STRATELLIGENCE
decision support

Comparison of hydrogen carriers

Multi-criteria analysis of supply chains in the Netherlands

Comparison of hydrogen carriers

Multi-criteria analysis of supply chains in the Netherlands

FINAL VERSION

Stratelligence and Dwarsverband
Leiden, September 2024
Commissioned by the
Ministry of Climate Policy and Green Growth

Publisher's details:

Cover photo: Adobe stock image (edited)

For more information about the content, contact:

Gigi van Rhee
Stratelligence
Rijnsburgerweg 161
2334 BP Leiden
The Netherlands
+31 71 573 08 20
info@stratelligence.nl
Leiden Chamber of Commerce no. 28112271

PREFACE

This study, *Comparison of hydrogen carriers, Multi-criteria analysis of supply chains in the Netherlands,* was commissioned by the Ministry of Economic Affairs and Climate – now the Ministry of Climate Policy and Green Growth – and conducted by Gigi van Rhee (Stratelligence) and Remco Hoogma (Dwarsverband), with input from Ekinetix.

The aim of the assignment was to collect a factual basis for drawing up a vision for hydrogen carriers. The sources consulted primarily consisted of publicly available studies. A key challenge was that complete and objective/factual data was not always available for all relevant indicators and potential hydrogen carriers. Some areas remain unexplored and undocumented. Also, one cannot gather hard facts about the future, only expectations. Accordingly, expert judgement was used to expand on the facts, drawing on the best available information from this study. To help readers properly assess the results in this report, we specify the objective sources, methods, and assumptions used, as well as any relevant caveats.

Our work draws on past and present studies by Berenschot and Arcadis (Social Cost-Benefit Comparison of Hydrogen Carriers *(Maatschappelijke Kosten en Baten Vergelijking (MKBV) Waterstofdragers)*), TNO (Netherlands Organisation for Applied Scientific Research) (inventory of hydrogen carriers), and the EU Joint Research Centre (cost analysis and an LCA study of hydrogen carrier imports). We would also like to express our gratitude to those who participated in the Delphi meeting and those who contributed to the expert sessions on external safety, cybersecurity and security, hydrogen chain reliability, and adaptability, as well as to the individual companies that shared valuable information. In a few instances, we have drawn on data sourced from confidential channels. This information has been anonymised and cannot be traced back to its source. In this context, a comparison with publicly available data was made every time, to assess whether the values provided were plausible.

Initially, the lead time covered a six-month period, from November 2023 through to the end of May 2024. Throughout the study, we met with the client group (Ministry of Climate Policy and Green Growth, Ministry of Infrastructure and Water Management) almost every week, and less often with a broader interdepartmental advisory group. Details of the study's approach and outcomes were presented during two stakeholder events hosted by the Ministry of Climate Policy and Green Growth and the Ministry of Infrastructure and Water Management, which centred on the vision for hydrogen carriers (24 January and 24 April). We have included feedback from the second meeting in this report. This prompted the revision of certain assumptions about the baseline situation (such as the use of CO_2 from an industrial point source rather than direct air capture by 2030 and DeNOx installations being used in the Netherlands). A number of additional sensitivity analyses were also conducted.

The study's results consist of rankings for hydrogen supply chains. However, these rankings should not be interpreted as final judgements on the preference for supply chains, nor as a means of labelling them as winners or losers. There are considerable uncertainties in the assumptions and data, given that these are projections about future technologies and chains, many of which are still untested at scale, and are dependent on developments in areas including macroeconomics, politics, innovation, industrial policy, etcetera. The results do, however, reflect current views on public interests and how hydrogen carriers are evaluated through the lens of these interests. The study's true value lies more in the collective effort to analyse and comprehend hydrogen carrier supply chains from the standpoint of various public interests and to evaluate their relative weight, rather than in the result (the ranking) itself. Balancing conflicting interests is generally the remit of politicians. Both the weighting obtained using the Modified Delphi approach and the alternative weightings from the sensitivity analyses are presented as part of the study's research results, not as specific advice for the client.

The world is constantly evolving, which means that information changes accordingly. With that in mind, we would like to propose that this analysis be repeated in another three to four years time. If needed, the methodology developed for this study can be reused, to ensure comparability and to pinpoint emerging trends and differences.

Gigi van Rhee, Stratelligence

Remco Hoogma, Dwarsverband

Leiden, September 2024

MANAGEMENT SUMMARY

THE STUDY

The Letter to Parliament dated 17 March 2023, which accompanied the final report of a study entitled External safety of future flows of hydrogen-rich energy carriers, announced a new vision for hydrogen carriers. To provide a cornerstone for that forthcoming vision, the Ministry of Climate Policy and Green Growth (KGG) commissioned this study, which compares various hydrogen carriers for specific chains within and through the Netherlands. The comparison draws on the public interests involved in the energy and raw materials transition, as detailed in the National Energy System Plan.

The *Hydrogen carriers comparison* study involves a comprehensive multi-criteria analysis (MCA) of various hydrogen carrier import chains, in terms of 10 key public interests. This pertains to the following public interests: Affordable, Economically Robust, Reliable, Safe & Secure, Sustainable, Fair, Participatory (detailed in this study as Accessible), Spatial Planning, and Environment; Adaptable has been added to this. This analysis seeks to organise the factual framework for the new vision, enabling ministries such as the Ministry of Climate Policy and Green Growth to make well-grounded policy choices. This pertains to policies regulating the physical flows of hydrogen carriers within and through the Netherlands, focusing on the extent to which, by what means, and under what conditions the government aims to facilitate and potentially incentivise these flows. The focus is on imports and physical flows destined for end use in both the Netherlands and further inland in Europe (especially Germany).

The study compares seven hydrogen carriers (hereafter referred to as carriers). Each of these carriers can be used to meet end user demand for hydrogen (end use is hydrogen, as indicated in the left-hand column of the table). Four carriers can also be used directly as raw material or fuel (end use is hydrogen carrier, as indicated in the right-hand column of the table).

End use is hydrogen	End use is hydrogen carrier
1. Liquid hydrogen, 2. Ammonia, 3. Methanol, 4. Liquid synthetic methane (LSM), 5. Methylcyclohexane[1] (MCH – a LOHC), 6. (Perhydro-)Dibenzyltoluene[2] (DBT – a LOHC), 7. Sodium borohydride.	1. Liquid hydrogen, 2. Ammonia, 3. Methanol, 4. (Liquid) synthetic methane (LSM). [LOHC = Liquid Organic Hydrogen Carrier]

For each public interest, the study determined an individual score for the carriers' supply chains. Each supply chain comprises the following steps: importing the carrier into the Netherlands (by sea), storage and transshipment at the port of entry, optional conversion into gaseous hydrogen at the port of entry, and transport of either the carrier or hydrogen after conversion (by road, rail, inland shipping, or pipeline over a typical 200 km route). The chain also includes decentralised

---

[1] The toluene (hydrogen lean) - methylcyclohexane (hydrogen rich) pair.

[2] The dibenzyltoluene (hydrogen lean) - perhydro-dibenzyltoluene (hydrogen rich) pair.

storage of the hydrogen carrier at the end user's site, possible decentralised conversion to hydrogen gas, or synthesis into a hydrogen carrier using hydrogen gas from the national hydrogen transport network (hereafter hydrogen network). The supply chains extend up to the point of delivery to the end user, or to fuelling stations or bunkering stations. As a result, the chains may differ in terms of the carrier, the end use (hydrogen or hydrogen carrier), the number of conversions involved, where conversion occurs (at the port or the end user's site), and the mode of transport.

The scores for each public interest were determined for the various supply chains, on the basis of literature review, in some cases supplemented by the expertise of companies and public sector organisations. Various stakeholders participated in a Delphi process to determine the weighting factors.[3] The 10 individual scores per public interest were combined with these weighting factors to produce a final score for each supply chain. These final scores reflect the extent to which the various supply chains align with the ten public interests.

This study does not address the issue of whether the requisite volumes and infrastructure can be achieved or allowed within the specified time frame. For the supply chains to be successfully integrated, it may be necessary to resolve bottlenecks in areas such as legislation, spatial footprint, network congestion, and available transport capacity.

THE RESULTS

Weighting factors

Figure 1 shows the Delphi group's weighting of the public interests. The Delphi group included representatives from various government agencies, supply chain stakeholders (including port authorities and trade associations), NGOs, knowledge institutions, and advisory bodies. Safe & Secure and Sustainable are by far the most heavily weighted public interests. Trailing quite some distance behind are Environment and Affordable. The remaining public interests collectively account for the final quarter of the points.

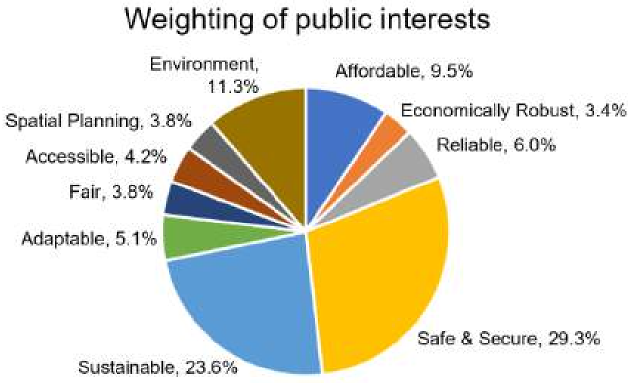


Figure 1: **Resultant public interest weighting for carriers, derived from Delphi scores**

---

[3] For more information about methodology, see main report and annexes.

Final scores

Four sets of final scores[4] have been determined, each for a specific situation, using the weighting factors established through the Delphi process and assuming the import of hydrogen carriers by ship from Morocco (3,000 km maritime transport). It starts with the baseline situation, followed by three variants. Two involve different locations and one concerns a different reference year.

- *Baseline situation:* This concerns the situation for end user groups located inland, at a distance of 200 km from the port of entry (the length of a typical route).
- *Port of entry:* The first variant on the baseline situation location applies to end users who utilise the hydrogen (or hydrogen carrier) directly at the port of entry. In this case, inland transport and decentralised storage are eliminated from the supply chain.
- *Transit and export:* The second variant involves a situation in which the hydrogen (or hydrogen carrier) is routed through the Netherlands for use in Germany or Belgium. In this situation, decentralised storage, conversion, and synthesis are eliminated from the chain.
- *2050:* The final variant involves a projection of the situation in 2050. Some scores of hydrogen carrier supply chains will alter for some public interests, as conditions will change compared to 2030.

A number of sensitivity analyses were also performed.

Figure 2 illustrates the final scores (the higher the better) for all the supply chains examined, split between hydrogen end use (left) and supply chains with hydrogen carrier end use (right) for the *baseline situation* in 2030.[5] The icons from left to right indicate the hydrogen carrier's mode of transport: by road, inland shipping, rail or pipeline, followed by either conversion to hydrogen gas or direct use. The icon furthest to the right in the left-hand infographic represents chains using centralised conversion of the hydrogen carrier at the port of entry, after which the hydrogen gas is transported through the national hydrogen network. The icon furthest to the right in the right-hand infographic represents chains where decentralised synthesis of the hydrogen carrier takes place at the end user's site using hydrogen supplied through the hydrogen network, following centralised conversion of the carrier to hydrogen at the port of entry.

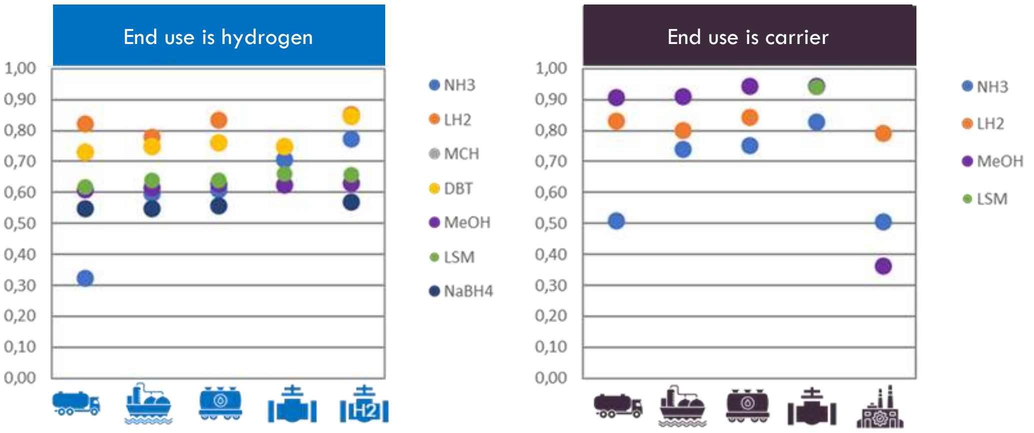
End use is hydrogen: If the end user uses hydrogen (shown on the left in Figure 2), the highest final scores are for supply chains using liquid hydrogen (orange dot) and for those featuring the centralised conversion of both LOHCs: MCH (grey) and DBT (yellow). Supply chains that feature centralised conversion at the port of entry, followed by injection into the hydrogen network, achieve the highest scores (on the left, column furthest to the right). These are followed by the decentralised conversion of ammonia (light blue), provided that it is transported through a pipeline, and the supply chains for LSM (green) and methanol (purple). The remaining ammonia chains, along with sodium borohydride (dark blue), bring up the rear.

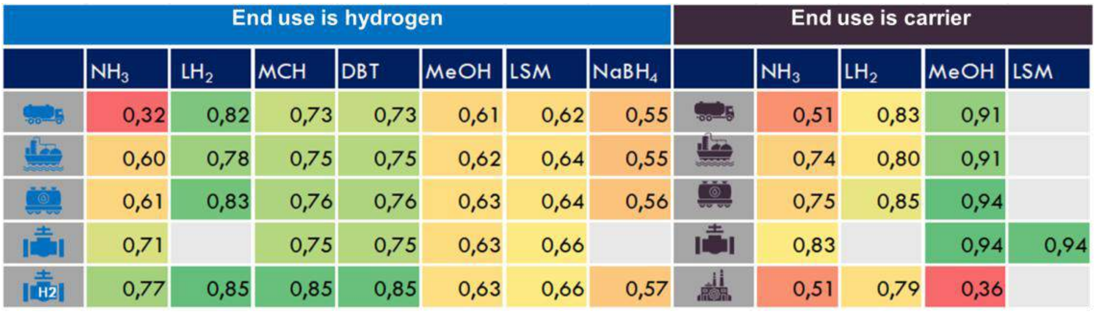
---

[4] For further details on the individual public interest scores, see Chapter 6 of the main report.

[5] For details of the variants' final scores, see Chapter 7 of the main report.

End use is hydrogen carrier: If the hydrogen carrier itself is used, the highest scores are achieved by the chains transporting methanol (purple) and methane gas from LSM (green) through a (natural gas) pipeline (right-hand side of infographic).[6] Next comes liquid hydrogen (orange) and finally ammonia (light blue). Supply chains relying on decentralised synthesis using hydrogen from the hydrogen network have the lowest final scores, except in the case of liquid hydrogen. The low final score is due to the costs and externalities associated with the extra step in the chain, synthesis; this is limited in the case of liquid hydrogen.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,32	0,82	0,73	0,73	0,61	0,62	0,55	🚚	0,51	0,83	0,91	
🚢	0,60	0,78	0,75	0,75	0,62	0,64	0,55	🚢	0,74	0,80	0,91	
🚆	0,61	0,83	0,76	0,76	0,63	0,64	0,56	🚆	0,75	0,85	0,94	
	0,71		0,75	0,75	0,63	0,66			0,83		0,94	0,94
H2	0,77	0,85	0,85	0,85	0,63	0,66	0,57	🏭	0,51	0,79	0,36	

Figure 2: **Final scores for supply chains in the 2030 baseline situation; hydrogen end use (left) and carrier end use (right) presented as a chart (above) and in table format (below)**

CONCLUSIONS

The results show that several supply chains have good final scores. The differences are often minimal (hundredths on a scale of 0 to 1) and are shaped by the weighting of public interests, by modelling assumptions, and by uncertainties present in the datasets – despite an extensive analysis of the literature. Over time, the final scores and rankings could change due to innovations and other factors. The highest scoring alternative will also vary, depending on the intended type of end use and on the end user's location. Therefore, if a diverse hydrogen market should develop, it seems likely that opportunities will arise for various hydrogen carriers and diverse supply chains.

---

[6] Any potential emissions from methanol and LSM that occur beyond the point of delivery to the end user are outside the scope of this study. The range of end use equipment is too extensive to factor into the MCA comparison.

Conclusions concerning the use of hydrogen gas or the direct use of carriers

The direct end use of hydrogen carriers is typically awarded a higher score than hydrogen use after conversion of the carrier. This applies particularly to methanol and LSM, because when used as a carrier no steam methane reformer is involved and, therefore, no greenhouse gas emissions occur.[7] Note: greenhouse gases may still be released in association with end uses that fall outside the scope of this study. Direct use of a hydrogen carrier, involving decentralised synthesis at the end user's site using hydrogen from the national hydrogen network, results in a lower score compared to other direct end use supply chains.

