goal of promoting green hydrogen policies in an essential, rather than token, fashion. The same applies with regards to the fourth parameter, namely whether hydrogen strategies and laws are decisively coupled with considerable public expenditure (national and EU financial sources) on hydrogen (R&D, subsidies and fiscal incentives to energy producers, construction/repurposing of storage and distribution infrastructure, etc). The role of private investments is not downplayed, but (as mentioned above) the role of state is considered critical for mainstreaming green HYDROGEN and integrating it into the energy system.

Furthermore, the existence of robust strategies and legal frameworks does not equate with consistent implementation of relevant policies. For example, the large number of hydrogen project announcements in the EU countries (840 have been identified by the European Clean Hydrogen Alliance) has been attributed to “strong political support” [43]; however, the vast majority of them “are still in the planning stage” [44], implying that strong political commitment remains a critical parameter. Thus, a fifth parameter is the timely implementation of foreseen initiatives and the achievement of set targets; correspondingly the existence of a monitoring and evaluation national mechanism is a factor that would fortify political commitment on hydrogen roll-out and would facilitate the actualisation of concrete results.

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[41] https://www.intereconomics.eu/contents/year/2021/number/6/article/green-hydrogen-in-europe-do-strategies-meet-expectations.html

[42] https://fleishmanhillard.eu/wp-content/uploads/sites/7/2022/02/FH-National-Hydrogen-Strategies-Report-2022.pdf

[43] https://hal.science/hal-04158824/document

[44] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0156&qid=1689756932873

Two additional possible parameters refer to the regional and international aspects of hydrogen policies. In countries (such as Austria) where subnational authorities enjoy considerable competencies in the enactment and implementation of energy policies, the aforementioned parameters should proportionately apply to regional hydrogen strategies and targets, i.e., territorial authorities should make efforts to harmonise their green hydrogen policies with the national policies; in countries with more centralized state administrations (such as Slovenia) the implementation of hydrogen strategies and policies should not lead to severe territorial divergences (between high-growth and lagging regions), or at least imbalances should be actively and quickly addressed. Moreover, a set of international factors could constitute a separate parameter; this could include tight coordination of hydrogen strategies at the EU level (a suggestion made by KSSENA, please refer to section A), transnational cooperation by countries and/or regions of the Alpine area, as well as other international/geopolitical developments (i.e., developments covered by "international factors" of the questionnaire). In this context, the establishment of a harmonized green hydrogen regulatory framework within the EU, including common safety standards, would be essential for the development of an integrated green hydrogen market. The same applies, on a smaller scale, for the Alpine area. Overall, international initiatives are expected to impact national policies and constitute a factor that will sustain the political commitment of national leaders and governments to facilitating and supporting green hydrogen initiatives.

Outcome 2 of "policy environment" refers to conditions that fall considerably short of most of those foreseen for Outcome 1. It is expected that all states of the Alpine region will have a dedicated green hydrogen strategy well before 2030; most probably, this strategy will contain certain targets regarding hydrogen production capacity. However, it is less certain whether national strategies will specify concrete targets regarding the penetration of green hydrogen in all transport sectors. Moreover, it may be the case that strategies on green hydrogen are not adequately coordinated with other decarbonisation strategies (e.g. within the framework of NECPs) and/or do not inform a coherent and comprehensive set of hydrogen-specific laws and regulations. Furthermore, hydrogen strategies and laws might be sufficiently developed, but this might be restricted to the regulatory level, i.e. is not backed up by public investment and concrete government mechanisms that effectively allow private actors access to financing opportunities. A main factor that may lead to a "Outcome 2" characterisation is the restrained character of public expenses in support of a country's hydrogen strategy. The commitment of adequate public funds to meet ambitious clean HYDROGEN target is not expected to be a smooth, conflict-free process, as it involves a change in priorities; thus, other policy areas or sectors will experience a reduction in public funding, something that could result in the expression of public opposition; thus, consistent devotion of adequate funds or resourceful generation of additional fiscal space can be considered as a litmus test for political commitment. An even more important indicator of a supportive policy environment is the successful implementation of renewable hydrogen policies; significant and consistent failure to achieve hydrogen targets or notable instability in the policy and legal framework would point out to low levels of political commitment. Political commitment at the national level will possibly decrease if peripheral (i.e. Alpine) and/or EU mechanisms of policy coordination become less pronounced, or if international developments (e.g. geopolitical crises, weakening of compliance to core climate change goals on behalf of powerful third countries) are interpreted by domestic policy makers as signals that clean hydrogen expansion is not a core component of green transition. Finally, grave inequalities among subnational units regarding green hydrogen roll-out could be considered, in conjunction with other failures, as an indicator of an ineffective policy environement.

C.1.ii Second driver: “technological advancements”

This second driver refers to technological improvements and the expansion of green hydrogen infrastructure that are deemed absolutely necessary for HYDROGEN roll-out in the Alpine region and for the attainment of targets set by the EU for 2030.

Technological improvements

Technological trends are closely interwoven with questions related to the cost of clean hydrogen (primarily production, but also distribution and storage cost) and, hence, its penetration in the energy market. For this reason, those factors which have emerged as important from partners replies are examined within the framework of this driver.

One of the most important parameters in mainstreaming green hydrogen remains the still not competitive price of green hydrogen. As a case in point, green hydrogen production costs are over 3 times higher compared to grey hydrogen[45] and over 2 times higher than those of blue hydrogen. There is currently the expectation that green hydrogen will become cost-competitive with grey hydrogen by 2030, but this is to a large degree dependent on improvements in the energy efficiency of electrolysers and lower green electricity prices.

Another parameter that possibly needs to be included in assessing technological advancements and their impact on green HYDROGEN production costs has to do with the production cost of “blue” hydrogen (which involves technologies of carbon capture and storage). Current estimations are conflicted, with some of them estimating that green HYDROGEN production costs will remain higher than those of

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[45] Green Hydrogen to Undercut Gray Sibling by End of Decade | BloombergNEF (bnef.com)

blue HYDROGEN (at higher levels of hydrogen demand)[46], while others project that by 2030 green hydrogen will generally be cheaper than (currently more affordable) blue hydrogen[47]. To the extent that blue hydrogen is often proposed as a short-term (transition) solution towards decarbonization[48], a lower-than-green HYDROGEN production cost could be considered as a barrier for achieving the ambitious goals for green HYDROGEN roll-out.

Cost of hydrogen production is closely related to technological improvements and can be considered as a proxy for electrolysers' cost-efficiency; thus, this factor that has received a relatively high score by H2MA partners is discussed with this framework. According to a recent review of studies focusing on (projections of) hydrogen cost, "the drivers for cost reduction are described as a combination of scale up, increased manufacturing volumes and technology improvements" [49]. Although concrete estimations vary and there are different assessments of the cost-efficiency of alternative water electrolysis technologies, a common finding of various studies is that the above drivers will lead to a decline in the cost of electrolysers towards 2030[50]. Whereas there is little, if any, disagreement on that, there is less certainty on whether an adequate level of private investments - an additional economic factor that received high score – will be devoted to clean hydrogen in order to facilitate innovations in electrolysis processes and achieve economies of scale. The precise directionality of causal interactions among relevant factors vary in the relevant literature, however it is generally accepted that increased R&D funding, production scale-up, technological innovation and automation are factors that lower investment costs and uncertainty and are positively correlated with electrolyser technical characteristics (efficiency, lifetime, etc) and clean hydrogen production costs[51].

Expansion of green hydrogen infrastructure

The EU has very specific targets regarding clean hydrogen production and electrolyser capacity for 2030. Following revisions made under the REPowerEU plan, core targets include the production of 10 million tonnes (Mt) of renewable hydrogen in the EU, which is estimated to necessitate an electrolyser capacity of 100 GW[52]; an

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[46] https://energypost.eu/green-or-blue-hydrogen-cost-analysis-uncovers-which-is-best-for-the-hydrogen-economy/

[47] https://www.iea.org/commentaries/is-carbon-capture-too-expensive; https://about.bnef.com/blog/green-hydrogen-to-outcompete-blue-everywhere-by-2030/.

[48] https://hal.science/hal-04158824/document

[49] https://www.sciencedirect.com/science/article/pii/S0360319922040253

[50] https://www.nature.com/articles/s41560-019-0326-1 ; https://www.sciencedirect.com/science/article/pii/S0360319922040253

[51] https://www.sciencedirect.com/science/article/pii/S0360319917339435 ; https://www.sciencedirect.com/science/article/abs/pii/S0360319917344956.

[52] In a less pronounced way, the EU has set a goal of 500 GW electrolyser capacity for 2050 (https://hal.science/hal-04158824/document).

additional 10 Mt of renewable hydrogen is aimed at being imported in the EU. The attainment of such goals necessitate nothing less of a paradigm shift: in 2020 clean hydrogen capacity was about 0.012 Mt in the EU, a negligible share of a total of hydrogen production capacity of 11.5 Mt; that year, about 90% of hydrogen demand in the EU was "grey hydrogen", i.e. produced through fossil fuels without carbon capture. The above imply that clean hydrogen production capacity needs to nearly double each year between 2020 and 2030 in order to achieve the 10 Mt target. Two individual factors pose important challenges towards this goal, electrolyser capacity and availability of renewable energy[53].

Regarding electrolysers, their capacity was around 160 MW in 2020; thus the 100 GW target for 2030 – and a recently set 17.5 GW intermediate target set by electrolyser manufacturers in Europe for 2025 – requires considerable investments in the forthcoming years[54]. Using as a case study the growth of solar photovoltaics (PV), i.e. similar, mass-produced technologies for renewable energy, a study has recently estimated that electrolysers capacities should even "outpace the best photovoltaic growth rates ever achieved" in Europe[55]. A similar study forecasts that even if electrolysis capacity in the EU follows the adoption rates of wind and solar power, it will remain considerably below 2030 targets and projected demand, even in the most "optimistic" scenario; "breakthrough" in capacity is projected to emerge at a later stage, around 2038 (something that will enable the attainment of 2050 goals)[56]. Both studies refer to the need for "unprecedented" or "emergency-like" efforts for the attainment of EU clean hydrogen targets, especially in the short term (i.e. 2030).

Regarding renewable energy, its production capacity needs to also be decisively scaled up in order to support the envisaged expansion of clean hydrogen production. Indicatively, at least half of the total investments needed for the upscale of clean hydrogen production is expected to be directed to expanding the renewable electricity production[57]. According to the European Commision's own estimations, an additional 150-210 GW of renewable power will be required by 2030, to support clean hydrogen production in order to achieve economies of scale and render its cost "competitive with its fuel alternatives"[58]. Thus, REPowerEU sets ambitious targets in

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[53] https://hal.science/hal-04158824/document, p.3-5.

[54] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

[55] https://hal.science/hal-04158824/document, p.15. In particular, this study estimated that an electrolyser capacity growth equivalent with that of solar PV in Europe during its 8 consecutive most successful years, would bring clean hydrogen production around 5.6 Mt by 2030; despite this considerabe upscale, this would 4.4 Mt short of the REPowerEU target of 10 Mt.

