# Focus

Roland Berger

**Hydrogen transportation** | The key to unlocking the clean hydrogen economy


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Money is pouring into clean hydrogen as policymakers and private investors increasingly realize that the fuel and feedstock will soon become a cornerstone of the energy transition and decarbonization efforts. But to date, a key component of the clean hydrogen economy has been overlooked – large-scale transportation to get clean hydrogen from production sites to points of use. This is a crucial puzzle to solve, as the most favorable production locations are found in often remote, renewable-rich areas, whereas demand will likely be highest in heavily industrialized and densely populated areas.

We believe this oversight must be urgently addressed. Global supply and demand centers will soon need to be connected to serve the growing demand for clean hydrogen, for example in steel production, yet cost-efficient hydrogen transportation methods remain elusive. High transportation costs significantly increase overall hydrogen costs, posing a challenge for the commercial viability of this emerging sector. The question is how to provide reliable large-scale hydrogen transportation that keeps costs in check and ensures the economic competitiveness of clean hydrogen.

This report provides answers. We assess three hydrogen carrier technologies – liquefied hydrogen, ammonia and liquid organic hydrogen carriers (LOHC) – and analyze their costs and feasibility, with a focus on Europe. We find that there is, as yet, no one-size-fits-all solution in terms of ease of use and cost. Choice is dependent on concrete use cases, transportation modes, distances and potential partner synergies. In addition, all the technologies still require substantial development work. We therefore believe that they will likely coexist in the short term, with ultimate success depending on cost-cutting potential, speed of market uptake and ease of use.

As we outline in our recommendations, the public and private sector in Europe must act to meet the challenges of large-scale hydrogen transportation. Public support will be needed to develop and test them until a dominant technology emerges. At the same time, industry needs to properly prepare for the ramp-up of carrier technologies, and providers must work on improving efficiencies and clean options. Those businesses that move fast stand to gain most in terms of positioning and cost reductions.

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# Introduction

## CLEAN HYDROGEN OFFERS A PATH TO DECARBONIZATION – PROVIDED IT CAN BE TRANSPORTED

The idea of powering our way to a carbon-free world using green electricity is highly appealing. Electricity is generated from renewable energy sources and used to power everything from domestic televisions to high-speed trains. In the process, climate targets are met, and fossil fuels become a thing of the past. Unfortunately, it's not that simple.

While green energy is now a vital part of the electricity mix, the share of electricity used in overall energy consumption is still meager. For example, renewable energy sources contributed 38% to the overall European electricity mix in 2020, overtaking fossil fuels. But the share of electricity in global final energy consumption was only 19% in 2018, and stagnating. Sectors such as heavy industry, with huge energy needs to process heat from burning fossil fuels, for example, making them difficult to electrify, and a lack of grid infrastructure to transport green power from areas of production to areas of demand, are largely to blame.

This is where green hydrogen ($H_2$) comes into play. It can be used as a renewable fuel or feedstock in all major $CO_2$-emitting sectors, including those where direct electrification is not possible. By producing the gas using electrolysis powered by renewable sources, green power becomes easier to store and transport as an energy carrier, enabling sector coupling. Besides green hydrogen that is produced from renewable energy sources, alternative technologies exist to produce hydrogen with low carbon content (so-called clean hydrogen). Those include e.g. blue hydrogen that is produced from fossil sources but with carbon capture, and pink hydrogen that is produced from nuclear power using electrolysis. Clean hydrogen can then be used as a combustion fuel in industrial or mobility applications, or be reconverted to electricity in a fuel cell. On the feedstock side, clean hydrogen can replace gray hydrogen in industrial processes, such as refining. Gray hydrogen is currently the most common form of manufactured hydrogen, usually produced from natural gas in a $CO_2$-intensive steam methane reformer (SMR).

The potential of clean hydrogen is huge. In Europe, total hydrogen demand is expected to grow to more than 45 m tons by 2050. Many sectors – from transportation to heating to heavy industry – are likely to turn to it as they seek to decarbonize over the next few decades, with investments in the technology already soaring. Indeed, clean hydrogen will become a cornerstone of the energy transition and decarbonization efforts around the globe. → A

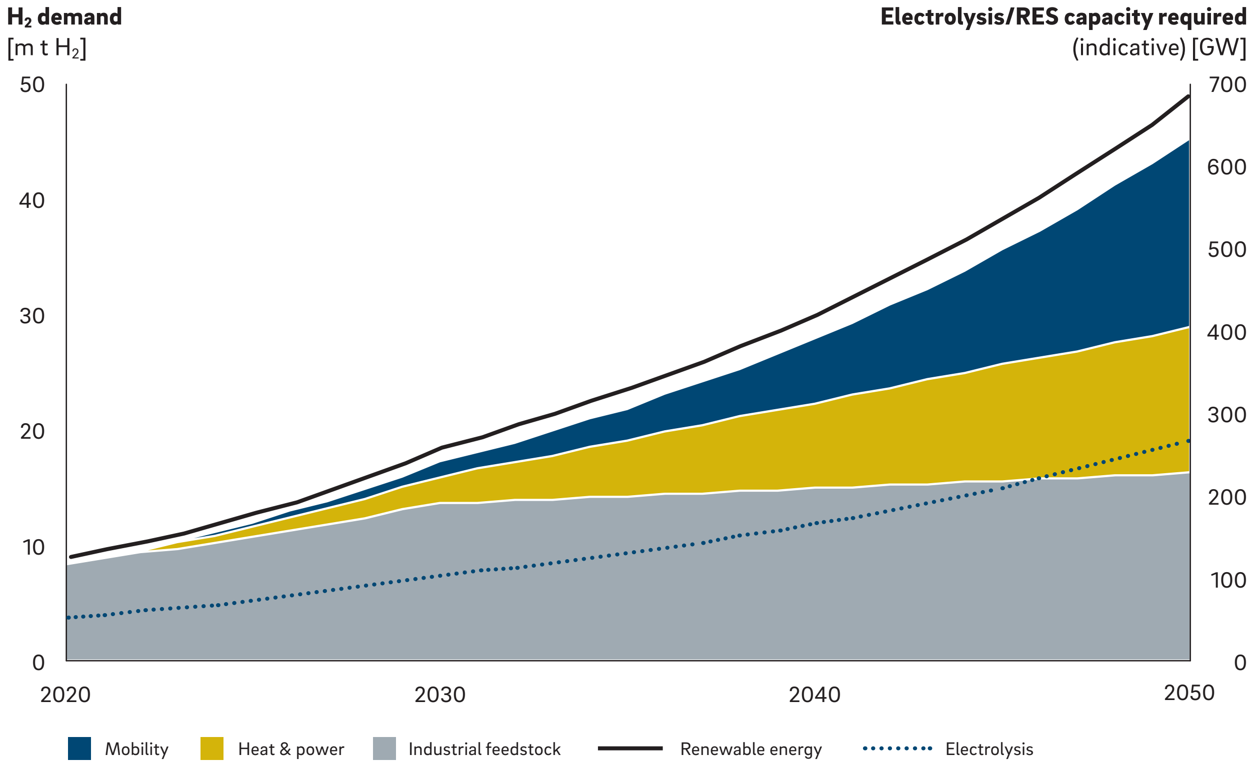
### INTRODUCING HYDROGEN TRANSPORTATION

Getting hydrogen from global production sites to end users at the lowest possible cost will be key to the success of the green economy. The potential for onsite green hydrogen production in European demand centers is limited. First, huge amounts of green electricity will be needed to power the hydrogen-producing electrolyzers. The conversion of the European steel industry to a more emission-friendly process by using hydrogen for the direct reduction of iron alone would require up to 10 m tons of hydrogen per year. Depending on the system efficiency, the production of green hydrogen for the steel industry would require roughly 60 GW of electrolysis capacity and 120-180 GW of renewable energy capacity. To put those numbers in perspective, Germany's total installed capacity of onshore and offshore wind power stands at 63 GW today. Second, the physical space required to achieve such capacities is substantial, especially in regions with less favorable conditions for renewables. Such space is rarely available. And third, the expansion of the electricity grid to transport such huge amounts of renewable energy is a difficult undertaking. Many ongoing high voltage grid projects face delays and those delays in fact hinder a faster renewable energy buildout in Europe.