Conclusions regarding the location of conversion

Centralised conversion at the port of entry offers an advantage over decentralised conversion inland. Centralised conversion avoids costs, energy losses, and transport emissions, as well as the environmental risks that transportation entails. As a result, converting carriers to hydrogen centrally at the port of entry and transporting it through the hydrogen network achieves a higher score than supply chains that involve decentralised conversion inland.

Conclusions regarding the location of end use

Comparison of the baseline situation with the port of entry variant, the transit and export variant and the sensitivity analysis for offshore storage and conversion reveals that the end use location affects the score and ranking. The scores for end use in the port and end use abroad exceed those for use in the Netherlands, 200 km from the port of entry (the baseline situation). This results from partial avoidance of the negative effects associated with the supply chain (transport and decentralised conversion). With offshore storage and conversion, some ammonia chains achieve higher scores than in the baseline situation, due to reduced exposure to safety and security risks.

The ranking of the various carriers remains largely unchanged, whether the end user is situated at the port, 200 km away, or in neighbouring countries. The top-scoring carriers remain liquid hydrogen and the two LOHCs for hydrogen gas end use, along with methanol and LSM for carrier end use.

Port of entry

End use in the port has the highest scores as it (almost) entirely avoids the costs and externalities of inland transport. Distribution to end users in the port involves such short distances that it has a negligible impact (rounded down to zero in the evaluation model) on the scores.

The transport mode used has a limited impact on the scores for the various carriers. Consequently, eliminating the impact of inland transport on end use in the port does not result in a substantial shift. There are two exceptions:

- The Safe & Secure score is heavily influenced by inland transport. Consequently, ammonia supply chains that involve inland transport are assigned a lower score, due to the associated risk of a toxic gas leak. Eliminating this chain step improves ammonia's score more than it does those of other carriers.
- The second exception concerns the two LOHCs. Because of the large number of logistical movements due to the low hydrogen content before conversion, and the need for a double set of pipelines due to the return flow, the impact of domestic transport is bigger.

---

[7] Steam reforming is the name for the conversion process in which the carbonaceous carriers methane or methanol are converted into hydrogen and CO2 using steam. In this report, it is occasionally referred to simply as 'reforming'.

The elimination of this factor leads to a relatively large improvement for transport by pipeline, rail, road, and water.

Transit and export to Germany

Following transit and export, end use in neighbouring countries eliminates the impact of two chain steps – decentralised storage at the end user's site and conversion in the Netherlands (where applicable). As a result, several supply chains achieve a marginally higher score. This mainly affects the ammonia chains and the LOHCs. Ammonia achieves a higher score as the safety and security risks, environmental emissions, and spatial footprint decrease (since decentralised storage and conversion take place abroad).

The scores for supply chains that do not involve decentralised conversion and storage are virtually the same as in the baseline situation. This applies to supply chains with centralised conversion for hydrogen end use, and also to the direct end use of the carrier after pipeline transport.

Storage and offshore conversion

The final score for the ammonia chains improves if storage and conversion take place offshore on an oil or gas platform, energy island, or floating installation in the North Sea. The score for the ammonia chain with offshore conversion is nearly as high as that for liquid hydrogen chains and LOHCs with centralised conversion. This is due to the reduced impact of incidents (external safety, cybersecurity, and terrorism) and environmental emissions. There is no meaningful net effect on the results for the other carriers, given the minimal impact on their scores. In conclusion, offshore storage and conversion could be advantageous for carriers with high safety and security risks.

Conclusions regarding the choice of modality

The results show that supply chains that use the hydrogen network after conversion at the port of entry have an advantage. The ranking of transport modes for hydrogen carriers typically shows that chains using the hydrogen network achieve the highest scores, followed by those in which the carrier is transported by pipeline. Rail or shipping chains usually come next, followed by road transport. The same ranking holds for chains involving end use of the carrier.

The impact of the chosen modality on the results is minimal, except when it comes to the public interests Safe & Secure, Reliable, and Accessible. As a result, ammonia benefits substantially from pipeline transport (for end use as a carrier) or from the hydrogen network (for end use as hydrogen). In terms of the public interest Reliable, water transport achieves a lower score due to the risk of disruptions caused by high or low water levels. When it comes to the public interest Accessible, the transport of methane gas from LSM through the natural gas network achieves a higher score than the transport of carriers through other pipelines or the hydrogen network, due to the former network's wide coverage and low transport costs.

Conclusions regarding the various types of end user

For each type of end user, only the relevant supply chains are compared.

Industrial clusters

Over the next few years, businesses in the ports of entry, inland at Chemelot, and in industrial clusters in Germany will be connected to the hydrogen network. This will ensure that all supply chains relying on the hydrogen network can be used. In terms of the source of the (imported) hydrogen in the hydrogen network, the preferred ranking from the perspective of the weighted public interests is: liquid hydrogen, the LOHCs, ammonia, LSM, methanol, and sodium borohydride.

Decentralised conversion to hydrogen is also a viable option for industrial clusters inland, or in Germany, that are located near a carrier pipeline. This results in a score for imported methanol and LSM that is comparable to conversion in the port of entry followed by transport through the hydrogen network. The scores for LSM and methanol, however, are significantly lower than those for the centralised conversion of liquid hydrogen and the LOHCs, followed by transport through the hydrogen network. The main factors behind this are the greenhouse gas emissions linked to the methanol and LSM chains. Mitigating the CO_2 emissions problem by means of direct air capture (DAC, capturing CO_2 from the atmosphere) or carbon capture and storage (CCS, CO_2 capture and storage) could potentially alter this situation. Decentralised conversion after pipeline transport results in a lower score for ammonia and the LOHCs than for supply chains that use the hydrogen network.

The end user's process specifications may necessitate the direct end use of carriers (e.g. as raw material or to obtain certain flame properties). The degree of flexibility shown when selecting from a range of carriers varies from one end user to another. Users do have a certain level of flexibility in deciding which fuel to use – methane, ammonia, or possibly methanol.

Cluster 6 industry

In general, unlike the industrial clusters, cluster 6 companies are unlikely to connect to the hydrogen network in the near future. These companies will require carriers to be delivered by road, water, rail, or pipeline.

In nearly every case, centralised conversion and transport through the hydrogen network will achieve a higher score, provided that cluster 6 companies have that option. Consequently, having no access to the hydrogen network is a disadvantage from the perspective of the weighted public interests. Liquid hydrogen and both LOHCs are the top choices for cluster 6 companies without access to the hydrogen network, with LSM and methanol, ammonia and sodium borohydride trailing quite some distance behind. After the hydrogen network, the carrier pipeline (which typically has equally limited availability) usually ranks as the second highest scoring mode, followed by rail, water, and road transport.

When it comes to the direct end use of a carrier, comparisons with other carriers are irrelevant in raw material applications, as that choice is dictated by the carrier's role in the production process (see Industrial clusters).

Fertiliser industry

In the ammonia-dependent fertiliser industry, direct use in the port, supplying ammonia by pipeline, and inland waterway transport (without any conversion before the raw material reaches the factory) has a higher score in terms of the weighted public interests than ammonia synthesis sourced from the hydrogen network (with both conversion and decentralised synthesis in the Netherlands). The conversion processes drive up costs, amplify energy losses, increase emissions, require more space and exacerbate environmental risks in the supply chain. The process of synthesising ammonia from hydrogen obtained through the steam reforming of methane gas sourced from LSM is likely to achieve a lower score because it includes several conversion steps (although it has not been specifically studied as a composite chain).

Power stations

With CO_2-free, flexible electricity generation, the highest score for the weighted public interests goes to the direct use of methane from LSM (transported through the natural gas network) in a power station, followed by hydrogen sourced from liquid hydrogen and the two LOHCs through the hydrogen network.

When used in a power station, the direct use of ammonia after pipeline transport has a higher score than the use of hydrogen derived from a centralised ammonia cracking process, although it achieves a lower score than hydrogen sourced from centrally vaporised liquid hydrogen and centrally dehydrogenated LOHCs. Transporting ammonia by inland shipping has a lower score than using hydrogen sourced from ammonia following centralised conversion. Our analysis is based on the premise that hydrogen, methane, and ammonia exhibit similar energy yields during combustion. Following transport by road, water, or rail, the decentralised end use of ammonia achieves notably lower scores than its direct use after pipeline transport, primarily because these modalities are rated lower in terms of the public interest Safe & Secure (due to the risk of toxic gas leaks and traffic accidents).

Roadside fuelling stations

For roadside fuelling stations, liquid hydrogen delivered by tank truck for customers of both liquid and compressed hydrogen typically earns the highest score. When we factor in an additional purification step, the supply of hydrogen to a fuelling station connected to the hydrogen network is only superior to transporting liquid hydrogen by road if the hydrogen in the network is sourced from either liquid hydrogen or the LOHCs. In many parts of the Netherlands, the hydrogen network will be too distant from fuelling stations for connections to be feasible. Even when it is nearby, the connection costs involved will often be prohibitive. Consequently, supplying hydrogen in its liquid state is generally the better option in most situations.

Bunkering stations

In the context of bunkering for the shipping industry, the conclusion is that supplying methanol and liquid hydrogen with tank trucks or bunker vessels (possibly to dedicated bunkering stations) scores higher for the weighted public interests than equivalent deliveries of ammonia.

Conclusions for various reference years

In the 2050 variant, LSM and methanol benefit greatly from the reduced CO_2 emissions achieved by sourcing CO_2 from DAC, instead of using an industrial point source for the synthesis process. As a consequence, the 2050 ranking deviates from the 2030 baseline situation. Methanol chains maintain top scores in hydrogen end use situations, while LSM chains now achieve scores similar to those of the LOHCs. The scores are marginally higher across the board (for all hydrogen carriers). This is a result of anticipated process improvements (energy efficiency and cost levels), alongside further advancements in technology readiness levels. The move to net-zero emission maritime transport[8] strengthens the position of all chains. The greatest impact is seen in high transport volume chains, such as those involving the LOHCs. Sodium borohydride chains achieve a better score as a result of reduced energy costs relative to the baseline situation.

---

[8] Net-zero refers to a situation in which greenhouse gas emissions are balanced by reductions in emissions. Even though CO_2 emissions may occur during transport, the same quantity of CO_2 is removed from the atmosphere as is emitted.

While the projected increase in volume (or import volume) does not alter the rankings, it does have implications for the real-world living environment due to capacity constraints on roads, rail, inland waterways, and available space.

Conclusions regarding the dominant factors affecting final scores

Key factors determining the final scores include material properties, the carrier's import costs, weighting factors, and for LSM and methanol whether to apply CCS or DAC. The selection of transport mode and the costs of the chain steps within the Netherlands have less impact on the overall score, as does sea transport distance and the use of more progressive assumptions regarding energy efficiency improvements in conversion and synthesis processes.

The impact of material properties

The key carrier properties that largely determine the final scores include the level of safety and security risk (public interest Safe & Secure), greenhouse gas (Sustainable) and other emissions (Environment), the energy intensity (Sustainable) of conversion, and how the requisite energy is sourced (electrical, use of the carrier, waste heat). The specific gravity and hydrogen content of the carriers used in conversion contribute to the import volume, a factor which, in turn, impacts all (or almost all) public interests.

- *Safe & Secure and Environment:* Ammonia ranks lower because of its low score for the public interests Safe & Secure and Environment, which the Delphi group weighted heavily, while at the same time its low score for Fair was assigned little weight. The top scores for ammonia chains are achieved in the case of direct end use after transport by pipeline, or when hydrogen gas is used following centralised conversion and transport through the hydrogen network. Experts rank chains involving ammonia transport through pipelines as the safest option. If hydrogen gas is needed, transporting it through the hydrogen network after centralised ammonia conversion is the safer option. On the other hand, transporting ammonia by road has a very low score.
- *Sustainable (greenhouse gases):* The carbon-based hydrogen carriers methanol and LSM achieve lower scores for hydrogen end use, because steam reforming produces CO_2 emissions.[9]
- *Sustainable (energy loss and material consumption):* For the public interest Sustainable, sodium borohydride is heavily impacted by the substantial energy losses incurred during production and recovery of the carrier material (in the exporting country), along with the high value of carrier material required in the supply chain.

---

[9] If the end use of methanol or methane involves combustion, then CO_2 will still be released into the atmosphere. When methanol and methane are used as raw materials, the carbon remains sequestered for a longer period, depending on the product.

The effect of import costs

Import costs are strongly determinant on total expenses and the score for the public interest Affordable. Any chain steps that take place in the Netherlands contribute far less to the costs. Ammonia and methanol benefit from this situation, as the selected source data (from HyDelta) shows they incur the lowest import costs. The benefit of these low import costs outweighs the drawback that some of these carriers are used to generate process heat during the conversion process. Sodium borohydride chains are particularly impacted by the high import costs involved.

The costs cited in the literature show considerable differences. That is why a sensitivity analysis was conducted using an alternative source of cost data. If the JRC cost data (high variant) is used, this leads to minor adjustments in the scores. Chains using ammonia and methanol (both priced higher in JRC than in HyDelta) achieve slightly lower scores, whereas those using liquid hydrogen (which is more expensive in HyDelta than in JRC) achieve slightly higher scores. While the top scoring chains for hydrogen gas and hydrogen carrier end use remain the same, there is a change in their relative rankings. Liquid hydrogen (hydrogen end use) and LSM (carrier end use) chains move up, while the LOHCs (hydrogen end use) and methanol (carrier end use) fall slightly.

Effect of weighting factors

The weighting of the public interests plays a key part in determining the final scores. This weighting effect is highlighted by three sensitivity analyses conducted using variations of the weighting factors derived from the Delphi process.

To illustrate the importance of weighting factors, the right-hand pie chart in Figure 3 shows the outcomes when priority is given to the public interest Affordable.[10] Relative to the weighting factors derived from the Delphi process, weighting of the public interest Affordable was doubled. In the cases of the public interests Safe & Secure and Sustainable it was halved. As a result, ammonia has moved closer to the top-scoring alternatives. Whether cracking is centralised or decentralised after transport by pipeline, ammonia now achieves the top score for hydrogen end use.

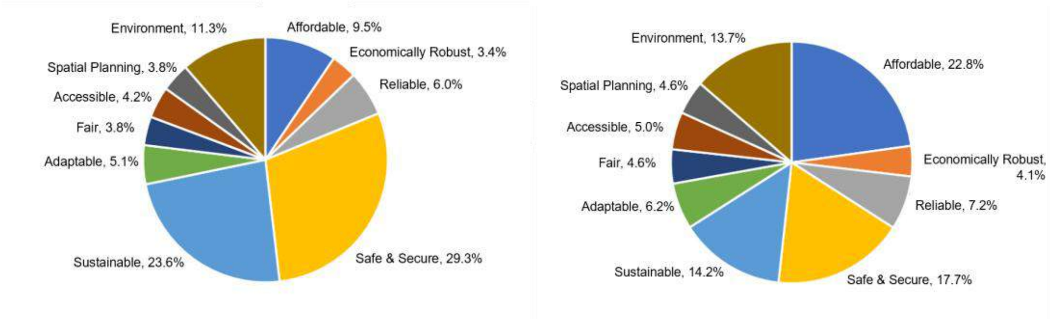
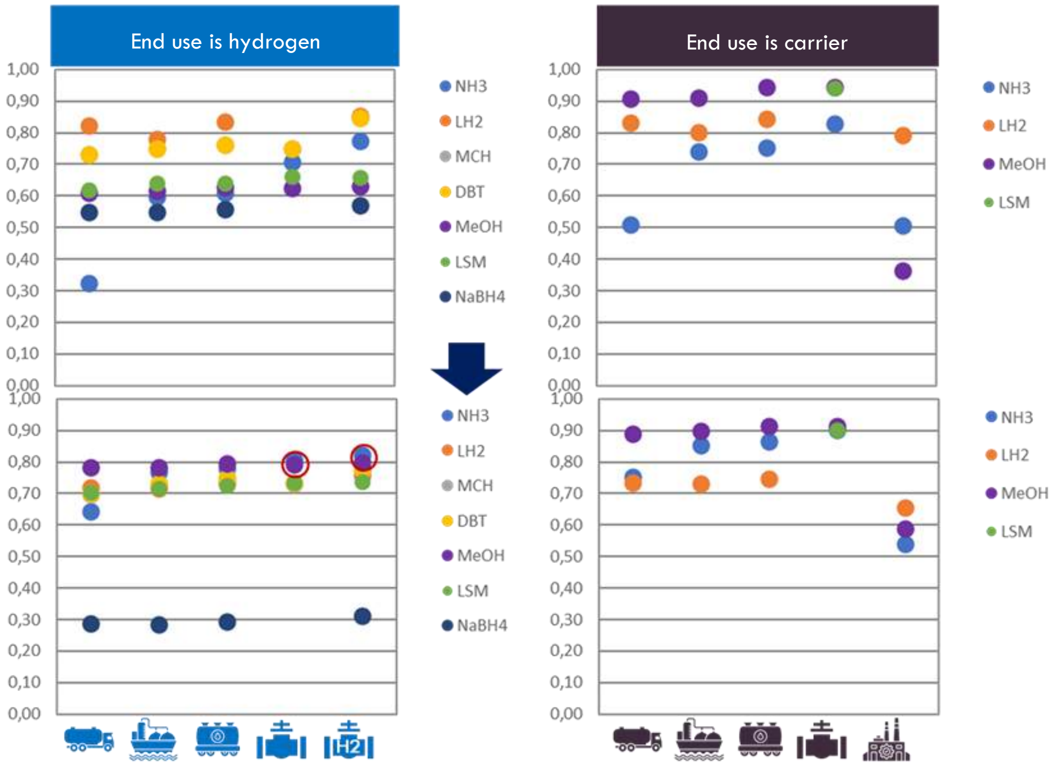


Figure 3: **Visual representation of the changed weighting; the Delphi baseline situation weighting is on the left, and the adjusted weighting is on the right**

---

[10] See the main report for details of additional sensitivity analyses on weighting factors.