[56] https://www.nature.com/articles/s41560-022-01097-4#Fig7

[57] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

[58] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

terms of RES infrastructure, e.g. a 3-4 times increase in installed solar PV by 2030, which need to be achieved over the next years.

A further parameter relates specifically to the dimension of hydrogen imports to Europe. Apart from the fact that about half of the aforementioned total of 1 trillion of projected investments are expected by the European Commission to be devoted to "international value chains to enable the import of 10 million tonnes of renewable hydrogen"[59], this goal necessitates that "hydrogen supply corridors" will have been completed or be in a highly advanced state by 2030. A recent report by the European Clean Hydrogen Alliance proposes the development of six supply corridors, necessary for the distribution of imported hydrogen across the EU. Hydrogen demand for industry, transport and power in the Alpine region will be primarily served by the "South Central HYDROGEN corridor"; green hydrogen from North Africa (primarily Algeria and Tunisia) will flow to those countries through the Italian peninsula, primarily via the repurposing of existing pipelines[60]. Limited advancement in the development and integration of the six corridors or particular difficulties in implementing the South Central corridor (something that may negatively affect Alpine countries) will constitute a barrier for the desirable level of green hydrogen roll-out.

Finally, the hydrogen storage capacity will need to significantly increase in order to support production increases and the expansion of green hydrogen use cases. Underground (geological) storage in either depleted gas reservoirs, salt caverns, or saline aquifers remains the most cost effective option for large scale, long term storage[61], highlighting the need to map and exploit suitable sites in order to reduce the overall green hydrogen costs.

Having described basic features and parameters of this driver, its two alternative outcomes can now be briefly outlined.

Outcome 1 of the "technological advancement" driver, essentially refers to a condition where EU targets set for 2030 are essentially attained, or a clear trend that leads to their fulfillment is visible; this will apply in proportion to each of the Alpine countries. In this condition, private investments throughout the entire clean hydrogen value chain (with an emphasis on electrolyser capacity / production) reach quickly very significant levels and are sustained until 2030. These investments include both production capacity in the EU (/Alpine region) and green HYDROGEN initiatives in third (neighboring) countries; moreover, the envisaged supply corridors (/the South-Central corridor) are operational until 2030. Investors are not

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[59] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

[60] https://www.entsog.eu/sites/default/files/2023-04/web_entsog_230311_CHA_Learnbook_230418.pdf

[61] Projecting the levelized cost of large scale hydrogen storage for stationary applications,
Zainul Abdin, Kaveh Khalilpour, Kylie Catchpole

discouraged by the possible lower production cost of alternative solutions (e.g. blue hydrogen) nor overly direct their capitals to other regions (e.g. the US). Thus a virtuous circle of high investment, technological innovation and economies of scale lead to visible reductions in green hydrogen production costs that render it competitive by 2030, something that opens a solid pathway for achieving further decarbonization targets towards 2050.

Outcome 2 depicts a non-favorable condition for the green hydrogen roll out, however this will still take place in the context of an overall expansion of the green hydrogen ecosystem in order to keep the scenario realistic. In this case however, investments on clean hydrogen are clearly increased in relation to 2020 levels; technological improvements still take place, imports rise and production costs start to decline. However, if the above improvements are rather moderate and not significant, the end state (i.e., in 2030) will diverge considerably, particularly with regards to green hydrogen economic viability and by extension the deployment of green hydrogen infrastructure thereby diverging from the set targets on electrolyser capacity and clean hydrogen production. Furthermore, an initial failure to achieve production expansion rates at least similar to those of the solar and wind power in the past years could be interpreted by investors as a signal that future importance of green hydrogen in the energy mic will be lower, leading them to direct their investments to alternative decarbonization technologies.

C.1.iii Four alternative scenarios for 2030

The final, seventh, step of the adopted scenario building technique is to synthesise alternative Outcomes of the proposed barriers into distinct scenarios (“storylines” or forecasts). Based on the selected drivers and the subsequent discussion, the following table summarises the four scenarios.

Table 3 Four alternative scenarios of hydrogen roll-out until 2030

Scenario 1 High political commitment, breakthrough technological advancements	Scenario 2 Tepid political commitment, breakthrough technological advancements
Scenario 3 High political commitment, moderate technological advancements	Scenario 4 Tepid political commitment, moderate technological advancements

SCENARIO 1: OPTIMISTIC

Assumptions

1. **Strong policy support**. National and territorial governments in the Alpine area work as catalysts for the growth of hydrogen economy, effectively implementing favorable policies, incentives, and regulations to encourage green hydrogen production and use. These can include:
    a) Subsidies and incentives, in the form of direct grants, tax credits or other financial benefits to hydrogen producers, designed to lower the cost of green hydrogen and make it competitive with other green technologies.
    b) Strong R&D funding, focused on hydrogen technologies, allocated to innovative research projects, pilot programs and collaborations with the private sector.
    c) Supportive regulatory framework, including safety standards, permits for hydrogen infrastructure development and streamlined approval processes to expedite green hydrogen projects.
    d) Carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems. These mechanisms make fossil fuels more expensive and incentivize the use of low-carbon energy sources, including green hydrogen.
    e) Public procurement for green hydrogen technological applications, is a way for the state to boost demand through becoming major consumer of green hydrogen, e.g., green hydrogen bus fleet, government-owned vehicles, regional transportations railroads etc.
    f) International cooperation and trade partnerships to facilitate cross-border mobility, through a harmonized regulatory framework, international initiatives and an efficient distribution of green hydrogen refueling stations across all roadways (e.g., on the TEN-T core and comprehensive network).

2. **Significant technological advancements**. Breakthroughs in hydrogen production, storage, and transportation technologies increase the cost-competitiveness of green hydrogen. The deployment of related infrastructure (such as RES production sites, green hydrogen production plants) is accelerated, while the repurposing of gas pipelines progresses as envisaged (although still at a relatively early stage). Key developments in this area include the following:
    a) Increase in renewable energy capacity, particularly wind and solar, ensuring a steady and cheap source of electricity for green hydrogen production.

b) Reduction of the levelised cost of electricity (LCOE) for renewables.
c) Innovations in water electrolyser (WE) technologies, particularly PEM (Proton Exchange Membrane) and alkaline electrolysers lll, that considerably increase their efficiency
d) Innovations in hydrogen storage systems, leading to higher hydrogen density, improved safety, and overall lower costs.

Outcomes

In this scenario, the combination of strong policy support and technological advancements leads to an accelerated roll out of the green hydrogen economy. By 2030, the increased cost competitiveness of green hydrogen along with the effective policy framework will lead to an increase in the green hydrogen use cases and an increase penetration in the heavy-duty vehicles market (and partial the train market). In parallel, the increase of green hydrogen initiatives, the common standards and regulations and the expanded green hydrogen infrastructure will lay the groundwork for the development of an integrated, large scale green hydrogen ecosystem in the Alpine area in the period 2030-2050.

More specifically, this optimistic scenario includes the following outcomes.

Increased Production

Innovations in water electrolysis, storage systems, and reduced LCOE for renewables contribute to the cost-effectiveness of green hydrogen production. By 2030, it is expected that green hydrogen will be competitive vis-à-vis grey hydrogen (or will be nearing that point depending on fossil fuel price evolution). The increase in green hydrogen competitiveness will slowly (at this stage) increase the use cases of green hydrogen (particularly in industry and mobility), and along with state-funded initiatives will lead to a steady increase in the demand for green hydrogen. As a result, the production of green hydrogen will steadily increase over this period. Under this scenario, closer transnational cooperation and a more effective national and regional policy environment will lay the foundations for the development of an integrated green hydrogen ecosystems in the Alpine area, allowing the uninhibited cross-border distribution of hydrogen and ensuring synergies in the hydrogen production.

Cost competitiveness

Government subsidies and incentives, coupled with economies of scale in the production, distribution and storage of green hydrogen, and increases in the efficiency of the electrolysis, is expected to lead to a significant decline in the cost of green hydrogen, potentially approaching the level of 2.5€/kg by 2030. Green hydrogen becomes highly competitive with fossil fuels in several applications, including industrial processes and the transportation sector. This competitiveness encourages OEMs to invest in the production of FCEVs with particular emphasis on long-haul heavy-duty trucks. Even though supply remains slightly higher than demand, demand is expected to further increase after 2030.

Hydrogen infrastructure

A surge in investment through more effective policy support along with the gradually increasing competitiveness of green hydrogen is expected to lead to a significant expansion of hydrogen infrastructure. This includes a) the development of a network of hydrogen refueling stations (HRS) for both passenger and commercial vehicles, evenly allocated across the TEN-T network along with storage facilities and b) progressive retrofitting of existing natural gas pipelines to accommodate hydrogen transportation enabling the efficient distribution of hydrogen in an emerging economy of scale. In addition, green hydrogen initiatives such as hydrogen valleys will increase in number (expanding to new countries/regions) and scale. Hydrogen production will remain localized but gradually the introduction of large scale green hydrogen plants will increase towards the end of the decade will change this picture.

Transportation

In terms of transportation, heavy duty transportation (particularly trucks) is expected to be one of the primary use cases of green hydrogen, supported by the development of a HRS networks that will cover the TEN-T network and the major cities in the area. Potentially, up to 15% of the trucks in the Alpine area will run on hydrogen by 2030, however this will depend on a number of parameters such as developments in electric mobility technologies and fossil fuel prices. The number of hydrogen passenger vehicles will increase but whether this will be a sustainable trend will largely depend on improvements in fuel cell technologies and their competitiveness vis-à-vis battery-based mobility applications. Railway transportation will be the other main area of development, with present initiatives showcasing their economic viability, initially not using green hydrogen but gradually transitioning to green hydrogen as its price becomes more competitive, and gradually new initiatives taking place in lines that are not suitable for electrification.

SCENARIO 2: POSITIVE GROWTH

Assumptions

1. **Discrepancies in supportive policies in different countries**. The discrepancies in policy support in this scenario reflect the diversity of government approaches and priorities in different countries within the Alpine space. While there is some level of support for hydrogen, it is not as strong or uniform as in the optimistic scenario, meaning that not all Alpine countries governments are equally committed to hydrogen initiatives. Also, while there is a regulatory framework in place for hydrogen production, it is not uniformly stringent nor are there common standards in all countries. Some countries establish clear and supportive regulations, including safety standards and streamlined approval processes, whereas others have more conservative or complex regulations, making it harder to launch hydrogen projects. In addition, a number of national and regional governments in the Alpine space may be more reserved in their support to green hydrogen owing to the relative lack of competitiveness of the green hydrogen technologies currently, and may favour alternative technologies. Transalpine cooperation on hydrogen projects remains limited. As a result, hydrogen production continues to grow because of technological advancements, but its cost competitiveness remains a challenge in many applications.
2. **Strong technological progress**. Steady improvements in hydrogen technologies contribute to a steady cost reduction over time. Renewable energy capacity increases, resulting in larger quantities and costs drop of green electricity. Water electrolysis technologies undergo significant improvements (similar to the previous scenario) and become more efficient and cost effective. Optimised storage options both for electricity (e.g., batteries) and hydrogen are realised and enable private investments in green hydrogen applications even without or with limited government subsidies.

