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The hydrogen economy



Compressors for a Lifetime

What it costs to produce hydrogen

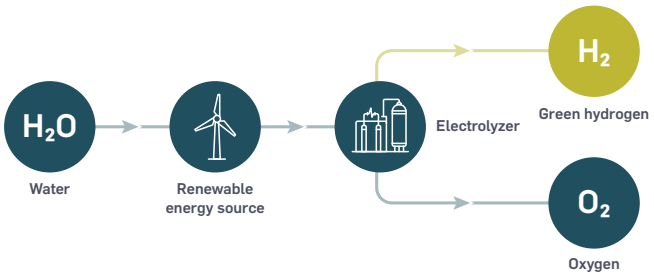
The global push for decarbonization has placed hydrogen firmly in the spotlight. As a clean and versatile energy vector, it holds the potential to power heavy industry, fuel transport and store energy free from greenhouse gas emissions during periods of low solar or wind output. Hydrogen can be produced in different ways. To understand its potential, we must first understand how it is made and what it costs to produce.

The industry often uses a color spectrum to classify hydrogen based on its production method and associated carbon footprint. Navigating this spectrum is the first step for any organization looking to invest in or adopt hydrogen technologies. This white paper dives into the different hydrogen production processes and analyzes the levelized costs of hydrogen (LCOH) that determine the commercial viability of each pathway.

Green hydrogen

Green hydrogen is produced through water electrolysis, a process that uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2). When powered by renewable sources like wind or solar, the entire process is virtually free of greenhouse gas emissions.

Green hydrogen

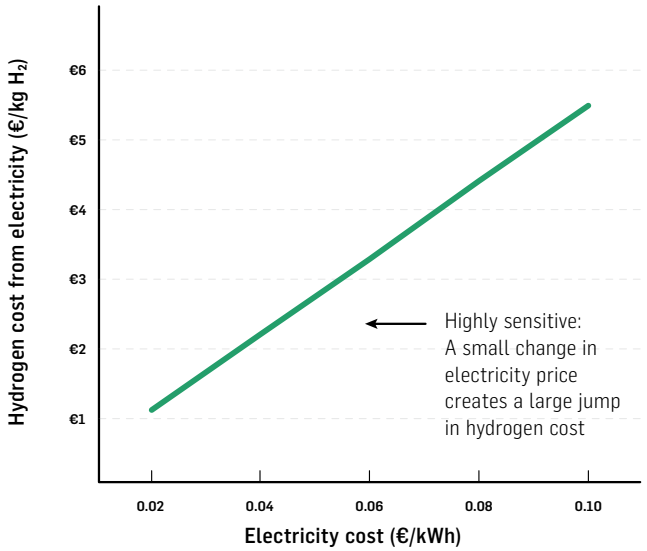


The cost of production: Green hydrogen

The cost of green hydrogen is overwhelmingly dependent on the availability of large scale renewable electrical power generation, the cost of electricity and access to sufficient quantities of fresh water.

Electrolysis is energy-intensive, requiring approximately ~45-60 kWh of electricity to produce a single kilogram of hydrogen. As the table illustrates, this creates a direct correlation between electricity prices and the minimum costs of hydrogen, even before capital and operational expenditures are considered (CAPEX / OPEX).

Green hydrogen cost vs electricity price @55 kWh/kg H_2



Efficiency of water electrolysis ~ 60% → Energy content of H_2 = 33 kWh/kg H_2 LHV (Lower Heat Value)

Advantages

- The production of green hydrogen does not generate carbon emissions.
- In regions with excessive renewable energy, green hydrogen production can absorb excess capacity – effectively storing surplus energy that would otherwise go unused, provided the electrolyzer plant operates with sufficient full load hours.

Disadvantages

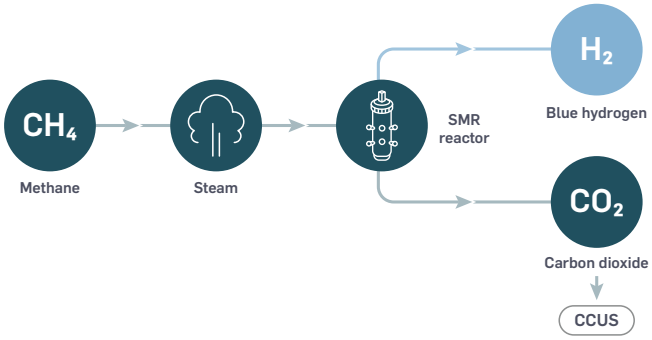
- Its high electricity consumption makes it commercially viable only in regions with abundant and low-cost renewable energy.
- Water electrolysis is potentially competing with scarce freshwater resources.

