SCIENCE FOR POLICY BRIEFS

Assessment of Hydrogen Delivery Options

Context

The recently launched European Hydrogen Strategy [1] recognises the important role that the transport of hydrogen will play in enabling the penetration of renewable hydrogen in Europe. Several Member States have published national hydrogen strategies [2], with some of them looking at the importation of hydrogen. For example, a bilateral agreement was signed recently to investigate the scope for Germany to import hydrogen produced from solar power in Australia. The development of an infrastructure connecting areas rich in renewable energy with areas with high demand for hydrogen will need significant investment and should therefore be planned in a sound manner. As there are multiple options available, it is necessary to investigate their advantages and disadvantages, in order to guide infrastructure development along the most effective path.

To implement the European Hydrogen Strategy it is important to understand whether it is cost effective to produce renewable hydrogen where renewable electricity is cheap and then to transport the hydrogen to the customer, or it is better to produce the renewable hydrogen close to the demand location. If transporting hydrogen makes sense, a second open question is how long the transport route should be for the cost of the hydrogen to still be competitive with locally produced hydrogen. JRC has performed a comprehensive study regarding the transport of hydrogen. This policy brief summarises the key findings.

Introduction

To achieve the objectives of the EU Hydrogen Strategy, access to sufficient amounts of renewable hydrogen at low cost will be essential in the coming years. The cost of hydrogen is determined by its production costs and its delivery costs. This study assesses the delivery cost of large amounts of renewable hydrogen over long distances.

The cost of producing renewable hydrogen in a specific location is influenced by the type of renewable energy sources available and their associated capacity factor. The cost of hydrogen delivery depends on the amount of hydrogen transported, the transport distance, the transport means used and the state in which hydrogen is transported (the 'packaging' mode). *In this brief, 'packaging' is used when referring to the form in which hydrogen is being delivered. 'Packing' refers to the compression or liquefaction of hydrogen or its conversion to a chemical carrier. 'Unpacking' means reversing that process in order to have purified, gaseous hydrogen at a defined pressure and purity at the use site.*

The packaging modes included in this study are: compressed hydrogen, liquefied hydrogen and chemical hydrogen carriers (ammonia (NH_3) and liquid organic hydrogen carriers (LOHC)). Methanol is not considered here because CO_2 is emitted when it is used. Offsetting these emissions through direct air capture of the carbon atoms used to make the methanol increases costs considerably compared to all the other options considered here.

Packing takes place in compression or liquefaction plants, or in chemical reactors for LOHC hydrogenation and ammonia synthesis. The main options included in this study for transporting hydrogen to a demand location are ships and (in the case of compressed hydrogen) pipelines. Trains and trucks are also considered when assessing hydrogen delivery cases where a distributed network of hydrogen demand locations is present. .

Following transport, unpacking is used to extract and/or process hydrogen, delivering it in a form that meets the purity and pressure requirements of its final use. Unpacking will require equipment such as compressors, pumps and/or evaporators, dehydrogenation reactors (for LOHC) or ammonia cracking plants. Additionally, purification systems may be necessary in this step.

Scope and methodology

To investigate which renewable hydrogen delivery pathways are favourable in terms of energy demand and costs, JRC has developed a database and an analytical tool to assess each step of the pathways, and used it to assess two case studies.

Case A is based on the delivery of 1 million tons of renewable hydrogen per year to a single industrial customer, via a simple transport pathway, through a dedicated pipeline or shipping route. The transport distance considered in case A is 2,500 km.

Case B intends to model a more complex delivery route. 100,000 tons of renewable hydrogen per year are delivered to a network of 270 hydrogen refuelling stations (HRS), each with a dispensing capacity of 1tH_2/day. The first leg of the transport route is similar to case A (2,500 km), then hydrogen is further distributed (within a radius of 500 km) through a combination of railway and road transport. In this case, the hydrogen delivered at the refuelling station should comply with the hydrogen purity and pressure levels required for mobility applications. (These are higher than for industrial uses.) For Case B, the scenario where hydrogen is distributed only by pipelines is not included in the analysis presented here. It requires a more complex analysis, which is part of ongoing work.

There is a significant level of technical uncertainty in the assessment presented here, for two main reasons. Firstly, there are, to date, few working examples of some of the processes examined, so data are scarce. Secondly, the scale of these prototypes is small. Nevertheless, this study allows for a semi-quantitative ranking of costs for hydrogen transport options within the technological field defined by the chosen set of assumptions.

