DEVELOPMENT GUIDELINE FOR LOCAL ALPINE GREEN HYDROGEN ECOSYSTEM

Capitalization of local Alpine green H_2 ecosystem

Interreg
Alpine Space

Co-funded by the European Union

AMETHyST

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1 INTRODUCTION

The transition to green hydrogen (H_2) represents a key opportunity for sustainable energy development in Alpine regions. However, there are some considerations to take into account. While hydrogen is often presented as a cornerstone of the sustainable energy transition, its production from renewable sources still faces high costs and unmet technological challenges. Without careful planning, H_2 projects could become inefficient investments rather than true solutions for decarbonization.

Hydrogen can be produced in multiple ways. As a matter of fact, out of roughly 230 Mt produced annually at global level, more than 95% is produced through Steam Methane Reforming (SMR), a process that uses methane gas both as a raw material and as an energy source. This process involves an emission ranging between 7.5 and 12 kg of CO_2 per kg of hydrogen produced [1, 2, 3]. In 2023, this process was responsible for the emission of 920 Mt of CO_2 [4]. This type of hydrogen is mainly used for the production of fertilizers.

The focus of AMETHyST INTERREG Project are Alpine valleys, where hydrogen can play a strategic role only where electrification is not a viable option. This means that H_2 should be considered primarily for sectors or areas where direct electrification is impossible, this is where investment flows should be channelled. For all other applications, electrification remains the priority as it is more efficient and economically sustainable.

It is also crucial to acknowledge that hydrogen has a low overall efficiency from production to final use. The conversion losses at each stage of the process result in a well-to-wheel efficiency often below 30%, and maintaining even this level requires highly optimized systems. As we move towards a cleaner energy system, we must ensure that the transition does not lead to an even less efficient energy landscape. Thoughtful planning, technology readiness and a clear strategic vision are essential to integrating hydrogen where it truly makes sense, at the same time avoiding unnecessary energy and financial waste.

This document provides a step-by-step methodology to guide the design, experimentation and assessment of green H_2 applications in Alpine contexts.

The methodology begins with an assessment of the local ecosystem, analyzing the availability of renewable energy sources, potential hydrogen demand and production capacity. It then focuses on the process flow, distinguishing key stages and evaluating the environmental and social impacts of H_2 deployment.

In the design phase, the methodology focuses on aligning production with demand, selecting the most suitable technologies, and conducting a techno-economic feasibility study to ensure long-term viability.

These guidelines build upon evidence from pilot testing carried out as part of project activities and provide a solid foundation for scaling up green H_2 solutions across different Alpine regions. The methodology is particularly valuable for public authorities (PAs) and H_2 project developers, facilitating informed decision-making and strategic planning.

2 ASSESSING GREEN H_2 ALPINE ECOSYSTEMS

In this first phase, the main characteristics of the territory are identified for the development of hydrogen ecosystems to determine the actual feasibility of the project and ensure a rational use of resources. This step is fundamental to avoid ineffective investments and to ensure that hydrogen is used only where it represents the most efficient solution compared to direct electrification.

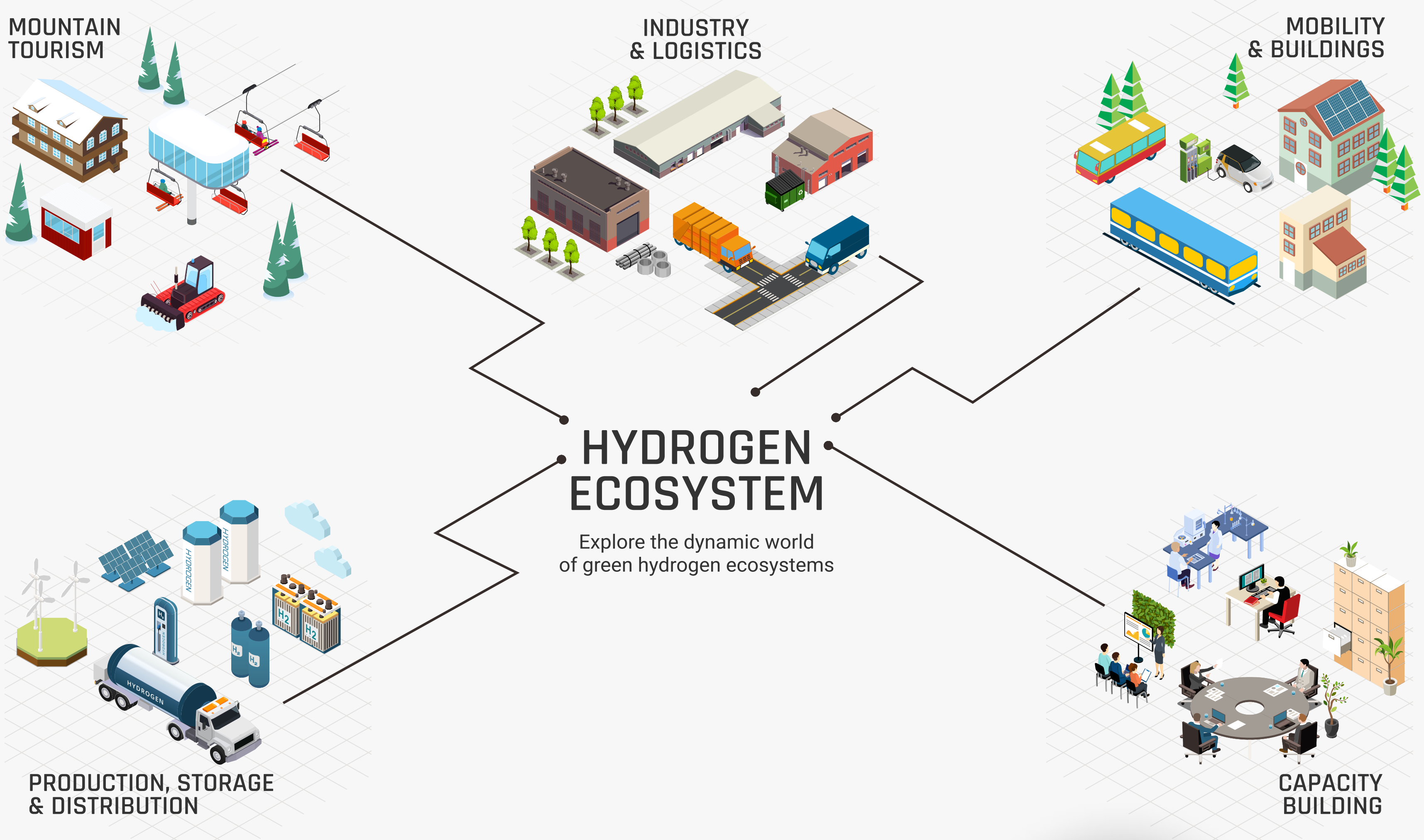
For the energy transition to be successful, it is necessary to exploit the potential of the territory and understand if it is suitable for the solution under examination, rather than imposing models from above, creating processes that over time invariably prove unsustainable, both economically and environmentally.

The potential analysis is structured in different levels:

- **Identification of the alpine reference region.**
- **Analysis of existing and available renewable energy sources:** the availability and potential of local energy production from renewable sources (photovoltaic, wind, hydroelectric, biomass) are analyzed to ensure that hydrogen production is truly green and sustainable.
- **Assessment of local hydrogen demand:** sectors and applications where hydrogen can be consumed are identified, for example in heavy transport, industrial processes difficult to electrify, or in isolated contexts where electrification is not feasible.
- **Evaluation of the energy network structure:** the local electricity grid is analyzed to understand if the available renewable energy is more effectively usable directly or if storage in the form of hydrogen is necessary to manage production surpluses or specific needs.
- **Analysis of hydrogen production potential:** it is assessed how much hydrogen could be produced locally compared to energy availability and existing or planned infrastructures.
- **Assessment of environmental and social impact:** in addition to technical aspects, it is essential to evaluate the ecological and social consequences of an H_2 ecosystem in the territory, ensuring that it is truly sustainable and accepted by the local community.

This preliminary phase allows to establish if hydrogen is a sensible choice for the considered territory or if other decarbonization strategies are more appropriate. An in-depth evaluation avoids waste of resources and allows to develop targeted projects, with a concrete and sustainable impact.