Outcomes

In this scenario, the progression of hydrogen adoption is more dictated by technological advances rather than driven solely by policy mandates. The level of policy support varies significantly across Alpine space countries, leading to disparities in infrastructure development. Accelerated technological innovations create opportunities for private sector investments in a green hydrogen market. Consequently, the market dynamics increase their importance in advancing the rollout of hydrogen, causing countries with slower adoption to potentially fall further behind.

Steady production increase

Hydrogen production grows steadily, with a moderate increase in the production of green hydrogen. This is due to technological innovations, including, availability of RES, optimisation of water electrolysis technologies and a drop of the LCOE for renewable current. In comparison to the first scenario, the developments will be more market driven due to the relative inefficiency of the implemented policies assumed under this scenario. As a result, the overall expansion of the production capacity is expected to be lower in this scenario. In addition, discrepancies between countries and regions are expected to increase under this scenario, with current hydrogen frontrunners further increasing their distance from other regions/countries.

Production cost

Hydrogen cost is considerably reduced, due to technological improvements. However, this reduction is expected to be more moderate on average due to less effective policy support. Despite the improvements, green hydrogen is still not fully competitive, but its market share is still expected to increase thanks to technological improvements and a policy framework that despite lacking effectiveness still includes financial incentives and other supportive measures to green hydrogen initiatives. As a result, in selected sectors, particularly within applications where electrification poses challenges like industrial applications and the long-haul transportation sector, green hydrogen can still increase its market share.

Gradual infrastructure development

Overall infrastructure development will be slower and less coordinated under this scenario, and as mentioned will be more market-driven than in the previous scenario (although state and EU policies, despite their relative ineffectiveness, are still expected to be the primary driver for investments at this stage). Hydrogen infrastructure develops gradually with more HRS built in strategic positions across the TEN-T network. Most of the TEN-T network in the Alpine space will be covered with HRS under this scenario, but station placement will not necessarily be coordinated leading potentially to inefficiencies. Local hydrogen ecosystems such as hydrogen valleys continue to develop and increase in number, however the (relative to scenario 1) lack of sufficient policy support limits this growth. Furthermore, the conversion of natural gas pipelines advances, but at a slower pace than initially anticipated, partly due to less political commitment and partly due to the slower expansion of green hydrogen use cases.

Transportation

Heavy duty vehicles will be the more accessible market under this scenario, similarly to the previous. Although the overall market share is expected to be lower due to less effective policy support a strong increase in the number of hydrogen heavy duty vehicles is still expected. Hydrogen-powered passenger vehicles will also increase in number but their growth may be undermined by developments in electric mobility (see previous scenario) and a more moderate expansion of the HRS network. The outlook of hydrogen-based railway transportation in the Alpine area is still positive under this scenario, however the increase in the number of new initiatives is expected to be more moderate and uneven due to less effective policy support.

SCENARIO 3: MODERATE GROWTH

Assumptions

1. **Significant policy support**. In this scenario, EUSALP governments are highly committed to promoting green hydrogen as a clean energy source. They implement ambitious policies and provide substantial financial support, including subsidies and incentives, R&D funding, supportive regulatory frameworks, and international cooperation agreements to advance the hydrogen industry.
2. **Moderate technological progress**. Hydrogen technologies see only moderate improvements, keeping production costs relatively high. Growth in renewable energy capacity falls short of expectations. Limited progress in electrolysis technology and a lack of significant advancements keep production costs high. This leads to slower adoption rates and inhibits the competitiveness of green hydrogen against conventional energy sources.

Outcomes

In this scenario, the Alpine region relies heavily on policy support to drive the green hydrogen rollout. While there is some growth in green hydrogen production, the limited technological progress and relatively high production costs pose challenges. Infrastructure development lags, and market penetration in the transportation sector is largely confined to countries with significant political commitment and financial backing. The overall progress in the green hydrogen industry in the Alpine region remains moderate, with substantial room for further technological advancements and cost reductions to achieve more significant growth post 2030.

Moderate production increase

Green hydrogen production experiences slow growth, with a predominant reliance on hydrogen from biomass gasification. Biomass gasification, though eco-friendly in comparison to fossil fuel-based hydrogen, might have limitations in scaling up production. It requires large amounts of feedstock, faces logistical challenges in collecting biomass, and remains less cost-effective. While there is a modest increase in green hydrogen production, the pace of growth remains restrained. Even with increasing interest in green hydrogen, there are still only a few new green hydrogen projects being initiated, and existing projects are not expanding as quickly as expected.

Relatively high cost

Despite government subsidies and incentives, green hydrogen production costs remain relatively high. The improvements in technology are not substantial enough to bring down costs significantly. As a result, green hydrogen continues to be more expensive than fossil fuels in most applications, potentially staying above 5€/kg in 2030, which hinders its widespread adoption.

Publicly backed infrastructure development

Infrastructure development for green hydrogen remains slow. There are limited private investments in hydrogen-related projects, including the development of HRS and pilot retrofitting gas pipelines. Progress is notably slower than anticipated, and the infrastructure is mostly supported by state efforts (e.g., tax credits and subsidies).

Government-supported market penetration in the transportation sector

The penetration of green hydrogen in the transportation sector remains limited to countries with strong political commitment and financial subsidies. Several regional authorities show political determination and support small-scale hydrogen projects, through development of hydrogen ecosystems to fuel small publicly operated fleets (e.g., urban buses). However, this transformation remains dependent on continued state support and subsidies and fails to find private investments in the long term.

SCENARIO 4: PESSIMISTIC - HYDROGEN STRUGGLE

Assumptions

1. **Fragmented and insufficient policy support**. While some countries have backed green hydrogen deployment during the last decade, several other have provided minimal or no support to hydrogen initiatives. Political commitment stays on paper while tangible financial incentives are absent.

Targets outlined in national and regional strategies are often vague and unquantified. The absence of concrete, results-focused commitment from some countries leads to an irregular and an uneven deployment of hydrogen. This disparity presents obstacles, particularly impacting transnational projects, cross-border mobility, and the transportation sector.

2. **Technological stagnation**. Hydrogen technologies show little to no innovation over the last decade. Existing water electrolysis technologies, while available, lack refinement and cost efficiency. The Levelized Cost of Electricity (LCOE) for renewables remains persistently high, and no new storage solutions have emerged. While some growth in renewable energy sources occurs, the primary focus of renewables is on electrification, leaving a limited supply of available electricity for hydrogen production, which maintains high production costs. In addition, only a few OEMs in Europe have ventured into producing FCEVs, as they prioritize electric vehicles instead.

Outcomes

In this scenario, green hydrogen faces significant challenges in production, cost competitiveness, infrastructure development, and market penetration, mainly due to fragmented policy support and technological stagnation. The overall growth and adoption of green hydrogen are hindered, making it less competitive and impactful in the energy landscape.

Insufficient growth of production

Green hydrogen production experiences limited growth due to unstable and inconsistent policies and inadequate funding which fails to create a conducive environment for investments. Industry players are reluctant to commit to green hydrogen production and big-scale hydrogen projects from several sources beyond green are to be found only in industrial applications that are difficult to electrify.

Sustained high cost

Cost-effective mass production of green hydrogen remains elusive due to lack of innovation in water electrolysis technologies, storage options, and the absence of refined, cost-effective solutions. Additionally, the limited availability of electricity from renewable sources dedicated to hydrogen production hinder the development of economies of scale. This condition makes hydrogen less competitive and hinders its integration into existing energy systems. Moreover, sustained high production costs and limited economies of scale further deter automotive manufacturers from expanding their hydrogen vehicle portfolios.

Insufficient infrastructure development

Insufficient policy support and technological stagnation hinder the development of adequate infrastructure for hydrogen uses. The absence of breakthroughs in hydrogen storage technologies leads to impractical and less efficient storage solutions. Advanced solid-state hydrogen storage methods that could have facilitated efficient long-term storage remain underdeveloped. The limited focus on retrofitting existing infrastructure for hydrogen distribution further delays progress. Repurposing natural gas pipelines for hydrogen transportation, which could be a cost-effective method, is hindered by a lack of incentives and policy frameworks. Solar and wind farms grow but they remain inefficiently connected to electrolysis facilities to produce green hydrogen. The absence of clear policy incentives further hampers this integration. As a result, uneven progress in infrastructure development occurs regionally, leading to disparities in the availability and accessibility of hydrogen. Regions in the Alpine area with stronger policy backing happen to have an HRS network, while others remain underserved.

Limited adoption in the transportation sector

The market penetration of hydrogen-based transportation faces significant limitations due to the hesitance of major automotive manufacturers to invest in a broad range of hydrogen-powered vehicles, including FCEVs, hydrogen buses, and applications in long-haul transportation, aviation, and railroads. Major automotive manufacturers prioritise battery electric vehicles (BEVs) over FCEVs. This focus on BEVs for consumer markets hinders the introduction and adoption of hydrogen-powered vehicles. In the long-haul transportation sector, the adoption of hydrogen fuel cell trucks is limited due to the lack of investment from manufacturers. Market share is increasing, primarily due to state support, but considerably less than prediction raising questions over the viability of hydrogen mobility. Initiatives in railway transportation persist but their sustainability is in doubt, largely preventing the implementation of other initiatives in the Alpine area. Hydrogen's utilisation in aviation and shipping for emissions reduction remains largely underexplored. This lack of diversification in the transportation sector results in missed opportunities for hydrogen adoption in alternative transportation segments.

C.2 Alternative scenarios for 2050

The scenario-building process that is applied here is identical to the one presented in the previous section (i.e., for 2050); thus, various details and explications of section C.1 will not be repeated here.

Firstly, factors were ordered according to their average score as follows:

Table 4 Factors assessed by partners for 2050 from highest to lowest score

1	Cost of hydrogen production (electrolysis from RES)	2,91
2	Development of hydrogen storage infrastructure	2,91
3	Cost of transport and distribution	2,82
4	Private investments and financing opportunities	2,82
5	High-efficiency electrolysers (resulting in cost-effective hydrogen production)	2,73
6	Existence of national/regional strategy	2,64
7	Existence of specific targets for green hydrogen at a set timeframe	2,64
8	Technological advancements in green hydrogen production	2,64
9	Development of hydrogen distribution infrastructure	2,64
10	Trade and supply chains disruptions	2,64
11	Operational costs (incl. maintenance)	2,59
12	Establishment of quality and security standards	2,55
13	Technological advancements in hydrogen storage technologies	2,55
14	Development of hydrogen production infrastructure	2,55
15	Disparities in standardisation and certification process	2,55
16	Geopolitical tensions (e.g. Russia's invasion in Ukraine)	2,45
17	International/transnational agreements	2,45
18	Existence of specific targets for Renewable Energy Sources (RES) in the energy mix	2,36
19	Government-backed guarantees (e.g., long-term revenue certainty)	2,27
20	Streamlined permitting and approval processes	2,27
21	Simplified administrative procedures	2,27
22	Changes in Climate change targets	2,27
23	Capital costs	2,18
24	Existence of incentives for the uptake of green hydrogen (e.g. fiscal incentives)	2,09

25	Government-led financial support	2,09
26	Support from public (incl. civil society)	1,82
27	Awareness on climate change	1,73
28	Customer demand for climate friendly products	1,55
29	Gaining a social license for operation	1,36

Subsequently, factors that are considered nearly-identical were merged. As it is depicted in the table, this process only minimally influenced factors with high scores; by focusing on the top 10, factors until rank 11 were selected.