## A: Hydrogen market

Demand in Europe will grow significantly, mainly driven by hydrogen's role in decarbonization

**$H_2$ DEMAND IN EUROPE BY SECTOR** [MT $H_2$] **AND REQUIRED ELECTROLYZER AND RES CAPACITY** [GW]




- $H_2$ is already a sizable market and is used as a feedstock in various industries
- Today's $H_2$ supply predominantly consists of gray $H_2$ produced from fossil sources
- Gray $H_2$ is expected to be replaced by decarbonized $H_2$, e.g. green $H_2$ produced from renewable energy sources
- Growth of $H_2$ demand is mainly driven by new applications and the use of decarbonized $H_2$ in the industry, heat & power, and mobility sectors
- Significant ramp-up of electrolysis and renewable energy capacity is required to meet the projected green $H_2$ demand

Source: Roland Berger

Therefore, green hydrogen will to a large extent be produced near the most cost-competitive renewable electricity hubs, for example the wind farms of the North Sea or solar parks of the Middle East. The difference in global production costs is substantial, varying by up to 250% between renewable resource abundant regions and less favorable regions. Even within the European Union, the cost differences are high, with a delta of more than 130% between Spain and Germany, for example.[1] → B

The hydrogen will then be shipped to areas of high demand by ground and sea transportation. But herein lies a major obstacle – large-scale conversion/reconversion and transportation of hydrogen is currently complex, energy intensive and expensive. While investments have poured into clean hydrogen, these have tended to focus on hydrogen production and end user applications. Transportation, as the "missing link", has been overlooked. Yet to ensure that clean hydrogen becomes economically competitive and widely adopted, new transportation solutions must urgently be found. This is particularly important as transportation costs can make up a significant part of final hydrogen costs – and therefore company bottom lines.

The key purpose of this report is to shed light on the potential of different existing transportation technologies to act as key enablers for the clean hydrogen economy. We focus specifically on the end-to-end transportation of hydrogen, rather than the transportation of hydrogen-based derivative products such as synthetic fuels directly to end users. As such, pipelines are considered but we focus on three flexible hydrogen carrier technologies: ammonia; liquefied hydrogen; and liquid organic hydrogen carriers (LOHC). This includes a comprehensive model comparing the cost of ownership of the technologies, based on four typical hydrogen transportation routes that are likely to emerge in the future. These range from large-scale harbor-to-harbor transportation from the Middle East to Europe to small-scale truck transportation up to 200 km.

Lastly, we offer recommendations for both government and industry players to improve infrastructure, reduce wider hydrogen costs and develop market rules. These make clear that policymakers, technology suppliers, project developers and energy companies need to take more dedicated action over the next few years to enable large-scale hydrogen transportation and make the clean hydrogen economy a reality.

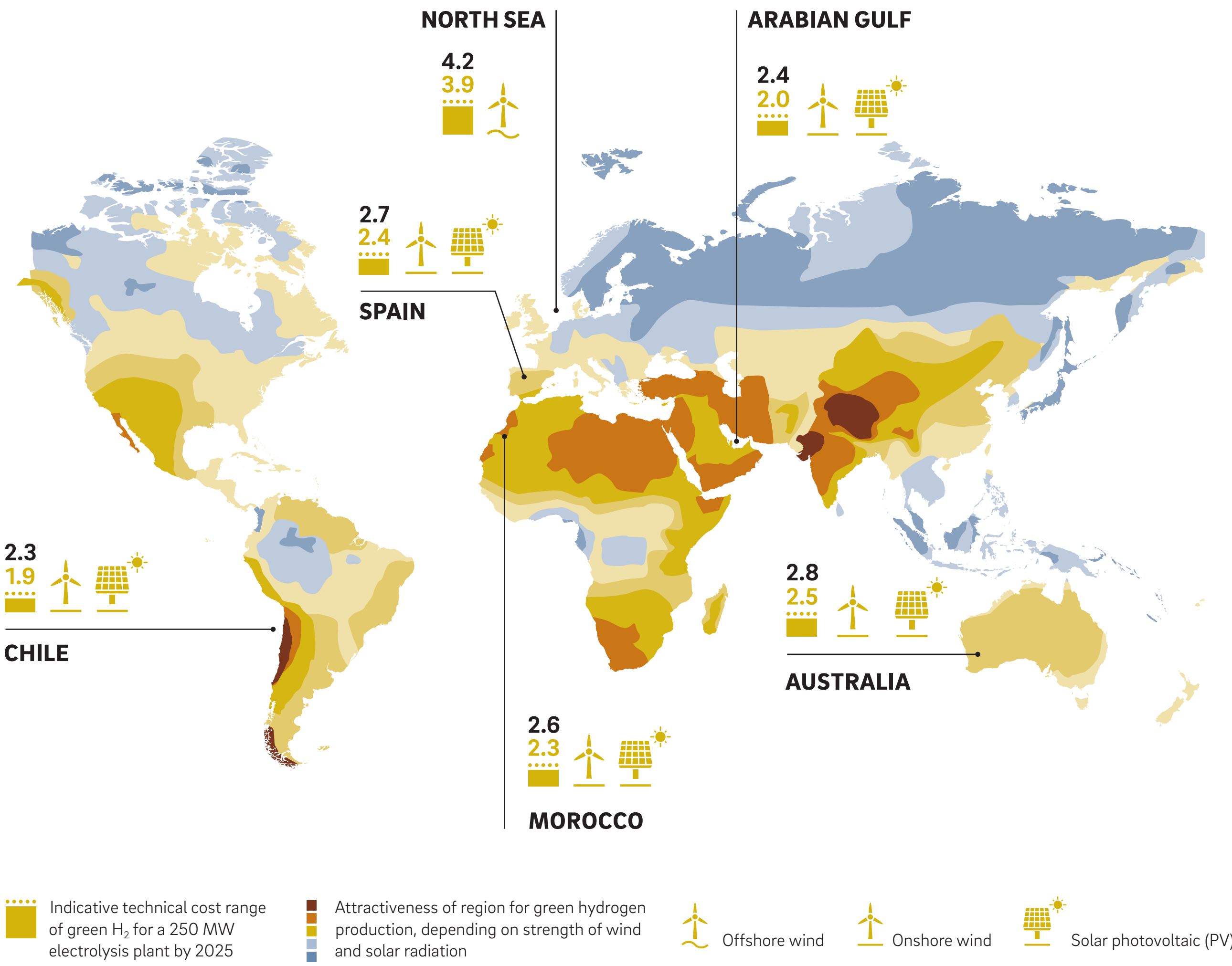
*So far, investments have tended to focus on hydrogen production and end user applications. Transportation, as the "missing link", has been overlooked.*

[1] IEA: The Future of Hydrogen

## B: Hydrogen production locations

Cost-competitive renewable electricity and green hydrogen production hubs are typically located distant from demand centers [EUR/kg]

INDICATIVE




Source: IEA, Roland Berger

# 1 / The technologies

## LARGE-SCALE HYDROGEN TRANSPORTATION OPTIONS EXPLAINED AND ASSESSED

To set up clean hydrogen supply chains and reap the low-cost potential of remote regions, there is an urgent need for viable, large-scale clean hydrogen transportation solutions. Four hydrogen transportation technologies have the highest potential: Pipelines that transport gaseous hydrogen; hydrogen transported as ammonia; liquefied hydrogen ($LH_2$); and hydrogen stored in liquid organic hydrogen carriers (LOHC). The three non-pipeline technologies are known as hydrogen carriers. Below we look at all four in detail.

### 1.1 PIPELINES (GASEOUS $H_2$)

**How it works:** Gaseous hydrogen can be transported in pipelines, like natural gas. Before injection, the hydrogen is mechanically compressed to the operating pressure of the pipeline. This is usually higher than the outlet pressure of electrolyzers. Depending on the pipeline's characteristics and local conditions, the hydrogen must be recompressed at certain distances along the pipeline before it reaches its destination. In addition, storage facilities (such as salt caverns or above-ground tanks) are required for buffering in case of volatile supply. As with natural gas pipelines, a mature hydrogen pipeline system with transmission and distribution grids also requires metering stations, control valves and gates to manage flows and ensure onward distribution to end users.