The image below highlights the key features of a hydrogen ecosystem. An interactive infographics can be found here https://skhyline.eu/.



Source: https://skhyline.eu/

IDENTIFICATION OF THE ALPINE REFERENCE REGION

The first step is the identification of the reference region, in terms of the territorial coverage considered beyond a purely political or geographical meaning. The modalities can be different depending on the context: the delimitation can be carried out according to geographical, boundary, population, etc. reasons. Beside the motivations and parameters taken into account, on the delimitation of the context depend the parameters to define a project that is sustainable in technical, economic, social and environmental terms.

RENEWABLE RESOURCES POTENTIAL

The European Commission has adopted a strategy that defines the conditions under which hydrogen, hydrogen-based fuels, and other energy carriers can be considered renewable fuels of non-biological origin 1 (RFNBO). These acts clarify the application of the additionality principle and entered into force on July 10, 2023.

The additionality principle for renewable hydrogen is defined in the EU Delegated Acts on Renewable Hydrogen - adopted in June 2023 - and provides for a gradual implementation. The implementation process foresees an initial transitional phase for projects starting before January 1, 2028, whereby the additionality requirements will be applied with flexibility. During this period, producers will be able to align hydrogen production with renewable sources on a monthly basis. Full implementation will be in force from January 1, 2030, when additionality will become stringent, requiring a more rigorous temporal match (likely hourly or daily). Member States may anticipate stricter rules as early as July 1, 2027.

The principle is applied through three main criteria:

ENERGY SOURCES:

- Electrolyzers must use electricity produced from new renewable plants (not existing at the start of the project).
- Permitted alternatives:
  - Connection to an electricity grid with ≥90% renewable energy on an annual average.
  - Emissions lower than 18 gCO_2eq/MJ (approximately 56 gCO_2/kWh).

TEMPORAL AND SPATIAL CORRELATION:

- Temporal: Renewable energy must be generated in the same period (hour/day/month) in which the electrolyzer operates.
- Spatial: Production must take place in the same electricity market zone (bidding zone) or in interconnected offshore zones.

CONTRACTUAL INSTRUMENTS:

- Power Purchase Agreements (PPA) with new renewable plants.
- Direct self-production of renewable energy.
- Until 2030, a monthly correlation between hydrogen production and renewable sources is allowed. For projects started before 2028, the use of grid electricity is allowed provided it is compensated by new renewable PPAs in the same Member State.

This framework aims to ensure that growing renewable hydrogen supplies are connected to new, rather than existing, renewable energy production, incentivising an increase in the volume of renewable energy available in the EU.

Based on this assumption, it is important to identify the renewable sources most present in the territory, or rather, those most available.

Once the system boundaries are known, the potential of renewable sources in the territory is analysed. A brief list of potential sources typical of alpine realities is provided below.

WOOD BIOMASS: this is among the most available sources in the alpine territory. Despite its diffusion and the increase in forest surface coverage in some territories, a realistic estimate of the biomass retrievable with sustainable land management is anything but simple. Given the current exploitation for heating purposes and the low yields for electrical conversion by combustion, hydrogen production by electrolysis based on this source is absolutely discouraged. Rather, technological advancements in hydrogen production by pyrolysis and gasification (TRL 5-6) are currently being explored.

PHOTOVOLTAIC: although this source is not favoured in the alpine environment given the limited productivity due to less insolation compared to lowland territories, new generation photovoltaics (especially bifacial solar panels) leave room for interesting solutions and up until a few years ago definitely less convenient. Other solutions that distribute production by mitigating production peaks in the central hours, rather than maximizing annual productivity, can be interesting. Redistributing production in the morning (east exposure) and evening (west exposure) can also be interesting. The JRC page is a good reference for evaluations in terms of production forecast of any new plant.

HYDROELECTRIC: although the diffusion of this source in the alpine environment is the first in importance for electricity production, alpine territories are often already widely saturated in terms of hydroelectric production plants. It is therefore advisable to evaluate any surpluses in existing plants, using them in hydrogen production rather than for grid injection. From an economic sustainability point of view, this possibility must be carefully evaluated, comparing the possible benefits of hydrogen production with direct sales to the electricity grid. In the case of installation of new plants, it is important to consider the requirements for the compliance with environmental standards and the minimum flow of the watercourse, especially considering the local variation of rainfall regimes due to climate change. In the case of basin plants, especially where pumping is possible, their use for hydrogen production is discouraged, it is rather recommended the exploitation for the storage capacity and therefore the mitigation of demand peaks.

WIND: although this source is not as widespread as the previous ones in the alpine environment, its use for renewable hydrogen production is not to be excluded. This is even more valid in terms of coupling it with photovoltaics, these sources are often complementary both in terms of hourly and seasonal production. The following pages are useful references for evaluating the production forecast of new plants at European and global scale.

IDENTIFY THE POTENTIAL DEMAND

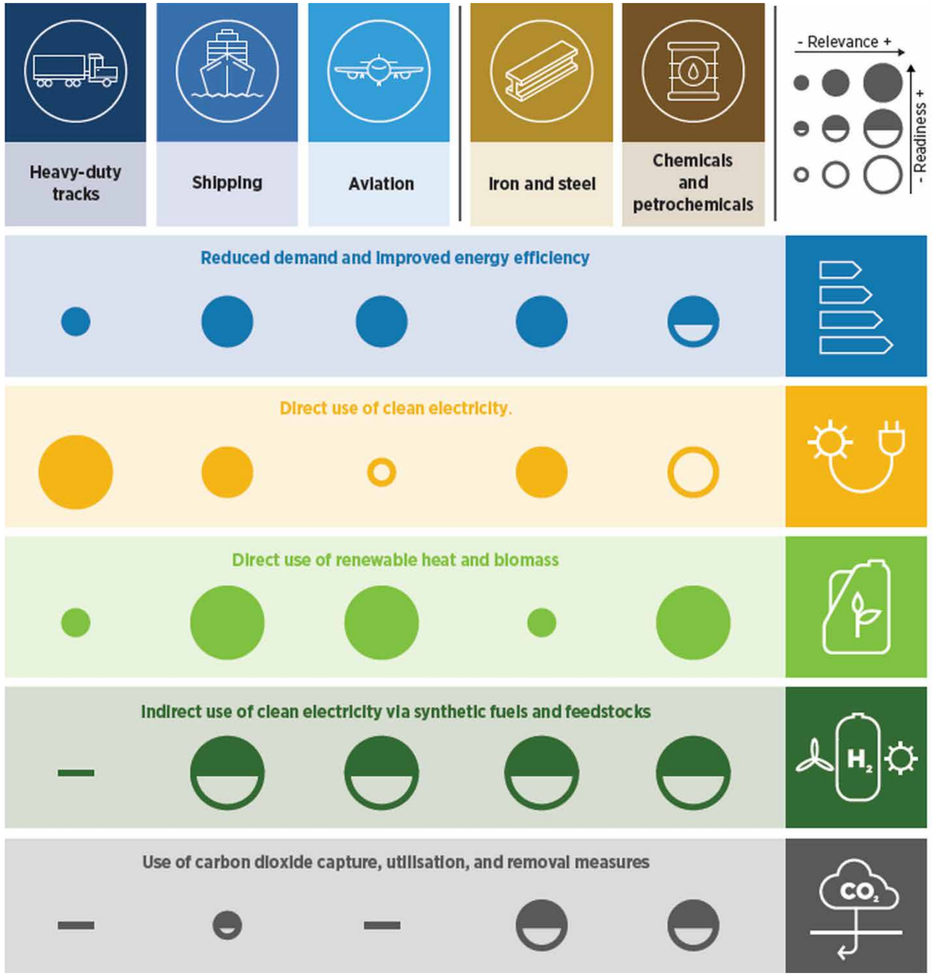
Another key aspect is the definition of potential demand is namely, what are the potential uses of hydrogen in the identified context? As previously emphasized, it is crucial to identify demand in applications and services where electrification is not feasible, given the lower efficiency of hydrogen compared to direct electricity use [5].