Grey and blue hydrogen

Today, the vast majority of the world's hydrogen is produced via steam methane reforming (SMR). In this mature process, methane (CH_4 – the main component of natural gas) reacts with steam to produce hydrogen and carbon dioxide (CO_2) as a byproduct. Grey hydrogen refers to hydrogen production where CO_2 is released into the atmosphere, contributing to global warming.

Blue hydrogen is an evolution of this process. It uses the same SMR method but incorporates Carbon Capture, Utilization and Storage (CCUS) technology to capture the CO_2 emissions before they are released.

Blue hydrogen



The cost of production: Blue hydrogen

For blue hydrogen, the key cost drivers are the price of natural gas and the costs of carbon capture, transportation and storage.

Metric	United States	Europe
Methane cost basis	$4/mmBTU (e.g. Henry hub)	€32.92/MWh (e.g. TTF)
Carbon capture and storage costs	€33/ton CO_2	€33/ton CO_2
Total estimated hydrogen cost	~ €1.26/kg H_2	~ €2.97/kg H_2

The lowest estimated cost for carbon capture and storage (CCUS) is approximately 33 EUR per ton of CO_2, which translates to 0.33 EUR per kilogram of hydrogen (based on 10 kg of CO_2 per kg of H_2 at 33 EUR/t CO_2).

However, CO_2 storage sites are often not located near SMR production facilities. The logistics involved; CO_2 liquefaction, transport by train or ship or pipeline and injection into storage, can significantly increase overall costs. Therefore, the implementation of blue hydrogen as a low-carbon energy vector certainly develops first in regions where SMR facilities are located near suitable CO_2 storage sites, ensuring both economic and logistical viability.

Advantages

- Blue hydrogen is a low-carbon energy option that can be produced at scale today by leveraging existing natural gas infrastructure. It is one cornerstone of low emission energy supply while renewable energy capacity and green hydrogen production continue to expand.
- When biogenic feedstock is used in SMR, the combination of SMR and CCUS can potentially result in a near below-zero CO_2 footprint.

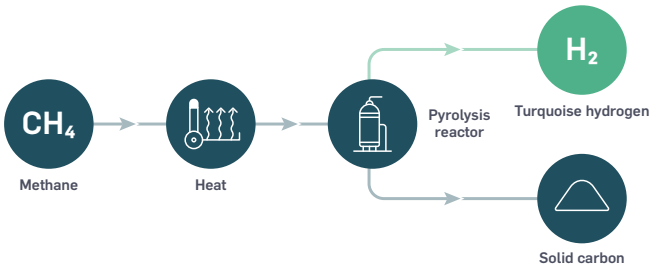
Disadvantages

- Blue hydrogen still relies on fossil fuels and carbon capture technologies are typically not 100% efficient, meaning some emissions persist.
- Its cost-competitiveness is highly sensitive to volatile natural gas prices and carbon tax policies.

Turquoise hydrogen

A promising new pathway is turquoise hydrogen. Produced through methane pyrolysis, this process heats methane in the absence of oxygen, splitting it into hydrogen gas and solid carbon (carbon black) that can be marketed to several industries.

Turquoise hydrogen



The cost of production: Turquoise hydrogen
This method offers a different economic model. It requires significantly less energy than electrolysis (~10-15 kWh/kg H_2) and avoids producing gaseous CO_2, thus avoiding high carbon penalties. Furthermore, it creates solid carbon black, a valuable commodity that can generate an additional revenue stream as it can be used in manufacturing tires, coatings and electronics. Feedstock cost remains the primary driver.

Metric	United States	Europe
Methane cost basis	$4/mmBTU (e.g. Henry hub)	€32.92/MWh (e.g. TTF)
Renewable energy costs	~ €1.08/kg H_2 • €0.09/kWh (renewable electricity) • 12 kWh/kg H_2 (for pyrolysis)	~ €0.96/kg H_2 • €0.08/kWh (renewable electricity) • 12 kWh/kg H_2 (for pyrolysis)
Total estimated hydrogen cost (incl. CAPEX & OPEX)	€2.00/kg H_2	€3.10/kg H_2