Instead of building new pipelines, existing natural gas pipelines can be repurposed to transport hydrogen. The injection of hydrogen into existing gas grids is also under discussion, with blends of up to 20% hydrogen currently being tested in pilot projects.

**Pros:** Hydrogen pipelines have low operational costs, long lifetimes and a proven record of successful operation in Europe and the US, often over several thousand kilometers. Pipelines can also act as a storage buffer, especially for off-grid green hydrogen production as their pressure can be adapted to ensure continuous supply – a key requirement for many offtakers. Compared to power cables, hydrogen pipelines have the additional advantage of a lighter environmental footprint. One pipeline can replace several cables that would need to be installed separately. The repurposing of existing pipelines is also advantageous in terms of public acceptance.

**Cons:** The high initial capital costs of new pipelines constitute a major barrier to expansion, and construction requires lead times exceeding ten years. It is also subject to highly complex permitting and authorization processes. The construction of cross-border pipelines involves additional complexity and cooperation. Large volumes of hydrogen are also necessary to achieve acceptable utilization rates. Moreover, due to the fixed routing, the many consumers that are not located along the pipeline cannot be supplied without additional investment in distribution infrastructure. In addition, unresolved regulatory questions, such as around natural monopolies, the combination with or separation from the natural gas grid and the allocation of cost to consumers, also create substantial uncertainty. Lastly, concerns remain about the viability of repurposing old natural gas pipelines due to material compatibility.

There's no doubt that pipelines are a low-cost option to deliver very large volumes of hydrogen and that they will play a major role in the supply of clean hydrogen in the future. However, even with a dedicated hydrogen pipeline in place, large residual hydrogen demand will go unsupplied due to its fixed routing and the high dispersion of large-scale hydrogen demand across geographies. The large consumers of today (fertilizer producers, refineries, other chemical plants, etc.) are widely distributed across Europe, and will be even more so in the future (for example, steel producers, e-fuel plants and mobility applications, smaller commercial users). In addition, pipelines will not be a feasible or the most cost-efficient option to support future import routes from outside the European Union. More flexible hydrogen transportation options will be needed to fill the gap and supply this part of the market.

This study therefore focuses on comparing the technologies that are best suited to flexibly supply potential offtakers not located along a pipeline grid, and that enable the long-distance transportation of hydrogen – hydrogen carriers. → C

## 1.2 AMMONIA

**How it works:** Ammonia ($NH_3$) is a bulk chemical that is normally synthesized from natural gas and mainly used as chemical feedstock, e.g. in fertilizer production. However, it can also serve as a clean hydrogen storage medium. The medium is produced by reacting hydrogen and nitrogen (derived from air via an air separation unit) to synthesize liquid ammonia, using a process that is very similar to the conventional production method (Haber-Bosch process). The liquid ammonia can then be transported in refrigerated tanks. Once it reaches its destination, the ammonia is broken down into its components, nitrogen and hydrogen, through an endothermic cracking process. The resulting gas mixture is then purified, and the nitrogen removed and released back into the atmosphere. Ammonia is already transported today, although most conventional ammonia is produced onsite at the place where it is further used.

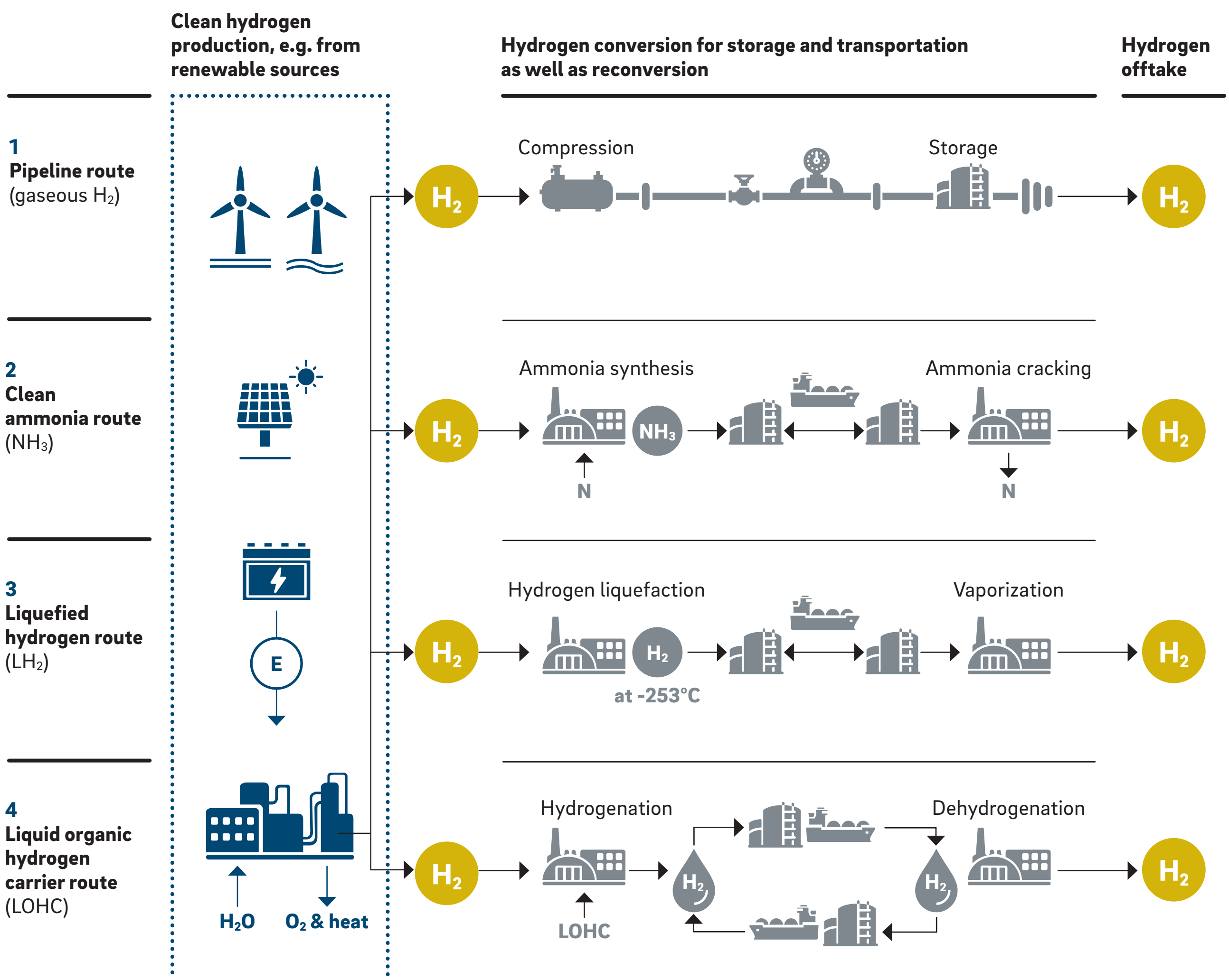
**Pros:** Ammonia synthesis is a well-established process and can be adapted to clean hydrogen where gray hydrogen is already used. This means that conventional ammonia production plants could potentially be retrofitted to produce clean ammonia. Even up until the 1960s, most fertilizers in Europe were produced from ammonia synthesized from hydropower-generated hydrogen. Production later shifted to natural gas when it became cheaper.[2] Due to the widespread use of ammonia as a chemical feedstock, the infrastructure for storing, transporting and handling the substance is already mature. And because it is a global commodity, standards already exist. Liquid ammonia also contains more hydrogen by volume than any of the other carriers discussed here.

**Cons:** Ammonia is a toxic fluid and precursor to air pollution as it forms particulate aerosols in the atmosphere. It can adversely affect human health as well as soil and water quality if released and its toxicity may ultimately limit the application for end uses outside large-scale industry. Due to the safety concerns, it is questionable whether authorities would permit the transportation and use of ammonia in populated areas. Major ports and seagoing vessels handling ammonia

*Due to the safety concerns, it is questionable whether authorities would permit the transportation and use of ammonia in populated areas.*

[2] IEA: Producing ammonia and fertilizers: new opportunities from renewables

## C: Leading carriers
The most common routes for large-scale hydrogen transportation




Source: Roland Berger

must also take extensive safety precautions against toxicity and explosion risks. In terms of production, Haber-Bosch plants cannot easily directly integrate an intermittent $H_2$ supply stream from renewable sources. The process is also energy intensive as high temperatures and pressures are required. In addition, the ammonia cracking process is at a very early stage of technological development. It has high energy needs and requires additional purification steps to make the hydrogen usable.