End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,64	0,72	0,70	0,70	0,78	0,71	0,29	🚚	0,75	0,74	0,89	
🚢	0,77	0,72	0,73	0,73	0,78	0,72	0,28	🚢	0,85	0,73	0,90	
🚆	0,78	0,73	0,75	0,75	0,80	0,73	0,30	🚆	0,87	0,75	0,91	
	0,81		0,73	0,73	0,79	0,74			0,90		0,91	0,90
H2	0,82	0,76	0,78	0,78	0,80	0,74	0,31	🏭	0,54	0,66	0,59	

Figure 4: **Sensitivity analysis of adjusted weighting prioritising the public interest Affordable; hydrogen end use and carrier end use**

The impact of CO_2 capture and storage (CCS)

The final scores for the carbon-based carriers are especially sensitive to the inclusion or exclusion of CCS. The process of capturing and storing CO_2 during conversion to hydrogen is, overall, very advantageous for methanol and LSM. The score for hydrogen supplied from methanol through the hydrogen network when CCS is applied matches that of hydrogen from liquid hydrogen supplied through that same network. It has a higher score than liquid hydrogen transported by road, rail, or water, following decentralised conversion. LSM also achieves a high score when CCS is used. A similar effect on the scores becomes apparent over time if DAC is involved in the synthesis of these carriers in the exporting country.

In conclusion, importing methanol and LSM for end use as hydrogen will only be relevant from a public interest perspective if CCS is introduced into the chain or if DAC becomes a viable option (by 2050). This probably also applies to the capture of CO_2, for example for use as a chemical feedstock (CCU), but that falls outside the scope of this study.

The effect of transport distance

Importing carriers from further afield (such as Argentina rather than Morocco) has very little impact on the final scores. The higher costs and emissions associated with longer shipping routes lead to a slight decline in most scores. The adjustments have a minimal impact on the rankings of the various chains. In conclusion, extending the transport distance has a negligible effect on the scores and rankings.

Progressive assumptions for 2050

More progressive assumptions about energy loss reductions in conversion processes have a minimal impact on the relative positions of these chains. While using the carrier as fuel in conversion processes (specifically, for ammonia, methanol, and LSM) does result in marginally higher scores, it does not affect the overall ranking. In conclusion, the more progressive assumptions have little impact on the final scores.

Conclusions for individual carriers

Building on the previous conclusions, the multi-criteria analysis allows us to reach specific conclusions regarding the various carriers.

Liquid hydrogen

In the various variants, liquid hydrogen consistently achieves the best score (or at least a high score), which means it effectively satisfies the various public interests. However, liquid hydrogen needs to be available in adequate quantities, which is not yet the case. The current technology readiness level of the various chain steps represents an ongoing challenge. Until such time as adequate import and distribution options become available, it will be necessary to seek alternative solutions.

LOHCs

Like liquid hydrogen, the LOHCs considered here achieve high scores and fit seamlessly into existing and freed-up infrastructure. Nonetheless, the hydrogen-lean variant involves a return flow, and the hydrogen content per unit of mass in conversion is low. This effectively doubles the storage requirement and makes transportation less efficient. Pipeline transport is particularly affected, as the standard diameter of existing pipelines that may be suitable for LOHCs is smaller than those used for other carriers. There must also be a return pipeline. Consequently, LOHCs achieve a substantially higher score when converted centrally at the port of entry than when transported as carriers.

Methanol

Methanol has an average score for hydrogen conversion in the baseline situation, but it actually achieves the highest score when used directly as a carrier, if CCS is applied, and for the 2050 variant (when DAC is applied). In conclusion, importing methanol for end use as hydrogen will only be relevant from a public interest perspective if CCS is introduced into the chain or if the CO_2 is sourced through DAC.

Methanol for direct end use achieves the highest score when transported by either pipeline or rail. This results from marginally reduced transport risks (Safe & Secure) plus slightly lower costs per tonne inland (Affordable and Accessible). The challenges posed by periods of high and low water levels impact transport by inland shipping (Reliable). Methanol can be swiftly integrated into the system as a hydrogen carrier.

LSM

Like methanol, LSM has an average score for conversion to hydrogen in the baseline situation, but it achieves a much higher score when used directly as a carrier, if CCS is applied, and in the 2050 variant. In conclusion, the import of LSM for end use as hydrogen will be worth considering if the CO_2 problem can be resolved. Under these circumstances, LSM would be a viable option for use in the near future (provided that CCS is available) and would achieve high scores for Reliable (minimal risks as there is an established fossil supply chain) and Accessible (limited extra costs inland compared to the port of entry).

Ammonia

Green ammonia is set to become available in the near future. It can be integrated seamlessly into the infrastructure created for grey ammonia. It has a low score for Safe & Secure, a public interest that carries considerable weight in the Delphi weighting process. Consequently, ammonia has a low final score, notwithstanding the high scores it achieves for other public interests. Because of its low score for Safe & Secure, centralised conversion – possibly conducted offshore – and transport through the hydrogen network are strongly favoured for hydrogen end use. When using ammonia directly, the hydrogen network option, combined with decentralised synthesis at the end user's site, is less appealing from the public interest perspective. To mitigate the risks of potential toxic gas leaks as much as possible, the preferred option is to use ammonia at the port of entry followed by transport inland by pipeline. In the absence of an ammonia pipeline (at present), the highest-scoring supply chains for direct end use are those involving transportation by rail or inland shipping.

Sodium borohydride

Sodium borohydride achieves high scores for Environment (negligible emissions to the environment), Safe & Secure (with dry storage there is only a minor explosion hazard), and Fair (since external costs represent only a fraction of the overall cost price). Even so, due to elevated costs, substantial energy loss, and high levels of costly carrier material use, it achieves a low final score. Sodium borohydride's specific properties mean that this carrier is potentially very well suited to niche applications. For instance, it is a solid, which makes it suitable for long-term energy storage. Nonetheless, as long as energy in the exporting country is not free, and boron is deemed to be a critical raw material, sodium borohydride's relatively low score is unlikely to improve.

TABLE OF CONTENTS

TERMS AND ABBREVIATIONS

AHP	Analytical Hierarchy Process
BZK	Ministry of the Interior and Kingdom Relations
CAPEX	Capital Expenditures
CC(U)S	Carbon Capture, (Utilisation) and Storage
CH_4	Methane (gaseous)
CO_2	Carbon dioxide
DAC	Direct Air Capture
DBT	Dibenzyltoluene, which together with perhydro-dibenzyltoluene forms a reversible LOHC pair (hydrogen lean and hydrogen rich respectively)
DME	Dimethyl Ether
DRC	Delta Rhine Corridor
FPSO	Floating Production, Storage, and Offloading
H_2	Hydrogen (dihydrogen is commonly referred to as hydrogen)
I&W	Ministry of Infrastructure and Water Management
J&V	Ministry of Justice and Security
KEV	Climate and Energy Outlook
KGG	Ministry of Climate Policy and Green Growth
LCA	Life Cycle Analysis
LH_2	Liquid Hydrogen
LNG	Liquid Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LSM	Liquid Synthetic Methane
MCA	Multi-Criteria Analysis
MCH	Methylcyclohexane, which together with toluene forms a reversible LOHC pair (hydrogen rich and hydrogen lean, respectively)
MeOH	Methanol
MKBV	Social Cost-Benefit Comparison of Hydrogen Carriers *(Maatschappelijke Kosten en Baten Vergelijking (MKBV) Waterstofdragers)* study comparing the hydrogen carriers ammonia and LOHC, commissioned by the Ministry of Infrastructure and Water Management
N_2O	Nitrous oxide ('laughing gas')
NGO	Non-Governmental Organisation
NH_3	Ammonia
NO_x	Nitrogen oxides
NPE	National Energy System Plan
OPEX	Operational expenses
S(N)CR	Selective (Non)-Catalytic Reduction
TRL	Technology Readiness Level
VIKOR	Ranking method for multi-criteria analysis, in Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje
SVHCs	Substances of Very High Concern

CHAPTER 1 INTRODUCTION

1.1 VISION FOR HYDROGEN CARRIERS

The Letter to Parliament dated 17 March 2023, which accompanied the final report of a study entitled External safety of future flows of hydrogen-rich energy carriers (Arcadis, Berenschot and TNO (Netherlands Organisation for Applied Scientific Research)), the Ministry of Climate Policy and Green Growth, and the Ministry of Infrastructure and Water Management announced a new vision for hydrogen carriers. To provide a cornerstone for the vision, the Ministry of Climate Policy and Green Growth commissioned a comparative study between various hydrogen carriers for specific chains within and passing through the Netherlands. The comparison is based on the public interests involved in the energy and raw materials transition, as detailed in the National Energy System Plan.

The 'Hydrogen carriers comparison' study involves a comprehensive multi-criteria analysis of various hydrogen carrier chains, in terms of the following 10 public interests:

- Affordable and Economically Robust
- Reliable and Safe & Secure
- Sustainable and Adaptable
- Fair and Participatory[11]
- Spatial Planning and Environment

The public interest Adaptable is not listed as such in the National Energy System Plan, but it has been included following discussions with the client.

This study seeks to organise the factual framework for the new vision, enabling ministries such as the Ministry of Climate Policy and Green Growth to make well-grounded policy choices. This pertains to policies regulating the physical flows of hydrogen carriers within and through the Netherlands, and the extent to which, by what means, and under what conditions the government aims to facilitate and potentially incentivise these flows. Here, the focus is on imports and transport for end use both within the Netherlands and further inland in Europe (especially Germany).

The study explored import, storage, transshipment, conversion, and transport (and the associated infrastructure) within the Netherlands, by the various modes of transport (road, rail, water and pipelines). Where particular hydrogen carriers are produced in the Netherlands, that segment of the hydrogen carrier chain will also be taken into account.

1.2 IMPORT OF HYDROGEN CARRIERS:

Over the past few years, numerous studies have focused on hydrogen and hydrogen carriers. While these studies have shed light on the technologies, subsystems, and costs associated with sustainable alternatives, they have done little to clarify the frequently complex and hard-to-quantify public interests involved or how to effectively tackle uncertainties during development and the transition to a new sustainable energy system.

---

[11] To avoid any confusion with participatory processes in this report, we refer to the public interest of Participatory (which is defined as the capacity for businesses to use imported hydrogen) as Accessible.

Over the past few years importing hydrogen carriers has emerged as a key issue, both concerning use in the Netherlands and transport onwards to neighbouring countries, especially Germany. The government, port authorities and industry stakeholders are working to secure import agreements with countries of origin, to construct receiving terminals in the ports of entry, and to create transport infrastructure (in particular, the national hydrogen transport network).[12]

The anticipated import volumes are substantial, as indicated in the aforementioned study by Arcadis, Berenschot, and TNO. These research agencies have already published a comparison of hydrogen carriers that focused on the aspect of external safety.[13] Nevertheless, other public interests also need to be addressed. Some of these were included in the recently finalised Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers by Arcadis and Berenschot. However, that analysis also overlooks several of the public interests cited in the NPE. Moreover, the range of hydrogen carriers featured in these studies is smaller than those compared in the multi-criteria analysis.

1.3 ABOUT THIS STUDY

This study was based on an analysis of current literature pertaining to the technological, cost, and market trends for hydrogen carriers. Our work draws on studies such as those conducted by Berenschot and Arcadis (Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers)[14], TNO (inventory of hydrogen carriers)[15], the Joint Research Centre (cost analysis[16] and an LCA study of hydrogen carrier imports[17]) and HyDelta[18] (costs associated with import chains). By integrating these sources with others, we have gained new insights. However, we have also identified various gaps and inconsistencies. No single study has covered the entire spectrum of hydrogen carriers selected for this study, nor addressed all of the relevant public interests involved.

As a result, we had to gather and evaluate our own baseline data, firstly to resolve discrepancies between figures cited in the literature and, secondly, to bridge any gaps by means of expert sessions and additional market information. We held expert sessions focusing on external safety, cybersecurity and terrorism, the reliability of hydrogen chains, and adaptability. Various individual companies have also contributed information. In a few instances, we have drawn on data sourced from confidential channels. This information has been anonymised and cannot be traced back to its source. In this context, a comparison with publicly available data was made every time, to assess whether the values provided were plausible.

Although the literature explores developments in the technology and market trends associated with hydrogen and its supply chains quite thoroughly, it offers little insight into the diverse public interests of end users, local residents, the wider community, and the natural environment, as

---

[12] Letter to Parliament on energy diplomacy and hydrogen imports, 2 June 2023

[13] Arcadis, Berenschot, *Ketenstudie omgevingsveiligheid van duurzame waterstofrijke energiedragers* (Chain study on the external safety of sustainable hydrogen-rich carriers), 4 October 2021. The 2023 study by TNO, Arcadis, Berenschot, entitled Environmental quality of future hydrogen-rich energy carrier flows, focused on the anticipated volumes per chain and the pressure on the Basic Network.

[14] Berenschot, Arcadis (2024), Social Cost-Benefit Comparison of Hydrogen Carriers *(Maatschappelijke Kosten en Baten Vergelijking (MKBV) Waterstofdragers).*

[15] P. Wammes and M. Weeda (2024), *Eigenschappen van waterstofdragers* (Properties of hydrogen carriers). *Een overzicht voor visievorming over import van waterstof* (Properties of hydrogen carriers. An overview for formulating a vision for hydrogen imports), TNO 2024 M10863.

[16] JRC1: JRC, Assessment of Hydrogen Delivery Options Feasibility of Transport of Green Hydrogen within Europe, 2022.

[17] JRC2: European Commission, Joint Research Centre, Arrigoni, A. et al (2024), Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe, Publications Office of the European Union, Luxembourg.

[18] HyDelta (2022), WP7B Technical analysis, D7B.3 – *Cost analysis and comparison of different hydrogen carrier import chains and expected cost development*, 31 March 2022.

mentioned in the National Energy System Plan. To assess hydrogen carriers against these public interests, we need a specific definition of each public interest. The National Energy System Plan provides only a limited elaboration. Consequently, we have developed our own insights, knowledge, and methodologies to identify useful indicators for this study. We based our methods on the available baseline data and benchmark figures. As a result, this study offers an innovative approach. We established the weighting factors used to determine the final scores by means of a Delphi approach involving 21 participants from diverse backgrounds (public sector, supply chain stakeholders, knowledge institutions, and NGOs).

Throughout the study, we met with the client group (Ministry of Climate Policy and Green Growth, Ministry of Infrastructure and Water Management) almost every week, and less often with a broader interdepartmental advisory group. Details of the study's approach and outcomes were presented during two stakeholder events hosted by the Ministry of Climate Policy and Green Growth and the Ministry of Infrastructure and Water Management, which centred on the vision for hydrogen carriers (24 January and 24 April 2024). Feedback from the discussions and meetings has been included in this report.

1.4 DOCUMENT STRUCTURE

The report consists of four parts and contains several annexes that provide additional background information.

Part A, methodology, addresses the methods used.

- Chapter 2 outlines the alternatives explored, specifically the selected hydrogen carrier supply chains and their associations with different end users.
- Chapter 3 explores the public interests involved and explains how we have defined them.
- Chapter 4 presents the methodology followed for the multi-criteria analysis.

Part B, outcome of the Delphi Session, describes the results of the Delphi approach in Chapter 5, specifically focusing on the weighting factors.

Part C, results, outlines the various outcomes, including the scores for the various public interests, the final scores, and the sensitivity analyses.