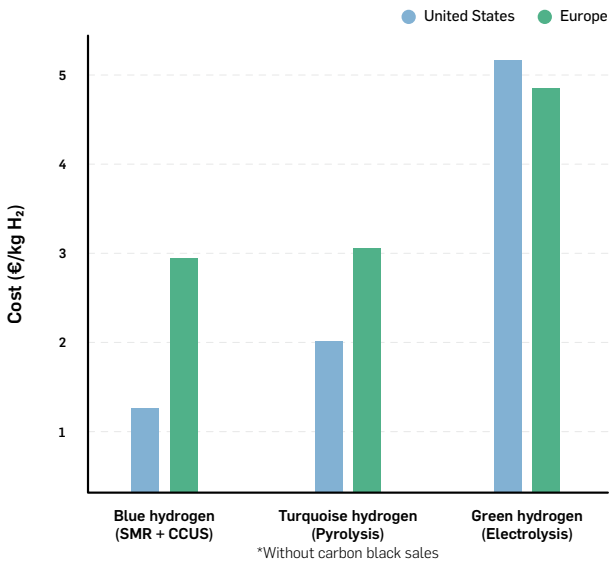
Advantages
- This innovative method avoids direct CO_2 emissions during production by pre-combustion removal of the carbon.
- Unlike electrolysis, methane pyrolysis does not require water, making it suitable for regions with limited freshwater resources.
- The solid carbon byproduct (carbon black) can be sold, potentially contributing to the revenue stream of pyrolysis plant operators.
- If the methane feedstock is biogenic, the methane pyrolysis contributes to a negative CO_2 footprint.
- Methane pyrolysis consumes significantly less green energy compared to water electrolysis.

Disadvantages
- The technology is still maturing and has not yet reached the industrial scale of SMR or electrolysis.
- The commercial success depends a lot on the volatile cost of methane.

The final cost comparison: Europe and the United States

The graph below displays the cost of producing three types of hydrogen: green, blue and turquoise hydrogen in Europe and in the United States.

The regional cost of hydrogen production (€/kg H_2)



Key factors driving hydrogen production costs

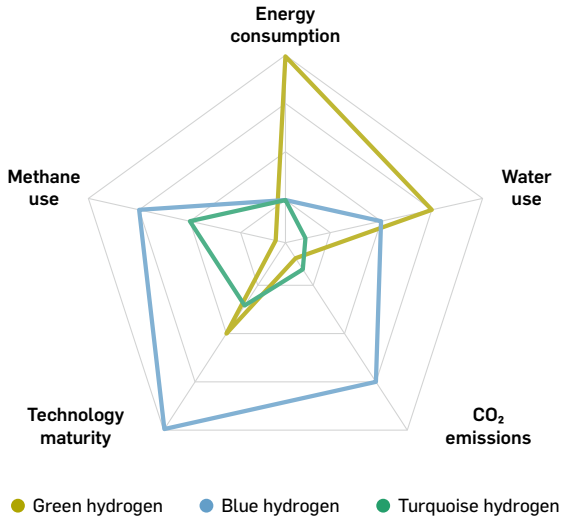
To make sound, long-term investment decisions, we must look deeper at the fundamental success factors that drive the investment's viability. The "best" hydrogen production method is not universal; it is a strategic choice determined by a region's unique resources, energy landscape, and policy environment.

Comparison metric	CH_4 SMR (Blue hydrogen)	H_2O Electrolysis (Green hydrogen)	(Green hydrogen) CH_4 Pyrolysis (Turquoise hydrogen)
Methane consumption (kg CH_4/kg H_2)	~5.6	/	~4
Energy consumption (kWh/kg H_2)	Included within the Methane consumption	~55	~10
CO_2 emissions (kg CO_2/kg H_2)	~10 (before capture)	0	~0
Water consumption (kg H_2O/kg H_2)	6 – 13	~10	0
Technology maturity	High	Medium	Low
Revenue streams / Products	H_2	H_2	H_2, solid carbon (CO_2 certificates)

A unified view of key metrics

To understand the trade-offs, we must compare these production pathways across the same critical metrics. The table above, based on our analysis, summarizes the key inputs and outputs for producing one kilogram of hydrogen.

To better visualize these trade-offs, the data can be represented as unique profiles. As the chart below shows, there is no single method that is superior on all metrics; each has a distinct shape of advantages and disadvantages.



This visual comparison leads us to the critical factors driving a project's viability.

Interpreting the data: What these factors mean in practice

This data reveals the critical trade-offs that every project developer must consider.

Energy consumption

The most striking difference is in energy demand. Green hydrogen via electrolysis requires approximately 5.5 times more electricity than turquoise hydrogen from pyrolysis. In a world of growing electrification and strained grids, this massive energy requirement is a significant challenge for green hydrogen, directly competing with other demands like electric vehicles and heating.