### 1.3 LIQUEFIED HYDROGEN ($LH_2$)

**How it works:** The volumetric storage density of hydrogen can be significantly improved through liquefaction, that is, cooling it below its boiling point of minus 253°C. After liquefaction, $LH_2$ is stored in specially insulated and double-hulled tanks. This limits heat transfer from the environment and subsequent losses due to evaporation, as built-up gas (boil-off) has to be vented. Under these conditions, $LH_2$ is already being transported via specially designed trailer trucks today. At the destination, $LH_2$ is usually vaporized into its gaseous form before use.

**Pros:** Liquefaction is a relatively well-established technology at small scale, does not require complex reconversion and provides high purity hydrogen to the end user. It is already used in certain special applications today, such as in the aerospace industry, and in some refueling stations.

**Cons:** The liquefaction process requires high amounts of energy due to both pre-cooling and the liquefaction process itself. Moreover, storage, handling and transportation of $LH_2$ are more complex compared to the other carriers. This is due to the specific storage conditions required to maintain the temperature below minus 253°C and limit convection, conduction and radiation. Boil-off losses can also become significant when $LH_2$ is stored and transported for long periods, resulting in lower flexibility in production and offtake patterns. In addition, large-scale $LH_2$ transportation via vessels is still in the prototyping phase, leading to substantial investment costs. In general, the infrastructure required for liquefied hydrogen is more capital intensive along the value chain in comparison to competing carriers.

### 1.4 LIQUID ORGANIC HYDROGEN CARRIERS (LOHC)

**How it works:** Liquid organic hydrogen carriers are easily transported chemical compounds that can be reversibly hydrogenated and dehydrogenated. The hydrogenation process involves chemically binding hydrogen to the liquid compound so that it can be transported at atmospheric pressure like many other oil-like substances. At the destination, the hydrogen is released via an endothermic (heat-requiring) dehydrogenation process. The dehydrogenated LOHC can then be transported back to the hydrogen source for reuse.

There are several organic carrier substances available, among which toluene, dibenzyltoluene and benzyltoluene (so-called heat transfer fluids) are the most common. Here we focus on benzyltoluene.

**Pros:** Benzyltoluene is easy and safe to store, transport and handle. It has good viscosity characteristics under ambient pressure and temperatures (even in cold conditions), much like diesel. This similarity enables the use of existing infrastructure, such as trucks, trailers and vessels, as well as storage containers. In addition, hydrogenated LOHCs do not incur hydrogen losses, allowing long storage durations and storage of large volumes. The LOHC hydrogenation process is also better able to integrate fluctuating hydrogen $H_2$ supplies from intermittent renewables compared to ammonia and $LH_2$.

**Cons:** The dehydrogenation of LOHC requires very high temperatures, pushing up energy costs. Large volumes of LOHC liquid are also required for the large-scale import and transportation of hydrogen, adding to capital costs and requiring the upscaling of production capacities. Furthermore, the production process of the carrier creates an additional $CO_2$ footprint, with the impact per unit of hydrogen dependent on the number of cycles the LOHC can perform. The long-term viability of LOHC in a real-life environment is also yet to be proven, although demonstration projects around the world point in a positive direction. → D

## D: Carriers compared

The main characteristics of the leading hydrogen transportation technologies

| Main characteristics | | Ammonia | Liquefied hydrogen | LOHC (benzyltoluene) |
|---|---|---|---|---|
| **Storage density** | Volum. [kg $H_2/m^3$ of carrier] | 121.2[1] | 70.8 | 55.2 |
| | Gravim. [kg $H_2$/t of carrier] | 177.5[1] | 1,000 | 62.7 |
| **Energy needs** | Conversion [MWh/t $H_2$] | 5.75 | 12.0 | 0.5 |
| | Reconversion [MWh/t $H_2$] | 11.2 | 0.6 | 15.0 |
| **Technological and process maturity** | Conversion – Small scale | ■■■ | ■■■ | ■■□ |
| | Conversion – Large scale | ■■■ | ■□□ | ■□□ |
| | Storage | ■■■ | ■■■ | ■■■ |
| | Transportation – Ship | ■■■ | ■□□ | ■■■ |
| | Transportation – Rail | ■■■ | ■□□ | ■■■ |
| | Transportation – Truck | ■■■ | ■■■ | ■■■ |
| | Reconversion | ■□□ | ■■■ | ■■□ |
| **Operational value propositions** | Advantages | • High storage capacity<br>• Mature value chain, except for cracking process | • No reconversion required<br>• High purity hydrogen | • Easy to store and transport (diesel-like liquid)<br>• Use of existing infrastructure |
| | Disadvantages | • Additional purification step needed<br>• High energy requirements for cracking process | • Boil-off losses along value chain<br>• High energy requirements for liquefaction<br>• Storage and transport complexity | • Number of cycles impact environmental footprint<br>• High energy requirements for dehydrogenation |
| | Safety | • Acute toxicity, flammable, explosive under heat, toxic to aquatic life | • Highly flammable with no visible flame, can form explosive mixtures with air | • Low toxicity, non-explosive, hazardous to aquatic environment |

[1] Properties of liquid ammonia

■■■ Proven & commercial ■■□ Prototype demonstrated ■□□ Technology validated or under development

Source: IEA, Roland Berger

# 2 / The costs

## A COMPARISON OF HYDROGEN TRANSPORTATION TECHNOLOGIES IN 2025 AND BEYOND

**OUR COST COMPARISON MODEL**

In addition to the practical pros and cons of hydrogen carriers, this report also compares the total cost of ownership (TCO) of the three technologies. We developed a model to estimate TCO in 2025, built around four scenarios with different routes, distances, transportation modes and scales (see box for more details). The technologies were tested in each of the four archetypes and compared, ensuring a level playing field.[3] In each archetype, the TCO comprises the costs of the following process: conversion – storage – transportation (via different modes) – storage – reconversion. The results are detailed in part A of this chapter. In part B, we consider the cost outlook for 2025 to 2035, focusing on areas likely to achieve significant cost reductions. → E

[3] Necessary safety installations that vary across technologies have not been considered. Costs can change once adapted to a specific use case taking specific locations, customer requirements and full scope of interfaces into account

**METHODOLOGY**

### The four archetypes

**1. Large-scale harbor-to-harbor:** The first archetype imagines the large-scale transportation of hydrogen from large conversion plants in the Middle East, with a hydrogen capacity per carrier of 200 tons per day (tpd). The carrier is then transported by sea vessel from the Arabian Gulf to Rotterdam. It is assumed that both ports have large-scale storage facilities. The offtake and reconversion of the carrier takes place in the port of Rotterdam, with a capacity of 100 tpd.

**2. Mid-scale multimodal transportation:** This archetype supposes the transportation of hydrogen from Romania to Germany by inland waterway and train, via a transshipment in Vienna, Austria. The added complexity of transshipment was introduced here and in archetype 3 to better model the reality of hydrogen supply chains. Conversion capacity is 20 tpd for each carrier. The reconversion capacity at the point of destination is 20 tpd for each carrier.

**3. Small-scale multimodal transportation:** The third archetype involves the transportation of the carrier via rail and truck from Italy to a 200 km radius around Innsbruck, Austria. The same amount of hydrogen is transported as in archetype 2, with the same conversion capacity of 20 tpd per carrier. But the offtakers are smaller and reconversion capacity is only 1.5 tpd.

**4. Small-scale truck-only transportation:** The final archetype considers a local supply scenario via truck. Conversion capacity and overall hydrogen production is the same as in archetypes 2 and 3, but the transportation distance is shorter and no transshipment or additional storage is needed. At the destination, the hydrogen is reconverted at a capacity of 1.5 tpd for each carrier.

**Key assumptions**

- In all cases, it is assumed that the transportation vessel (ship, train, truck) returns empty to the port of origin, or in the case of LOHC, with the dehydrogenated carrier.
- All vessels are assumed to be dedicated to hydrogen transportation and are individually sized for each respective technology (taking safety margins into account).
- In all cases, adequate storage facilities are assumed at the points of departure and destination, and, where relevant, the point of transshipment.