Some examples of applications are listed below:

- Heavy transport on rugged or steep terrains
- Industries requiring high-temperature heat
- Use of heavy vehicles for tourism-related applications (e.g. snow groomers)

The use of hydrogen for domestic heating is generally discouraged due to the low overall efficiency of the green hydrogen production-to-use chain, particularly when assessed from an exergetic or second-law efficiency perspective. The multiple conversion steps involved — from electricity to hydrogen and back to thermal energy — result in significant exergy losses, making direct electrification or alternative renewable solutions markedly more efficient. It is therefore necessary to identify hard-to-decarbonize sectors in the region and evaluate potential uses of hydrogen compared to other carbon free technologies, especially within respect a potential electrification. It's useful to estimate the potential demand in terms of quantity and, where possible, thermodynamic conditions (particularly the state of aggregation and operating pressure of the devices). These parameters are fundamental in assessing the upstream process.

Image taken from IRENA Technical Report, 2024 [6].



Summary of the key technological pathways and readiness assessment for selected sectors

HOW TO LINK PRODUCTION AND DEMAND?

Once the production and utilization potentials have been identified, supply and demand must be cross-referenced. A first estimate must be made in quantitative terms, evaluating annual production and annual demand. Priority is given to the availability of electricity for hydrogen production, the main driver for determining production. If demand is lower than production, it is advisable to deepen the economic evaluation to optimize the size of renewable plants and ensure their economic/financial sustainability.

Further qualitative analysis must be conducted, namely evaluating production in seasonal terms. In the case of PV plants, production will be higher in summertime, for wind power it will be the opposite. In terms of demand, does it have a recognized peak? Or is it constant throughout the year?

The greater the decoupling between production and demand, the greater the need for storage, which will lead to an increase in the cost of the entire production system.

POTENTIAL ENVIRONMENTAL AND SOCIAL IMPACT

When developing a green hydrogen ecosystem and within the analysis of the context, human activity and environmental and social challenges need to be assessed.

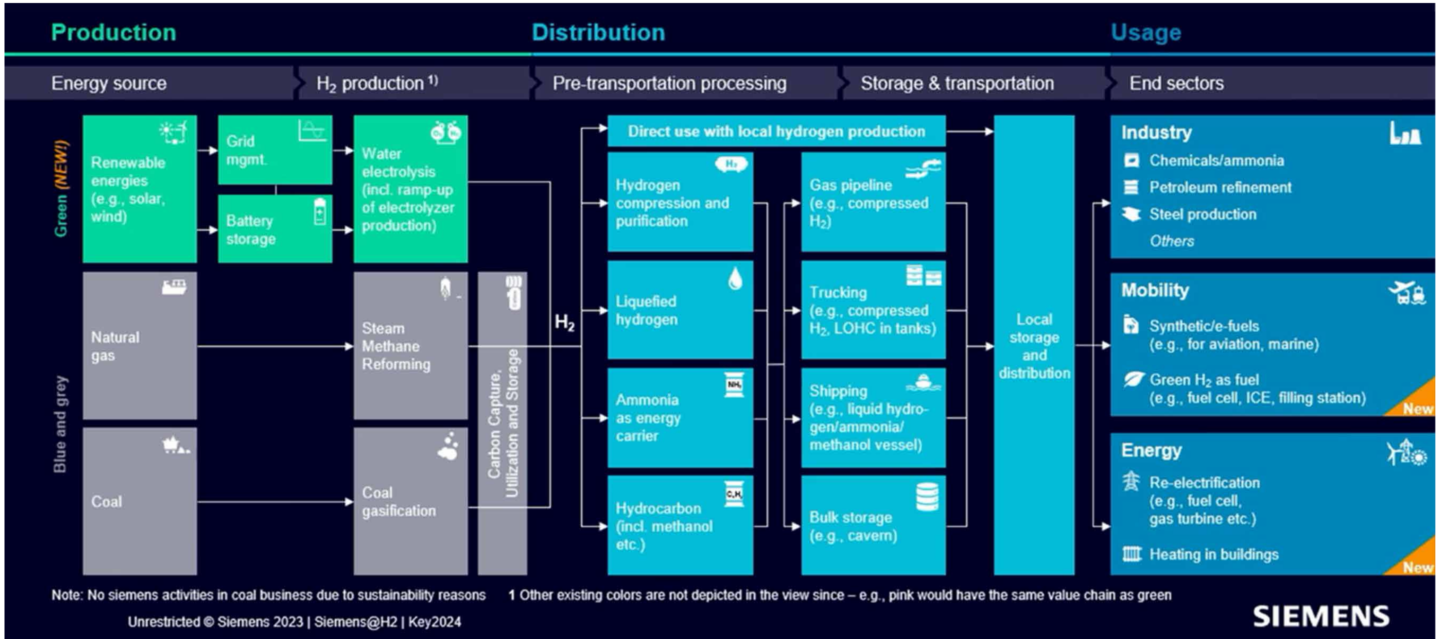
1. At the social level, community engagement is crucial to avoid NIMBY (Not In My Backyard) phenomena, which are increasingly common today. Public acceptance is vital for the successful implementation of hydrogen projects, as local opposition could delay or derail initiatives. Transparent communication about the benefits of hydrogen, such as reduced emissions and improved air quality, alongside addressing concerns about safety, environmental impact, and resource use, is key to winning public support.

2. From an environmental perspective, the production and use of hydrogen must be carefully managed to minimize ecological footprints. For instance, while hydrogen can decarbonize hard-to-abate sectors like heavy transport and high-temperature industrial processes, its production must rely on renewable energy sources to avoid shifting emissions upstream. Additionally, the infrastructure for hydrogen storage and distribution should be designed to minimize land use and visual impact, particularly in sensitive alpine environments.

3. One controversial issue could be related to water usage [7]. For example, in the case of hydrogen use in ski resorts, the water required for hydrogen production would add to the water already needed for artificial snow production. It is estimated that producing one kilogram of hydrogen requires 30-50 liters of water [8]. This could exacerbate water scarcity issues, particularly in alpine regions where water resources may already be under stress due to climate change and high demand for tourism-related activities.

UNDERSTAND THE PROCESS FLOW

The last step of this preliminary process is the visualization of the various stages in technical terms: production, storage, transport, utilization. Each of these phases involves specific infrastructures, which are currently quite expensive. For the optimization of the entire process, it is necessary to visualize the linkages already in the preliminary phases. Moreover, it is essential to engage all relevant stakeholders and foster dialogue, knowledge exchange and consultation, especially with regard to production and utilization. The main driver is, in fact, the demand for fuel. Last but not least, it is helpful to verify the possible sources of funding and incentives. The following image is taken from the presentation at Key Energy 2024, "Un partner tecnologico e affidabile lungo la catena del valore dell'idrogeno", from Valentina Dondi, Sales Director Chemical O&G Vertical market, Siemens Spa.



Production of green hydrogen and usage in industry, mobility, and energy as emerging elements in the hydrogen value chain

3 DESIGN GREEN HYDROGEN ALPINE ECOSYSTEMS

The focus is now on choosing the most suitable technologies for the identified ecosystem. Even though hydrogen technology is undergoing rapid growth and market adaptation, the supply chain is not fully mature yet. This inevitably impacts on the costs of the associated technologies. Costs can vary greatly depending on the technology selected even within the same process phase, and it is often difficult to make deterministic evaluations on technical parameters due to the lack of data in the literature. The reason is that many technologies have not been tested yet for long periods of time under prolonged stress conditions. In many cases, it is necessary to make reference to scientific publications to keep up with the evolution of hydrogen technologies.

The key point is that one technology is often not worth the other in terms of costs/benefits, and it is very difficult to maintain adequate sustainability criteria without considering the ecosystem as a whole and not in separate compartments. For example, compressing hydrogen to 500 or 1000 bar downstream of the electrolyzer, entails a significant difference in terms of costs and efficiency for the entire process.

COUPLE DEMAND WITH PRODUCTION

As already mentioned, the first step to be taken is the coupling between supply and demand.

The more the production of hydrogen coincides in temporal terms (on different scales: seasonal, monthly, daily) with the consumption needs of users, the more the 'downtime' is reduced, but above all the size of storage is reduced, which can have a significant impact on the final CAPEx, if poorly sized. These considerations are taken into account in the evaluation of logistics and transport.