Water consumption

Both steam methane reforming (SMR) and electrolysis are water-intensive processes. Methane pyrolysis, in contrast, requires no water feedstock, giving it a powerful advantage in arid regions where water is a scarce and valuable resource often contested by agriculture and municipalities.

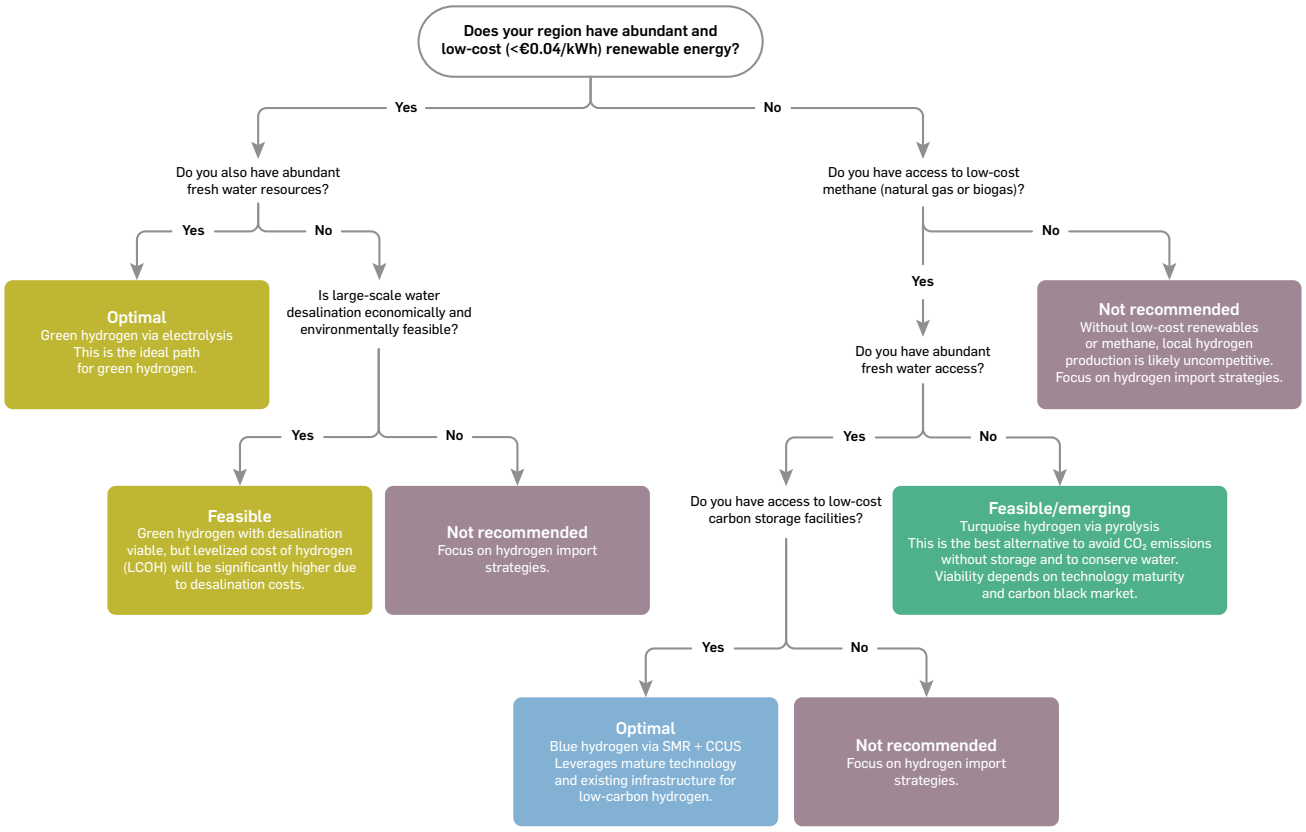
Feedstock and infrastructure

Blue and turquoise hydrogen leverage methane from existing natural gas pipelines, LNG import terminals, or biogas facilities. This ability to use mature, existing infrastructure is a major advantage for scaling quickly and cost-effectively compared to building entirely new ecosystems.

Applying the factors: Which hydrogen path for which region?

Understanding these factors allows us to move from theory to strategy. The optimal production path becomes clear when viewed through a logical decision-making framework based on a region's unique strengths and constraints.

The decision-making process for choosing a hydrogen production pathway



As the decision tree illustrates, the ideal pathway depends on a series of key local conditions

The case for green hydrogen (Electrolysis)
This is the solution of choice in regions with a surplus of **low-cost, renewable energy and abundant fresh water**. Locations like Norway and Quebec, with vast hydropower resources, or future solar hubs are ideal candidates for large-scale green hydrogen production.