- Chapter 6 presents the normalised indicator scores for hydrogen carrier supply chains, arranged by public interest for a range of end users.
- Chapter 7 shows the results of combining the indicator scores with the weighting factors. Rankings are presented that encompass several usage sites, reference years, and end users. This chapter also incorporates the results of the sensitivity analyses.

Chapter 8 in Part D outlines this study's conclusions and recommendations.

The annexes offer details about the data sourced from the literature for each public interest and, in some instances, about the findings of expert sessions on more qualitative indicators that are not extensively documented in the literature. This chapter also provides background information, including details of the sources and assumptions used, the normalisation techniques, and the VIKOR methodology.

COMPARISON OF HYDROGEN CARRIERS
PART A: METHODOLOGY

CHAPTER 2 THE CHAINS AND END USERS STUDIED

This study had to contend with the challenge of including a wide range of hydrogen carriers and chains with various end users and sites, all while ensuring that the study remained manageable. In cooperation with the client, we reached decisions that culminated in 48 different chains. The findings and key considerations are detailed below.

2.1 SELECTION OF HYDROGEN CARRIERS

The selection criteria for the hydrogen carriers to be analysed (often referred to simply as 'carriers' in this study) were as follows:

1. Does the literature that has been supplied and the data we have gathered ourselves contain sufficient information about the chain to evaluate the hydrogen carrier, as quantitatively as possible, in terms of the defined public interests?
2. Is there policy in place regarding the hydrogen carrier, and/or are there specific policy questions to be answered?
3. Have any initiatives been launched to import the hydrogen carrier into the Netherlands? We are aware that this is just a snapshot, and appreciate that the situation in the reference years of 2030 and 2050 may be very different.

The left-hand column of the table below lists the hydrogen carriers selected for preliminary screening. Many more potential hydrogen carriers could also be considered: TNO has compiled a report outlining all currently known hydrogen carriers and derivatives, together with applications of the various hydrogen derivatives.[19] The other columns address the three criteria.

---

[19] P. Wammes and M. Weeda (2024), *Eigenschappen van waterstofdragers* (Properties of hydrogen carriers). *Een overzicht voor visievorming over import van waterstof* (Properties of hydrogen carriers. An overview for formulating a vision for hydrogen imports), TNO 2024 M10863.

Table 1: Summary of various hydrogen carriers

Hydrogen carriers (preliminary screening)	Chain information in literature	Is there policy in place, are there any new questions?	Known import initiatives
Liquid H_2	Multiple studies, costs, technology, energy, external safety	No policy, new development	Amsterdam: Sunoco (formerly Zenith) et al. Rotterdam: Shell, ENGIE, Vopak et al. (cancelled)
Ammonia	Multiple studies, costs, technology, energy, external safety	Existing policy is undergoing review for the domestic transportation of NH_3	Terminals in Rotterdam, Vlissingen, Chemelot (now handling grey NH_3 with potential for green NH_3)
LOHC ('liquid organic hydrogen carrier') reversible pairs: **1. Benzene-Cyclohexane (CHE)** **2. Toluene-Methylcyclohexane (MCH)** **3. Dibenzyltoluene perhydro-dibenzyltoluene (DBT)** **4. N-ethylcarbazole - perhydro-N-ethylcarbazole (NEC)** **5. 1,2-Dihydro-1,2-azaborine (AB) – 1,2-BN Cyclohexane (BNC)** **6. Naphthalene-Decalin (DEC)**	Multiple studies, especially on MCH and DBT, costs, technology, energy, external safety. Other LOHCs, mainly chemical-technical evaluations, no chain information	No policy, new development	Rotterdam: Chiyoda MCH Amsterdam: Hydrogenious (D)BT HyMove pilot project at a brickworks, using NEC from Hynertec
Methanol*	Multiple studies, both for H_2 transport and for direct end use	Existing policy, no policy questions	Rotterdam and Amsterdam Terminals (now handling grey methanol, potential for e-methanol)
Liquid synthetic methane (LSM)	Some studies on use as H_2 carrier, many on LNG chain	Existing policy for LNG, policy questions if any in relation to CO_2 capture and storage or use (or reuse)	Unknown, but opportunities may exist through GATE and Eemshaven
Formic acid*	Few studies, some about production (Top Sector Energy)	No policy, new development	No known import initiatives. There is an aspiration to achieve production in the Netherlands (Coval/Twence)
Powders (Na- or K-borohydride, metal hydrides)	Few studies in the supplied literature, but some (albeit minimal) information exists in academic publications	No policy, new development	No known import initiatives. There are aspirations for production or delivery in the Netherlands (Electriq, H2Fuel)

*) Occasionally, these are classified as LOHCs, i.e., LOHC with CO_2 as a hydrogen-lean carrier (e.g. the National Institute for Public Health and the Environment (RIVM), 2022).

The literature also includes references to the LOHC ethylene glycol/ester, Fischer-Tropsch products (synthetic gasoline, diesel, or kerosene), dimethyl ether (DME), indirect transport using (reduced) iron powder, oxymethylene ether, hydrazine, silanes (hydrosil), metal-organic frameworks (MOF), and gas hydrates. These carriers were excluded from the preliminary screening as they had an unfavourable score for one or more of the three criteria. This mainly concerns new options for which there is limited chain information, or hydrogen derivatives that are largely blended into existing infrastructure for direct end use and which are not currently seen as candidates for conversion to hydrogen (such as e-petrol, e-diesel, e-kerosene, DME, etc.), or substances that do not carry hydrogen but remove oxygen from water by means of an oxidation reaction, thereby releasing hydrogen (such as iron powder in a steam-iron process).[20]

The decision was taken to exclude formic acid from the study. Information regarding the formic acid chain is limited. There are no plans to import this substance, and it remains unclear whether hydrogen-producing nations intend to pursue export opportunities. The same is true of borohydride, but because it is a solid – which potentially reduces storage and transport risks – it has been deemed to be a more appealing candidate for comparison than yet another liquid. Should sufficient chain information on additional carriers emerge in the upcoming years, it may become feasible to explore these substances.

As a result of our deliberations, the multi-criteria analysis study was conducted using the following seven hydrogen carriers:

- Liquid hydrogen (LH_2): hydrogen gas liquefied by deep cooling;
- Ammonia (NH_3): pressurised liquefied ('warm ammonia') or cold liquefied ('cold ammonia') gas;[21]
- Two reversible LOHC pairs (hydrogen lean and hydrogen rich respectively), namely Toluene - methylcyclohexane (TOL-MCH, in short: MCH) and Dibenzyltoluene - perhydrodibenzyltoluene (H0-DBT - H18-DBT, in short: DBT). These are liquids that can store and release hydrogen;
- Methanol (MeOH): exists as a liquid under normal conditions;
- Liquid synthetic[22] methane (LSM): methane gas (CH_4) liquefied by deep cooling;
- Sodium borohydride (NaBH4): a powdery solid capable of storing hydrogen and releasing it when it comes into contact with water.

The premise is that these hydrogen carriers are produced or – in the case of LOHC systems – charged with hydrogen using only renewable energy.

These hydrogen carriers can be classified into two categories (see Figure 5):

1. The hydrogen carrier only acts as a carrier. This concerns three carriers: methylcyclohexane (MCH), (perhydro-)dibenzyltoluene (DBT), and sodium borohydride.
2. The hydrogen carrier can be used as a carrier *and* as a raw material or fuel. This concerns four carriers: liquid hydrogen, ammonia, methanol, and liquid synthetic methane.

---

[20] The concept of 'metal fuels' involves introducing iron powder, which is burned (oxidised with oxygen, releasing hydrogen), followed by recovery from iron oxide ('rust') in a country that has access to inexpensive renewable hydrogen or another reducing agent. Iron powder and iron oxide are easily transported. The technology is currently at the pilot/demonstration stage (including a project in the Dutch province of Noord-Brabant).

[21] Ammonia is transported internationally by sea in a cooled liquid state. The inland transport of cooled liquid ammonia by road and rail is prohibited. Inland shipping typically transports it as a pressurised state under pressure (cooled liquid is also permitted). See Table 1.1 in the Event Safety Institute report. Both occur in storage.

[22] This concerns synthetic methane, used as a substitute for fossil methane.

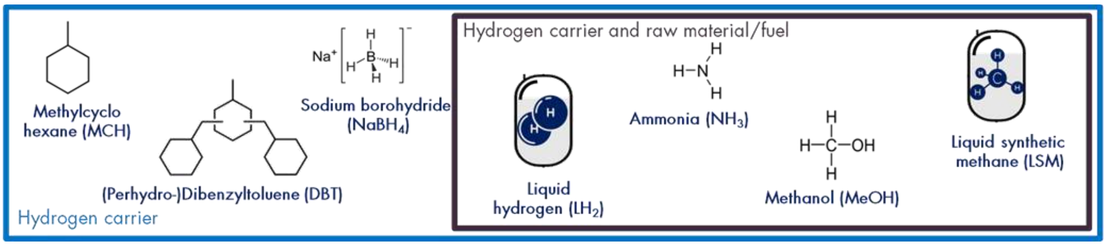


Figure 5: Subdivision of hydrogen carriers into two groups

2.2 SELECTION OF CHAINS

This study focuses primarily on the chain from the moment of import to the point at which hydrogen or its carrier is first delivered to the end user's site. The chains to be studied are made up of the following steps (see Figure 6):

- Importing the hydrogen carrier into the Netherlands. This only falls within the scope in terms of chain effects relevant to assessing the chains within the Netherlands, including total costs, energy efficiency, emissions, and import supply security, without a breakdown into the contributions of raw materials, production (of hydrogen and hydrogen carrier synthesis in the exporting country), and transport to the Netherlands. Chain effects such as those related to external safety and spatial requirements are only taken into account for the section of the chain within the Netherlands. Hydrogen gas that is produced domestically (whether onshore or offshore) falls outside the scope of this study.
- Storage and transshipment of the hydrogen carrier at the port of entry.
- The potential conversion of the hydrogen carrier to gaseous hydrogen at the port of entry. The term 'conversion' is used to describe the decomposition of hydrogen carriers to release hydrogen gas. It involves processes including evaporation, reforming, cracking, and dehydrogenation. The term 'synthesis' refers to the process of either bonding hydrogen gas to a hydrogen carrier or transforming it into one. While liquefaction (by deep cooling) and the hydrogenation of LOHCs are technically not forms of synthesis, we nevertheless include these processes in this category.
- Transporting the hydrogen carrier or hydrogen gas after the conversion step. Such transport can be carried out by road, rail, inland shipping, or pipeline. Gaseous hydrogen is transported exclusively through the hydrogen network, not by road, water, or rail (in this study, although some small-scale transport by these methods does occur in reality). We base the comparison on a typical 200 km route through the Netherlands, as used in the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers[23] by Berenschot and Arcadis. This typical route includes both urban and non-urban settings. The use of typical transport routes eliminates any discrepancies between the ports of entry and between the distances to various end user sites.
- Decentralised storage of the hydrogen carrier at the end user's site.

---

[23] Berenschot, Arcadis (2024), Social Cost-Benefit Comparison of Hydrogen Carriers *(Maatschappelijke Kosten en Baten Vergelijking (MKBV) Waterstofdragers).*

- A potential decentralised process for converting the hydrogen carrier into hydrogen gas or the decentralised synthesis of a hydrogen carrier, using hydrogen gas sourced from the national hydrogen network.[24]
- End use in the industrial, energy, or transport sectors is outside the scope of this study: the chains extend only to the point of delivery to the end user, or to the fuelling station or bunkering station.[25] A more comprehensive understanding would require an exploration of various applications beyond the point of delivery (whether as a raw material for various processes, or as a fuel for various types of equipment). This is beyond the scope of this study, as the hydrogen carrier policy relates to the supply chain and does not address end user sustainability.

Before presenting the public interests covered in the following chapter, it is important to note that, for the public interests Affordable and Sustainable, the costs, greenhouse gas emissions, and energy losses in the import chain and in the Netherlands are factored in up to the point of delivery to the end user or to a fuelling station. When it comes to other public interests (e.g. Safe & Secure, Spatial Planning, Environment), only the impact within the Netherlands is taken into account (also up to and including the point of delivery). The public interest Fair does take account of the environmental impact in the exporting country.

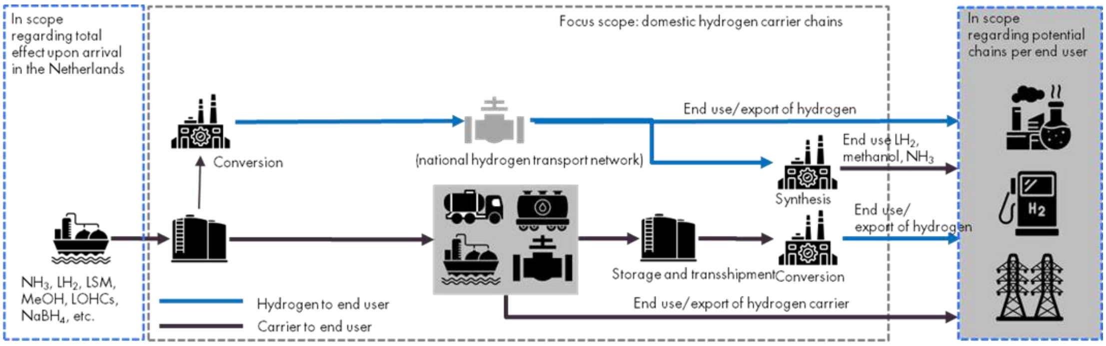


Figure 6: **Scope of the multi-criteria analysis study**

We have divided all the potential chains into 10 types or groups, for the purpose of analysing and presenting the results.

We begin by differentiating between two types of chains: 1) those where the imported hydrogen carrier is converted to gaseous hydrogen at the port of entry and transported through the national hydrogen transport network, and 2) those where the imported hydrogen carrier is transported across the Netherlands as a hydrogen carrier. See arrow no. 1 in Figure 7.

The second differentiation is between: 1) chains that culminate in the delivery of hydrogen gas to the end user's site, and 2) chains that deliver hydrogen carriers to the end user's site as a raw material or fuel. See arrow no. 2 in Figure 7. Together with the first differentiation, this creates four groups or main routes.

---

[24] For example, ammonia synthesis using hydrogen from the hydrogen transport network, or hydrogen liquefaction after cracking imported ammonia.

[25] End use in the built environment and agriculture is also an option, though the volumes involved are expected to be small.

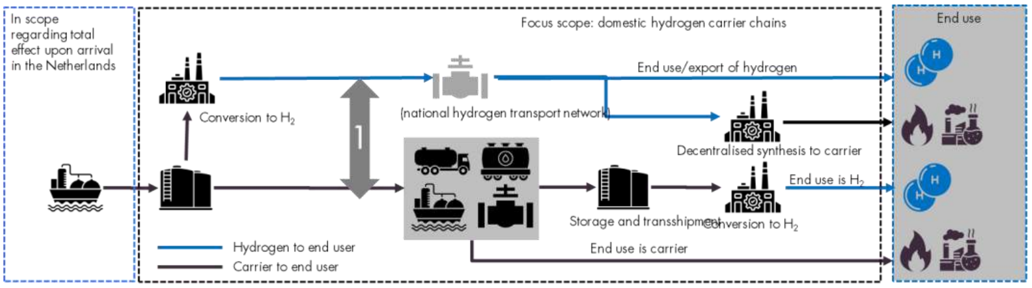


Figure 7: Four main routes; inland transport as hydrogen or a hydrogen carrier, and end use as hydrogen or a hydrogen carrier

Lastly, various modalities can be used to transport hydrogen carriers as carriers, namely road, rail, inland shipping, and pipelines. For the transportation of pressurised hydrogen gas, we focus exclusively on the national hydrogen transport network. This results in a total of 10 groups of chains: 2 x 4 transport modalities for the carrier plus 2 x the national hydrogen transport network for transporting gaseous hydrogen.