The "clustering" of top factors, following the same process as in the previous section, was the next step. Whereas the character of clusters is not differentiated, their relative significance is (a finding that reflects changes in the priorities implied in the replies of H2MA partners, as identified in section A.2). The first cluster contains factors economic in character, mostly cost-related, namely green hydrogen production costs, transport and distribution costs, private investments and financing opportunities, and operational costs. The second cluster has a technology-related dimension, as it contains "development of hydrogen storage infrastructure", "technological advancements in green hydrogen production" and "development of hydrogen distribution infrastructure"[62]. Two out of the three remaining factors have a "policy" character, i.e. "existence of national/regional strategy" and "existence of specific targets for green hydrogen", whereas the other factor ("trade and supply chains disruptions") was included in questionnaire's "international" category. This shift in the importance of the various factors (i.e., the relative rise of significance of economic factors (in comparison with 2030), the relative decline of policy/political factors and the continuing prioritization of technological/technical factors as the most significant for the expansion of clean hydrogen) reflects the current view that green hydrogen is expected to become cost-competitive as early as 2030 and that thereafter the importance of policy support (particularly in terms of financial incentives and public investment) will gradually diminish and that the private sector will become the main growth driver.

The specification of two key drivers for 2050 builds on partners' feedback as well as the present views (mentioned above) regarding the long term development of the green hydrogen ecosystem. Thus, it is proposed that these two key drivers are "economic feasibility" and "technological advancements".

It should be noted that scenario-building for 2050 implicitly or explicitly refers to developments throughout the (rather extended) 2030-2050 period. Moreover, this

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[62] This cluster nominally contains also "high-efficiency electrolysers (resulting in cost-effective hydrogen production", however this factor is merged with "cost of hydrogen production".

suggests that developments within this timeframe will be importantly influenced by the realities of 2030. The above factors understandably add uncertainty in the discussion of drivers and scenarios for this period. This is reflected both in the – often significant - divergences observed in various existing forecasts of clean hydrogen demand, but also in the less detailed and concrete character of EU documents that refer to this period.

C.2.i First driver: “economic feasibility”

This first driver includes all “economic” factors that emerged in the top 10 section, as identified above. It is proposed that the “political” and “international” factors of this top category should be considered as components of this driver.

The justification of this choice is easier in relation to the “trade and supply chain disruptions”. This barrier was included in the international category based on assumptions that relate such disruptions with geopolitical crises (e.g. war in Ukraine) or largely unforeseen global events (e.g., the Covid-19 pandemic). However, irrespective of the concrete character of its etiology (political, health, environmental, or other), its consequences have primarily an economic character. It is assumed that such disruptions will increase production costs, in this case related to critical raw materials employed in green hydrogen infrastructure (for example electrolysers) and/or transport costs (e.g. of ammonia or liquid hydrogen).

It is less obvious why policy-related factors such as the existence of a national strategy or of specific targets for green hydrogen should be included in this primarily economic driver. It should be reminded that “drivers” do not constitute (mere) clusters of factors, but rather broader trends and processes. In this sense, as for the period up to 2030 policy factors were considered crucial for driving private investments and demand, for the post-2030 period the core challenge refers to market growth of clean hydrogen, as aforementioned. Hence, if in the current, forming period of clean hydrogen its establishment as an alternative fuel and energy source is policy-driven, its development in the subsequent phase is expected to be market-driven. In other words, becoming competitive in the energy market will be the crucial test for green hydrogen existence as a viable option and this, in turn, will largely define the need and the content of concrete policies (strategies, targets, etc).

Turning to the discussion of possible developments regarding this driver, virtually all available forecasts and reports on clean hydrogen anticipate that its use as an energy carrier will be very limited in 2030 and will start to occupy a meaningfully sizeable portion of the market(s) (although always a minor one) around 2040; indicatively, a DNV report forecasts that in 2030 global demand for hydrogen will be around 25 Mt (almost exclusively in the manufacturing sector), around 100 Mt in 2040 and around

220 Mt[63]. Regarding hydrogen demand in Europe, in particular, by employing the median value of the (highly divergent) forecasts concentrated in the aforementioned webpage of the European Hydrogen Observatory, it turns out that whereas total hydrogen demand in Europe is expected to increase 4 times between 2030 and 2050 (from 344 to 1386 Twh, or 42 Mt), in the transport sector specifically it will increase more than 15 times (from 32 to 537 Twh, or 16 Mt)[64].

Thus, the consensus in the relevant literature seems to be that in 2030 clean hydrogen will only have made the first steps in "market penetration" (second phase) and will have more or less reached a stage of "technological readiness" (first phase). During 2030-2050 the second phase will be concluded before "market growth", i.e. the third phase green (when "hydrogen becomes a well-known and widely used energy carrier") fully develops.

Hydrogen cost is a central, if not the most important, dimension of the "economic feasibility" driver. A recent study on behalf of the Clean Hydrogen Partnership assesses various components of green hydrogen production cost[65]; indicatively, the cost for solar PV energy (a major source of renewable energy that will be used in the electrolysis process) is assumed to decrease about 30% between 2030 and 2050, whereas the cost for alkaline electrolysis is assumed to have a similar trend (around 35% decrease). Another study (on behalf the European Hydrogen Backbone[66]) forecasts a larger decrease (close to 50%) in the cost of clean hydrogen plants between 2030 and 2050; this will bring the cost of clean hydrogen from above 2 €/kg in 2030, to less than 1,5 €/kg in 2050. A close-to-50% reduction in the cost of green (hydrogen) technologies between 2025 and 2050 is also projected by a recent Deloitte report[67].

Turning to other major components of clean hydrogen costs, low cost of storage is assumed to be one of hydrogen competitive advantages *vis à vis* other energy carriers; according to the same study, the cost of battery storage is between 3 and 12 times more expensive than hydrogen storage in salt caverns[68]; however, it should be

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[63] DNV, 2022, p.6.Regarding the transport sector in particular, although its share will be negligible until 2030, by 2050 it is projected that more than half of hydrogen demand will be in the transport sector (in the form of hydrogen derivatives, such ammonia and methanol).

[64] Own calculation based on European Hydrogen Observatory website, "Scenarios for future hydrogen demand", https://observatory.clean-hydrogen.europa.eu/tools-reports/scenarios-future-hydrogen-demand.

[65] Deloitte, 2023, https://www.clean-hydrogen.europa.eu/system/files/2023-04/Study%20on%20hydrogen%20in%20ports%20and%20industrial%20coastal%20areas.pdf,p.233-5.

[66] Guidehouse, 2021, https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021.pdf , p.59-60.

[67] Deloitte, 19 June 2023, *Green hydrogen: Energizing the path to net zero*, https://www.deloitte.com/global/en/issues/climate/green-hydrogen.html , p.16.

[68] Guidehouse,2021, p.82-3.

noted that research on this storage option is ongoing and that its application until now has been minimal.

Regarding the transportation cost of clean hydrogen, various parameters need to be taken into consideration. Assuming the large-scale utilisation of green hydrogen, for transport routes within or near Europe, pipelines of at least 36-inches diameter have been assessed as more cost-effective options than any shipping method (liquid hydrogen, ammonia). Pipelines of larger diameter (48-inches) tend to have lower cost per kg transported, despite the higher capital cost involved; however, this advantage is to a point diminished due to higher costs of compressor power and safety considerations; repurposed pipelines (currently used for natural gas) represent a less costly option, although exact costs of repurposing need more studies to be defined[69].

Sustained high levels of investment constitute another significant parameter of the economic feasibility driver. Concrete amounts, however, are difficult to specify, especially beyond 2030. As aforementioned, the EU has recently estimated that a total amount of close to 1 trillion of investments will be needed until 2030; 335 to 471 bn are estimated for clean hydrogen produced in the EU, about 2/3 of which will be needed for additional energy from RES; 50-75 bn will be directed to electrolysers and 28-38 bn for storage; an additional 500 bn of investments will be directed to “international value chains” with the goal to annually import an additional of 10 Mt of clean hydrogen[70]. It may be noted that these estimations have been published after the introduction of REPowerEU; other EU estimations from previous years are significantly less ambitious[71]. Recent Deloitte reports make diverse estimations on the amount of investment needed. A 2022 report distinguishes between two energy transition pathways for Europe until 2050: a “technology diversification” pathway, which foresees a more pronounced role for natural gas and blue hydrogen technologies (among other components) and a “renewable push” pathway, which includes more ambitious goals (especially for 2030) and puts a stronger focus on green technologies from early on; accordingly, cumulative investments are about 25% higher in the second pathway and are projected to reach € 2.5 trillion (vs € 1.9 trillion) by 2050, reflecting the higher need for electrolyser capacity[72]. More recent studies estimates the total amount of investment for hydrogen supply chain in Europe at 1.2 trillion dollars until 2050, with total global investment reaching 9,4

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[69] Guidehouse, 2021, p.70-78.

[70] European Commission, 16 March 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0156&qid=1689756932873

[71] For example see European Commission and European Investment Bank, 2022, *Unlocking the hydrogen economy — stimulating investment across the hydrogen value chain*, https://www.eib.org/attachments/publications/unlocking_the_hydrogen_economy_en.pdf, p.9.

[72] Deloitte, 2022, *Hydrogen4EU: Charting Pathways to enable net zero*, https://www.hydrogen4eu.com/, p.81

trillion (75% of which specifically on green hydrogen); the report assumes that "[t]his endeavor is likely manageable if the decline in spending on oil and gas can be channeled to clean hydrogen[73]". The aforementioned amounts clearly imply massive investments on clean hydrogen (primarily on electrolysers and renewable energy), however it is evident that a high degree of uncertainty currently exists on how large these investments should be, which should be their annual growth rate, etc.

Other components of clean hydrogen's production cost are operational and maintenance costs, as well as the financing cost; each of these segments is estimated to increase by another 30% the total levelized cost of green hydrogen (especially in promising for producing green hydrogen, yet political "risky" countries[74].

The above discussion constitutes an attempt to present parameters and possible trajectories of clean hydrogen cost for the 2030-2050 period. A widely shared view is that the potential of clean hydrogen supply exceeds demand by 2050[75]. However, this does not necessarily imply a rapid expansion of green hydrogen after 2030; according to a view, cost reduction is one of the key drivers for clean hydrogen growth (along with policy support and technological developments), however it is "notoriously difficult to predict[76].