## E: Every which way

An overview of the four archetypes used in our cost-comparison model

### ARCHETYPE 1:
### Large-scale harbor-to-harbor


| | |
|---|---|
| **$H_2$ p.a.** | 73,000 t |
| **Conversion capacity**[1] | 2 x 100 tpd |
| | Storage capacity at each location, size dependent on carrier |
| | ~12,000 km via vessel (one-way) |
| | ~46 days per round trip (incl. port days) |
| **Reconversion capacity**[1] | 100 tpd |
| | Large-scale offtakers (e.g. refineries, fertilizer, steel) |

### ARCHETYPE 2:
### Mid-scale multimodal transportation


| | |
|---|---|
| **$H_2$ p.a.** | 7,300 t |
| **Conversion capacity**[1] | 20 tpd |
| | Storage capacity at each location, size dependent on carrier |
| | ~1,428 km via vessel + ~350km via train |
| | ~12 days per round trip (vessel) + ~0.8 days (train) |
| **Reconversion capacity**[1] | 20 tpd |
| | Mid-scale offtakers (e.g. industry for gradual gray $H_2$ replacement) |

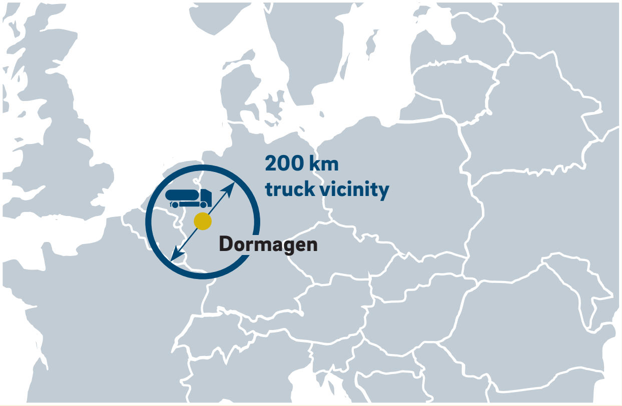
[1] In tons per day (tpd)

Source: Roland Berger

**ARCHETYPE 3:**
**Small-scale multimodal transportation**


| | |
|---|---|
| **$H_2$ p.a.** | 7,300 t |
| **Conversion capacity[1]** | 20 tpd (14x 1.5 tpd) |
| | Storage capacity at each location, size dependent on carrier |
| | ~800 km via train + ~200 km via truck |
| | ~1.1 days (train) + truck trip |
| **Reconversion capacity[1]** | 1.5 tpd |
| | Small-scale offtakers (e.g. HRS, SOFC) |

**ARCHETYPE 4:**
**Small-scale truck-only transportation**




| | |
|---|---|
| **$H_2$ p.a.** | 7,300 t |
| **Conversion capacity[1]** | 20 tpd (14x 1.5 tpd) |
| | Storage capacity at each location, size dependent on carrier |
| | ~200 km via truck |
| | <1 day |
| **Reconversion capacity[1]** | 1.5 tpd |
| | Small-scale offtakers (e.g. HRS, SOFC) |

## COSTS IN 2025

### ARCHETYPE 1

Ammonia and LOHC have a very similar TCO for hydrogen transportation. Both are within a range of 2.2 to 2.3 EUR per kilogram of hydrogen, making them the lowest-cost options. In the case of ammonia, reconversion (cracking it back into hydrogen) makes up more than one third of its overall cost. This shows that clean ammonia could be especially attractive to decarbonize the sectors where it is already used as a bulk chemical derived from natural gas, instead of using it as a hydrogen carrier. With LOHC, the large volumes of carrier required to store and transport the hydrogen, combined with the long distance involved in this archetype, increase its capital expenditures.

Transportation via $LH_2$ is the most expensive technology, with TCO for hydrogen transportation of 2.8 EUR/kg. The major contributing factors are the boil-off due to long storage times both on the vessel and onsite, the high amounts of energy required for liquefaction and the relatively capital-intensive large-scale liquefaction plants and other infrastructure compared to the other carriers.

The so-called landed cost of hydrogen, which comprises the TCO for hydrogen transportation plus production costs, gives an idea of total overall costs of hydrogen. We assume production costs for all carriers of 2.0 EUR/kg. This archetype therefore suggests that the landed cost of hydrogen for large-scale, imported clean hydrogen could reach 4.2 to 4.8 EUR/kg in 2025, depending on the carrier method. → F

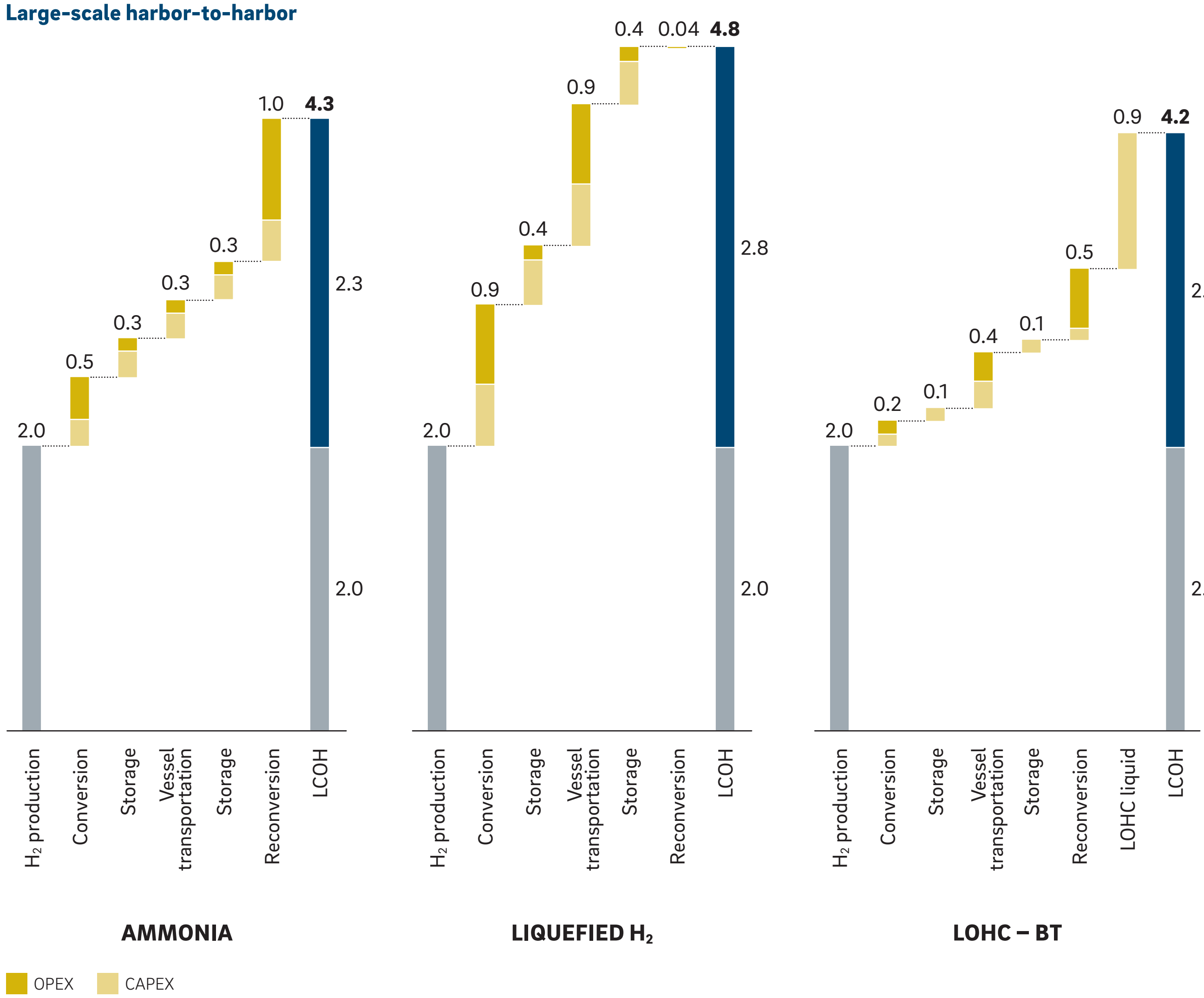
### ARCHETYPE 2

LOHC is the cheapest option for this archetype, benefiting from its ease of storage and handling in multimodal transportation. Yet its TCO for hydrogen transportation is slightly higher than for archetype 1, at 2.4 EUR/kg, due to smaller economies of scale. Using ammonia as a carrier also turns out to be more costly, with a TCO of 3.1 EUR/kg. A key factor here is ammonia's more expensive transportation costs compared to LOHC. $LH_2$ is again the most expensive option, at 4.7 EUR/kg. Storage and transportation alone contribute more than 50% to the overall cost, pushed up by the long journey duration and the need for storage along the way as well as when transloading the $LH_2$ to the next transportation medium.