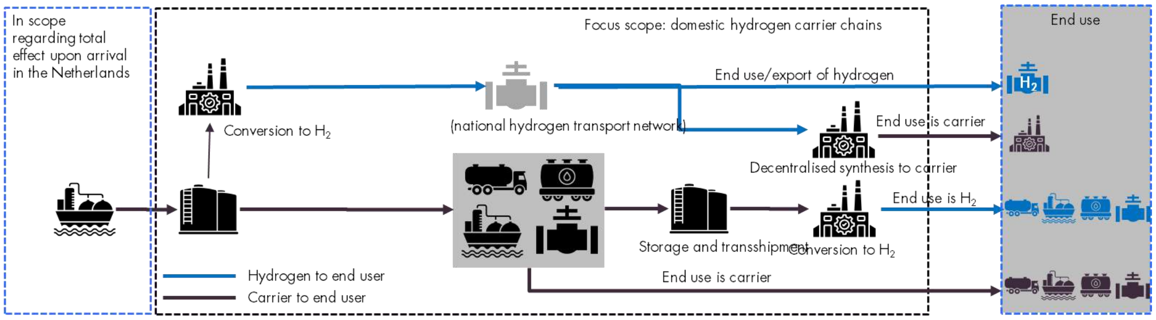


Figure 8: Different modalities per chain; 10 types of chains

Table 2: Ten chain types

Type	Explanatory notes
Type 1	Transport by road and conversion to hydrogen at the end user's site
Type 2	Transport by water and conversion to hydrogen at the end user's site
Type 3	Transport by rail and conversion to hydrogen at the end user's site
Type 4	Transport of carrier through pipeline and conversion to hydrogen gas at the end user's site
Type 5	Conversion to hydrogen gas in the port of entry and transport through the hydrogen network to the end user
Type 6	Transport of the carrier by road to the end user's site (without conversion)
Type 7	Transport of the carrier by water to the end user's site (without conversion)
Type 8	Transport of the carrier by rail to the end user's site (without conversion)
Type 9	Transport of carrier through pipeline to end user (no conversion)
Type 10	Conversion to hydrogen in the port of entry, followed by transport through the hydrogen network and decentralised synthesis of the same carrier (or a different one) at the end user's site

2.3 COMBINATIONS OF CHAINS AND HYDROGEN CARRIERS

Based on all the selected hydrogen carriers and types of supply chains, there are a great many potential chains. To limit the range of options to some extent, we have introduced additional selections:

- Direct end use only involves gaseous and liquid hydrogen, ammonia, and methanol, not LOHCs or sodium borohydride. The direct use of liquid synthetic methane, for the transport sector for example, is also deemed to be beyond the scope of this study. The assessment is limited to the use of synthetic methane gas sourced from liquid synthetic methane supplied through the natural gas network.
- Regarding transport by road, we assume that this option is generally accessible to all end users, including those in industrial clusters who can also use pipelines, shipping, or rail transport. This is likely only true during the initial phase of the hydrogen network, but it could also signify a deliberate choice by companies, particularly those with minimal volume demands.
- Businesses in the 'sixth' cluster (located throughout the Netherlands outside the five major industrial clusters) can essentially be serviced by a range of transport modalities. In reality, their options depend on their proximity to water, a railway line, the hydrogen network, or (in rare cases) whether they are directly connected to a pipeline.
- Concerning decentralised conversion to hydrogen gas, we assume that fuelling stations or bunkering stations lack sufficient space. The only exception is the evaporation of liquid hydrogen at roadside fuelling stations, which requires very little space.
- In the context of end use in the shipping sector, we assume that the ammonia, methanol, and liquid hydrogen used will be brought in by water or road.
- Decentralised synthesis of hydrogen carriers in the Netherlands, using hydrogen sourced from the national hydrogen network, is only considered for ammonia, methanol, and liquid hydrogen, not methane. The synthesis is modelled on the premise that the conversion uses hydrogen derived from a prior conversion of *the same* substance.[26]

Furthermore, since some combinations of modes of transport and carriers are highly impractical, these choices narrow down the list to 48 hydrogen carrier supply chains, which have been studied (Table 3). An explanation of the right-hand side of the table (end user types) is provided in Chapter 2.4.

Every combination listed in the table has been assessed, irrespective of current market trends (including short-term trends) or estimates (which vary) of the feasibility of some alternatives from a market perspective. For the purposes of this report, the absence of regulations (for instance, concerning the transport of liquid hydrogen by inland shipping) or restrictive regulations that are in effect (like a ban on the bulk transport of sodium borohydride) has not been considered as a reason for not evaluating a given supply chain.[27] Regulations can always be revised (in time) if there is a compelling reason to do so.

---

[26] Attempts to model chains with an average hydrogen composition within the transport network proved to be impractical. When it is more advantageous from the public interest standpoint for a synthesis to utilise hydrogen sourced from the prior conversion of a different substance we will draw attention to this.

[27] Due to the ban on bulk transport, we assume that sodium borohydride is shipped in waterproof packaging (due to its reactivity with water) in big bags inside containers. Shipping these smaller packages may involve extra operations in the logistics chain. This will impact both the monetary and external costs of transporting sodium borohydride, but as the scale of this effect remains unclear, the scores have not been revised accordingly.

Table 3: The hydrogen carrier supply chains examined

	Imported carrier	Conversion in port of entry	Transport medium	Transported carrier	Conversion, synthesis	Carrier for end use	Fertiliser industry	Power stations	Other industry-wide clusters	Cluster 6 industry	Roadside fuelling station	Bunkering station
Type 1: transport by road and conversion to hydrogen at the end user's site												
1	NH_3	-	road	NH_3	cracking	H_2	▨	▨	▨	▨		
2	LH_2	-	road	LH_2	evaporation	H_2	▨	▨	▨	▨	▨	
3	MCH	-	road	MCH	dehydrogenation	H_2	▨	▨	▨	▨		
4	DBT	-	road	DBT	dehydrogenation	H_2	▨	▨	▨	▨		
5	MeOH	-	road	MeOH	reforming	H_2	▨	▨	▨	▨		
6	LSM	-	road	LSM	reforming	H_2	▨	▨	▨	▨		
7	$NaBH_4$	-	road	$NaBH_4$	dehydrogenation	H_2	▨	▨	▨	▨		
Type 2: transport by water and conversion to hydrogen at the end user's site												
8	NH_3	-	Ship	NH_3	cracking	H_2	▨	▨	▨	▨ *		
9	LH_2	-	Ship	LH_2	evaporation	H_2	▨	▨	▨	▨ *		
10	MCH	-	ship	MCH	dehydrogenation	H_2	▨	▨	▨	▨ *		
11	DBT	-	ship	DBT	dehydrogenation	H_2	▨	▨	▨	▨ *		
12	MeOH	-	ship	MeOH	reforming	H_2	▨	▨	▨	▨ *		
13	LSM	-	ship	LSM	reforming	H_2	▨	▨	▨	▨ *		
14	$NaBH_4$	-	ship	$NaBH_4$	dehydrogenation	H_2	▨	▨	▨	▨ *		
Type 3: transport by rail and conversion to hydrogen at the end user's site												
15	NH_3	-	train	NH_3	cracking	H_2	▨	▨	▨	▨ *		
16	LH_2	-	train	LH_2	evaporation	H_2	▨	▨	▨	▨ *		
17	MCH	-	train	MCH	dehydrogenation	H_2	▨	▨	▨	▨ *		
18	DBT	-	train	DBT	dehydrogenation	H_2	▨	▨	▨	▨ *		
19	MeOH	-	train	MeOH	reforming	H_2	▨	▨	▨	▨ *		
20	LSM	-	train	LSM	reforming	H_2	▨	▨	▨	▨ *		
21	$NaBH_4$	-	train	$NaBH_4$	dehydrogenation	H_2	▨	▨	▨	▨ *		
Type 4: transport of the carrier by pipeline and converting it to hydrogen at the end user's site												
22	NH_3	-	pipeline	NH_3	cracking	H_2	▨	▨	▨	▨ *		

	Imported carrier	Conversion in port of entry	Transport medium	Transported carrier	Conversion, synthesis	Carrier for end use	Fertiliser industry	Power stations	Other industry-wide clusters	Cluster 6 industry	Roadside fuelling station	Bunkering station
23	MCH	-	pipeline	MCH	dehydrogenation	H_2	🟦	🟦	🟦	🟦 *		
24	DBT	-	pipeline	DBT	dehydrogenation	H_2	🟦	🟦	🟦	🟦 *		
25	MeOH	-	pipeline	MeOH	reforming	H_2	🟦	🟦	🟦	🟦 *		
26	LSM	evaporation	natural gas network	CH_4	reforming	H_2	🟦	🟦	🟦	🟦 *		
Type 5: conversion to hydrogen gas at the port of entry and transport through the H_2 network to the end user's site												
27	NH_3	cracking	H_2 network	H_2	-	H_2	🟦	🟦	🟦	🟦 *	🟦 *	
28	LH_2	evaporation	H_2 network	H_2	-	H_2	🟦	🟦	🟦	🟦 *	🟦 *	
29	MCH	dehydrogenation	H_2 network	H_2	-	H_2	🟦	🟦	🟦	🟦 *	🟦 *	
30	DBT	dehydrogenation	H_2 network	H_2	-	H_2	🟦	🟦	🟦	🟦 *	🟦 *	
31	MeOH	reforming	H_2 network	H_2	-	H_2	🟦	🟦	🟦	🟦 *	🟦 *	
32	LSM	reforming	H_2 network	H_2	-	H_2	🟦	🟦	🟦	🟦 *	🟦 *	
33	$NaBH_4$	dehydrogenation	H_2 network	H_2	-	H_2	🟦	🟦	🟦	🟦 *	🟦 *	
Type 6: transport by road to end user's site (without conversion).												
34	NH_3	-	road	NH_3	-	NH_3	🟦	🟦	🟦	🟦		🟦
35	LH_2	-	road	LH_2	-	LH_2			🟦	🟦 [28]	🟦	🟦
36	MeOH	-	road	MeOH	-	MeOH			🟦	🟦		🟦
Type 7: transport by water to end user's site (without conversion)												
37	NH_3	-	ship	NH_3	-	NH_3	🟦	🟦	🟦	🟦 *[28]		🟦
38	LH_2	-	ship	LH_2	-	LH_2			🟦	🟦 *		🟦
39	MeOH	-	ship	MeOH	-	MeOH			🟦	🟦 *		🟦
Type 8: transport by rail to end user's site (without conversion)												
40	NH_3	-	train	NH_3	-	NH_3	🟦	🟦	🟦	🟦 *		
41	LH_2	-	train	LH_2	-	LH_2			🟦	🟦 *[28]		

---

[28] E.g. the electronics and semiconductor industry. Liquid hydrogen is used extensively in the manufacture of LEDs, displays, and semiconductors. Hydrogen molecules have beneficial properties, such as their excellent thermal conductivity and suitability for use as an etching medium.

	Imported carrier	Conversion in port of entry	Transport medium	Transported carrier	Conversion, synthesis	Carrier for end use	Fertiliser industry	Power stations	Other industry-wide clusters	Cluster 6 industry	Roadside fuelling station	Bunkering station
42	MeOH	-	train	MeOH	-	MeOH			🟦	🟦 *		
Type 9 transport of the carrier by pipeline to the end user's site (without conversion)												
43	NH_3	-	pipeline	NH_3	-	NH_3	🟦	🟦	🟦	🟦 *		🟦 *
44	MeOH	-	pipeline	MeOH	-	MeOH			🟦	🟦 *		🟦 *
45	LSM	evaporation	natural gas network	CH_4	-	CH_4	🟦	🟦	🟦	🟦		
Type 10: conversion to hydrogen in port of entry, transport through the H_2-net and decentralised synthesis of the carrier at the end user's site.												
46	NH_3	cracking	H_2 network	H_2	synthesis	NH_3	🟦		🟦	🟦 *		
47	LH_2	evaporation	H_2 network	H_2	synthesis	LH_2			🟦	🟦 *[28]		
48	MeOH	reforming	H_2 network	H_2	synthesis	MeOH			🟦	🟦 *		

*) an option for some, but not all, cluster 6 companies, fuelling stations, and bunkering stations.

2.4 RELEVANCE OF CHAINS FOR THE VARIOUS TYPES OF END USER

Some of the supply chains listed in Table 3 are not relevant for every type of end user. In this study, we have identified six types of end user:

- Fertiliser industry
- Power stations
- Other industrial applications in one of the five industrial clusters
- Cluster 6 industry
- Roadside fuelling station
- Bunkering station for shipping

It is assumed that large transport flows of hydrogen (or hydrogen carriers) proceed from the ports of entry to industrial clusters for fertiliser production (using ammonia or hydrogen as a raw material), power stations (using hydrogen, methane, or ammonia as fuel), or other industries (refineries, steel industry, and chemical industry, using hydrogen as a fuel/raw material). Smaller volumes pass from the ports of entry to sectors outside the clusters (cluster 6: ceramics, metal industry, waste/recycling) and to roadside fuelling stations and riverside bunkering stations. The choice of available transport modes, combined with the type of end use, dictates which supply chains end users can access. By 2030, many major industrial users will be located close to the national hydrogen transport network, unlike many fuelling stations. In Table 3, the blue-coloured cells indicate whether the chain involved is a feasible option for the corresponding type of end user.

Fertiliser industry

Ammonia is a key intermediate product in fertiliser production. In standard ammonia production, synthesis uses nitrogen sourced from the air and hydrogen from steam methane reforming. Dutch fertiliser plants are sited within the industrial clusters. They have three choices: importing ammonia, decentralised synthesis of ammonia using hydrogen sourced from the hydrogen network, or synthesis of ammonia using hydrogen from the steam reforming of methane gas from LSM supplied through the natural gas network.

Power stations

When wind and sun do not provide sufficient electricity, there is a need for flexible power in the electricity grid. Currently, this power output is provided by natural gas power plants. A range of solutions are available for developing CO_2-free flexible power output. Within the scope of this study, we have limited ourselves to three options: the use of synthetic methane from LSM in power stations, and the use of hydrogen or ammonia in modified power stations.

Given the quantities needed and the requirement for security of supply, it is imperative to connect to the natural gas network, the hydrogen network, or to an ammonia pipeline. Delivery of ammonia by ship coupled with large-scale storage at the power station may also be a viable option.

The combustion of hydrogen, methane, or ammonia produces NO_X emissions. While emissions due to end use are beyond the scope of this study, we will nevertheless touch on them briefly here. According to TNO[29], when combined with techniques such as flue gas recirculation and the catalytic (or non-catalytic) reduction of NO_X (SCR/SNCR[30]), the combustion of hydrogen or ammonia can achieve NO_X emissions comparable to those produced by burning natural gas. As ammonia itself contains nitrogen, additional measures are needed to mitigate NO_X emissions when it is used directly as a fuel. Ammonia combustion can involve techniques such as SCR and dual-stage combustion, initially in a low-oxygen environment, followed by a phase with excess oxygen. The process of oxy-fuel combustion (in oxygen rather than air, at extremely high temperatures) using hydrogen and natural gas produces very low NO_X emissions, but it yields high NO_X emissions when ammonia is used.

Other industrial applications in one of the five industrial clusters

The national hydrogen transport network will initially link up the five large-scale industrial clusters in the Netherlands: Northern Netherlands, North Sea Canal region, Rotterdam/Moerdijk, Zeeland/West-Brabant and Chemelot, which is located in the province of Limburg. Any companies in these clusters that require hydrogen can connect to the hydrogen network.

We anticipate that deliveries to the industrial clusters by road, rail, or inland waterways will be minimal, except during the network's initial phase and in situations where the distance to the hydrogen network is too large, or where other factors make it impractical. In that case, the businesses in question are considered to be cluster 6 companies (see further details).

Besides situations involving the end use of hydrogen, there could also be a demand within the industrial clusters for the direct end use of specific carriers, either as raw materials or as fuels to comply with specific process requirements (in the ceramics sector, for instance[31]). In that case,

---

[29] Pieter Kroon, *Waterstofverbranding en stikstofemissies* (Hydrogen combustion and nitrogen emissions), TNO report R10343 14 April, 2023.

[30] Selective (Non)-Catalytic Reduction

the comparison with all other carriers is irrelevant, as the role of the carrier in the production process is the deciding factor in the choice.

Cluster 6 industry

Energy-intensive businesses are distributed throughout the Netherlands. Many of these are located outside the five industrial clusters, and are sometimes referred to as the 'sixth cluster'. Cluster 6 companies situated near the hydrogen network will be able to connect to it, in which case the comparison outlined for industrial clusters becomes applicable. The remaining cluster 6 companies will have to be supplied with hydrogen carriers by road, water, rail, or pipeline. The practicality of different transport modes depends on the company's location.

Roadside fuelling stations

Hydrogen is gaining recognition as an energy carrier in transportation, especially for heavy road vehicles, as an alternative to – or complementing – battery-electric mobility and biofuels. There are various ways by which fuelling stations can be supplied. The scope of this study covers the supply of liquid hydrogen to fuelling stations in tank trucks and by connecting fuelling stations to the hydrogen network (which necessitates an extra purification step). At the station, liquid hydrogen can either be delivered directly to vehicles or converted to a compressed state (350-700 bar) beforehand, by evaporation. Both variants may be combined at a single fuelling station. In theory, fuelling stations can also facilitate the decentralised conversion of hydrogen carriers other than liquid hydrogen into hydrogen. This option has not been included in our comparison due to its substantial spatial requirements, both in physical terms and with regard to safety. However, the extra purification step for fuelling stations that connect to a pipeline has smaller spatial requirements and is therefore considered.