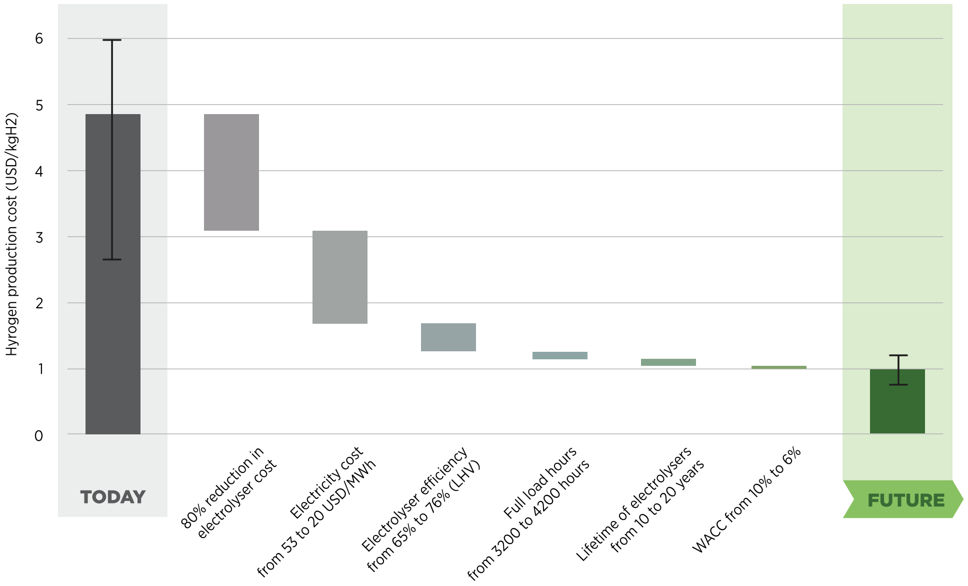
In other words, matching supply and demand should be inherent to early stages of the renewable generation plant design. It is evident that the same reasoning does not apply for already existing plants. In this case, it should be evaluated whether the investment in terms of hydrogen production is convenient compared to the injection of electricity into the grid.

The integration of other production plants/consumption users that are not localized in the considered area should be assessed on a case-by-case basis. It is evident how minimizing the distance decreases transport costs, both in energy and economic terms.

The graph below indicates an exploded view of the production-side costs to be considered in qualitative terms.

Following image taken from IRENA Technical Report, 2020 [9].

A combination of cost reductions in electricity and electrolysers, combined with increased efficiency and operating lifetime, can deliver 80% reduction in hydrogen cost.

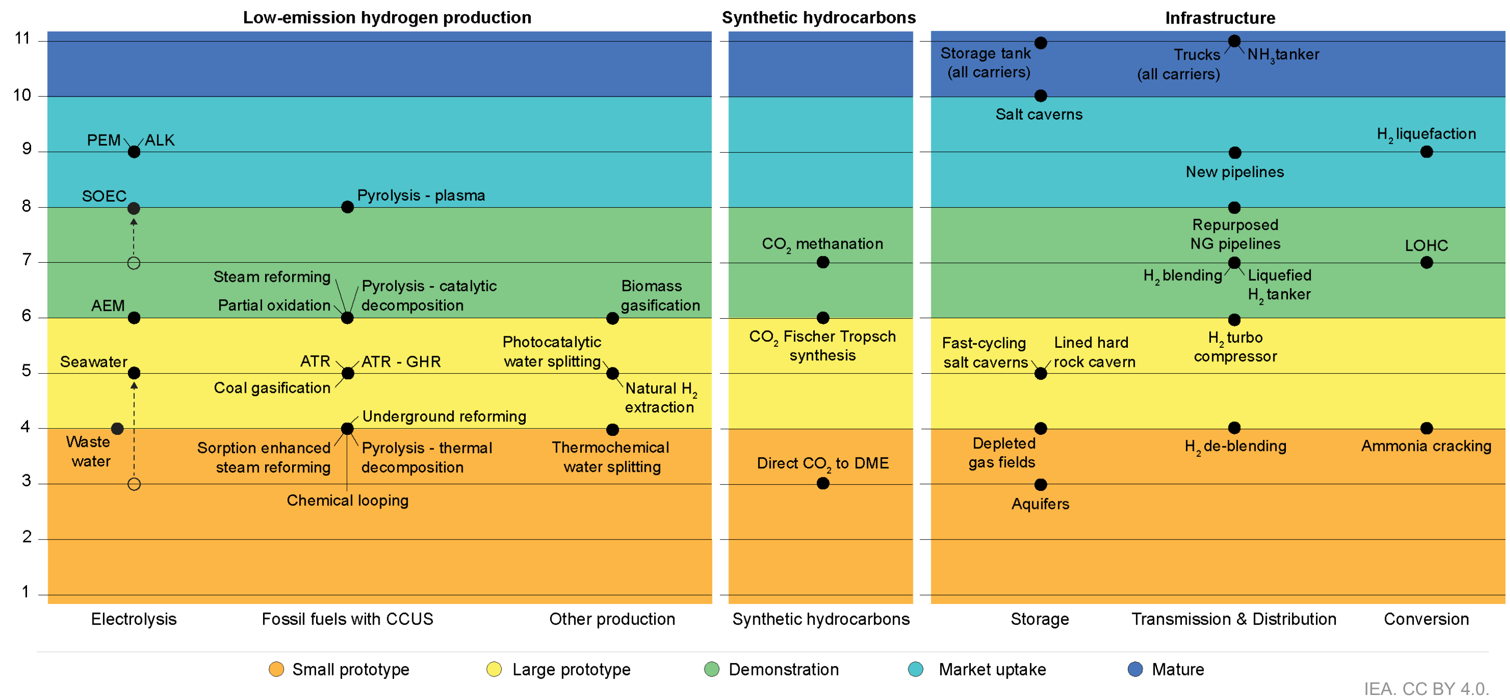


Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

SELECT THE MOST SUITABLE TECHNOLOGIES

Moving on to the selection of the technology, the choice depends on the characteristics of the plant. Firstly, it is essential to be up-to-date with the technological advancements in the field. Secondly, selecting a market-ready technology is a precondition for a successful project. The ability of evaluating the maturity level of technologies on the market is as valuable as thorough planning. The following image is taken from the [IEA (International Energy Agency) website](#).

Technology readiness levels of production of low-emission hydrogen and synthetic fuels, and infrastructure



Notes: AEM = anion exchange membrane; ALK = alkaline; ATR = autothermal reformer; CCUS = carbon capture, utilisation and storage; CH_4 = methane; DME = dimethyl ether; GHR = gas-heated reformer; LOHC = liquid organic hydrogen carrier; NH_3 = ammonia; PEM = proton exchange membrane; SOEC = solid oxide electrolyser cell. Biomass refers to both biomass and waste. Arrows show changes in technology readiness level as a consequence of progress in the past year. For technologies in the CCUS category, the technology readiness level refers to the overall concept of coupling production technologies with CCUS and high CO_2 capture rates. Pipelines refer to onshore transmission pipelines. Storage in depleted gas fields and aquifers refers to pure hydrogen and not to blends. LOHC refers to hydrogenation and dehydrogenation of liquid organic hydrogen carriers. Ammonia cracking refers to low-temperature ammonia cracking. Technology readiness level classification based on [Clean Energy Innovation (2020)](#).

Sources: [IEA Clean Tech Guide (2023)](#); IEA Hydrogen Technology Collaboration Programme.