The case for blue hydrogen (SMR with CCUS)
This path is most competitive in regions with **both low cost natural gas and accessible geological formations for CO_2 storage**. The US Gulf Coast and Middle East are a prime example, with its abundant gas reserves and nearby depleted oil and gas wells perfect for cost-effective carbon sequestration.

The case for turquoise hydrogen (Methane Pyrolysis)
This innovative method finds its niche in regions that have **access to methane at reasonable costs but face constraints on water, renewable energy, or both**. It is also uniquely suited for areas with local industries that can use the solid carbon byproduct, such as tire or battery manufacturing, creating a circular, value-added economy.

How much does it cost to pack and deliver hydrogen

Once a molecule of hydrogen is created, it begins a complex journey to the end-user. The "midstream" stage is technically challenging, contributing significant costs to the entire value chain. It includes hydrogen packing, transportation, and storage. It is essential for any organization looking to build a realistic and profitable hydrogen project to understand each stage, as they significantly impact the final "delivered" cost of hydrogen.

"Packaging" hydrogen for transport, different paths to go

Hydrogen is the lightest element in the universe, meaning it has a very low density in its natural gaseous state. To transport it economically, it must be "packaged" to increase its energy density, reducing the transportation costs. There are different strategies for this:

Liquefied Hydrogen (LH_2)
By cooling hydrogen to a cryogenic -253°C (-423°F), it turns into a liquid. This significantly increases its density – by roughly a factor of approx. 790, making it an effective way to transport large volumes over long distances, particularly by sea.

Liquefying hydrogen at scale demands relatively little power – around 8 to 10 kWh per kilogram of hydrogen. However, the development of large-scale hydrogen liquefaction plants and the necessary LH_2 storage infrastructure at export and import terminals is still far from mature.

Additionally, LH_2 carriers required for transporting larger quantities of LH_2 currently have a rather low technology readiness level. Advancements in LH_2 tank technology, which determine insulation quality, will influence hydrogen costs, as the boil-off gas (BOG) losses add to the delivered price at import terminals. The goal will be to restrict the boil-off gas to the amount required for powering the LH_2 carriers' propulsion and onboard energy systems, avoiding the need to flare excess hydrogen.

Once LH_2 shipping technologies mature, the high efficiency of this pathway could make it a highly attractive option for long-distance hydrogen transport.

Compressed Gaseous Hydrogen (CGH_2)
When pipeline access near the hydrogen consumer is unavailable, a practical solution for short-distance transport is to compress hydrogen gas to high pressures (200-700 bar) in high-pressure tubes housed in 20- or 40-foot containers or on dedicated trailers. With 700-bar trailers, hydrogen can be fed to a great extent to end-users when regulations allow transportation at this pressure level without installing compression equipment at their facilities.

The depreciation of the high costs associated with high-pressure vessels or containers must be factored in throughout their round trip, including when hydrogen is filled into them, stored inside and dispensed from the container. During a round trip, the depreciation can easily amount to between €0.20 and €0.40 per kg of hydrogen per day, indicating that a long round trip duration makes CGH_2 container transport and storage per kg of hydrogen rather uncompetitive.

GH_2 container/trailer transport costs

Round trip duration (days)	H_2 cost for container/trailer depreciation per kg H_2 min (EUR)	H_2 cost for container/trailer depreciation per kg H_2 max (EUR)
1	0.2	0.4
2	0.4	0.8
3	0.6	1.2
4	0.8	1.6
5	1	2
6	1.2	2.4
7	1.4	2.8
8	1.6	3.2
9	1.8	3.6
10	2	4

Several project developers have already realized that long-distance container transport with extended round trips is not a feasible solution.

Hydrogen pipeline feed and transport

Hydrogen pipelines can be utilized if they are located near both hydrogen production and consumption sites. Compressed to the pipeline pressure, the hydrogen can flow from the pipeline injection point to the consumer. When hydrogen is produced by pressurized electrolyzers located close to consumers, compressors may not even be required to move the molecules from production to consumption.

The estimated cost of transporting hydrogen via pipeline is projected to range from €0.07 to €0.23 per kilogram per 1'000 km. This price variability is determined by a variety of pipeline related parameters such as:

- Pipeline diameter and material: Larger diameters reduce cost per kg of hydrogen, but increase capital investment.
- Hydrogen demand: Higher throughput lowers the levelized cost.
- Compressor stations: Required for long distances, adding to both capital and operational costs.
- Pipeline pressure and terrain: Affect construction complexity and energy use.
- Repurposing vs. new build: Repurposing existing natural gas pipelines can reduce costs but may require significant upgrades due to hydrogen embrittlement and leakage risks.