*Clean ammonia could be especially attractive to decarbonize the sectors where it is already used as a bulk chemical derived from natural gas, instead of using it as a hydrogen carrier.*

**F: Carrier break down**
The landed cost of hydrogen, incl. production, storage and transportation for archetype 1 in 2025 [EUR/kg $H_2$]

**ARCHETYPE 1:**
**Large-scale harbor-to-harbor**




Source: Roland Berger

**ARCHETYPE 3**

Ammonia and LOHC again have a very similar TCO of 2.8 EUR/kg. While ammonia synthesis and its subsequent transportation are more expensive than LOHC due to greater handling and storage complexity, ammonia profits from a lower reconversion cost. For LOHC, dehydrogenation is the major cost driver, contributing more than 60% to the overall TCO. Energy use and cost of dehydrogenation can be optimized if heat produced from other processes is used.

$LH_2$ costs in this archetype are higher than the other two carriers but lower than in archetype 2, at 3.5 EUR/kg. The main reasons are the smaller storage requirements and lower travel time (more than 12 days in archetype 2, less than 2 days in archetype 3), which result in lower storage costs and lower daily boil-off losses. At the same time, the small offtaker in archetype 3 is more continuously supplied, so does not have the same large storage requirements as in archetype 2.

**ARCHETYPE 4**

In this scenario, $LH_2$ is the cheapest transportation option at 2.1 EUR/kg, followed by LOHC and ammonia at 2.2 EUR/kg. Due to the short distance and consequently shorter travel time, the storage and transportation costs in this case are not the major cost drivers, as in the other scenarios. Instead, the conversion and reconversion costs play the significant role. As the vaporization of $LH_2$ is not cost intensive, it has a cost advantage in this archetype. → G

## CONCLUSIONS: IS THERE A "WINNER"?

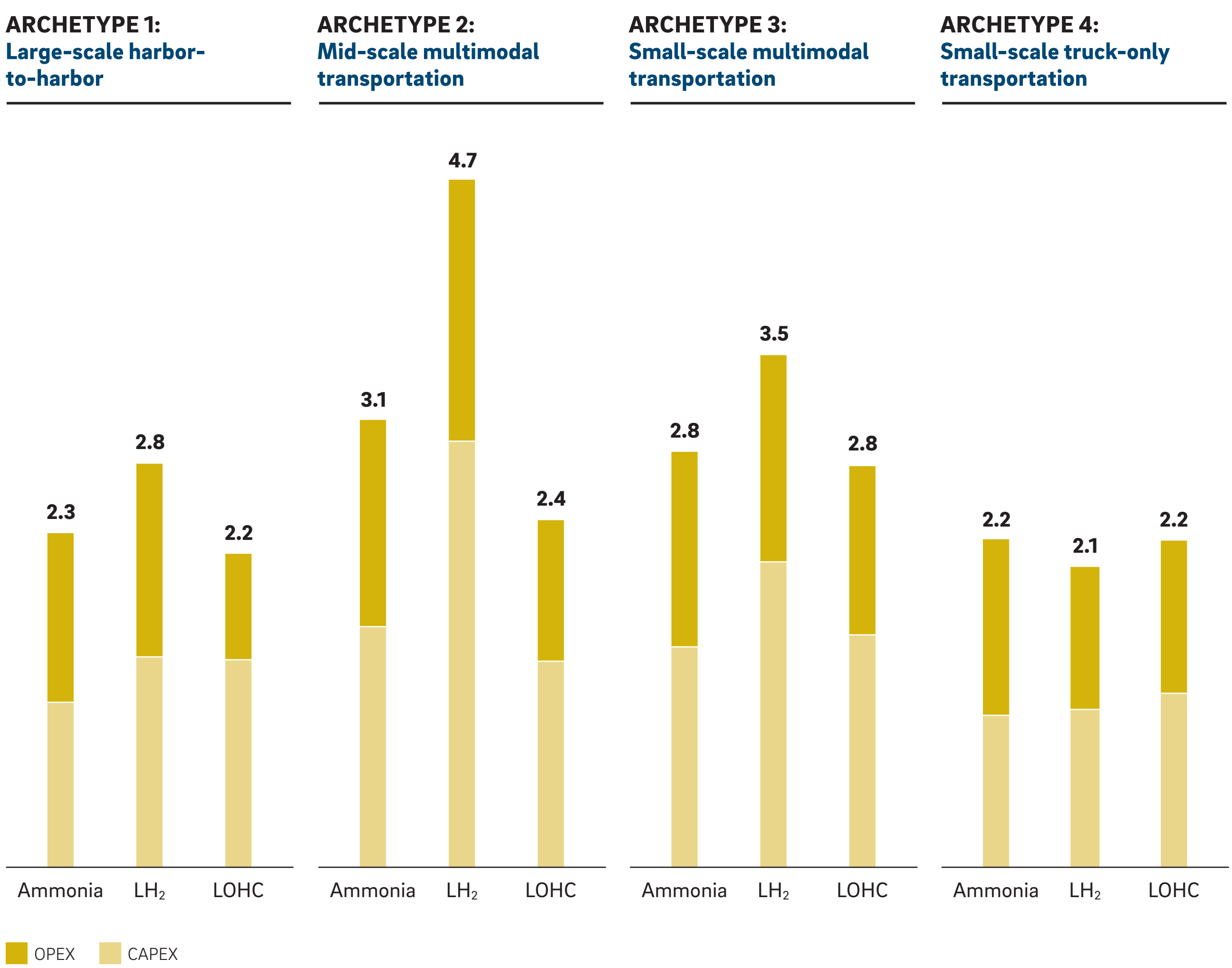
The model shows that there is no one single carrier that best fits all of the transportation archetypes analyzed. So, in real-life scenarios, the operational value proposition of a carrier must be weighed up in addition to comparing the costs of each carrier.

For example, although $LH_2$ has the highest costs, it might still be the favored solution in cases where high-purity hydrogen is required and reconversion at the offtaker's site is not possible or wanted. And although ammonia is a low-cost option for small-scale multimodal transportation, there will likely be safety regulations in place that limit its application or increase the overall cost for ammonia, making LOHC the better option. Heat integration of existing sources at the offtaker might also bolster the case for using ammonia and especially LOHC and could lead to lower required temperatures. Ultimately, the best option for a specific supply route needs to be determined on a case-by-case basis according to individual circumstances.