The energy demand for the packing and unpacking of hydrogen is generally assumed to be met by electricity. However, there are some exceptions, such as for the ammonia cracking process, where the energy demand is assumed to be met using a mix of ammonia and hydrogen as fuel, or LOHC dehydrogenation, where the energy for this process could also be supplied by hydrogen or by a source of waste heat (the latter examined only in Case A).

The size and type of the required transport fleet depends on the packaging mode. These means of transport are at different stages of technological readiness. For example, LOHC can be transported in conventional oil tankers, and ammonia can be transported in refrigerated chemical tankers. By contrast, liquefied hydrogen will need to be transported in large carriers with a similar design to liquefied natural gas (LNG) carriers, and compressed hydrogen will be delivered in tanker ships analogous to those transporting compressed natural gas (CNG).

Pipelines are assumed to be newly built, and to connect the hydrogen production site directly to the consumption location.

It is assumed that hydrogen production, packing and shipment sites will be located close to renewable electricity generation, benefiting from relatively low electricity prices equivalent to the generation cost. By contrast, the price of electricity used during transport (e.g. pipeline compressors) and for unpacking is assumed to be higher, i.e. the local retail price for large European industrial consumers. To assess what difference electricity costs make, two scenarios are explored: **(1) Low price (Lo)**, with a production site electricity cost of EUR 10/MWh and a consumption site electricity cost of EUR 50/MWh; **(2) High price (Hi)**, with a production site electricity cost of EUR 50/MWh and a consumption site electricity cost of EUR 130/MWh. For case A (industrial use of hydrogen), waste heat at 300°C is also assumed to be available, at a cost of EUR 20/MWh.

Although the focus of the study is on the cost of delivery of hydrogen, a hydrogen production cost also has to be estimated to account for the costs related to the use of hydrogen as fuel for providing heat and to hydrogen losses along the delivery chain (fuel for ammonia cracking, for example, or boil-off of liquefied hydrogen). A production cost of hydrogen by electrolysis is derived from the electricity price scenarios described above, based on several further assumptions regarding electrolyser capital cost and operational hours. For **Lo** the estimated hydrogen cost is EUR 1.5/kg H_2, while in **Hi** it is EUR 3.5/kg H_2. With these values, it can be estimated that, within the range of electricity prices at the production site of EUR 10-EUR 50/MWh, an increase of EUR 10 per MWh would add EUR 0.5 per kg H_2 to the hydrogen production costs.

In this study, the blending of hydrogen with natural gas is not considered a suitable means for the bulk delivery of hydrogen. It is surmised that it could not be ensured that the hydrogen supplied by the hydrogen producer would reach the hydrogen consumer over long distances in the required quantities and at comparable cost with other transport options.

It is assumed that compressed hydrogen is stored in salt caverns near the points of production and consumption. It should be pointed out that local geology might not permit this.

Results

The hydrogen delivery costs calculated for case A (See Figure 1) suggest that transport options based on compressed gas (by ship or by pipeline) are the most competitive solution, alongside LOHC by ship if waste heat is available at the consumption site at the assumed price. Liquefied hydrogen transported by ship would not be much more expensive.

Figure 1 shows that the hydrogen delivery costs of chemical carriers are more dependent on energy prices than are those of other packaging modes.

In terms of electricity price differences, from the results shown in Figure 1 it can be estimated that, for distances of 2,500 km between hydrogen production and hydrogen demand locations (compatible with a potential internal EU hydrogen market), imports of hydrogen can economically be competitive if the renewable electricity generation cost differences are above EUR 20/MWh, considering the boundary conditions for this scenario (Case A, low electricity price).

Figure 1 also shows how the total costs of the different hydrogen delivery options for case A are split between packing costs, unpacking costs, and costs related to storage plus the use of a transport fleet.

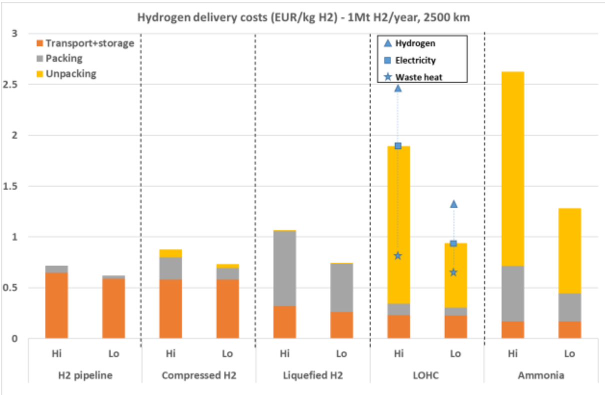

Figure 1 Hydrogen delivery costs for case A. Hi and Lo electricity prices for each carrier. Except for pipelines, all the transport options consist entirely of shipping.