Finally, an essential aspect of assessing the economic feasibility of green hydrogen is related to developments in alternative technologies (e.g., electric mobility) and the competitive advantages (or lack thereof) of these technologies vis-à-vis green hydrogen, which will ultimately determine the use cases and market penetration of green hydrogen. In this context, cost reduction (as well as other improvements) should not be viewed only in comparison to fossil fuels (grey hydrogen in this case) but in comparison to similar developments in other green technological pathways, which further complicates the issue and increases the uncertainty of any long-term predictions.

Based on the above, *outcome 1* of this driver refers to a situation of a continuous fall in cost production of clean hydrogen in Europe that is already evident in 2030. Costs of production (electrolysers), storage (salt caverns, depleted gas fields) and transport have a declining trend in a way that reduces investment risks; this is necessarily related to technological advancements. Reliable signals that clean hydrogen will become a cost-effective energy solution, competitive to alternative technologies such as batteries in specific segments of the transport sector (such as heavy-duty vehicles, shipping, aviation), but also in comparison with blue hydrogen by 2040[77], will further encourage private investors, including those from the fossil fuel economy, to turn to clean hydrogen. The continuing expansion of RES,

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[73] Deloitte, 19 June 2023, *Green hydrogen: Energizing the path to net zero*, p.46-7.

[74] Deloitte, 19 June 2023, *Green hydrogen: Energizing the path to net zero*, p.19,22.

[75] Deloitte, 19 June 2023, *Green hydrogen: Energizing the path to net zero*, p.19.

[76] https://www.nature.com/articles/s41560-022-01097-4#Fig7

[77] Deloitte, 19 June 2023, *Green hydrogen: Energizing the path to net zero*, p.16.

especially solar PV and wind power, which will further compress the energy costs is an absolutely necessary condition for this trajectory. Moreover, this positive state of affairs entails a viable clean hydrogen economy in Europe; having met 2030 targets for hydrogen refueling stations and a dense network of (primarily repurposed) pipeline network, as well as storage facilities across the continent. A stable and ambitious policy environment that emphasizes the attainment of hydrogen -related targets will continue to be important for rapid market growth of clean hydrogen, despite the fact that public investment will not continue to rise (precisely because this will not be needed). In Alpine countries, this outcome will be characterized by further investments on photovoltaic solar panels, emphasis on local hydrogen production, the smooth repurposing of the existing dense natural gas network, the reorientation of the existing automotive industry to hydrogen solutions and the acceleration of efforts on the exploitation of salt caverns.

Outcome 2 of this driver refers to a situation where, in brief, the cost of clean hydrogen fails to follow in a consistent manner the anticipated positive scenario, something that results in moderate market penetration. An underachievement in various 2030 targets – e.g. a policy failure to create a stable regulatory framework that will by then mitigate current investment risks, or the lack of adequate advancements in clean hydrogen technologies and the lagging deployment of the necessary infrastructure (e.g. of refueling stations) – will likely constitute an antecedent condition of this suboptimal state of affairs. A failure of green hydrogen production cost to fall decisively below the 2 €/kg threshold by 2040 constitutes, perhaps, a key indicator of this failure. Further possible causes of this outcome include anomalies in the constant expansion and/or the decline of production costs of RES, as well as larger than expected difficulties in repurposing existing natural gas pipelines or in securing the safe storage of hydrogen in salt caverns; such features will be especially crucial for the countries of the Alpine region.

C.2.ii Second driver: “technological advancements”

This driver consists of “technological” and “technical/infrastructural” components, as outlined in section C.1.iii. The importance of this driver is highlighted by its continuing presence throughout the period until 2050. Focusing more on the three aforementioned factors that emerged as more significant from H2MA partners’ replies, “technological advancements in green hydrogen production” refers primarily to the efficiency of electolysers and electrolysis cost (although the first dimension has been merged with the “cost of production” factor it is briefly discussed here). PEM electrolysis and alkaline electrolysis (AEL) constitute the two prevalent electrolysis technologies; various estimations exist regarding the competitive advantages of each one of them, including assessments that regard them as generally equivalent. According to a recent study, an increase in the efficiency of both technologies is to be expected between 2030, with PEM electrolysis demonstrating a higher increase (from 64.5% to 80%, in comparison with an increase form 69% to 75% for AEL). Cost reductions in both technologies have already taken place and are projected to continue through 2030[78] until 2050, by at least 25% to 35% throughout this later period. Decreases in operation and maintenance costs are also expected between 2030 and 2050, as well as extension of the service life of certain components[79].

The capacity of electrolysers in Europe is expected to further grow between 2030 and 2050; however, in contrast to 2030 neither exists an explicit target, not estimations agree. In its 2020 *Hydrogen Strategy*[80], the EU has set a target of 500 GW renewable electrolyser capacity by 2050, a target that is reproduced by certain studies[81]. However, this target was set before the more ambitious strategic plan of REPowerEU (2022); indeed, a recent Deloitte report estimates a far larger amount of electrolyser capacity by 2050, ranging from 950 GW to 1450 GW. The latter estimation corresponds to the more consistent with REPower EU plan "renewable path" trajectory, which actually entails a larger increase of installed electrolyser capacity between 2030 and 2040, rather than the following decade[82]. In any case, the upscaling of hydrogen production – in the form of annual full load hours or electrolyser plant size – is up to a point clearly associated with significant cost reductions (especially in CAPEX)[83].

Developments in storage and distribution infrastructure are also expected to drive the market growth of clean hydrogen. During the 2030-2050 period, apart from expanding the capacity of salt caverns, the utilization and conversion of depleted gas fields (and aquifers, secondarily) - as underground hydrogen storage infrastructure will be crucial[84]. It has been estimated by a recent dedicated study that "the total capacity through conversion of existing and planned sites is 920 TWh", which corresponds to a sufficient 30% storage share of a moderate scenario of 2,500 Twh hydrogen demand for 2050; crucially, a significant share of such "porous reservoirs" are situated in a number Alpine territories (e.g. Austria, northern Italy,

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[78] Fraunhofer, 2021, *Cost Forecast for Low Temperature Electrolysis – Technology Driven Bottom-Up Prognosis for PEM And Alkaline Water Electrolysis Systems*, https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/cost-forecast-for-low-temperature-electrolysis.pdf, p.68.

[79] Deloitte, 19 June 2023, *Green hydrogen: Energizing the path to net zero,* p.59.

[80] European Commission, 8 July 2020, *A hydrogen strategy for a climate-neutral Europe*, p.8.

[81] https://hal.science/hal-04158824/document, p.11; https://www.nature.com/articles/s41560-022-01097-4.

[82] Deloitte, 2022, *Hydrogen4EU: Charting Pathways to enable net zero*, p68.

[83] https://www.sciencedirect.com/science/article/pii/S0360319922040253; https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/cost-forecast-for-low-temperature-electrolysis.pdf

[84] https://hydrogeneurope.eu/wp-content/uploads/2022/12/52_S5_1.pdf

southeast Germany)[85]. Regarding distribution infrastructure, it has been estimated that the attainment of REPowerEU plan targets necessitate about 53,000 km of pipelines by 2040 across Europe; the recent Deloitte report is ambitious that the cross-border pipeline network will chiefly consist of repurposed natural gas facilities, noting also that in the more rapid green transition scenario ("renewable push pathway") pipeline capacity needs will be lower (e.g. due to less hydrogen imports)[86]. Apart from the above components of "technological advancements", technologies related to the conversion of hydrogen to other fuels (e.g. used in aviation and shipping) and to transporting clean hydrogen to various end-users are also necessary for hydrogen growth.

Outcome 1 of this driver refers to a state of affairs in 2050 that is characterized by a higher efficiency of electrolyser capacity, reduced cost of water electrolysis due to such technological improvements and the upscaling of production, the conversion of underground porous reservoirs to hydrogen storage infrastructure of sufficient capacity (about 1/3 of the projected demand) and by an expanded pipeline network across Europe. In this positive trajectory, the Alpine region will benefit from the availability of an existing gas pipeline infrastructure, the availability of large volumes of underground storage capacity, and its very geographical location at the centre of the continent - in vicinity to projected frontrunner hydrogen economies such as Germany - that enables maximum benefits from the projected achievement of economies of scale in the green hydrogen sector.

Outcome 2 of this driver refers to minor or moderate advancements in the technological and technical sphere of clean hydrogen. Possibly due to less than expected investments in electrolysis technologies (i.e. an underperformance of the economic driver), the efficiency of electrolysers fails to reach a level that will make it cost competitive in a wide range of applications and facilitate economies of scale. Furthermore, moderate improvements in fuel cell technologies or conversely significant improvements in alternative green technologies such as electric mobility might limit the market share of hydrogen-based technologies in certain sectors, even if green hydrogen production costs have fallen significantly. Another possible cause of this suboptimal outcome is the slower than expected increase in RES production, which may undermine the capacity to produce green hydrogen.

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[85] A. Cavanagh et al,, 2022, *Hydrogen storage potential of existing European gas storage sites in depleted gas fields and aquifers*, HyUSPRe, https://www.hyuspre.eu/wp-content/uploads/2022/06/HyUSPRe_D1.3_Hydrogen-storage-potential-of-existing-European-gas-storage-sites_2022.06.29.pdf, p.3-4.

[86] Deloitte, 2022, *Hydrogen4EU: Charting Pathways to enable net zero*, p.76-7.

C.2.iii Four alternative scenarios for 2050

Having briefly described the content of the selected two drivers for 2050, it is now possible to move on to the synthesis of their alternative outcomes.

Table 5 Four alternative scenarios of clean hydrogen growth until 2050

Scenario 1 (High economic feasibility, breakthrough technological advancements	Scenario 2 Suboptimal economic feasibility, breakthrough technological advancements
Scenario 3 High economic feasibility, moderate technological advancements	Scenario 4 (pessimistic) Suboptimal economic feasibility, moderate technological advancements

Before moving on to discuss the four alternative scenarios, it might be useful to briefly present certain EU targets and various estimations (specifically those made in the Guidehouse 2021 report[87] and the Deloitte 2022 report[88]) related to hydrogen's share in different transport sectors, i.e. the field that H2MA focuses on.

Beginning from some general estimations, according to Deloitte, hydrogen will represent 25-30% of final energy consumption on transport by 2040 and 40-45% by 2050 (assuming it has reached 9% in 2030). Guidehouse estimates hydrogen demand per country for the transport sector; for the countries of the Alpine space a sevenfold increase is projected between 2030 and 2040, whereas as for the 2030-2050 entire period the increase is between 12 and 19 times[89]. **Heavy-duty vehicles (HDV)** represent a priority sector for hydrogen, as aforementioned. Deloitte ambitiously forecasts that this sector (including buses) will be hydrogen-powered at a 90% rate by 2050 (or 13 million vehicles out of a total of 15 million. Guidehouse's more restrained forecasting refers to a 55% hydrogen share in HDVs (freight vehicles) by 2050[90] (6% in 2030 and 30% in 2040) and a 25% share in buses, which will essentially

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[87] Guidehouse, 2021, https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021.pdf , p.88-90.