ELECTRIC ENERGY SUPPLY

The supply methods can be of different types:

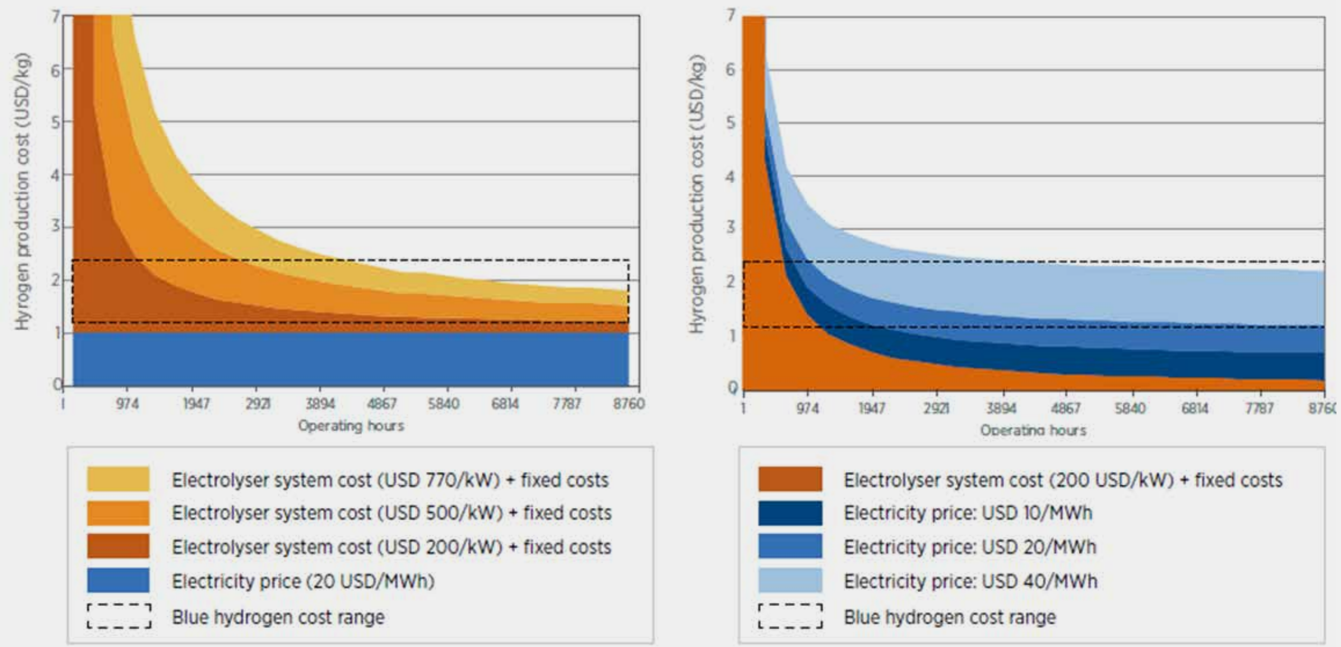
RENEWABLE PLANT + GRID CONNECTION (PPA): in this case the supply costs, which vary from day-to-day, will have to be evaluated. Therefore, convenience forecast estimates will be necessary compared to the hourly cost of energy. If the objective is to maximize financial and economic parameters, it should be evaluated which are the time intervals when hydrogen production is convenient compared to the transfer of energy to the grid. If, on the other hand, the objective is to maximize hydrogen production, the tendency will be to consume all self-produced energy with a convenience evaluation compared to the purchase of electricity from the grid. Following these evaluations, the use of electrical storage can also be considered.

ISLAND PLANT: the objective is to maximize self-consumption. It is recommended to use a suitably sized battery for minimum daily storage of electricity. Usually, optimization is carried out by identifying the intersection point between the self-consumption and Capacity Factor (CF) curves. For the first case, the trend is monotonically increasing with the size of the electrolyzer, while for the second, the CF curve is usually monotonically decreasing. This parameter is identified as energy used for hydrogen production / energy potentially producible by the electrolyzer in the year [electrolyzer size x 8760].

GRID CONNECTION ONLY (PPA): mainly economic-financial evaluations are considered. This last case is strongly discouraged, both for the dependence on the electrical system and for the introduction of the additionality principle mentioned previously.

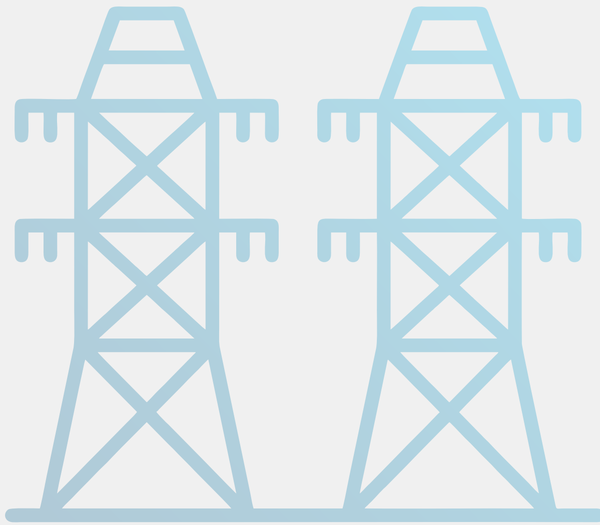
Influence of the Capacity Factor on the cost of hydrogen production; qualitative indication. The following image is taken from IRENA Technical Report, 2020 [9].

Hydrogen production cost as a function of investment, electricity price and operating hours.



Note: Efficiency at nominal capacity is 65% (with an LHV of 51.2 kWh/kg H_2), the discount rate 8% and the stack lifetime 80 000 hours.

Based on IRENA analysis.



HYDROGEN PRODUCTION

Water electrolysis remains the most mature and promising technology for producing renewable hydrogen from non-carbon sources. It involves the use of electrolyzers, i.e. devices that use electrical energy to dissociate the hydrogen and oxygen atoms of the water molecule. These electrolyzers can be of different types: AWE (Alkaline Water Electrolyzer), PEM (Proton Exchange Membrane), AEM (Anion Exchange Membrane), and SOEC (Solid Oxide Electrolyzer Cell). For the first three, more technologically mature, the energy requirement for the production of one kg of hydrogen is between 50 and 65 kWh of electricity. Since the calorific value of hydrogen is 33.3 kWh/kg, the electrolysis process has an efficiency (of the first principle) around 55-70%. Solid oxide electrolyzers, unlike the previous ones, operate at high operating temperatures (600°C-900°C), allowing the splitting of steam into hydrogen and oxygen, through the use of a solid oxide ceramic membrane.

The cost of hydrogen production technologies today is still very high, the setup of a hydrogen production plant involves high investment (CAPEX) and non-negligible operating (OPEX) costs. Just think of the component related to electrical energy: assuming a cost of 0.15 €/kWh, it is noted that for the sole production of one kg of hydrogen, more than 8 € are spent with the solutions existing today.

The result is that the current cost estimate for one kg of green hydrogen produced is much higher than the 2-3 €/kg for fossil-derived hydrogen, under optimal conditions. This price plays a heavy role and makes incentives necessary to have a minimum of competitiveness in the market. To make the investment more appealing, utilization factors play an important role: in the case of grid balancing, these hardly exceed 20%, a very low value that strongly compromises the economic sustainability of the investment. Thinking of an electrolyzer coupled to a photovoltaic plant dedicated to it (and in the absence of a battery), the hours of use are about 2,000 per year, making the cost of capital a critical parameter to address [9].

Taking into consideration the technical side, the different electrolyzer technologies present different behaviors with respect to variations in intensity and frequency of the electric energy input. In general, all of them undergo frequent on and off. These have an impact on the efficiency of the device both during operation and at the life cycle level. The point is that, considering the whole life cycle, it is difficult to give a weight to the loss of efficiency as a function of the number of shutdowns, mainly due to the lack of data covering the entire life cycle and to the novelty of the technologies (in order of maturity: AWE, PEM, AEM and SOEC [10]).

Moreover, the on and off times vary according to the technology. For a PEM, the shutdowns can last for some minutes, for an alkaline ten of minutes, for a SOEC up to an hour [9, 11]. It is evident that for a balanced use, or to mitigate overgeneration/curtailment, there are many variables to factor in and the existing technologies must be further deployed. For this use, the SOEC is certainly the least suitable type of electrolyzer for the reasons already mentioned.

Similar considerations apply for variations in terms of input energy and frequency changes. Also in this case, the most suitable type for variable loads and frequency response (Fast Frequency Response) would be PEMs. However, the production methods and the quality of the product must be carefully evaluated directly with the supplier and on a case-by-case basis. Besides the operating conditions, mainly pressure and temperature, the quality of the electrodes and stacks can make a difference. Certainly, a battery can reduce these problems by increasing the useful life of the product (as well as the utilization factor in the case of production from intermittent RES plants), albeit adding a non-negligible cost to the system [11, 12, 13].

Again, more data and information are needed to assess the degradation caused by non-stationary uses depending on the technology and the conditions of use.