In the case of hydrogen delivered by pipeline, costs are mostly related to infrastructure (pipelines and compressors) suggesting that repurposing existing natural gas pipelines for hydrogen transport would significantly decrease the associated delivery cost, making this option even more competitive. The natural gas industry estimates that cost savings could be more than 50% compared to a newly built pipeline [3].

For LOHC and ammonia, packing and unpacking costs dominate, while transport costs represent a small fraction of the total. This indicates that they could be cost competitive for distances longer than the 2,500 km considered in case A. This is confirmed by Figure 2, where the influence of transport distance between a single production and delivery point on the hydrogen delivery price is shown. For this analysis, 1 Mt of hydrogen per year and the low electricity cost scenario have been considered. Three different regions can be identified, with the most cost effective transport pathway changing depending on the distance.

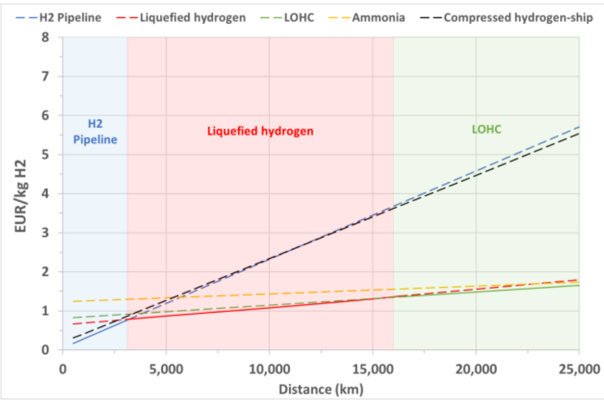

Figure 2 Hydrogen delivery costs for a simple (point to point) transport route, for 1 Mt H_2 and low electricity cost scenario.

For short distances (up to 3,000 km), compressed hydrogen gas appears to be the cheapest option, particularly in the case of pipelines. For longer distances, liquefied hydrogen and LOHC (even without cheap waste heat) are the options with the lowest costs. Of the two, liquefied hydrogen shows a slightly better performance. However, boil-off losses of liquefied hydrogen increase with distance, reducing the competitiveness of this pathway. Above about 16,000 km, chemical carriers (both LOHC and ammonia) could be the preferred option for hydrogen delivery.

A more distributed delivery scenario involving smaller quantities of hydrogen (case B) leads to different conclusions. Transport and storage costs increase significantly in this scenario, in particular penalising the packaging solutions with lower gravimetric density (i.e. compressed hydrogen). Liquefied hydrogen therefore appears as the cheapest option for the scenario considered here (Case B, see Figure 3), also because achieving the purity level required by HRS is more demanding for chemical carriers.

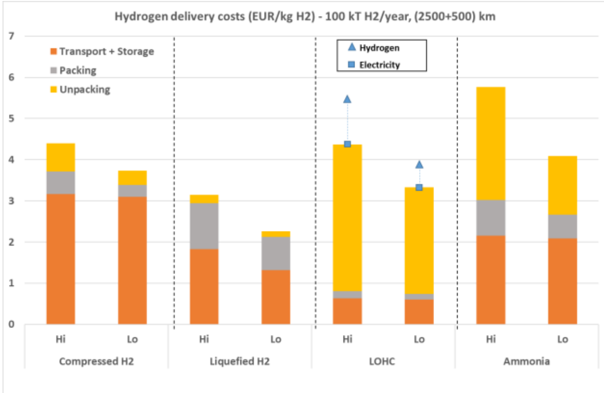

Figure 3 Hydrogen delivery costs for case B. Hi and Lo electricity prices for each carrier. Transport options involve a combination of shipping, train and truck.

While comparing hydrogen costs between case A and case B (Figure 1 vs Figure 3) it should be noted that a smaller amount of hydrogen is distributed in the latter case. Economies of scale also influence the final cost of hydrogen, particularly the cost shares related to the packing and unpacking processes.

Conclusions

There is no single optimal hydrogen delivery solution across every transport scenario. The most cost effective way to deliver renewable hydrogen depends on distance, amount, final use, and whether there is infrastructure already available.