[88] Deloitte, 2022, *Hydrogen4EU: Charting Pathways to enable net zero*, https://www.hydrogen4eu.com/, p.52-5.

[89] Indicatively, the demand in Austria for the transport sector is projected at 0,3 Twh in 2030, at 2.1 Twh in 2040 and at 5,6 in 2050.

[90] In yet another Deloitte study, the 55% share referes to the ambitious scenario; the conservative scenario projects only a 25% of HDV to be powered by fuel cells in 2050 and the moderate scenario a 49% share (see Deloitte, 2023, https://www.clean-

be achieved by 2040.[91] Recently, a proposal for a regulation on behalf of the Commission makes alternative projections for the share of hydrogen – powered HDVs in the new stocks, starting from 8%-13% in 2030 and reaching 27%-48% in 2050[92]. Again, the wide discrepancies in the future projections highlight the inherent uncertainties in the multiple factors that determine the development of the green hydrogen ecosystem.

Regarding the use of hydrogen in **trains**, in theory there is considerable potential for the period until 2050. Despite the fact that 75% of locomotives currently operating in rail freight are electrified, more than 50% of the locomotive fleet in the EU still run on diesel[93]. The deployment of hydrogen-power trains has already begun, with Germany being at the forefront of this process; according to France Hydrogène, "rail transport is one of the most advanced in terms of penetration of hydrogen technologies"[94]. However, present prospects for the future use of hydrogen in the non-electrified part of the railway system (around 40% of main European system) appear at best uncertain and under-specified. Indicatively, according to EARRL (the European Association of Rail Rolling Stock Lessors), the development of dual mode battery/electric locomotives constitute the more realistic solution; while it is recognized that hydrogen is more effective than batteries for long distances and heavy loads, it is nevertheless more expensive and more dangerous (especially in tunnels), besides other "barriers" related to current low-production capacity of clean hydrogen[95]. Moreover, the state of Baden-Württemberg (the territory of which is mostly part of the Alpine space) has recently announced that "hydrogen trains will no longer be considered [in the near future] as a possible replacement for diesel locomotives", following a dedicated study that estimated a much higher cost for hydrogen in comparison with "battery hybrid" trains[96]. Key available policy

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hydrogen.europa.eu/system/files/2023-04/Study%20on%20hydrogen%20in%20ports%20and%20industrial%20coastal%20areas.pdf, p.64).

[91] The share of hydrogen in passenger cars and light-medium duty vehicles is projected to be negligible.

[92] European Commission, 14 February 2023, https://climate.ec.europa.eu/system/files/2023-02/policy_transport_hdv_20230214_impact_assessment_en_0.pdf, p.32. It can be noted that even the most conservative scenarios are considerably higher than previous targets ("the baseline") set before the instroduction of REPowerEU..

[93] *Railtech.com*, "Over half of EU locomotives still run on diesel: the road to net zero", 9 May 2023, https://www.railtech.com/rolling-stock/2023/05/09/over-50-of-eu-locomotives-still-run-on-diesel-the-road-to-net-zero/?gdpr=accept.

[94] France Hydrogène,2021,*Position Paper On the "Fit for 55" Package*, https://s3.production.france-hydrogene.org/uploads/sites/4/2021/11/France_20Hydrog_C3_A8ne_20Position_20Paper_20on_20Fit_20for_2055_20Package_20-_20September_202021.pdf, p.4-5.

[95] Railtech.com, 2023, Over half of EU locomotives still run on diesel: the road to net zero".

[96] *Hydrogeninsight,* "'Will no longer be considered' | Hydrogen trains up to 80% more expensive than electric options, German state finds", 20 October 2022,

documents reflect this current lack of certainty on whether hydrogen use in trains represents a cost-efficient (and superior to full electrification) option of railway decarbonization. For example, whereas the recently introduced Alternative Fuels Infrastructure Regulation (ARIF) sets for a number or areas (e.g. hydrogen refuelling stations) concrete targets, regarding railway infrastructure (Article 13) foresees only that member states “shall assess the development of alternative fuel technologies and propulsion systems for rail sections that cannot be fully electrified for technical or cost-efficiency reasons, such as hydrogen or battery-powered trains,[97]. Similarly, the Alpine Convention as aforementioned only makes a passing, non-committing reference to hydrogen in Climate Action Plan 2.0 targets[98]. The above lead to the conclusion that it is rather difficult to determine alternative concrete scenarios regarding the use of clean hydrogen in the Alpine space for the period 2030-2050; thus, only general assessments will be made.

In **aviation**, the use of "sustainable aviation fuels” (SAf) and synthetic fuels, i.e. hydrogen based fuels is deemed to be the core option for this sector’s decarbonization. Deloitte projects their share in aviation around 5% in 2040 and between 25-36% in 2050. Guidehouse projects a 50% share, if synthetic kerosene (e-kerosene) is taken into account. This estimation is closer, yet still at a certain distance from the targets of the recently adopted "ReFuelEU Aviation” regulation[99], set at a 70% share of SAF in 2050 (35% specifically for synthetic fuels); this constitutes a considerable increase of this share form 6% in 2030 and 34% in 2040.

In the **maritime sector (international shipping),** a Deloitte 2023 forecasts that hydrogen derivatives (ammonia, e-methanol) will represent a share between 65% (ambitious scenario) and 15% (conservative scenario) of tonne miles, despite the fact that in 2030 this share will be at best 2%. Similar projections for domestic shipping are made[100].

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https://www.hydrogeninsight.com/transport/will-no-longer-be-considered-hydrogen-trains-up-to-80-more-expensive-than-electric-options-german-state-finds/2-1-1338438.

[97] European Union, 13 July 2023, *REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU*, https://data.consilium.europa.eu/doc/document/PE-25-2023-INIT/en/pdf.

[98] “Public transport solutions should also, as far as possible, build on low-carbon technologies (e.g. electric buses, electrified or hydrogen railways”.

[99] European Council, 12 October 2023, “Infographic - Fit for 55: increasing the uptake of greener fuels in the aviation and maritime sector”, https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/.

[100] Deloitte, 2023, https://www.clean-hydrogen.europa.eu/system/files/2023-04/Study%20on%20hydrogen%20in%20ports%20and%20industrial%20coastal%20areas.pdf, p.62-3.

Having in mind these estimations of possible trajectories until 2050, the four alternative scenarios can be fleshed out.

SCENARIO 1: OPTIMISTIC – CLEAN CHYDROGEN BOOM

Assumptions

3. **High economic feasibility**.
   The various components of this driver, crucially those related to the levelized cost of hydrogen (LCoH), demonstrate highly positive trends that lead to economies of scale. In particular:
   g) Production cost of hydrogen shows a consistent downward trend this period; a significant decrease in the cost of PV and onshore wind power (close to 30%) is key driver for this development, as well a decrease in the cost of alkaline electrolysis (see also below).
   h) Storage and transportation costs are also compressed significantly; this relates to the availability of adequate underground storage facilities throughout Europe and in the Alpine region, on the one hand, and to a similarly unproblematic and cost-effective repurposing of natural gas pipelines.
   i) Private investments across the clean hydrogen value chain exceed 1 trillion between 2030 and 2050, on top of an almost equal amount for the period up to 2030. Alpine economies are included in the top destinations of clean hydrogen investments.
   j) Other factors, such as lack of disruption of global supply chains (which would otherwise have increased transport cost) and continuing, target-oriented political commitment on behalf of national governments also contribute to this optimal economic performance.

4. **Significant technological advancements**. Breakthroughs in electrolyser efficiency, as well as in storage and distribution are pivotal for the creation of economies of scale. In particular:
   e) Electrolysis technologies, especially PEM and alkaline electrolysers, are importantly improved during the 2030-2050 period. Small but critical increases in efficiency are coupled by a significant decrease (of about 30%) in the cost of these technologies.
   f) Innovations in hydrogen storage (including efficient addressing of safety considerations regarding depleted gas fields and salt caverns) and hydrogen conversion to other fuels, as well as the existence of a

pipeline network above 50,000 km across Europe importantly facilitate the rapid and successful penetration of clean hydrogen in various sectors, especially transport.

Outcomes

It is plausible to assume that this optimistic scenario will be based on the prior actualisation of the optimistic scenario for 2030: clean hydrogen technologies will have reached an adequate degree of technological readiness at all stages, but primarily regarding production (electrolysers' efficiency), EU targets on distribution infrastructure (refuelling stations) will have been met and hydrogen use in certain sectors (esp. industry and transport) will have begun. These developments are directly related to policy-related successes to attract and accelerate private investments, including crucially in R&D. Starting from such an advanced position, further technological advancements and market growth of green hydrogen will be facilitated. In effect, technological and economic developments form a virtuous circle: heightened investments in RES and electrolysers will lead to a massive increase in the scale of clean hydrogen production, which will (further) lower production costs, something that will bring clean hydrogen only second to electricity in most sectors. In this scenario, green hydrogen becomes the dominant form of hydrogen, displacing grey and blue hydrogen in the market. This scenario will enable countries and regions of the Alpine space to benefit from their aforementioned comparative advantages (a natural gas network, availability for massive underground hydrogen storage, an advanced industrial sector).

Increased Production and cost competitiveness

Increased efficiency in water electrolysis and the size of electrolysers (between 1MW - 10MW) and reduced LCOE for renewables result in a total electrolyser capacity potentially above 1000 GW throughout Europe, with certain Alpine countries being among lead producers. The cost of clean hydrogen sharply falls below 2 €/kg and is close to 1 €/kg by 2050. At this stage, production is largely based on large scale green hydrogen plants, suitably situated across Europe. Hydrogen distribution is based on a trans-European pipeline network, largely based on repurposing the existing gas pipelines, a process that will be completed by the end of this time period.

Transport

The development of a transalpine network of pipelines and refueling stations will enable the rapid penetration of clean hydrogen in the heavy-duty vehicles sector, perhaps becoming the dominant technology in this niche. Developments in passenger vehicles will be influenced by the situation in 2030 and determined by the competitiveness of fuel cell vehicles vis a vis battery-based vehicles. Train transportation is expected to have been fully electrified or be hydrogen based by 2050, representing a significant green hydrogen use case in the transport sector. The development of hydrogen corridors from ports to the European hinterland, will also benefit the Alpine region. The economies of scale that will have been achieved will enable hydrogen growth in more demanding transport sectors in the Alpine space, such as aviation and shipping.