Bunkering stations for shipping

The shipping sector is exploring various sustainable alternatives to existing fuels, including liquid hydrogen, methanol, ammonia, LSM, and sodium borohydride. To promote their use in shipping, various market initiatives have been developed for these carriers. LNG ('fossil LSM') and methanol are already being used to a certain extent in container vessels, cruise ships, ferries, etc. with support from bunker vessels operating in Rotterdam. Some initial pilot projects have been launched (outside the Netherlands) to explore the use of LSM, liquid hydrogen, and ammonia. The Port of Amsterdam is conducting small-scale tests with sodium borohydride. These energy carriers can be supplied to vessels from tank trucks, bunker vessels, or landside bunkering stations.

---

[31] Besides hydrogen, LSM is another option in this context. Uncertainty surrounds the future of gas quality, along with the availability and pricing of hydrogen, which is why the industry values flexibility. "In the ceramics sector, hydrogen is used as a substitute fuel, however it does require certain modifications to the production process, unlike biomethane. The design of the kiln determines whether or not hydrogen can be used, and modified burners would also be needed. Firing the kiln with hydrogen generates higher temperatures, which in turn raises NO_X emissions. These factors, together with the potentially adverse impacts of the fuel switch on product quality, require further research before hydrogen can be regarded as a viable fuel replacement." "There is still some uncertainty regarding the necessary modifications to the burners (further research is recommended), how using hydrogen for firing will impact the quality of the ceramic products, and what the associated techno-economic characteristics (CAPEX and OPEX) of hydrogen burners in the ceramics sector might be." Besier, Jorick, Marc Marsidi (2020), Decarbonisation options for the Dutch ceramic industry, PBL Netherlands Environmental Assessment Agency and TNO, 21 December.

The chains for the end use of gaseous hydrogen are not considered here. There is a general consensus that the density of hydrogen gas is not adequate for use in vessels.[32] In conclusion, it is theoretically possible to bunker LOHC, dehydrogenate it aboard a ship (or at a bunkering station), and use the hydrogen for propulsion. It is not known whether any initiatives have been launched to develop this approach.[33] As with roadside fuelling stations, there is usually insufficient space (both in physical terms and with regard to safety) at bunkering stations to accommodate a hydrogen conversion system.

2.5 VARIANTS

In this study, we explore a range of situations, or 'variants', for each chain. The baseline situation concerns the reference year 2030, regarding the use of hydrogen (or hydrogen carriers) inland. We refer to 2030 as a reference year, but it in fact concerns a reference period from 2030 to 2035.

This involves the following variants:

- *Alternative site:* The situation for end users who utilise the hydrogen (or hydrogen carrier) directly at the port of entry. In this case, inland transport and decentralised storage are eliminated from the supply chain. Decentralised conversion coincides with the centralised conversion.
- *Alternative site:* The situation in which the hydrogen (or hydrogen carrier) passes through the Netherlands for use as hydrogen (or as a hydrogen carrier) in Germany or Belgium. In this situation, decentralised storage, conversion, and synthesis are eliminated from the chain.
- *Alternative reference year:* Projecting ahead to 2050. Some scores of hydrogen carrier supply chains will alter for some public interests, as conditions will change compared to 2030. When we refer to 2050, this also implies a time frame (i.e., 'around 2050'), just as it does for 2030.

There is no need to assign a separate variant to every group of end users. The chains and their respective scores do not differ. However, the degree of flexibility each end user enjoys in selecting a specific chain does differ. For example, fuelling stations that are not connected to the hydrogen network cannot make use of chains that transport hydrogen through that network, nor is cracking ammonia a viable option for fuelling stations. Consequently, they have fewer options than industrial complexes that are connected to the hydrogen network and are also capable of converting hydrogen carriers into hydrogen themselves.

2.6 DIFFERENCES IN VOLUME BETWEEN CHAINS

For each supply chain, we work on the basis that a uniform volume of hydrogen equivalents is delivered to the end users. Chain losses can occur, depending on the hydrogen carrier and type of chain involved. Consequently, the required import volumes of carriers will vary, while the quantity of hydrogen equivalents supplied to end users remains constant. By factoring in the differences in specific gravity, we have translated the differences in volume into the quantities needed for storage and logistical movements. The differences in volume affect nearly every public

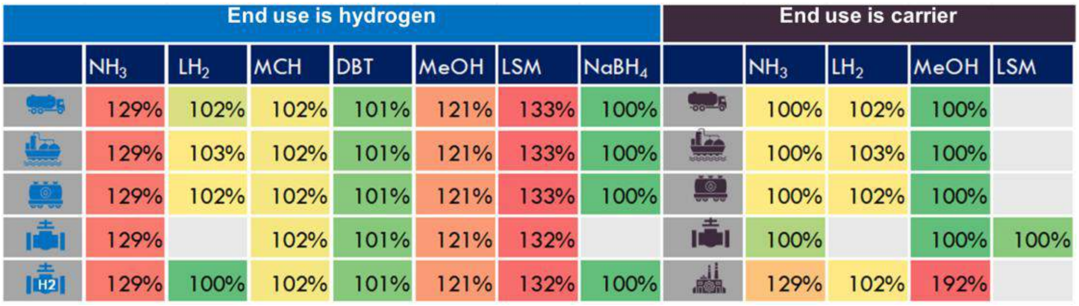
---

[32] One exception is the use of interchangeable shipping containers, loaded with hydrogen gas cylinders, in the inland container shipping sector. The cylinders are filled at electrolyser plants. However, this supply chain is beyond the scope of this study. The containers could also be filled at a fuelling station connected to the hydrogen network. That would bring this option within scope of this study. However, we have not explored this possibility in detail.

[33] In HyDelta, this approach has indeed been taken for maritime transport. We did not adopt this.

interest, since higher volumes result in more external effects (impacting Safe & Secure, Sustainable, Environment, and Fair), higher costs (impacting Affordable, Economically Robust, Fair, and Accessible), or require more and larger facilities (impacting Adaptable and Spatial Planning).

Most of these losses occur during the conversion steps from hydrogen carriers to hydrogen gas, where the carrier is also used as a fuel source for generating process heat. These are ammonia (cracking), methanol and LSM (steam reforming). When using conversion and decentralised synthesis within the Netherlands (type 10 chain), the volume loss increases proportionally. Slight losses occur when transporting liquid hydrogen or hydrogen gas through the hydrogen network, and methane gas derived from LSM through the natural gas network. In addition, when liquid hydrogen, LSM, and ammonia are stored in centralised or decentralised facilities, there are also slight losses. The volume[34] calculations in the chains are clarified in Annex B.



End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚛	129%	102%	102%	101%	121%	133%	100%	🚛	100%	102%	100%	
🚢	129%	103%	102%	101%	121%	133%	100%	🚢	100%	103%	100%	
🚆	129%	102%	102%	101%	121%	133%	100%	🚆	100%	102%	100%	
	129%		102%	101%	121%	132%			100%		100%	100%
H2	129%	100%	102%	101%	121%	132%	100%	🏭	129%	102%	192%	

Figure 9: Required import volume of chains relative to end use (100%) – hydrogen end use and carrier end use

---

[34] Even though we express the quantities of hydrogen carriers in kilotonnes (a unit of mass), we still refer to 'volume' to maintain consistency with the previously mentioned 'volume study'.

CHAPTER 3 ELABORATION OF PUBLIC INTERESTS

This chapter explores the range of public interests, showing how these are elaborated into indicators. The focus is on public interests as defined in the National Energy System Plan (NPE)[35]:

- Affordable and Economically Robust
- Reliable and Safe & Secure
- Sustainable
- Fair and Accessible (Participatory)[36]
- Spatial Planning and Environment

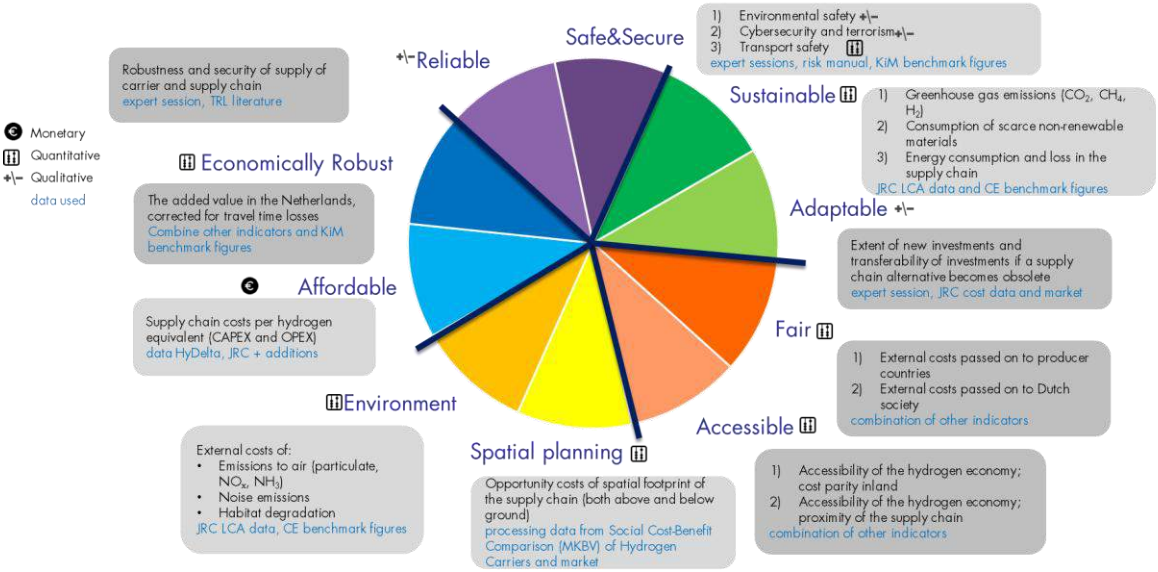


Figure 10: Summary of 10 public interests with their corresponding 16 indicators

One public interest missing from the NPE is adaptability. After consulting with the client, we included this as an additional public interest. Given the unpredictable future course of hydrogen (and hydrogen carrier) developments, adaptability is key. Most of these technologies and chains, which are still to reach scale, are dependent on developments in areas including macroeconomics, politics, innovation, industrial policy, etc. Thus, the market needs to be agile if it is to respond effectively to changing conditions. The capacity for flexibility differs from one chain to another, each of which are assessed and compared accordingly. This highlights the need for specifics on the flexibility and resilience of infrastructure and market positions across each hydrogen carrier

---

[35] Ministry of Economic Affairs and Climate Policy (2023), National Energy System Plan.

[36] To avoid any confusion with participatory processes in this report, we refer to the public interest of Participatory (which is defined as the capacity for businesses to use imported hydrogen) as Accessible.

and transport chain. Are there any lock-ins or lock-outs[37], and what lead times and costs are required to implement shifts or adjustments?

The term 'Participatory' is often interpreted as the degree of stakeholder involvement in the policy process. This doesn't differentiate between the various hydrogen carrier chains in this study. It could, more appropriately, be regarded as a boundary condition in the cabinet's vision for hydrogen carriers. Accordingly, the term 'Accessible' will be used throughout the remainder of this report to denote companies' abilities to use imported hydrogen.

Table 4: Indicators per public interest (same sequence as the NPE)

Public interest	Indicators
Affordable	• Cost to the end user per hydrogen equivalent (€ per kilotonne (kt))
Economically Robust	• Economic added value per hydrogen equivalent for the Netherlands, minus congestion costs and the social costs involved in infrastructure use (€ per kt)
Safe & Secure	• External safety (Potential casualties per year per kt) • Cybersecurity and terrorism (Potential casualties per year per kt) • Transport safety (€ per year per kt)
Sustainable	• Greenhouse gas emissions (Costs of greenhouse gas emissions (CO_2, CH_4, H_2, N_2O) per year per kt) • Critical raw material consumption (Value of material in € per kt) • Energy loss (MJ per kt)
Adaptable	• Scale of high-risk (not flexibly deployable) investments, meaning additional investments that cannot be repurposed and would need to be written off if the chain's development falls short (€ per kt).
Fair	• Extent to which externalities are passed on to producer countries and the rest of the world (cost of import externalities in € per kt divided by import costs in € per kt) • Extent to which chain externalities are passed on to Dutch society (externality costs of the supply chain in the Netherlands, in € per kt, divided by chain costs in the Netherlands, in € per kt).
Accessible	• Level playing field in terms of costs for end users inland versus those at the port of entry (€ per kt inland divided by € per kt at the port of entry) • Proximity to modes of transport on industrial estates (percentage of industrial estates parks with access to the mode of transport)
Spatial Planning	• Opportunity costs of the supply chain's spatial footprint (value in € per kt)
Environment	• External costs arising from emissions (ammonia, particulate matter, and nitrogen oxides), noise emissions, habitat degradation, ecotoxicity, methane-induced smog, and environmental incidents (€ per year per kt)

Figure 10 summarises the public interests involved. In this context, we have adopted the same sequence as the NPE, with Adaptable being included after Sustainable. For the purposes of this study, each public interest has been elaborated by translating it into one or more indicators. These are listed in Figure 10 and Table 4. The remainder of this chapter provides more in-depth information on the public interests concerned. A short overview of the key sources used is also included. See Annex A for more details on the sources and assumptions used in the modelling. Annexes B and C explore the methods used to calculate scores per chain for each public interest involved.

---

[37] Lock-ins restrict switching between options, as early choices make strategic shifts challenging and costly (e.g. due to investments that have not yet been written off). Lock-outs are alternatives that become unavailable due to earlier decisions or a lack of timely foresight.

3.1 AFFORDABLE

The public interest Affordable concerns the total supply chain costs up to the point of delivery to the end user. These costs are presented as total costs per kt of hydrogen equivalent (H_2-eq), based on the projected volumes for 2030 and 2050. These are investment costs (CAPEX) and operational costs (OPEX). The investment costs are written off over the lifespan of the investment. This lifespan may vary – for example, investment in a plant typically has a shorter lifespan than investment in a pipeline.

When determining some of the other public interests in this MCA, various elements of the total costs are required. We use the following categories for this purpose:

1. Costs of imported carrier upon arrival in the Netherlands,
2. Costs of transshipment/storage at the port of entry,
3. Costs of centralised conversion to hydrogen,
4. Costs of transport and storage, and
5. Costs of decentralised conversion to hydrogen or synthesis of the carrier.

The resulting costs are significantly affected by the assumptions made. Consequently, we attempted to use the same source for different carriers whenever feasible. The key sources are HyDelta and the Joint Research Centre (JRC), which offer the most comprehensive and transparent information on the costs associated with importing hydrogen carriers. We factored in the transport costs in the Netherlands, using benchmark figures from the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers, Panteia, and the Netherlands Institute for Transport Policy Analysis (KiM).[38] HyDelta and the JRC study provide little or no information on LSM, sodium borohydride, or MCH. We added further sources[39] to these and, wherever feasible, applied the same assumptions as those used in the JRC study. We decided not to include the costs of end use equipment, since this encompasses a broad spectrum of technologies (fuel cells, burners, turbines, internal combustion engines, process reactors, etc.).

3.2 ECONOMICALLY ROBUST

The public interest Economically Robust emphasises the Netherlands' current (and future) earning capacity. To this end, we estimated the added value for the Netherlands across the various chains. Added value (absolute) is calculated as the difference between 1) projected domestic or export revenues, including profit margins, and 2) the costs associated with imports. Consequently, chains that incur low import costs achieve high scores, even if the storage, conversion, and transport costs in the Netherlands are high. After all, the associated expenditure ultimately benefits the Dutch economy.[40]

The future sale price (needed to calculate the added value) remains the most unpredictable factor. We presume that end users have no preference regarding which chain supplies the hydrogen. Accordingly, we have applied a uniform sale price per hydrogen equivalent across all chains: 12 euros per kilogramme of hydrogen. To ensure a fair comparison between chains with and without

---

[38] Panteia (2023), Cost Figures for Freight Transport – final report, commissioned by the Netherlands Institute for Transport Policy Analysis (KiM), January 2023.

[39] For LSM: Agora Industrie, Technische Universität Hamburg (2023), Wasserstoff-Importoptionen für Deutschland. *Analyse mit einer Vertiefung zu Synthetischem Erdgas (SNG) bei nahezu geschlossenem Kohlenkreislauf*, September. For sodium borohydride: e.g. Ainee, Ibrahim, Mark Pakevicius and Craig E Buckley (2023), Chemical compression and transport of hydrogen using sodium borohydride, *Sustainable Energy & Fuels*, 2023, 7, 1196-1203. For MCH: market information and, e.g. Aziz, Muhammad, Takuya Oda, Takao Kashiwagi (2019), Comparison of liquid hydrogen, methylcyclohexane and ammonia on energy efficiency and economy, 10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China, Energy Procedia 158 (2019), 4086-4091.