For distances compatible with the European territory, compressed and liquefied hydrogen solutions, and especially compressed hydrogen pipelines, offer lower costs than chemical carriers do. The repurposing of existing natural gas pipelines for hydrogen use is expected to significantly lower the delivery cost, making the pipeline option even more competitive in the future. By contrast, chemical carriers become more competitive the longer the delivery distance (due to their lower transport costs) and open up import options from suppliers located, for example, in Chile or Australia.

Unpacking chemical carriers accounts for a significant share of their total cost, mostly due to the processes' high energy demand and the fact that unpacking plants are likely to be placed in locations with a relatively high electricity price. Optimization of unpacking processes has a key role to play in increasing the competitiveness of the chemical carrier pathways.

Policy considerations

Set against renewable hydrogen production costs of EUR 1.5- 3.5 /kgH_2, the contribution of hydrogen delivery costs to the final hydrogen price is not negligible. Nevertheless, delivery costs may be low enough to facilitate the competitiveness of imports of renewable hydrogen from cheaper production locations, particularly for a single point-to-point delivery route. As outlined in Figure 3, for a network of distributed hydrogen consumers, the cost of hydrogen delivery may represent the highest share of the total hydrogen cost at the demand site. For this use case, even with limited renewable energy resources and consequently higher renewable electricity prices, on-site hydrogen production may be more competitive than imported hydrogen. However, it should be noted that the analysis presented here did not consider the delivery of hydrogen by pipelines for this scenario (case B). This option could become the most suitable option in a highly distributed scenario.

One of the main challenges for the delivery of large amounts of renewable hydrogen is the current lack of infrastructure (e.g. liquefaction plants, ammonia cracking or LOHC dehydrogenation solutions), both in terms of number of facilities and their size. This challenge becomes more relevant when considering the amounts of renewable hydrogen the EU will demand in the coming years, as outlined in the European Hydrogen Strategy [1].

Aggressive and cost-effective implementation of the Strategy warrants improved understanding of the costs of renewable hydrogen. In addition to the delivery aspects covered in this brief, more studies are needed to accurately compare actual hydrogen production costs in the EU against the costs in places with cheaper renewable resources (e.g. Chile, Australia or Western Africa). More clarity is also essential regarding the actual future demand for renewable hydrogen and renewable hydrogen-derived chemicals in the EU, and how much of that demand could be covered with hydrogen produced in the EU at a competitive price. The large scale importation of green chemicals could have a significant impact on the European chemical and fertilisers industry.

An established large-scale hydrogen delivery chain would emit much greenhouse gas if fossil fuels were used to fulfil its energy needs. Therefore the definition, certification and labelling of renewable hydrogen should not only consider its production, but also the full delivery chain.

Recommendations

There are several technological challenges to be overcome to enable competitive delivery of hydrogen over long distances:

- Significant improvements over the current state of the art and upscaling of several orders of magnitude are necessary for the technologies involved in the hydrogen delivery chain. Major investments should be mobilised in the short term for the technologies considered necessary to reach the performance and scale required to reach the objectives of the EU Hydrogen Strategy. Investigating the technical limits and optimisation margins and reducing energy demand, in particular for the upscaling of packaging technologies to the required sizes, is necessary.

- In addition, the possibility of flexible operation of conversion/packaging plants in order to profit from favourable low electricity prices should be investigated, in order to bring down costs.

- Since a major cost component for hydrogen transport through pipelines is the construction cost of new infrastructure, actions aimed at understanding the techno-economic potential for repurposing natural gas pipelines should be supported.

- Research on the potential hazards (e.g. toxicity, flammability) associated with hydrogen packaging solutions is needed due to their presence in new settings. This research should lead to the development of adequate technological solutions and the elaboration of safety regulations.

- Modelling of the cost and availability of renewable energy in different geographical locations (within and outside Europe) is of paramount importance for understanding the economic feasibility of hydrogen transport over long distances.

Future work

The study is currently focused on hypothetical transport cases within and into Europe. Further case studies are to be conducted, also considering longer transport routes. A full report of the findings will be published, with a more detailed analysis of the results obtained and full references. In a second step, the environmental impact assessment of hydrogen delivery options will also be developed.

References

[1] A hydrogen strategy for a climate-neutral Europe, COM(2020) 301

[2] National hydrogen strategies, Hydrogen Europe, December 2020

[3] European Hydrogen Backbone, July 2020

Contacts:
Rafael.Ortiz-Cebolla@ec.europa.eu (valid until 30/06/2021)
Francesco.Dolci@ec.europa.eu
Eveline.Weidner@ec.europa.eu