SCENARIO 2:

Assumptions

1. **Rapid technological advancements**. Advancements in electrolyser efficiency, hydrogen conversion technologies (e.g. relevant for aviation and shipping) and hydrogen storage materialize (or seem highly possible) take place in a mode that resembles the optimist scenario.
2. **Suboptimal economic feasibility**.
   Despite the existence of an encouraging technological environment that in principle facilitates market penetration of clean hydrogen, the rate of clean hydrogen penetration at various sectors is rather slow and/or weak. Alternatively, clean hydrogen develops in a highly asymmetric way, i.e. it makes impressive gains in a limited number of sectors (e.g. in industrial heat), but has a negligible presence in other sectors. Another possibility is that at each given time during the 2030-2050 period, green H2 production is more costly (in terms of production, storage and/or transportation) in comparison to other competitive alternative energy sources and technologies; thus, it never manages to take off as a viable decarbonisation option. A further possible (stand alone or complimentary to the above) reason might be underinvestment in solar and wind power or the emergence of barriers in the process of connecting green hydrogen production and demand with RES. Possible disruption of supply chains might contribute to the rise of the transport cost; policy gaps or asymmetries possibly also contribute to a not highly supportive for investments political environment.

Outcomes

This scenario represents a combination of breakthrough technological advancements and suboptimal economic performance. The most probable prior development for this scenario is the actualisation of “scenario 2” for 2030 (i.e, a combination of breakthrough technological advancements with tepid political commitment). It is clearly an intermediate scenario; technological maturity in clean hydrogen technologies and technical readiness regarding infrastructure aspects are present, but green hydrogen use cases are limited to a number of sectors that are hard to electrify. Ambitious targets regarding investments (of over 1 trillion for this period only) in fields such as R&D and RES are only partly met, something that could result in an electrolyser capacity in the range of 500 GW across Europe and a price not below to 1.5 €/kg, something that in principle would be detrimental to the competitiveness of clean hydrogen. In this scenario, moderate market growth and difficulty to achieve economies of scale (despite an adequate level of technological readiness in 2030) in the clean hydrogen sector, means that clean hydrogen falls short of realizing its full potential in the Alpine space.

Transport

In this scenario transport application focus on heavy duty vehicles and secondarily on railway transportation. Market penetration is significant in both areas, but the market share of hydrogen-based transportation is lower compared to the previous scenario. In the Alpine space, transport sectors such as aviation and shipping remain all but outside the reach of clean hydrogen technologies.

SCENARIO 3: MODERATE GROWTH – POLICY LED DEPLOYMENT

Assumptions

1. **High economic feasibility**.
   Costs related to energy produced from solar and wind power, storage and transportation show a clear downward; moreover, national hydrogen strategies and related target-oriented policies exist across the Alpine countries and Europe at large.
2. **Moderate technological advancements**.
   Current forecasts of a significant improvement in the efficiency of electrolyser technologies fail to materialize. Alternatively, even if electrolyser efficiency is improved, limited advancements in the conversion of hydrogen (which is currently expected to enable its transportation or use in aviation) or failure to find affordable solutions to the safe underground storage of hydrogen, lead to slower than expected market penetration of clean hydrogen. Failures in the actualisation of currently forecasted technological advancements in energy production from RES will be sufficient to derail clean hydrogen production, which is heavily based on wind and solar power.

Outcomes

This scenario rests on the assumption that despite a high level of economic feasibility that characterises clean hydrogen, relative technological advancements remain moderate or very asymmetrical. Similarly, to scenario 2, clean hydrogen appears not to be an economically viable option; *however*, the main reason here is technological and/or infrastructural in character. In other words, lack of highly encouraging developments and trends in the technological sphere lead to underinvestment in clean hydrogen, despite the existence of available capitals. Lack of considerable advancements in relevant technologies and infrastructures by 2030 (i.e. "scenario 3" for that timeframe), will possibly lead to a trajectory similar to the one described here; in other words, persisting underperformance in the technological sector will lead to the actualisation of the various "conservative" scenarios of the relevant literature.

Transport

The situation in the countries of the Alpine space will resemble the above outlined picture and will be similar to scenario 2. Clean hydrogen will have a presence only in autonomous sectors of hydrogen technologies that will reach, contrary to the general trend, an adequate level of maturity or in sectors (in transport and beyond) that lack of any other alternative will lead to the adoption of clean hydrogen, despite its suboptimal technology and/or its high cost. Moreover, moderate advancements in hydrogen conversion technologies constitute an individual factor for clean hydrogen's small share in sectors like aviation and shipping. Similarly, lack of optimal technological solutions to repurposing natural gas pipelines and/or depleted gas fields prevent clean hydrogen from gaining an important share even in sectors like heavy-duty vehicles.

SCENARIO 4: PESSIMISTIC

Assumptions

1. **Moderate technological advancements**.
   In all or most of the components of this technological driver – electrolyser capacity and efficiency, technologies related to safe and efficient hydrogen storage and distribution, hydrogen conversion - results are moderate or inconsistent during this period.
2. **Suboptimal economic feasibility**.
   Primarily production cost, but possible also storage and transport cost, do not decrease enough in order to render clean hydrogen cost efficient. Lack of adequate investment levels represent a major driver behind these failures, which is in turn related to unfavourable developments in clean hydrogen technologies.

Outcomes

Scenario 4 constitutes the pessimistic scenario for clean hydrogen's position in Europe by 2050. Most probably it will be a continuation of poor developments already evident in 2030 (scenario 4), i.e. an instance of path dependence, or a failure of in-between situations (represented by scenarios 2 and 3 for) to take off after 2030. This scenario is based on the assumption that moderate technological advancements and suboptimal economic feasibility prospects for clean hydrogen create negative feedback loops. Starting from inadequate levels in technology, infrastructure and investment (government-led and private) in 2030, clean hydrogen enters the period that decarbonization efforts are expected to peak globally (in view of the 2050 landmark) from a disadvantaged position. Continued failures in cost-effective electrolysis processes keep investment risks at high levels; although improvements might take place in certain fields (i.e., the availability of storage facilities), they prove incapable of breaking this close interdependence between technological advancements in production and achieving economies of scale.

Transport

Persistently high production costs will not enable clean hydrogen to occupy a significant share, even in sectors like heavy-duty vehicles in the Alpine space. Alpine economies will, as a result, have to diverge their investment capitals to other technologies, most probably to electricity and batteries, or to non-hydrogen based fuels. In fact, better than expected developments in alternative/competing green technologies constitute a possible underlying factor that will drive this scenario in the Alpine region and throughout Europe. To the extent that decarbonization targets are attained this, of course, will have limited overall negative effects (apart from costs related to failed hydrogen investments or "sunk costs").

D. Guidelines

The outlined scenarios have as primary target to offer to H2MA partners a conceptual framework that will assist them in orientating and situating their organisations in the broader discussion regarding the use of hydrogen and the roll-out of clean hydrogen; secondarily, this framework may be used as a repository from which H2MA partners can draw selected elements and utilize certain tools in order to formulate positions, design strategies and determine actions related to the deployment of clean hydrogen in their territories.

Apart from the end outcome of the present report, i.e., the scenarios, it is suggested that various elements of the scenario-building process might be helpful to H2MA partners; hence the list of (indicative) guidelines that follows covers these areas as well.

The analysis of **partners' feedback**, presented primarily in section A:

- Provides an opportunity to partners to formulate a clear picture about each other's views and priorities, as well as the issues that each one faces regarding clean hydrogen.
- Through the ordering of factors based on their significance, it enables partners to form a common understanding of the various dimensions and variables and develop a shared focus on those factors and categories that appear more important for the roll-out of clean hydrogen.
- It provides a straightforward account on how various factors and drivers interact, thus enabling the filtering of complex and often contradicting developments and processes related to green H2 growth.
- Overall, this analysis may be treated as a common conceptual framework upon which H2MA partners may discuss experiences and issues, account for various developments and coordinate their actions within the framework of the project.

Moreover, the presentation and discussion of the **selected methodology** for scenario-building:

- Briefly discusses the concept of a "scenario", thus potentially directing partners in what to expect from and how to utilize scenarios and forecasts that appear in academic and policy papers *vis à vis* various climate change themes in general and clean hydrogen in particular.

- Provides a basic introduction to available forecasting and scenario-building methods and techniques, some of which might be pertinent for H2MA partners' present and future activities.

- Presents a qualitative method of scenario building, which constitutes a flexible and simple technique that may be used in the design of scenarios in other future projects and endeavours.

Section C of this report presents the process of building the alternative scenarios and discusses their content. **This central part of the report:**

- Offers an updated overview of key issues, core questions, policy targets and forecasts related to the development of clean hydrogen in Europe; this represents a brief mapping of the current situation and the surrounding debates, which in itself constitutes a potentially valuable tool, since the broader policy regime of clean H2 is under construction and is characterised by a certain degree of uncertainty and fluidity (e.g. the REPowerEU plan led to an upscaling of policy targets for clean hydrogen and rendered previous analyses and forecasts partially outdated).
- Discusses various parameters and features of the identified key drivers, such as examples of hydrogen-related policies and particular technological and technical aspects of clean hydrogen; these may be utilized by H2MA partners as sources not only in other activities of the project, but also in other projects and actions related to decarbonisation and the role of clean hydrogen.
- Provides a basic understanding of key priorities and developments in process in relation to clean hydrogen and presents alternative ways of their actualisation. In particular, some basic insights from the scenarios might be the following:
- The attainment of core targets related to electrolyser capacity, clean hydrogen production and hydrogen imports (initially for 2030) necessitates unprecedented efforts and rates of expansion; this represents a crucial point of convergence in policy and academic documents and should constitute a starting point in designing and implementing strategies and actions.
- Another basic point of convergence (based on REPowerEU) is that the timeframe of “greening” of hydrogen production has moved earlier, in contrast with previous discussions that implicitly or explicitly assigned a more central role to “blue” hydrogen processes.
- It appears as necessary for national and/or regional governments of the Alpine space to conclude soon their national hydrogen strategies (if not this is yet the case) and proceed to the formulation of a dedicated regulatory framework that will specify concrete actions.
- Pertinently, there is a consensus that the absolutely necessary massive private investments on clean hydrogen-related projects (throughout the

period until 2050) rely on the activation of a comprehensive set of public incentives in the short-term; adequate public funding and careful prioritization (e.g. on R & D) on behalf of public authorities are imperative at this stage.

- Another key insight that emerges from the scenarios and the related discussion is the close interaction of technological advancements and private investments; decisive steps forward in one sector (e.g. massive installment of electrolysers or upscaling of their capacity), leads to positive developments in the other (production cost reductions); vice versa, failures or gaps in one sector create risks of a broader derailment of the ambitious goals for clean hydrogen's growth.
- An accelerated rate of deploying renewable energy sources (especially wind and solar power) will not only contribute to the broader decarbonization process, but will also represent a key positive driver for clean H2 expansion.
- Regarding H2MA's particular focus, the broader policy environment and estimations of economic feasibility suggest positive prospects for clean hydrogens' penetration initially in the heavy duty vehicles and railway transportation, and subsequently in the aviation and maritime sectors; however, additional concerted efforts should be made (perhaps including at the policy level, e.g. the Alpine Convention Climate Action Plan 2.0) in relation to the role of hydrogen in rail.
- In any case, the massive use of clean-hydrogen deployment in the transport sector is by all accounts expected to happen after 2030. Although R & D, pilot and demonstration projects should materialize through national and transalpine partnerships until then, a focus in developing distribution and storage infrastructure by 2030 appears necessary. In particular, this includes the conclusion of a network of hydrogen refueling stations (at a minimum as foreseen by the recent Alternative Fuels Infrastructure Regulation), the partial repurposing of the natural gas pipeline grid and the designation of routes that will connect it to possible sites of underground hydrogen storage.