[40] We assume that these expenses are fully absorbed in the Netherlands. Where foreign shareholders and the procurement of capital goods from abroad are involved, some of these costs will be absorbed by entities in other countries.

conversion to hydrogen, we corrected the prices of chains that use the carrier as an end product (ammonia, methanol, methane) by deducting the costs of conversion to hydrogen from these carriers' sale prices.

We corrected the added value to reflect any extra congestion costs and expenses incurred by using road, water, and rail infrastructure. These costs do not affect the scores for the public interest Affordable because they are borne by society.

The economic activity and added value associated with imported hydrogen or hydrogen carriers influence added value in related sectors and create high-quality jobs at companies that use hydrogen, through the exchange of knowledge between companies and by fostering a more favourable business climate for these sectors. It is difficult to quantify the exact effect for the situation today and even more challenging for the future. We assume that added value serves as a reliable approximation in this context as well.

3.3 RELIABLE

The public interest Reliable emphasises the security of prompt hydrogen carrier delivery without major price fluctuations. It can also involve the prevention of high-risk strategic dependencies. However, as we do not use specific information regarding the exporting countries, we cannot express this aspect (strategic dependencies) in an indicator for the supply chain. This report, therefore, centres around the security of prompt delivery due to the reliability of imports, conversion steps, and transport in the Netherlands.

This is influenced by the following factors:

- the TRL (Technology Readiness Level) associated with hydrogen carrier production from hydrogen in exporting countries (the higher the level, the more reliable it is),
- the TRL of ocean-going vessels capable of transporting the carrier (the higher the level, the more reliable it is) and the availability of such vessels,
- the chemical stability of the carrier (the more resistant the substance is to internal and external influences or disturbance parameters such as boil-off or reaction with moisture, the more reliable the delivery),
- the TRL for hydrogen carrier storage (the higher the level, the more reliable it is),
- the TRL for conversion and potential synthesis of the hydrogen carrier (the higher the level, the more reliable it is),
- the TRL of the carrier's mode of transport in the Netherlands (where higher levels of security of supply/TRL reflect greater reliability in the chain) and the availability of suitable means of transport, and
- the security of supply and robustness of the transport mode (the greater the number of potential routes, the smaller the risk that the loss of a single route will render delivery impossible).

Literature sources are lacking for some of these factors, particularly concerning their relativel evaluation. Thus, in consultation with a panel of experts, we determined the scores for each step of the chain qualitatively, taking their relationship to other steps into account.

3.4 SAFE & SECURE

We defined the public interest Safe & Secure using three sub-indicators: 1) external safety (unintentional incidents), 2) safeguards against cyber attacks and terrorism (intentional incidents), and 3) transport safety. In relation to safety, we focused on immediate threats to people's health and safety. The public interest Environment addresses long-term effects on human health, such as a heightened risk of cancer or respiratory illnesses resulting from exposure to hazardous substances. Impacts on nature resulting from incidents are also an integral part of the public interest Environment.

External safety

External safety concerns the risks to Dutch society posed by potential incidents during the storage and transshipment, conversion, or transport[41] of hydrogen carriers. Because hazardous substances are involved, there is a risk of injury, environmental degradation, and damage to property. The actual risk involved depends on the impact of an incident and the probability that it will occur.

The scoring methodology used for external safety draws upon the Dutch government's regional risk profile method and the country-wide national security risk analysis (slightly simplified). Together with a panel of experts, we evaluated the probability and impact of incidents involving various hydrogen carriers, for each incident scenario (such as leakage or explosion) and each step in the chain. The risk (number of potential casualties) was calculated by multiplying the probability by the impact. We derived the scores for each supply chain by totalling the risks for each step of the chain in question. Incidents can occur in urban, rural, or industrial areas. The assessment is based on the 'worst-case' situation.

Cybersecurity and terrorism

Cybersecurity and terrorism involve the risks of a targeted cyber attack or terrorist attack. These risks are not the product of human error or technical failures. They result from intentional actions designed to disrupt society. As with external safety, we draw upon the regional risk profile method and the country-wide national security risk analysis. Together with a panel of experts, we assessed the risks of cyber incidents and terrorist attacks for various hydrogen carriers in each step of the chain. We integrated these probabilities with the potential impacts previously identified in the environmental risk indicator, yielding a cyber risk and terrorism risk for every step of the chain. The scores for each supply chain were calculated by adding together the individual chain steps.

Transport safety

Transport safety entails assessing the transport risks (accident risks) associated with the number of vehicle and vessel movements (or extra movements) involved in transporting hydrogen carriers. These transport risks are calculated by multiplying the total tonne-kilometres for each chain by the corresponding shadow costs per tonne-kilometre. This methodology is standard practice for determining transport safety risks.

The shadow costs, as established by CE Delft, are also used in the KiM Freight transport knowledge base.[42] The costs cover medical expenses, production losses, handling charges, and

---

[41] When transporting hydrogen carriers, the focus is on casualties resulting from the release of hazardous substances, rather than an 'ordinary' collision or accident. The latter falls under transport safety.

[42] CE Delft (2022), *De prijs van een reis, de meest recente kentallen voor Nederland* (The price of a journey, the most recent benchmark figures for the Netherlands), and KiM (2023), *Kennisbasis goederenvervoer 2023* (Freight transport knowledge base 2023).

material costs linked to fatalities, as well as to individuals with severe and minor injuries. Benchmark figures are available for transport by road, water, and rail. Transport by pipeline is expected to eliminate traffic accidents entirely, allowing us to avoid any expenses related to transport safety.

3.5 SUSTAINABLE

The public interest Sustainable comprises three sub-indicators: 1) greenhouse gas emissions, 2) energy loss and 3) material consumption.

Greenhouse gas emissions

Across the various hydrogen supply chains, small quantities of carbon dioxide, methane, hydrogen, and/or nitrous oxide (N_2O) are released during production, conversion, storage, and transport. These emissions drive climate change, either directly (carbon dioxide, methane, nitrous oxide) or indirectly (hydrogen). Emission types and volumes vary greatly from one chain to another. Emission level estimates for various steps in the chain are drawn primarily from the literature, particularly JRC2.[43]

Transport-related CO_2 emissions result from the use of fossil fuels (expected to remain dominant in 2030, but will be mostly phased out by 2050). CO_2 is used in the synthesis of methanol and LSM. During conversion to hydrogen gas or carrier end use, this CO_2 is released again. This 'embedded' CO_2 is factored in when calculating a chain's greenhouse gas emissions if it was sourced from industrial CO_2 (as assumed for 2030) but not if sourced from direct air capture (as assumed for 2050).

Minor methane losses may also occur in the LSM chains and when transporting methane through the natural gas network. Small amounts of hydrogen escape during the conversion of various hydrogen carriers to hydrogen and while it is being transported in liquid or gaseous form. In addition, JRC2 indicated that small amounts of N_2O are emitted during ammonia conversion.

To calculate the overall impact for each chain, we express methane, hydrogen, and nitrous oxide emissions in terms of CO_2 equivalents based on their Global Warming Potential compared to CO_2. Some substances have a higher Global Warming Potential (per kilogram) than others. Our approach uses the Global Warming Potential of these substances over a 100-year time frame. For each chain, we multiply the CO_2 equivalent emissions by the CO_2 price.

Energy loss

Energy loss can be broken down into two components. The first of these involves the energy needed to produce hydrogen in the exporting country, bind it to a hydrogen carrier or liquefy it, ship it and store it within the Netherlands, transport it onward, and convert it into hydrogen or another product for end use. The energy loss associated with producing or capturing CO_2 (including direct air capture) is factored in here. The second component is the energy required to replenish the amount of hydrogen (or hydrogen carrier) that is lost throughout the process, whether from unintended emissions or from its planned use as fuel in various steps of the chain, making it inaccessible for end use. Together, these components make up the total energy input required to supply 1 kt of hydrogen to the end user. We express this total energy input in terms of the energy contained in 1 kt of hydrogen.

The amount of renewable energy required to produce an energy equivalent volume of hydrogen (carriers) for end users impacts process efficiency and, as a result, affordability. It is also particularly significant in terms of energy use, given the global renewable energy shortage.

---

[43] European Commission, Joint Research Centre, Arrigoni, A. et al. (2024), Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe, Publications Office of the European Union, Luxembourg.

Details of the projected energy requirements and losses during production and transport were sourced from the literature, particularly JRC2.

Material consumption

We gauged material consumption by examining the impact on limited resources needed within the hydrogen supply chain. This covers various catalysts and carrier materials sourced from raw materials designated as critical by the EU[44]. The latter category pertains to boron, a key element in the production of borohydride. In an ideal situation, the loss of scarce materials would also be factored in. However, information on this topic remains limited. Accordingly, we have restricted our focus to the amount of material (in grams per kilogramme of hydrogen) required to meet annual demand (source: JRC2). This range of materials is unified under a common denominator by multiplying each by its current market price. Thus, the comparative indicator for each chain is the value of the demand for scarce materials per kt of hydrogen equivalent.

3.6 ADAPTABLE

Given the uncertainties about the development of hydrogen carriers and hydrogen chains, adaptability is essential. As a result, economic operators face investment risks. For this reason, it is advantageous if a chain requires fewer minimal high-risk investments or if plants and transport systems are sufficiently flexible to serve other purposes.

The level of adaptability is expressed in terms of the value of extra investments that cannot be repurposed. This is the 'value at risk'. Working with a panel of experts, we assessed the extra investments required as a proportion of total investments and determined their potential for reallocation. For each chain, the final indicator is the scale of investment needed that cannot be reallocated at a later stage, expressed as kt per hydrogen equivalent. The greater the level of high-risk investments, the lower the adaptability score. Details of the investments needed for each chain were mainly sourced from JRC1.

3.7 FAIR

Fair relates to an equitable distribution of benefits and burdens. We use two sub-indicators to quantify the public interest Fair at the level of producing countries, at the level of importing, or transit countries: 1) passing on the external costs of imports to the producer countries, and 2) passing on the external costs of the supply chain in the Netherlands to Dutch society at large.

The distribution of benefits and burdens becomes less equitable when a significant portion of the unpriced (external) effects of imports – such as their environmental impact and greenhouse gas emissions – falls on the producer countries, or when a relatively large number of external effects from the hydrogen carrier supply chain are felt in the Netherlands. In this case, the 'true price' is significantly higher than the invoiced cost.[45]

We have also explored alternative interpretations of the Fair concept. These interpretations either failed to deliver any distinctive assessments or the appropriate data per chain was lacking. For instance, the only effective way to establish whether the benefits of hydrogen carrier production accrue to the residents of an exporting country or to foreign investors is to analyse the situation on a country-by-country and project-by-project basis. That is outside the scope of this study.

---

[44] Website European Commission on Critical Raw Materials.

[45] 'True price' is a concept that encompasses the market price along with all external costs (social and environmental costs). True price is a tool for exposing the hidden costs associated with the production of goods and services.

External costs passed on to producer countries

In this study, the fairest chains are considered to be those where the true price closely matches the import cost price. For this purpose, we calculated the total value of the external effects of imports and divided that figure by the import costs in the Netherlands. The higher the result, the greater the extent to which external costs are passed on producer countries, making the outcome less fair and leading to a lower score for this public interest.

The import costs are assessed against the public interest Affordable. The external effects of imports are partly derived from the LCA study in JRC2[46], along with environmental cost factors from CE Delft.[47]

Passing on the external costs of chains within the Netherlands

As an indicator of fairness for the Netherlands (or its residents), we calculated the total value of external effects per chain within its borders and divided this by the associated costs of chain activities in the country. This means the costs of transshipment and storage, transport, and the conversion steps[48]. These costs are assessed against Affordable. In the Netherlands, external costs consist of:

- monetised greenhouse gas emissions,
- monetised environmental impacts, and
- the costs incurred by transport safety.

These have been calculated for the public interests of Sustainable, Environment, and Safe & Secure.

3.8 ACCESSIBLE

In this study, we quantify the public interest Accessible using two sub-indicators: 1) the cost disparity between hydrogen users inland and those at ports of entry (level playing field in terms of costs), and 2) proximity or degree of accessibility to supply chains.

Accessible cost level (inland versus port of entry)

We compare the accessibility of hydrogen carrier cost levels for various inland end users to the costs incurred by users at ports of entry. In these ports, the costs per hydrogen equivalent are minimal, since transport costs in the Netherlands do not apply. The indicator is the ratio between costs further inland in the Netherlands or Germany (at the end of a typical 200 km route) and those at the ports of entry. When costs further inland are significantly higher, the resultant disparity makes it more difficult for companies based in these areas to compete with those at one of the ports of entry. We appreciate that this might be a desirable effect, in terms of providing a competitive edge over neighbouring countries.

The variables for this comparison were derived from the figures for the public interest Affordable.

Accessible network / proximity for end users

To determine the accessibility of various hydrogen carriers for end users inland, we employed a methodology inspired by the proximity factor used in other domains (see CBS proximity statistics). We quantify this indicator by defining it as the proportion of industrial estates linked to the

---

[46] European Commission, Joint Research Centre, Arrigoni, A. et al. (2024), Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe, Publications Office of the European Union, Luxembourg.

[47] CE Delft (2023), *Handboek Milieuprijzen* (Environmental Prices Handbook 2023), *Methodische onderbouwing van kengetallen gebruikt voor waardering van emissies en milieu-impacts* (Methodological substantiation of benchmark figures used for valuation of emissions and environmental impacts).

[48] In our analysis, the conversion step at the end user's site is omitted in the case of exports to Germany.

transport mode. In terms of delivery by road and through the natural gas network, this is 100%. Delivery by rail and water is based on data from the IBIS database.[49] We estimated the percentage of industrial estates expected to have access to specific pipelines or the hydrogen transport network by identifying the municipalities along the planned routes of the Delta Rhine Corridor and the national hydrogen transport network. To provide a rough approximation, we use the number of industrial estates in these municipalities as a percentage of the total number of industrial estates in the Netherlands (see Annex C for the relevant figures).

3.9 SPATIAL PLANNING

The processes of hydrogen carrier production, conversion, transport, and storage require space (physical space). Given the limited availability of space in the Netherlands, both above and below ground, the various supply chains will have a significant impact with regard to the use of space, spatial integration, and the quality of the living environment.

We estimated the land area (industrial land) required, measured in square metres, for conversion and synthesis plants, as well as for transshipment facilities and storage facilities. This was valued against the average price for industrial land. Additional space will be required for laying pipelines and, where necessary, creating connections to the hydrogen network. In the context of space on an industrial estate, it is assumed that this will involve a strip of land, valued at the price for industrial land, which can no longer be utilised for other purposes (opportunity costs). In the context of laying pipelines in natural and agricultural areas, we have based our calculations on the average price of agricultural land.

3.10 ENVIRONMENT

Here, the term Environment includes the impacts of various emissions that damage the environment as well as the health of people and animals. For this comparison, the public interest Environment covers the costs associated with nitrogen emissions, particulate matter, ammonia emissions, habitat degradation, noise pollution, ecotoxicity, and methane-induced smog, including, where possible, the costs of environmental impacts in case of incidents such as spills. Insofar as they occur in the Netherlands, these costs are factored into the public interest Environment. Fair is the only public interest that takes account of environmental impacts in other countries.

The following effects result from emissions of nitrogen, ammonia, particulate matter and/or methane:

- Health costs associated with inhaling pollutants.
- Buildings and materials suffer damage because (1) nitrogen oxides cause façades to corrode, and (2) they become contaminated by particles and dust.
- Decline in agricultural crop yields caused by factors such as acidifying substances and secondary ozone.
- The ecological damage caused by air pollutants significantly impacts ecosystems and biodiversity.

Noise-related costs are defined as the burden imposed on third parties (e.g. local residents) by traffic noise, when this triggers physical or psychological complaints in these individuals. We have omitted three other detrimental effects of noise due to a lack of reliable data. These are a decline in productivity, disturbances to quiet areas, and impacts on ecosystems.

Transport causes a range of adverse effects on nature and landscapes, classified as habitat degradation (damage to the natural habitats of animal and plant species). This involves habitat loss resulting from the encroachment of transport infrastructure, as well as habitat fragmentation or

---

[49] IBIS database: Integrated Business Park Information System, downloadable at https://provincies.pleio.nl/

barrier effects due to major and expansive primary infrastructure (such as motorways and railways). This is in addition to the habitat degradation caused by environmentally harmful substances other than NO_x and particulate matter. Where they contribute to climate change, greenhouse gas emissions, both direct and indirect (carbon dioxide, methane, hydrogen, and nitrous oxide), are included in the assessment of the public interest Sustainable. To this end, methane's effects are divided into climate-related impacts and those arising from ecotoxicity and methane-induced smog.