*There is no single carrier that best fits all of the transportation archetypes. In real life scenarios, the operational value proposition of a carrier must be weighed up in addition to comparing the costs of each carrier.*

**G: Costs in 2025**

Comparison of total cost of ownership for hydrogen transportation by archetype and carrier [EUR/kg $H_2$]




Source: Roland Berger

## H: Costs in 2035

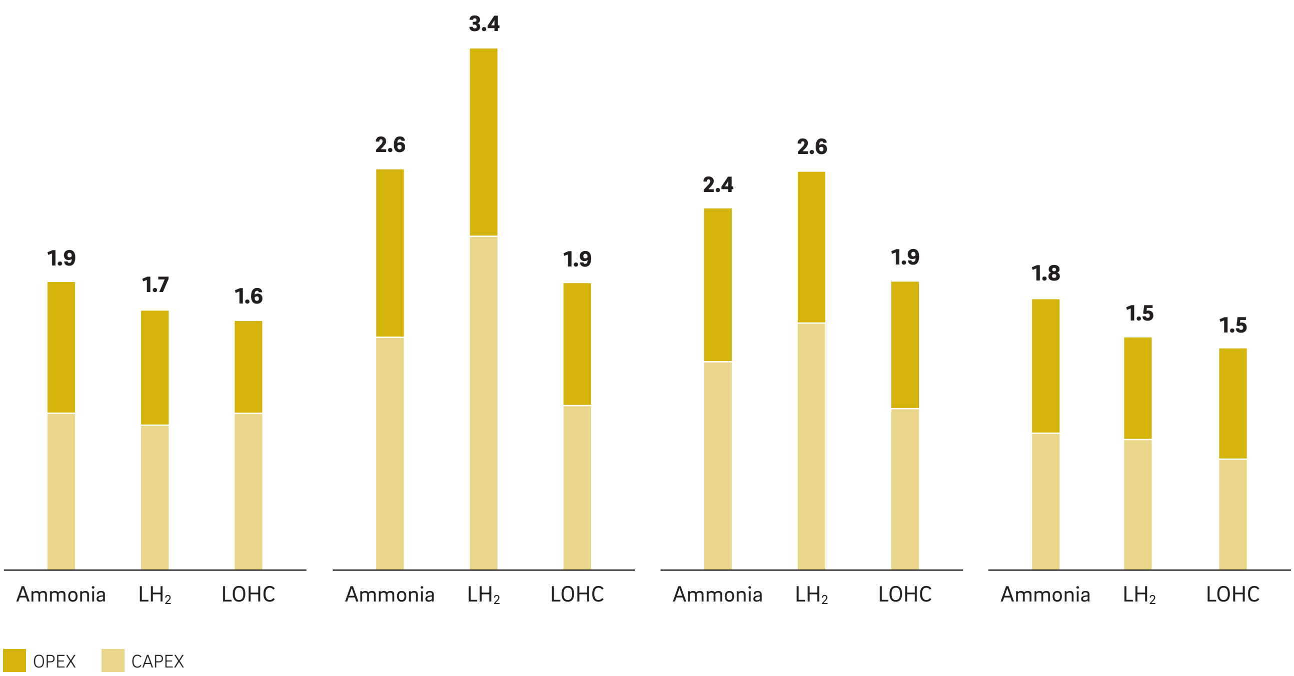
Comparison of total cost of ownership for hydrogen transportation by archetype and carrier [EUR/kg $H_2$]

**ARCHETYPE 1:** **Large-scale harbor-to-harbor**

**ARCHETYPE 2:** **Mid-scale multimodal transportation**

**ARCHETYPE 3:** **Small-scale multimodal transportation**

**ARCHETYPE 4:** **Small-scale truck-only transportation**




Source: Roland Berger

## COST OUTLOOK FOR 2025-2035

Assuming a fast scale-up of the hydrogen transportation market, all carriers will experience significant cost reductions in the coming decades. Substantial cost improvements can be expected for the relatively new LOHC technology, as scale and learning effects materialize. A combination of increasing equipment production volumes, economies of scale for bigger plants, reductions in the cost of the carrier substance and technological improvements in terms of materials, plant efficiency and standardization for both hydrogenation and dehydrogenation plants all bode well. They could see the landed cost of hydrogen for large-scale imports to Rotterdam fall as low as 2.6 EUR/kg in 2035 (versus 4.2 EUR/kg in 2025), assuming production costs of 1.0 EUR/kg. → H

A different cost development path is to be expected for ammonia. Its synthesis is already a well-established and fully commercial process, meaning cost reductions related to conversion, storage and transportation may be limited. However, major cost reductions can be expected from the additional cracking and purification part of the value chain when ammonia is used as a hydrogen carrier, as well as reductions in energy needs.

A decrease in investment costs as well as energy needs is also expected for the liquefaction of hydrogen. However, effects are expected to be lower than in the LOHC value chain and ammonia cracking due to the use of the technology already being relatively widespread. In addition, significant reductions in investment costs for $LH_2$ storage are already factored in, including transportation and stationary storage, and an improvement in boil-off losses. → I

The full commercialization of the carrier technologies will be accompanied by cost reductions in their respective conversion and reconversion plants. This means that the direct costs of transporting the carriers (storage, transportation and handling) will become increasingly important for the overall cost profile. LOHC has an inherent operational advantage here compared to the other carriers. This becomes particularly apparent in the 2035, full-commercialization scenario. Here, conversion and reconversion costs will have decreased substantially and LOHC's particular cost advantages when looking at more complex and storage-intensive transportation routes (archetype 2 and 3) will become clearer.

*The full commercialization of all available carrier technologies will be accompanied by cost reductions in their respective conversion and reconversion plants.*

## I: Cutting costs

Assumed carrier cost reduction drivers along the value chain, between now and 2035

| $H_2$ VALUE CHAIN | $H_2$ CARRIERS: Ammonia | $H_2$ CARRIERS: $LH_2$ | $H_2$ CARRIERS: LOHC |
|---|---|---|---|
| Conversion | Ammonia synthesis via Haber-Bosch process fully commercialized and used at large scale | Decrease in investment cost[1]<br>Decrease in energy needs | Decrease in investment cost<br>Decrease in electric energy needs |
| Storage and transportation | Storage and transportation of ammonia fully commercialized and available at large scale | Decrease in investment cost for large-scale stationary storage, vessels and trains<br>Decrease in investment cost for small to mid-scale stationary storage and trucks | LOHC can use existing infrastructure from conventional and fully commercialized products |
| Reconversion | Decrease in investment cost<br>Decrease in electric energy needs<br>Decrease in thermal energy needs | Well-known and simple process with limited cost reduction potential<br>Reduction of boil-off losses along the entire value chain | Decrease in investment cost<br>Decrease in electric energy needs<br>Decrease in thermal energy needs |

0% to -10% | -10% to -25% | -25% to -40% | More than -40%

[1] For large-scale liquefaction plants (200 tpd)

Source: Roland Berger

# 3 / The challenges

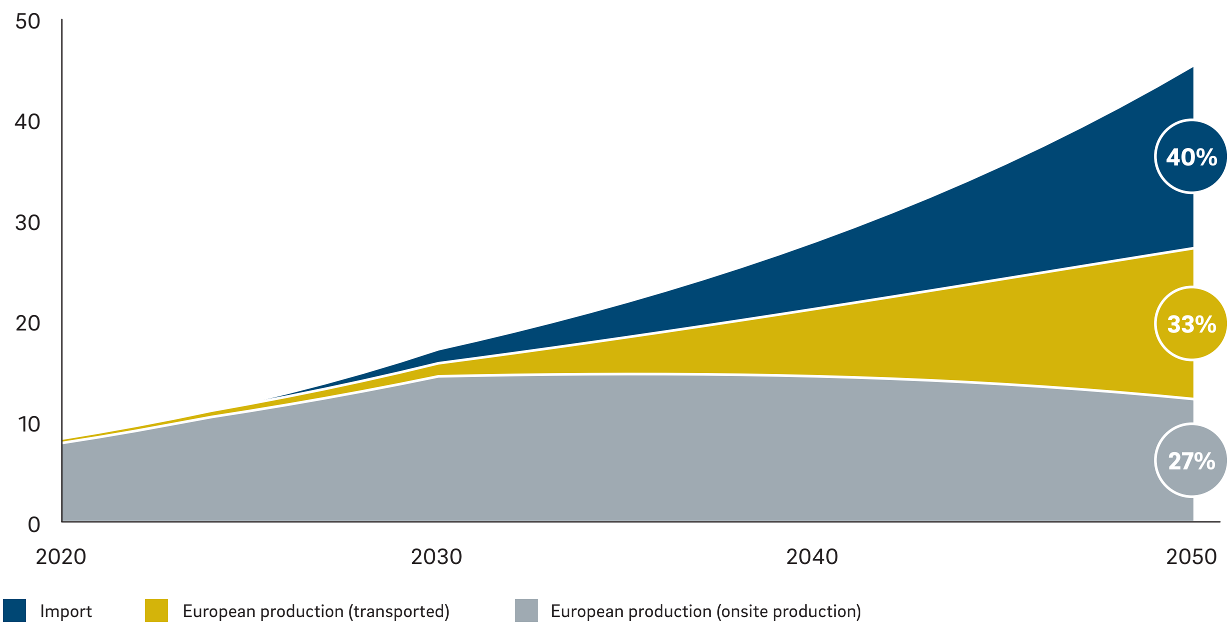
## VIABLE HYDROGEN TRANSPORTATION REQUIRES HUGE INFRASTRUCTURE INVESTMENT

Today, only a small amount of the hydrogen produced in Europe (conventional or from renewables) is transported. Rather, most is produced onsite from natural gas for cost and logistics reasons. But our TCO results show that transporting hydrogen from non-European renewable resource abundant regions with low hydrogen production costs can be economically attractive by 2025. The same applies to intra-European transportation. Indeed, if sufficient amounts of clean hydrogen cannot be produced onsite, or production costs are greater than 4.0 EUR/kg, transporting hydrogen could be the preferred option.