Do not forget to check on the purity of the hydrogen released by the electrolyzer: a critical parameter for its various applications. In fuel cells, extremely high purity (typically ≥99.999% or 5.0 grade hydrogen) is essential because even trace impurities can poison catalysts, dramatically reducing efficiency and lifespan. In direct combustion, hydrogen purity requirements are slightly lower (around 99.9% or 3.0 grade), but contaminants can still alter combustion behavior and emissions. When storing hydrogen in metal hydrides, moderate to high purity (usually ≥99.99% or 4.0 grade) is necessary, as impurities can degrade the hydride materials and reduce storage efficiency. Different types of electrolyzers produce hydrogen with varying purity levels: alkaline electrolyzers typically yield hydrogen with a purity around 99–99.9%, requiring additional purification for sensitive applications; PEM (Proton Exchange Membrane) electrolyzers, thanks to their solid electrolyte and compact design, deliver hydrogen with purities of 99.999% or higher, making them ideal for fuel cells; AEM (Anion Exchange Membrane) electrolyzers, still under development, aim to combine the low cost of alkaline systems with purities approaching those of PEM (about 99.9–99.99%); SOEC (Solid Oxide Electrolyzers), operating at high temperatures, can produce hydrogen of very high purity (often ≥99.999%), but they are more complex and better suited for integration with industrial processes. Choosing the right electrolyzer depends heavily on the required hydrogen purity for the intended application.

Useful tables for the evaluation of optimal parameters according to the potential are inserted below, a table taken from the IEA report with reference to the different technologies available on the market [9].

Parameter	Alkaline Electrolysers	PEM Electrolysers	AEM Electrolysers	Solid Oxide Electrolyzers
Nominal Current Density	0.2-0.8 A/cm²	1-2 A/cm²	0.2-2 A/cm²	0.3-1 A/cm²
Voltage Range (Limits)	1.4-3 V	1.4-2.5 V	1.4-2.0 V	1.0-1.5 V
Operating Temperature	70-90°C	50-80°C	40-60°C	700-850°C
Cell Pressure	< 30 bar	< 30 bar	< 35 bar	1 bar
Load Range	15%-100%	5%-120%	5%-100%	30%-125%
H_2, Purity	99.9%-99.9998%	99.9%-99.9999%	99.9%-99.999%	99.9%
Voltage Efficiency (LHV)	50%-68%	50%-68%	52%-67%	75%-85%
Electrical Efficiency (Stack)	47-66 kWh/kg H_2	47-66 kWh/kg H_2	51.5-66 kWh/kg H_2	35-50 kWh/kg H_2
Electrical Efficiency (System)	50-78 kWh/kg H_2	50-83 kWh/kg H_2	57-69 kWh/kg H_2	40-50 kWh/kg H_2
Lifetime (Stack)	60 000 hours	50 000-80 000 hours	> 5 000 hours	< 20 000 hours
Stack Unit Size	1 MW	1 MW	2.5 kW	5 kW
Electrode Area	10 000-30 000 cm²	1 500 cm²	< 300 cm²	200 cm²
Cold Start (To Nominal Load)	< 50 minutes	< 20 minutes	< 20 minutes	> 600 minutes

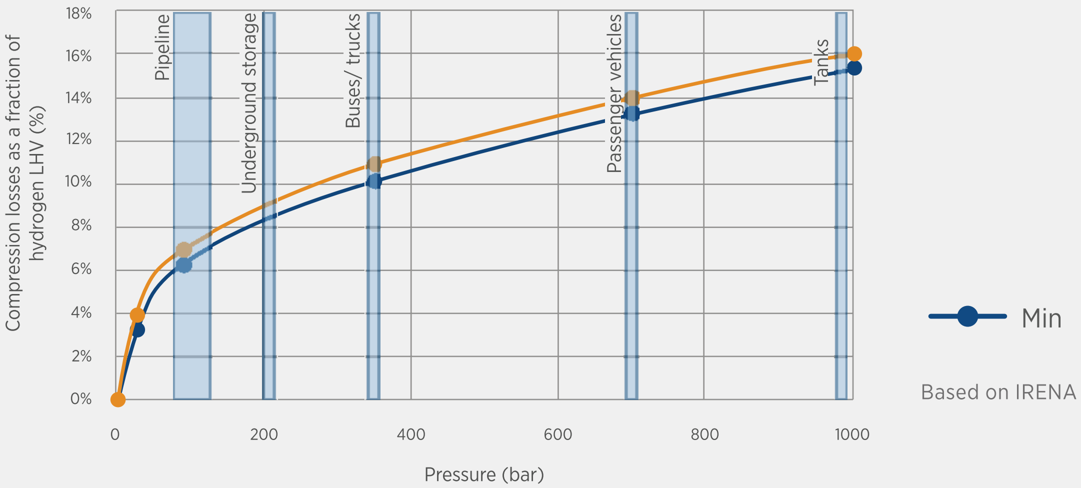
HYDROGEN STORAGE

The hydrogen released from the production phase will be in a gaseous state at the operating pressure of the electrolyzer, minus losses. At this stage, to reach the storage pressure - usually around 200 bar - it will normally pass through a compressor, which will bring the hydrogen to the designated pressure conditions.

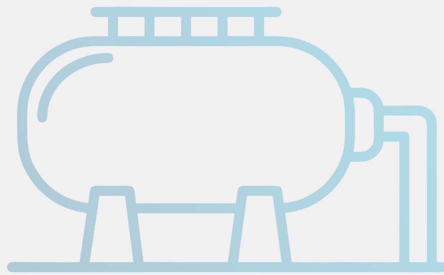
The choice on the type of compressor needs to be evaluated carefully. It is known that the pumping power is proportional to both the density and the compression ratio. Since the density of the element is the lowest in the entire universe, the costs in this phase are to be minimized as much as possible, both in energy and economic terms. An important factor to consider will be the outlet pressure from the electrolyzer: the higher this parameter, the more the compression ratio will be reduced. To make the process less energy intensive, it is advisable to increase the compression as much as possible in the electrolyzer, the inlet fluid being water in liquid form. The proposed approach aims to strategically managing pressure conditions in the electrolysis process: since liquid water is nearly incompressible, pressurizing the water feed before it enters the electrolyzer requires significantly less energy compared to compressing gaseous hydrogen output after electrolysis. The net result is a reduction in overall system energy consumption per unit of hydrogen produced, particularly valuable for large-scale industrial applications where compression energy represents a major operational cost.

An indicative graph of the energy spent in this phase is shown below, depending on the outlet pressure from the compressor, which varies depending on the final use [9].

Energy losses for the multi-stage mechanical compression of hydrogen.



Based on IRENA analysis based on BNEF, 2019.



The most common technologies today are cylinders and metal hydride storage.

Hydrogen storage cylinders are divided into five main categories, called Type 1, 2, 3, 4, and 5, each characterized by distinct materials and technologies.

Type 1 cylinders are made entirely of steel, a robust and reliable material, but heavy. This makes them inefficient in terms of weight/capacity ratio, although they are economical and widely used in stationary applications where weight is not a critical factor.

Type 2 cylinders have a metal core, typically in steel or aluminium, externally reinforced with composite materials. This configuration allows to reduce weight compared to Type 1, maintaining good mechanical resistance.

Type 3 cylinders represent a further step forward: the core is in aluminium, light and resistant, wrapped in a composite material structure. This combination makes them ideal for mobile applications, such as hydrogen vehicles, where weight is a crucial factor.

Type 4 cylinders, on the other hand, are made with a polymer core reinforced by composite materials, completely eliminating metals. They are the lightest and most suitable for high-efficiency applications, but also the most expensive to produce.

Type 5 cylinders are an emerging technology, without a metal core and entirely based on composite materials. They are still in the experimental phase, but promise to revolutionize the sector thanks to their lightness and storage capacity.

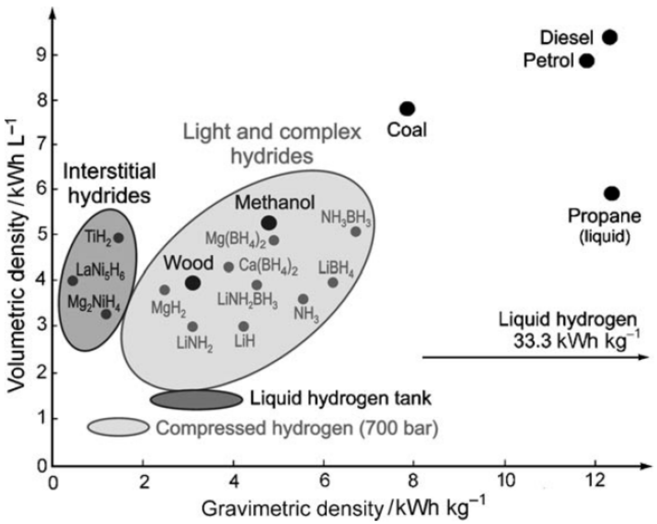
Image taken from the web. For more information, visit [14].