ANNEX I. 2030 partner inputs

FACTOR AREAS	2030 Partner inputs											
	KSSENA (SI)	BSC Kranj (SI)	EMS (FR)	PVF (FRA)	FLA (IT)	CMT (IT)	RL (IT)	4ER (AT)	COD (AT)	KPO (DE)	ITALCAM (DE)	***avergage score***
1 POLICY SUPPORT: GOVERNMENT-LED COMITTMENT TO GREEN HYDROGEN												2.79
Existence of national/regional strategy	3	3	3	3	3	3	3	3	3	3	3	3
Existence of specific targets for green hydrogen at a set timeframe	3	3	3	3	3	2	2	3	3	3	3	2.81
Existence of specific targets for Renewable Energy Sources (RES) in the energy mix	3	3	3	3	3	2	2	3	3	3	3	2.81
Existence of incentives for the uptake of green hydrogen (e.g. fiscal incentives)	3	3	3	3	2	3	3	3	3	3	3	2.90
Government-backed guarantees (e.g., long-term revenue certainty)	2	3	3	3	3	2	2	2	2	3	3	2.54
Establishment of quality and security standards	3	3	3	3	3	3	3	3	3	2	2	2.81
Streamlined permitting and approval processes	2	3	2	2	3	3	3	3	3	3	3	2.72
Simplified administrative procedures	3	3	2	2	3	3	3	3	3	3	2	2.72
OTHER: **KSSENA** (Common form and concept of all national hydrogen strategies, dictated by the EU: 3 / Developmemt of KPI's of national hydrogen strategies by EU: 3 / The EU should prescribe a precise procedure for developing a strategy and measuring KPIs: 3) **BSC Kranj** (European directive for standards on duties and taxes: 3) **EMS + PVF** (Developing uses with local authorities and ecosystems: 3 / Having more visibility of the vehicle market offer: 3 / Policy to support H2 specialist education: 3 / Policy to support research and innovation: 3)												

FACTOR AREAS	KSSENA (SI)	BSC Kranj (SI)	EMS (FR)	PVF (FRA)	FLA (IT)	CMT (IT)	RL (IT)	4ER (AT)	COD (AT)	KPO (DE)	ITALCAM (DE)	***avergage score***
2 ECONOMIC FACTORS												2.55
Cost of hydrogen production (electrolysis from RES)	1	3	3	3	3	3	3	3	3	3	2	2.72
High-efficiency electrolysers (resulting in cost-effective hydrogen production)	2	3	2	2	3	3	3	3	3	2	2	2.54
Cost of transport and distribution	3	3	2	2	3	2	2	3	3	2	2	2.45
Capital costs	1	3	2	2	2	2	2	3	3	2	2	2.18
Operational costs (incl. maintenance)	1	3	2	2	2	2	2	3	3	1	3	2.18
Government-led financial support	3	3	3	3	3	3	3	3	3	3	3	3
Private investments and financing opportunities	2	3	3	3	3	3	3	3	3	2	3	2.8
OTHER: **KSSENA** (Education of private individuals and third parties by the state on the roll-out of hydrogen technologies: 3) **BSC Kran**j (Equal opportunities, competitive market:3)												
3 TECHNICAL FACTORS												2.81
Technological advancements in green hydrogen production	3	3	3	3	3	2	2	3	3	2	3	2.72
Technological advancements in hydrogen storage technologies	3	3	3	3	2	2	2	3	3	2	3	2.63
Development of hydrogen production infrastructure	3	3	3	3	2	3	3	3	3	3	3	2.90
Development of hydrogen distribution infrastructure	3	3	3	3	2	3	3	3	3	3	3	2.90
Development of hydrogen storage infrastructure	3	3	3	3	3	3	3	3	3	2	3	2.90
OTHER: **BSC Kranj** (High safety standards: 3 / Measurement monitoring standards and independent monitoring, efficient and swift fineing system: 3) **EMS + PVF** (Progress made in competing technologies (like electric batteries): 2) **4ER + COD** (Development of infrastructure for hydrogen imports: 3)												

FACTOR AREAS	KSSENA (SI)	BSC Kranj (SI)	EMS (FR)	PVF (FRA)	FLA (IT)	CMT (IT)	RL (IT)	4ER (AT)	COD (AT)	KPO (DE)	ITALCAM (DE)	***avergage score***
4 INTERNATIONAL FACTORS												2.36
Geopolitical tensions (e.g. Russia's invasion in Ukraine)	1	2	2	2	3	3	3	3	3	2	3	2.45
Trade and supply chains disruptions	2	2	2	2	2	2	2	3	3	2	2	2.18
Disparities in standardisation and certification process	2	3	3	3	2	2	2	2	3	2	3	2.45
Changes in Climate change targets	1	3	3	3	3	2	2	2	3	2	2	2.36
International/transnational agreements	1	2	3	3	3	2	2	3	3	2	2	2.36
OTHER: KSSENA (Financial crisis periods (the impact of the current general inflation in EU):3)												

5 PUBLIC ACCEPTANCE												2.06
Awareness on climate change	2	1	2	2	3	3	3	2	3	2	3	2.36
Customer demand for climate friendly products	1	1	2	2	3	2	2	3	2	1	3	2
Gaining a social license for operation	2	1	1	1	2	1	1	3	3	1	3	1.72
Support from public (incl. civil society)	2	1	1	1	3	3	3	3	3	1	3	2.18

ANNEX II. 2050 partner inputs

FACTOR AREAS	**2050 Partner inputs**											
	KSSENA (SI)	BSC Kranj (SI)	EMS (FR)	PVF (FRA)	FLA (IT)	CMT (IT)	RL (IT)	4ER (AT)	COD (AT)	KPO (DE)	ITALCAM (DE)	***avergage score***
1 POLICY SUPPORT: GOVERNMENT-LED COMITTMENT TO GREEN HYDROGEN												2.38
Existence of national/regional strategy	1	3	3	3	3	3	3	2	2	3	3	2.63
Existence of specific targets for green hydrogen at a set timeframe	2	3	3	3	3	3	3	2	2	3	2	2.63
Existence of specific targets for Renewable Energy Sources (RES) in the energy mix	1	3	3	3	2	2	2	2	2	3	3	2.36
Existence of incentives for the uptake of green hydrogen (e.g. fiscal incentives)	1	1	3	3	1	3	3	2	2	3	1	2.09
Government-backed guarantees (e.g., long-term revenue certainty)	1	1	3	3	3	2	2	2	2	3	3	2.27
Establishment of quality and security standards	3	3	2	2	3	3	3	3	3	2	1	2.54
Streamlined permitting and approval processes	2	3	2	2	2	2	2	3	3	3	1	2.27
Simplified administrative procedures	2	3	2	2	2	2	2	3	3	3	1	2.27

OTHER: **KSSENA** (Common form and concept of all national hydrogen strategies, dictated by the EU: 1 / Developmemt of KPI's of national hydrogen strategies: 3) **EMS + PVF** (Developing uses with local authorities and ecosystems: 2 / Having more visibility of the vehicle market offer: 2 / Policy to support H2 specialist education: 3 / Policy to support research and innovation: 3)

FACTOR AREAS	KSSENA (SI)	BSC Kranj (SI)	EMS (FR)	PVF (FRA)	FLA (IT)	CMT (IT)	RL (IT)	4ER (AT)	COD (AT)	KPO (DE)	ITALCAM (DE)	***avergage score***
2 ECONOMIC FACTORS												2.59
Cost of hydrogen production (electrolysis from RES)	3	3	3	3	3	3	3	3	3	3	2	2.90
High-efficiency electrolysers (resulting in cost-effective hydrogen production)	3	3	3	3	3	3	3	3	3	2	1	2.72
Cost of transport and distribution	3	3	3	3	3	3	3	3	3	2	2	2.81
Capital costs	2	3	3	3	2	1	1	3	3	2	1	2.18
Operational costs (incl. maintenance)	3	3	3	3	2.5	2	2	3	3	1	3	2.59
Government-led financial support	3	1	2	2	1	3	3	2	2	3	1	2.09
Private investments and financing opportunities	2	3	3	3	3	3	3	3	3	2	3	2.81
OTHER: **KSSENA** (Education of private individuals and third parties by the state on the roll-out of hydrogen technologies: 1)												
3 TECHNICAL FACTORS												2.65
Technological advancements in green hydrogen production	3	3	3	3	3	2	2	3	3	1	3	2.63
Technological advancements in hydrogen storage technologies	3	3	3	3	3	2	2	3	3	2	1	2.54
Development of hydrogen production infrastructure	2	3	3	3	3	3	3	3	3	1	1	2.54
Development of hydrogen distribution infrastructure	1	3	3	3	3	3	3	3	3	3	1	2.63
Development of hydrogen storage infrastructure	3	3	3	3	3	3	3	3	3	2	3	2.90
OTHER: **KSSENA** (State regulation of the price of altenative fuels,including hydrogen: 3 / Ensuring lower prices for locally produced hydrogen - State and EU regulation: 3) **EMS + PVF** (Progress made in competing technologies (like electric batteries): 3) **4ER + COD** (Development of infrastructure for hydrogen imports: 3)												

FACTOR AREAS	KSSENA (SI)	BSC Kranj (SI)	EMS (FR)	PVF (FRA)	FLA (IT)	CMT (IT)	RL (IT)	4ER (AT)	COD (AT)	KPO (DE)	ITALCAM (DE)	***avergage score***
4 INTERNATIONAL FACTORS												2.47
Geopolitical tensions (e.g. Russia's invasion in Ukraine)	2	1	3	3	3	2	2	3	3	2	3	2.45
Trade and supply chains disruptions	3	3	3	3	2	2	2	3	3	2	3	2.63
Disparities in standardisation and certification process	3	1	2	2	3	3	3	3	3	2	3	2.54
Changes in Climate change targets	3	3	2	2	3	2	2	2	2	2	2	2.27
International/transnational agreements	3	3	2	2	3	2	2	3	3	2	2	2.45
OTHER: **KSSENA** (Financial crisis periods (the impact of the current general inflation in EU):3)												
5 PUBLIC ACCEPTANCE												1.61
Awareness on climate change	2	1	1	1	3	2	2	1	1	2	3	1.72
Customer demand for climate friendly products	2	1	1	1	2	2	2	1	1	1	3	1.54
Gaining a social license for operation	2	1	1	1	2	1	1	1	1	1	3	1.36
Support from public (incl. civil society)	2	1	1	1	3	2	2	2	2	1	3	1.81