It's not just the TCO results that point to the future economic viability of hydrogen transportation. In the coming decades, two trends will contribute to the overall development of the transportation market. First, demand for clean hydrogen from new sectors will increase, and second, clean hydrogen will need to replace the primarily gray hydrogen produced onsite today. The European Union's Hydrogen Strategy, announced in 2020, aims to mobilize support and stimulate investment to build a full-fledged hydrogen ecosystem from 2025. Presuming it is realized, the hydrogen transportation sector will develop and deliver clean hydrogen in growing quantities. We estimate these will reach more than 800,000 tons from 2025 onwards, initially due to intra-European

**J: On the up**

Projected hydrogen demand in Europe by supply route [m t $H_2$]




Source: Roland Berger

transportation and then increasingly from non-EU imports. After 2030, assuming additional regulatory pressure on $CO_2$-emitting sectors, transported clean hydrogen will reach a price level that is competitive enough to enable large industrial offtakers to decarbonize on a large scale by replacing onsite production with transported clean hydrogen. → J

As we saw in the cost model, no hydrogen transportation technology has clear advantages over its rivals. All options still need to be proven on a large scale and have differing needs in terms of technological maturity, operational performance, efficiency and costs. It seems likely that different hydrogen transportation technologies will continue to be present in the market during the ramp-up and scaling phase. Which technology will eventually come out on top largely depends on the speed of market uptake in the coming years, the ability to significantly bring down costs and whether it proves a safe and easy-to-operate solution.

No matter which technologies survive, achieving decarbonization will require massive investment, especially in hydrogen production (to increase green electrolyzer capacities) and renewable energy sources. This must be targeted at regions with the highest renewables potential both in Europe and beyond. It is therefore understandable that current investment discussions are largely focused on these upstream issues, as well as enabling offtake downstream. But it must be remembered that hydrogen-driven decarbonization will not be possible without midstream transportation. In the coming years, major investments in the transportation infrastructure are required to enable a hydrogen economy at scale. Thus, the transportation and storage components of the full hydrogen value chain require much more attention if the hydrogen economy is to be scaled up.

So, the question is, how can governments and industry further advance transportation technologies, and what actions and investments are required?

**INFOBOX**

## Not green yet: Hydrogen's $CO_2$ footprint

Even when hydrogen is produced via electrolysis from 100% renewable electricity, it is not necessarily 100% green from an end-to-end perspective. Emissions can still arise from conventionally powered conversion and reconversion processes, for example, as well as vehicle/ship transportation and the production of transportation vectors (steel pipes, LOHC materials etc). But the $CO_2$ footprint of hydrogen is becoming increasingly important to offtakers, who want their hydrogen to be as green as possible – and are prepared to pay more if it is greener than other options.

The $CO_2$ footprint of hydrogen greatly depends on the specific requirements of the project and processes for which it is being used. These include the location, transportation carrier and method, energy supply and where most energy is needed in the value chain. This means many opportunities exist to lower the $CO_2$ footprint. For example, in the case of liquefied hydrogen, most energy is needed upstream to liquefy the hydrogen (which takes place where the hydrogen is produced). Additional renewable resources could therefore be used to supply the necessary energy for liquefaction. This could mean lower emissions than using ammonia or LOHC as transportation carriers if, for instance, they rely on natural gas or "gray" grid access to crack the ammonia or dehydrogenate the LOHC at the point of destination.

In the future, it will be obligatory to fully understand and minimize a project's $CO_2$ footprint. Regulation will play a decisive part here, as will potential future certification schemes for clean hydrogen. However, as yet, the setup of the certification process is still ongoing (e.g. via the CertifHy project in the EU), and unless global standards are drawn up, rules may differ from region to region.

# 4 / Recommendations

## WHAT GOVERNMENT AND INDUSTRY MUST DO TO ENABLE LOW-COST HYDROGEN TRANSPORTATION

Policymakers, technology suppliers, project developers and energy merchants will all need to take dedicated action in the coming years to meet the goals of cost-efficient, low-carbon hydrogen transportation technologies, a successful hydrogen economy and, through them, decarbonization. Here we make six recommendations for government and industry.

### GOVERNMENT

**1.**

**Governments must strongly encourage further research and development of all hydrogen carriers to realize a cost-efficient supply for all offtakers and applications**

Policy decisions will play a key part in setting the course to efficiently leverage large-scale hydrogen transportation technologies.

Liquid $H_2$, LOHC and ammonia reconversion are not yet deployed at industrial scale. The envisaged cost reductions can only materialize if significant further R&D investments take place in the short term.

**2.**

**Public financing must be used to fund anchor projects, helping to cut hydrogen transportation costs and develop hydrogen markets**

Current market development is driven by captive projects. These are integrated supply chains that de-risk both the required upstream large-scale investments in renewables and electrolyzers and midstream transportation by obtaining captive, long-term offtake agreements. For example, in Europe, so-called "Important Projects of Common European Interest" (IPCEI) will become the major contributors to intra-European, clean hydrogen supply. Similar captive projects are being developed in the Middle East (with a focus on supplying Europe and Asia), in the Asia- Pacific region and South America. These projects will need support in the form of direct CAPEX and OPEX subsidies to close the economic gap that results from comparatively high clean hydrogen production and transportation costs and today's willingness to pay for clean products.

In a mid- to long-perspective, policy and regulation must create a level playing field for clean hydrogen. Quotas for industry and heavy duty transportation sectors can stimulate demand for clean hydrogen, and tighter $CO_2$ regulation must make the use of fossil-based solutions more expensive. This will enable the development of international merchant markets for hydrogen as a clean commodity, as happened in the global LNG market.

**3.**

**Enabling market rules must be urgently put in place to trigger necessary investment in hydrogen transportation infrastructure and carrier technologies**

The setting of global standards for hydrogen transportation via the different carrier options will ensure a safe, efficient and transparent level playing field for cross-national projects. These standards need to define the product quality as well as safety and environmental requirements. First movers in the sector who establish large-scale hydrogen import/export hubs, port clusters or industrial hubs will be able to create standards that will set the scene for the coming decades. These standards will also be the enabler for the diversification of hydrogen imports and resulting security of supply.

## INDUSTRY

### 4.

### Industry needs to increase its engagement in hydrogen transportation, and prepare for the industrial ramp-up of the carrier technologies

Large-scale hydrogen transportation is a new field of business for energy companies and merchants, as well as logistics companies, offering tremendous opportunities with further hydrogen market uptake. But the sector is not yet commercially developed, and requires considerably more investment from businesses.

Established energy and technology players should study and eventually deploy the new hydrogen transportation technologies in the integrated clean hydrogen supply chain projects that are currently in the making. New players will emerge and take a pioneering role to push the deployment of the new technologies.

### 5.

### Carrier providers need to focus on improving their efficiencies, integrating clean energy intakes and managing the more volatile energy supplies of renewable sources

The gaining of efficiencies is especially important around the energy-intensive carrier conversion and reconversion processes, which often contributes a major part of a carrier's overall cost. Also key are green options for energy intake and integrating plants with off-grid electrolyzers, which might have volatile production patterns.

### 6.

### Businesses that move fast and quickly gain experience will be able to better position themselves in the market and set market standards

Early movers might be able to secure advantageous positioning by leveraging first operational experiences, realizing cost reductions. In addition, the hydrogen transportation segment provides excellent growth perspectives for strategic investors that engage early on and secure a strategic market position. Financial investors have shown increasing interest in this new field of activity and are prepared to take a co-investment role.

# CREDITS AND COPYRIGHT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