[95]	Sub-Type Classification	Liner	Wrap Extent	Winding Method	Resin Type	Fiber Type	Low Cost	Recyclability	Light Weight
TYPE II	Type II—FSW [1]	Metal	Cylinder	Wet	TS	CF	+++	++++	+
	Type II—MSW	Metal	Cylinder	Wet	TS	SW	+++++	+++++	+
TYPE III	Type III—FSW [1]	Metal	Full	Wet	TS	CF	+++	+++	++
	Type III—MSW	Metal	Full	Wet	TS	SW	++++	++++	+
TYPE IV	Type IV—FSW [1]	Plastic	Full	Wet	TS	CF	+	++	+++++
	Type IV—FST	Plastic	Full	Tape	TS	CF	+	++	+++++
	Type IV—FPT	Plastic	Full	Tape	TP	CF	+	+++	+++++
	Type IV—FPW	Plastic	Full	Wet	TP	CF	+	+++	+++++
	Type IV—MSW	Plastic	Full	Wet	TS	SW	++++	++++	+++
TYPE V	Type V [2]	Liner-less	Full	Tape	TS/TP	CF	++	++	+++++

An alternative to cylinders is represented by metal hydrides, which store hydrogen in solid form. These materials absorb hydrogen within their crystal structure, releasing it when heated. They offer high safety and a higher storage density compared to cylinders, but require controlled temperature and pressure conditions, making the process more complex and expensive. Moreover, metal hydrides are still in development for large-scale commercial applications, with challenges related to material costs and heat management.

Solid-state hydrogen storage using adsorbent materials like MOFs (Metal Organic Frameworks) and activated carbons operates through physisorption at cryogenic temperatures (77-150K). These porous materials offer fast kinetics and low energy release requirements (20-30 kJ/mol), currently reaching TRL 4-5. While they provide excellent safety and cycling stability, their main limitations are low gravimetric capacity (<5 wt%) and the need for cryogenic conditions. Advanced materials like MOF-210 demonstrate 0.075 g H_2/g capacity at 77K/100 bar, but practical applications require improved thermal management systems. Research focuses on optimizing pore structures and hybrid materials to enhance performance under milder conditions.

In summary, composite cylinders (Type 3 and 4) are currently the most balanced solutions for mobile applications, while Type 1 and 2 remain valid for stationary uses. Type 5 and metal hydrides represent promising technologies for the future, but require further development to become competitive in terms of costs and technological maturity. Image taken from [14]."



TRANSPORT

The transport of hydrogen, both in gaseous and liquid form, represents one of the key challenges for its adoption as a large-scale energy carrier. The two main modes, gaseous and liquid transport, offer different solutions based on logistics needs, volumes to be handled and distances to be covered. Each of these modes has distinctive characteristics, advantages, and limitations that influence its applicability in specific contexts.

As for the transport of gaseous hydrogen, this mode is mainly based on the use of pipelines or high-pressure cylinders. Pipelines are particularly suitable for long-distance transport and capillary distribution in industrial or urban areas. Dedicated pipeline networks already exist in some countries, such as Europe and North America, demonstrating the feasibility of this solution. However, the construction of new infrastructures requires significant investments and the use of special materials, capable of resisting hydrogen-induced embrittlement. Cylinders, on the other hand, are used for road or rail transport, often grouped in bundles to increase capacity. This mode offers great flexibility, but is limited by the amount of transportable hydrogen and logistics costs, especially when it comes to moving large volumes over long distances.

Moving on to the transport of liquid hydrogen, this mode exploits the higher energy density of hydrogen in liquid form, which occupies a significantly smaller volume compared to the gaseous form. Liquid hydrogen is transported in cryogenic tanks, designed to maintain cryogenic temperatures (-253°C, 20 K) throughout the journey. This method is particularly efficient for applications requiring high quantities of hydrogen in confined spaces, such as in the aerospace sector or in some industrial applications. However, the liquefaction process is very energy-intensive and expensive, and maintaining cryogenic temperatures during transport requires advanced technologies and high-efficiency insulating materials. Despite these challenges, liquid transport is a consolidated solution in contexts where energy density is a critical factor.

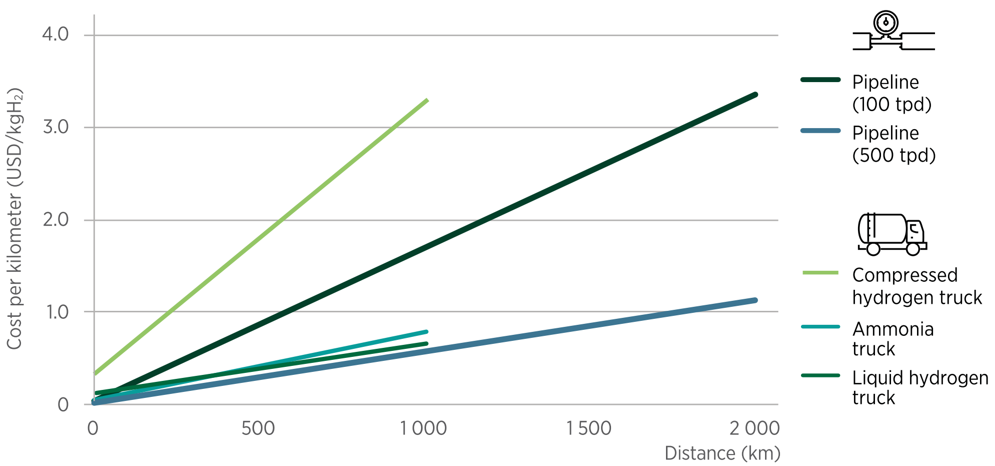
In terms of costs, gaseous transport via pipelines is generally cheaper over long distances, but requires high initial investments for the construction of infrastructures. Cylinders, on the other hand, are more expensive for large volumes and over long distances, due to logistics costs. Liquid transport, on the other hand, has high operating costs related to the liquefaction process and the cryogenic technologies necessary for maintaining temperatures.

From the point of view of technological maturity, both modes are well established. Gaseous transport has been widely used for decades, with pipeline networks and high-pressure cylinders employed in various sectors. Liquid transport, on the other hand, is a mature technology in specialized contexts, such as aerospace, but requires more complex and expensive infrastructures.

Finally, regarding complexity, liquid transport is undoubtedly more challenging, requiring cryogenic infrastructures and advanced insulating materials. Gaseous transport, on the other hand, is simpler, but pipelines require specialized materials to avoid hydrogen-induced embrittlement problems.

In conclusion, the choice between gaseous and liquid transport depends on specific needs, the distance to be covered, and the volume of hydrogen to be handled. While gaseous transport is ideal for distribution networks and stationary applications, liquid transport is preferable when energy density and volumetric efficiency are priorities. Both modes play a crucial role in the hydrogen transport landscape, contributing to its diffusion as a sustainable energy carrier. Image taken from IRENA Technical Report, 2021 [16].

Costs for hydrogen transport as a function of the distance by selected transport mode



Notes: Costs presented do not include conversion costs. Final costs in any transport mode depend on many variables and the values here presented are indicative. Weighted average cost of capital = 7%; useful life of infrastructure= 20 years; tpd = tonnes per day.

Source: Elaborated from IEA (2019); Nazir et al. (2020); Singh, Singh and Gautam (2020); Teichmann, Arlt and Wasserscheid (2012).

DISTRIBUTION

Hydrogen distribution systems are a fundamental element to ensure the supply and use of this energy carrier in applications such as sustainable mobility, industry, and power generation. Hydrogen distribution mainly occurs through refueling stations, which must be designed to ensure efficiency, safety, and rapid refueling times, especially in high-demand contexts such as public transport or commercial vehicles. Two main configurations stand out in this area: the single-tank system and the multi-tank cascade system. These solutions differ not only in complexity and costs, but also in their impact on compression power and energy consumption, critical aspects for the operational efficiency and economic sustainability of the entire distribution chain.