Hydrogen carriers

To achieve easier transport, the methods described below involve chemically bonding hydrogen to a stable liquid molecule. The three leading carriers are:

Ammonia (NH_3)

Hydrogen is combined with nitrogen from air separation units in a Haber-Bosch ammonia production plant and the resulting ammonia can be transported as a liquid under moderate pressure.

The main advantage of this hydrogen transportation route is that ammonia production processes, along with the infrastructure for large-scale storage and shipping, are already well-established and partially in place. The efficiency of the process ranges at <44% and the maturity of the most critical elements of this path makes this the solution of choice for today's projects.

Ammonia packaging	kWh/kg H_2
Electrolysis	55
Air separation unit (N_2)	0.66
Ammonia (Haber Bosch) production plant	5.6
Ammonia cracker	14
Total	**75.26**
Round trip efficiency	44%

Table: Energy demand and efficiency (compared to the energy content of hydrogen (33 kWh/kg (lower heat value – LHV)) for ammonia as a hydrogen packing path

Liquid Organic Hydrogen Carriers (LOHC)

Hydrogen is absorbed to a stable organic liquid – LOHC (e.g. covalent bonding to Benzyltoluene).

"Hydrogenation" takes place at the production site under elevated temperatures, consuming about 9 kWh of energy. Later, hydrogen is released from the LOHC at the point of use through desorption, which requires an additional ~10 kWh of energy.

LOHC can be transported over long distances under normal atmospheric conditions using standard product tankers and road tanker trucks, offering a high degree of safety. In addition to the LOHC hydrogenation equipment at the location of hydrogen production and the hydrogen desorption equipment at the point of hydrogen consumption tank, infrastructure for both states of LOHC, with and without the hydrogen bonded to the LOHC, must be provided to enable a circular logistic of the liquid hydrogen carrier.

LOHC packaging	kWh/kg H_2
Electrolysis	55
LOHC hydrogenation	9
LOHC de-hydrogenation	10
Total energy demand	**74**
Round trip efficiency	45%

Table: Energy demand and efficiency (compared to the energy content of hydrogen (33 kWh/kg (lower heat value – LHV)) for LOHC as a hydrogen packaging path

Metals as energy vectors

Metals can also be used to store or transport larger quantities of energy, even in the absence of hydrogen. The energy storage mechanism in that case is the production of metals like aluminium or iron from their oxides.

When these metals are exposed to water (H_2O) they reduce the water to metal oxide (Al_2O_3 or Fe_3O_4) releasing hydrogen.

While the iron oxidation reaction is endothermic, the aluminium oxidation reaction, once ignited, is exothermic, generating heat at very high temperatures (around 1'000 °C), which can be recovered for use in industrial processes.

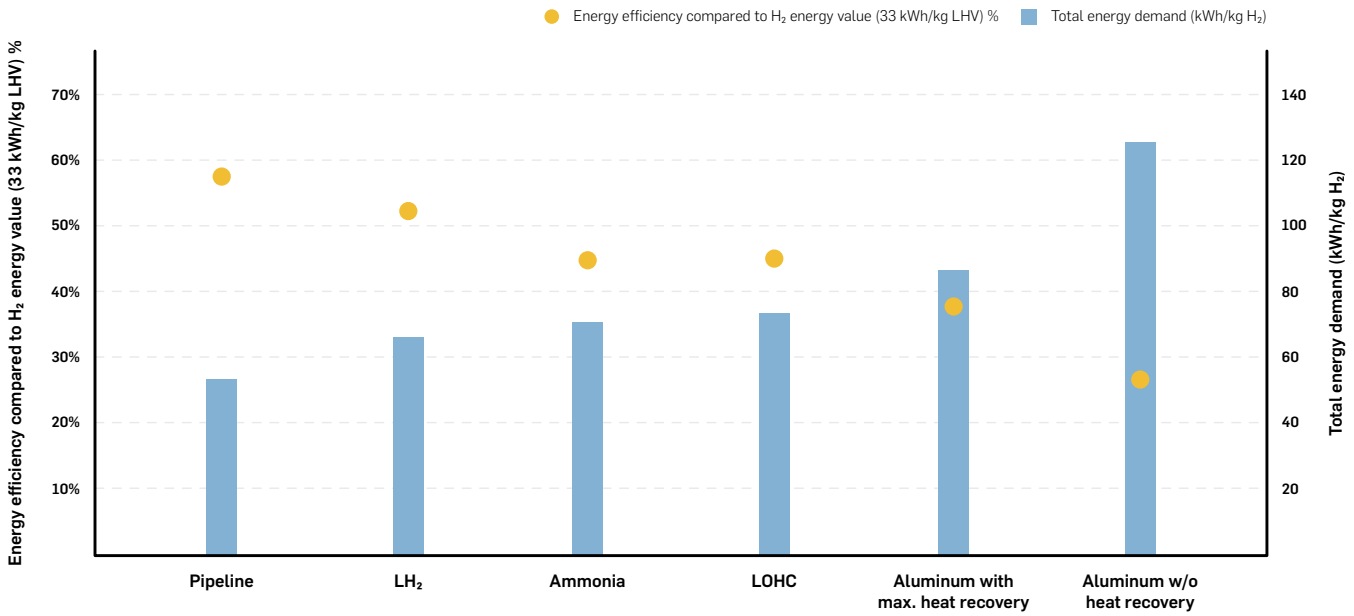
Aluminium: $2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2$