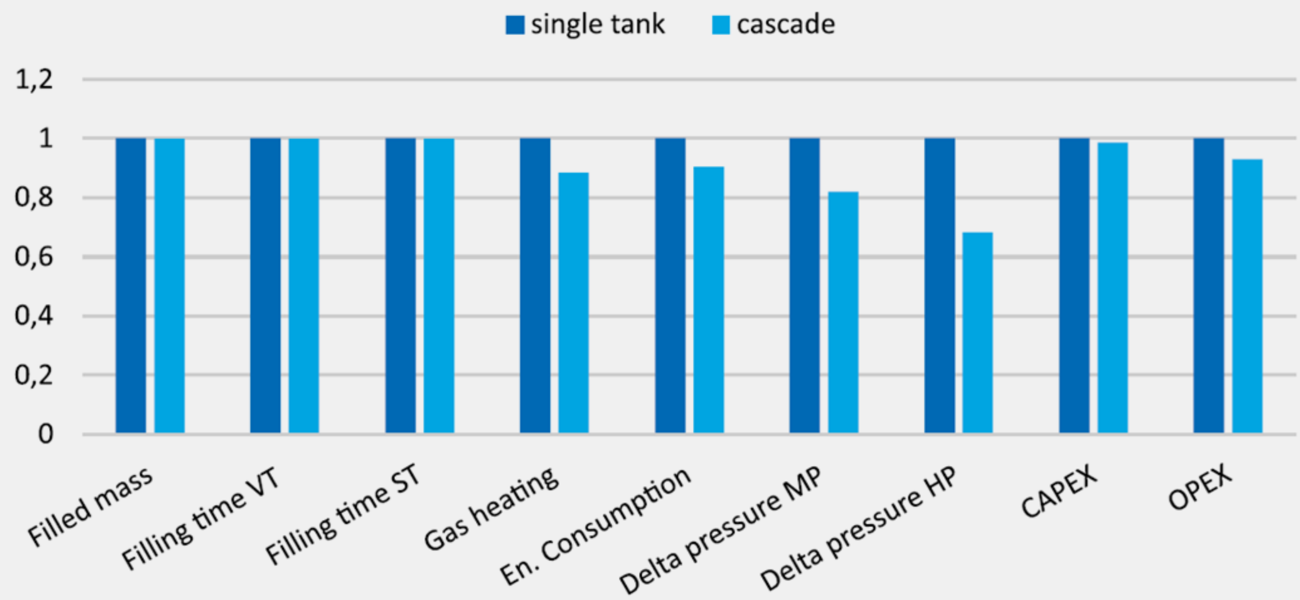
In the multi-tank cascade system, the use of multiple tanks at different pressures allows to optimize the compression process. During refueling, hydrogen is transferred from high-pressure tanks to intermediate-pressure tanks and finally to the vehicle, reducing the need for additional real-time compression. This approach reduces the required compression power and, consequently, the overall energy consumption, as it exploits pressures already available in the tanks. Furthermore, the gradual management of pressures minimizes energy losses during transfer, improving system efficiency.

Conversely, the single-tank system requires continuous compression to maintain a constant high pressure, necessary to ensure acceptable refueling times. This translates into higher energy consumption, as the compressor must operate at full capacity to compensate for the pressure drop during hydrogen transfer. In high-demand contexts, such as bus refueling stations, this configuration can lead to significant energy consumption peaks, increasing operating costs and reducing overall efficiency.

The choice between the two solutions therefore has direct implications on compression power and energy consumption. The cascade system, although more complex and expensive to implement, offers an energy advantage thanks to the reduction of the required compression power and the optimized management of pressures. This makes it particularly suitable for high-volume applications, such as bus refueling, where energy efficiency and refueling times are critical. The single-tank system, on the other hand, is simpler and cheaper initially, but can be less energy-efficient, especially in high-demand contexts.

In summary, the choice between the two configurations must consider not only the initial costs and management complexity, but also the impact on compression power and energy consumption, key factors for the economic and environmental sustainability of the hydrogen infrastructure.

Image taken from Caponi et al. [17], more information in the article.



Normalized comparison between single-tank and cascade system for the most important techno-economic parameters.

END USES

The development of a hydrogen ecosystem in an alpine environment has some disadvantages like lower availability of space and/or land cost, lower solar irradiation, harsh climate and geographic conditions (steep roads, presence of snow, etc.). These are all factors that hinder the competitiveness of production costs of green hydrogen compared to similar ecosystems at lower altitude. Nevertheless, the underlying principle is that hydrogen should be used where the energy system cannot be electrified.

There is a distinction to be made here between alpine valleys and remote areas, the latter being characterized by low population density and difficulty of access, ranging from municipalities in remote areas to high-altitude shelters.

In the case of valley bottoms, or wide valleys with (relative) availability of space and resources, the criteria are those already considered, taking into account, on the economic side, the logistics difficulties and the characteristics of the territory. The main difference compared to lowland contexts is probably linked to mobility applications where heavy electric vehicles may be disadvantaged by steep slopes or intense cold. However, careful evaluation is needed with respect to the entire supply chain in terms of energy as well as economic efficiency.

For mobility, hydrogen is particularly suitable for powering heavy or service vehicles, such as off-road vehicles, track maintenance vehicles, or freight transport vehicles in inaccessible areas. In these cases, electrification may prove impractical due to long distances, lack of charging infrastructure, or low temperatures, which reduce battery efficiency. In the case of areas with particularly harsh climates, mobility applications will focus on internal combustion engines rather than on the use of fuel cells.

Another possibility is the use of hydrogen-based energy storage systems to integrate local renewable sources, such as small hydroelectric, wind, or photovoltaic plants. In these areas, renewable energy production can be intermittent or exceed local demand. Hydrogen, produced by electrolysis during periods of energy surplus, can be stored and converted back into electricity via fuel cells when needed, ensuring a stable and continuous energy supply. However, this use should not be the norm in terms of economic profitability as it displays low-capacity factors and big uncertainties in the return on investment for the reasons already described. These systems should therefore be considered as a service for energy supply, self-consumption and maximization of exploitation in terms of local resources, certainly not as an economic investment.

Besides the Hard-to-Abate sector, other applications include the domestic heat demand sector in extreme remote areas like Alpine refuges. However, this application is not economically competitive compared to conventional uses and for this reason solutions of this type should only be applied in disadvantaged contexts.

The following table shows the degree of purity required by hydrogen for different end uses:

Application	Required Purity	Typical Electrolyzer Technology
Fuel cells	≥99.999% (5.0 grade)	PEM, SOEC
Direct combustion	≥99.9% (3.0 grade)	Alkaline (with purification), AEM, PEM
Storage in metal hydrides	≥99.99% (4.0 grade)	PEM, AEM, Alkaline (with purification)

TECHNO-ECONOMIC ASSESSMENT

Once the technical variables have been defined and the supply and demand potential has been assessed, it is possible to move forward to the economic evaluation. To assess the feasibility of a project at a preliminary phase, it is strongly recommended to request quotes directly from the companies that produce the necessary technologies. The costs of the same technology can vary significantly depending on the different producers. At this stage of development of the hydrogen sector, price uncertainty is a non-negligible, indeed, often decisive factor. The greater the correctness of the cost information, the greater the correctness in forecasting the economic flows for the entire duration of the project. This will make a difference between a successful and profitable project, and a failed one at a loss.

The cost of hydrogen depends on several factors and it is extremely variable from country to country even at the European level:

- the energy infrastructure, in particular the cost of the kWh of electricity
- the incentives made available at European, national, and local levels
- the strategy identified by area (for example, in Spain, they are pushing a lot on the production from RES, in Italy on infrastructures)
- the reference legal framework
- the maturity of the chosen technology
- the technical competence of the supplier

In this regard, it is recommended to use the H_2FAsT financial evaluation simulator tool developed within the AMETHyST project and available on the SkHyline platform. The tool is designed to maximize the effectiveness and efficiency of hydrogen production based on a given amount of renewable energy available without grid support. Rather than providing specific design recommendations, it delivers a plant configuration that maximizes the economic sustainability of the hydrogen production site according to specific technical and economic optimization criteria. Producing green hydrogen in an economically sustainable way is not a given. The intermittent nature of energy production from renewable sources, plant design choices, and especially the configuration of various elements, make all the difference. This is why this tool is crucial in a preliminary phase, helping to assess the risk level based on the available resources.

On the SkHyline platform, it is possible to access the evaluation tool as well as the guidelines and a video tutorial that guides step-by-step through the utilization and application of the tool in real case scenarios.

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