Aluminium with max. heat recovery	kWh/kg H_2	Aluminium w/o heat recovery	kWh/kg H_2
Aluminium oxide electrolysis	124	Aluminium oxide electrolysis	124
Hydrogen generation (steam reduction) heat recovery 100%	-38	Hydrogen generation (steam reduction) no heat recovery	0
Total energy demand	**86**	**Total energy demand**	**124**
Round trip efficiency	38%	Round trip efficiency	27%

Table: Energy demand and efficiency (compared to the energy content of hydrogen (33kWh /kg (lower heat value – LHV)) for aluminum as a hydrogen packaging path

Below is an overview of process efficiencies and cost drivers, primarily influenced by the power consumption required for these processes.

Total energy demand for hydrogen packaging



Choosing the right mode for packaging and transport

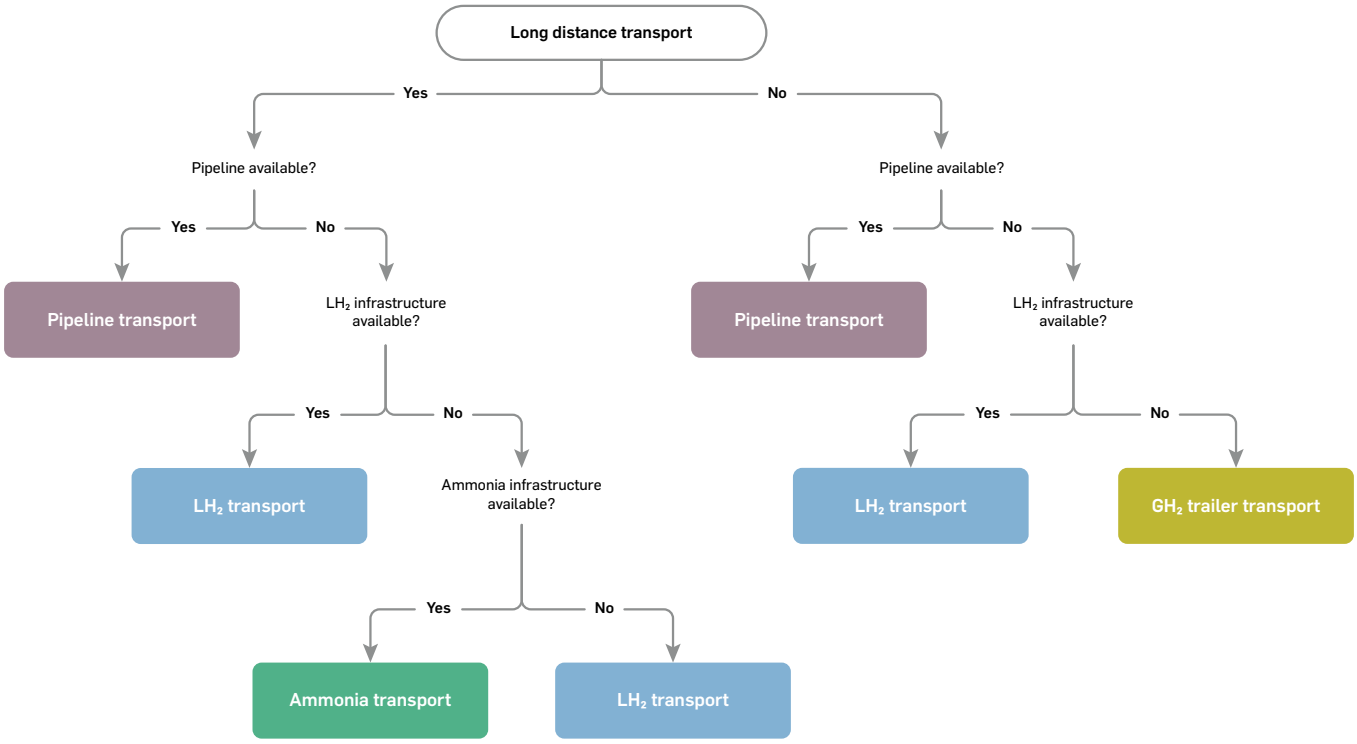
The need to transport hydrogen arises mainly from two factors:

- Meeting the energy import needs of regions unable to satisfy demand through domestic production and storage.
- Hydrogen production can be more cost-effective in remote exporting regions with lower energy prices, which also reduces packaging and transportation costs compared to domestically produced and stored hydrogen.

The distance of hydrogen transport and the environmental factors like energy costs, feedstock and infrastructure availability predefine the chosen hydrogen production and packaging method and the mode of hydrogen transport from the production hub to the point of use.

The infographic below outlines the decision-making process for selecting the optimal hydrogen packaging and transport method:

The decision-making process for hydrogen packaging and transport method



Alternative energy transport vectors: Synthetic Hydrocarbons (e.g. methane)

Synthetic Hydrocarbons can be used as an energy supply vector for storage and the transportation of energy.

Synthetic Hydrocarbons used as an energy carrier will not be converted back into hydrogen. Therefore, a direct comparison with other value chains is of limited relevance, as these hydrocarbons can be utilized directly as low-carbon feedstock in the chemical and petrochemical industries or as fuel. That said, examining the issue from another angle may provide useful insights.

One of the simplest hydrocarbons – synthetic methane, is synthesized through the Sabatier process:
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$.

Synthetic methane can be transported through existing natural gas infrastructure: it can be injected into pipelines, stored in underground caverns, or liquefied at -163 °C for shipment via LNG tankers and trailers.

However, hydrocarbons – including methanol and synthetic kerosene – used as energy carriers share a common challenge. In addition to requiring green hydrogen, these energy carriers also need carbon dioxide (CO_2) sourced in compliance with emission regulations, which means securing sufficient biogenic CO_2 or CO_2 obtained through direct air capture (DAC) technology.

Both supply chains of CO_2 within this path are critical.

- **Biogenic CO_2 supply challenges**
  To scale up synthetic hydrocarbon production, large quantities of biogenic CO_2 must be available near the production facility or transported there. A scarce or fragmented biogenic CO_2 supply chain could significantly limit the expansion of synthetic hydrocarbon plants.
- **Direct air capture CO_2 supply challenges**
  Because atmospheric CO_2 concentration is relatively low (~420 ppm), capturing these molecules requires significant capital and operational expenditure. With current technology, direct air capture costs around €800-900 per ton of CO_2, with projections to decrease to €150-350 per ton as the technology matures and scales.

The table below compares the cost of synthetic methane with that of green hydrogen, factoring in CO_2 sourced from biogenic sources and direct air capture.

Methane costs comparison at production site

Production	Feedstock costs [0.5 kg H_2 & 2.74 kg CO_2/kg CH_4]	Total feed stock costs [€/kg CH_4]	Plant CAPEX/ OPEX 1.0-2.5 [€/kg CH_4]	Total costs €/kg methane	Energy costs (LHV) [€/kWh]
Synmethane (Biogenic CO_2 at €30/t)	H_2: ~€1.23/kg CH_4 CO_2: ~€0.08/kg CH_4	1.31	~2	3.31	0.24
Synmethane (DAC CO_2 at €800/t)	H_2: ~€1.23/kg CH_4 CO_2: ~€2.19/kg CH_4	3.42	~2	5.42	0.39
Fossil methane imported to EU (TTF 10/2025)	€31.44/megawatt hour (MWh)	/	/	1.75	0.13

The table above highlights the range of synthetic methane cost scenarios, excluding transportation to the EU.

Before transport via pipeline or LNG tanker, the cost of synthetic methane is estimated to range between:

- ~190 % of TTF tradable natural gas (biogenic CO_2 (€30 per ton))
- ~300% of TTF tradable natural gas (DAC CO_2 (€800 per ton))

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