Inland transport by road, water, and rail generates NO_x, particulate matter emissions, and noise pollution, as well as causing habitat degradation. There is also the potential for environmental incidents. As inland shipping operates farther away from residential areas, it is not expected to generate any noise pollution. Benchmark figures are available for these effects (source: KiM), which we integrate with data on transported tonne-kilometres per supply chain. The use of electric pumps, means that pipeline transport generates no NO_x, particulate matter emissions, or noise emissions.[50]

The processes of converting and storing hydrogen carriers also generate emissions. Both LOHC conversions and ammonia-to-hydrogen chains generate NO_x emissions, while the latter also produce ammonia emissions (source: JRC2). We were unable to locate sufficient data on noise emissions, particulate matter, and habitat degradation at conversion plants.

Estimating the impact of environmental incidents in terms of their order of magnitude involves multiplying the probability of such incidents by the volume released and the shadow costs associated with emitting the substance into the environment.

---

[50] In 2030, electricity generation will still contribute to NO_x emissions. These have been factored in for processes and transportation that use electricity.

CHAPTER 4 MULTI-CRITERIA ANALYSIS METHODOLOGY

This chapter details the methodology used for the multi-criteria analysis. Multi-criteria analyses are used in a range of fields, including those related to energy issues. This methodology is used to effectively factor in dissimilar criteria that cannot be easily grouped into one rubric, in a manner similar to the difficulty of comparing apples, pears and lemons. We adopted a multi-criteria analysis approach, representing public interests with indicators that are quantified wherever possible, monetised when feasible, and qualitatively reviewed by experts in other cases.

A multi-criteria analysis typically involves seven substantive steps:

1. Identifying the alternative options (the supply chains to be assessed, see Chapter 2),
2. Establishing the criteria (the public interests, see Chapter 3),
3. Determining the score for each alternative option (the supply chains to be assessed),
4. Normalising the scores based on the criteria (the public interests),
5. Assigning weights to the criteria (the public interests),
6. Ranking the alternatives (the chains to be assessed),
7. Sensitivity analysis.

The first two steps were detailed in the previous two chapters. This chapter briefly covers the remaining steps. We occasionally use additional methods in some parts of the multi-criteria analysis. Each of these is briefly outlined as well.

4.1 DETERMINING THE SCORE FOR EACH PUBLIC INTEREST

The scoring for public interests is primarily guided by information from existing literature. Where possible, interviews and expert insights were used to fill any blank spots in this information. A supply chain's score for a public interest like Affordable can be effectively expressed in euros. We can quantify and, where possible, monetise scores for Environment (e.g. emissions of environmentally harmful substances per chain), Safe & Secure (potential number of fatalities and injuries) or Spatial Planning (spatial footprint) using shadow costs or land prices. Since this is a methodological approach using virtual euros, we treat the indicator as a quantitative measure rather than a monetary one. In specific instances, monetisation can be helpful, particularly for comparing different forms of land use.[51] Indicators that could not be objectively quantified in this study, such as Cybersecurity, Fair, and Adaptable, were determined using an indicator specially developed for the purposes of this study, combined with expert judgement. This sometimes entailed an established qualitative ranking method, like those used for external safety and cybersecurity, or a newly developed indicator tailored to public interests such as Adaptable and Reliable.

4.2 NORMALISING THE SCORE FOR EACH PUBLIC INTEREST

Once the scores for each public interest have been determined, they are normalised. This enables the scores to be consolidated into a final score for each chain, regardless of the differing units

---

[51] Spatial footprints can be compared in terms of hectares if the land type and its use are identical. In other cases, monetising the spatial footprint can be useful for comparison purposes. For example, if a supply chain uses agricultural land with a pipeline running under it, the land can still be used for farming. In contrast, another chain's spatial footprint might be on industrial land, in which case the land cannot simultaneously serve other purposes.

(kilograms, ++, euros). To this end, each chain is mapped onto a new 0-to-1 scale for every public interest. We use a linear min-max normalisation method for this purpose. This is the most widely used method.[52]

The literature on MCA studies proposes various approaches to scaling between 0 (the minimum) and 1 (the maximum): local and global normalisation.

In local normalisation, the chain with the best score is awarded the highest value (=1), while the worst-performing chain is assigned the lowest value (=0). For instance, this means that the chain with the lowest costs (= ranking highest in terms of Affordable) is awarded the top score of 1. Chains with performance levels that are neither the best nor the worst in terms of Affordable are assigned a value between 0 and 1. Those with a cost level midway between the cheapest and most expensive chains are awarded a normalised score of 0.5.

One drawback of this type of normalisation is that the evaluation is largely dependent on the specific chains assessed and their scores in terms of the individual public interests. The minimum and maximum values are each determined by the score of one specific chain. If the gap between the minimum and maximum changes, for instance during a sensitivity analysis, the normalised scores can fluctuate considerably. After all, sensitivity analysis scores may sometimes fall outside the bandwidth of the original score. This, in turn, modifies the impact of the weighting factors and, consequently, the final score. As a result, comparisons become more difficult to interpret.

In global normalisation, the theoretical minimum and maximum scores for each public interest are used to align scores on a comparable scale, irrespective of the exact scores of the chains being studied. Using this approach, the scores consistently fall within a 0 to 1 scale, and the bandwidths between minimum and maximum and the impact of the weighting factors remain the same. This is an advantage. One drawback is that it is not always possible to readily determine the theoretical maximum and minimum values. In this study, this applies to the public interest Sustainable – greenhouse gas emissions, for instance. It stands to reason that the ideal theoretical score would be zero emissions. Identifying the worst score, however, is not straightforward. This should at least match the highest emission recorded in any of the chains reviewed in this study, including the sensitivity analysis, but it could potentially be higher.

One benefit of global normalisation is that introducing new hydrogen carriers or chains with scores outside the bandwidth of the other chains does not alter the results of those chains. Additionally, deleting a hydrogen carrier or chain from the results does not lead to any potential shifts in the minimum and maximum scores.

For this reason, we adhere to the global normalisation method as much as possible in this study, as this helps to prevent any adverse shifts in scores, even during extra sensitivity analyses. In situations where establishing both the theoretical minimum and maximum wasn't feasible, we selected the highest or lowest score from all chains reviewed across the different variants[53]. Details of the method used to determine the minimum and maximum normalisation values for each public interest are set out in Annex D.

---

[52] Min-max normalisation is one option, but other methods are also available. These are more complex and not as widely used. For instance: 1) Z-score normalisation, where scores are converted to z scores by subtracting the mean and dividing by the standard deviation, and 2) Decile ranking, where scores are ranked and divided into ten equal parts (deciles). Each score is then replaced by the midpoint of the corresponding decile. 3) Vector normalisation, where each vector (set of scores) is normalised to a length of 1 by dividing the vector by its Euclidean length.

[53] In two of the sensitivity analyses performed, the worst score occasionally appeared to be just outside the bandwidth used for the normalisation. In these cases, we adjusted the score for that public interest to match the worst score for the normative bandwidth. This simplification has a minimal effect and does not alter the conclusions reached.

4.3 ASSIGNING WEIGHTS TO THE PUBLIC INTERESTS

As the top score in Affordable, for example, doesn't automatically have the same public value as the top score in Sustainable, a comparative weighting of public interests is needed to consolidate the scores into a single final score. It is not simple to determine this weighting objectively or to provide sufficient scientific evidence. There are two reasons for this:

1. One party may prioritise Environment over Affordable or Safe & Secure, while another party may assign the highest priority to the public interests Affordable or Safe & Secure. As this involves the broader valuation of public interests, we sought to engage as many parties with the most diverse range of backgrounds possible, rather than relying solely on us as researchers or the ministry to determine the weighting. We used a Modified Delphi approach to achieve the most balanced weighting of various public interests and participant input possible (within time and budget constraints) and to ensure that the discussion remained as factual and objective as possible.
2. Identifying the appropriate weighting factors is challenging, even for participants who aim to establish an objective ranking by themselves. For this reason, we used a structured approach known as the Analytic Hierarchy Process (AHP) to help determine the weighting factors. This method involves comparing two alternatives at a time, each with distinct public interests, and indicating a preference for one over the other. Using a mathematical approach, we can then derive the most representative weighting for all public interests from the results.

Integrating a Modified Delphi approach with AHP in this way enables us to achieve the most objective weighting possible. A total of 21 individuals from a range of organisations took part in this process (see Table 5).

Further details on the methods used can be found in Annex E. The results for the weighting factors are presented in Chapter 5.

Table 5: Organisations that supplied participants for the Delphi process (a total of 21 participants)

Government authorities (8)	Supply chain stakeholders (8)	NGO & knowledge and consultancy institutions (5)
Ministry of Climate Policy and Green Growth (KGG)	Port of Amsterdam	International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)
Ministry of Infrastructure and Water Management (IenW) (2x)	Port of Rotterdam	Natuur en Milieu (Nature and Environment)
Ministry of the Interior and Kingdom Relations	Royal Inland Navigation Netherlands (KBN)	Netherlands Institute for Public Safety (NIPV)
Ministry of Justice and Security	NLHydrogen	Netherlands Environment Assessment Agency (PBL)
DCMR Environmental Protection Agency	Association of Pipeline Owners in the Netherlands (VELIN)	Utrecht University
Association of Provinces of the Netherlands (IPO)	Association for Energy, Environment and Water (VEMW)	
Kennemerland Security Region/Safe Energy Transition Programme	Royal Association of the Dutch Chemical Industry (VNCI)	
	Association of Dutch tank storage companies (VOTOB)	

4.4 RANKING THE ALTERNATIVES

A simple multi-criteria analysis combines the scores for public interests with the weighting factors to yield a final score. This score, referred to as the 'Nuts' (Utility) score, is an indicator of societal utility. The most attractive chain is subsequently identified by listing the supply chains in descending order of their Utility scores. The chain with the highest Utility score is preferred, followed by the chain with the next highest score, and so on.

Such an approach singles out the highest Utility score and disregards the fact that a chain might have a very low score for one particular public interest. However, this can often have a substantial impact on negotiations concerning alternatives in real-world situations. Those who view a particular public interest as pivotal will insist on a threshold score for that interest and will reject any chain with the lowest score for that interest. As a result, we rank the alternatives (the chains) in a more sophisticated manner.

The VIKOR Multicriteria Optimization and Compromise Solution[54] determines the attractiveness of a supply chain by measuring its proximity to the ideal score for each public interest and its distance from the least favourable/worst possible score for each of those interests. Although it is possible to weigh these two scores against one another, a 50-50 weighting is generally used. Accordingly, the preferred supply chain is the one that performs best for this combination. This is a chain that is reasonably close to the best score for each public interest and reasonably far from the lowest score for each of those interests.

TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) offers an alternative approach. This approach also determines the attractiveness of an alternative by measuring how far it is from the ideal score for each criterion (public interest) and from the least ideal/worst possible score, but always with 50-50 weighting. Furthermore, key criteria (i.e., those allocated

---

[54] In Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje

higher weighting factor through the AHP process) receive a higher weighting. The distances to the ideal score and the least ideal score for that criterion carry more weight in the evaluation.

Given that the TOPSIS method amplifies the impact of the weighting factors, we opted for the VIKOR method over TOPSIS in this study. Annex F contains further details regarding the VIKOR method, together with a numerical example.

4.5 SENSITIVITY ANALYSIS

Finally, we carried out a range of sensitivity analyses on the results. This process involved the following sensitivity analyses:

- Sensitivity to various weighting factors. The results of the Delphi analysis may be open to varying interpretations. For this reason, sensitivity to an alternative weighting was measured (impact on ranking). In this instance, we determined the final score's sensitivity to:
    - weighting factors derived from an allocation of 100 points, as opposed to the Delphi scores;
    - a set of weighting factors where Affordable is assigned twice the weight derived from the Delphi scores, while the weights of Sustainability and Safe & Secure are each halved relative to the weighting factors obtained from those scores;
    - public interests weighted *equally* (each was allocated 10%).
- Sensitivity to sea transport distance. The distance travelled by ship to reach the Netherlands varies according to where the hydrogen carrier is produced. This impacts the costs, energy loss, emissions during maritime transport, and, ultimately, ranking.
- Sensitivity to the volume of hydrogen carriers transported (impact on individual scores for each interest and, ultimately, on ranking).
- Sensitivity to storing and converting hydrogen carriers offshore, as opposed to onshore facilities at a port of entry. This could impact individual scores for public interests, especially Safe & Secure and Environment and, ultimately, the ranking.
- Sensitivity to more progressive assumptions for energy loss, emissions, and certain costs in 2050 than in the baseline situation for that year.
- Sensitivity to the use of an alternative source for the cost estimates for imported hydrogen carriers. We used HyDelta data for the baseline situation, and the high variant from JRC1 for the sensitivity analysis.
- Sensitivity to the use of CO_2 capture in the Netherlands during the steam reforming of LSM and methanol.

COMPARISON OF HYDROGEN CARRIERS
PART B: RESULT OF DELPHI SESSION

CHAPTER 5 WEIGHTING RESULTS

We determined the weighting factors for the final score using a Delphi approach, combined with AHP, together with a broadly representative group of 21 participants (see Chapter 4.3). This chapter examines the results obtained: the weighting factors.

When a public interest was represented by more than one indicator, the results of the Delphi approach were also used to determine the weighting of various sub-indicators. This applies to the public interests Safe & Secure, Sustainable, Fair, and Accessible.

It is important to note that no questions asked in the Delphi approach involved direct comparisons of specific hydrogen carriers. This was to ensure that balancing the various public interests remained as objective as possible. The weighting results apply just as well to the current set of seven hydrogen carriers as they would to any other set of carriers.

5.1 PUBLIC INTEREST WEIGHTING FACTORS

Figure 11 illustrates the results of the public interest weighting, following the analysis of the responses to the paired questions. The Delphi group gave by far the greatest weight to Safe & Secure and Sustainable. Trailing quite some distance behind are Environment and Affordable. The remaining public interests collectively account for the final quarter of the points.

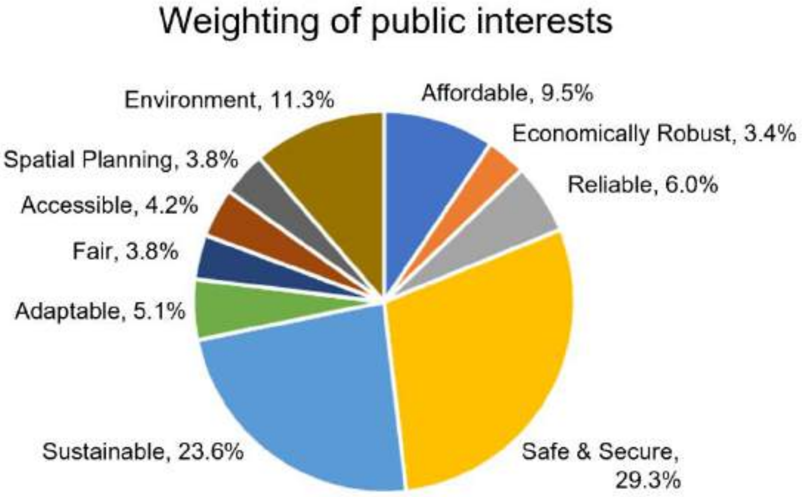


Figure 11: Resultant public interest weighting for hydrogen carriers, derived from Delphi scores

Chapter 5.4 presents the rationale used by Delphi session participants to determine the final weighting. Below is a summary of the main arguments.

A key argument cited by participants for the high score for Safe & Secure is that reducing the risk of incidents (especially those involving toxic gas clouds) is crucial for securing acceptance and support for the energy transition, which ultimately influences the pace and execution of climate plans. The participants acknowledged that integrating hydrogen use more widely will inevitably pose safety challenges. For this reason, the existing space in 'safety zones' needs to be managed efficiently. Chains that require larger safety zones per hydrogen equivalent than others tend to be less efficient.

The participants assigned a high weighting to Sustainable because the ultimate goal of the energy and raw materials transition, including the use of green hydrogen (carriers), is to reduce greenhouse gases. A failure to achieve this reduction when importing the carriers would be counterproductive. The Delphi group stated that high greenhouse gas emissions are just a way of deferring the problem to the future.

The participants assigned a fairly high weighting to Environment, recognising that emissions of hazardous substances reduce biodiversity, which destabilises ecosystems and poses health risks. This endangers everyone, and threatens the economy as well. In areas with a limited nitrogen deposition allowance, high NO_X emissions could lead to projects being cancelled.

The public interest Affordable is seen as essential by participants, as the cost price is currently a hurdle to the rollout of hydrogen chains. Lower cost prices would help initiatives to gain traction. Without this, sustainable, affordable alternatives to fossil fuels will remain out of reach. The Delphi group notes that hydrogen affordability is critical for building viable business cases and securing and retaining societal support.

5.2 WEIGHTING FACTORS FOR INDICATORS

Four of the ten public interests are represented with two or three indicators, whose scores cannot directly be totalled. Weighting factors were established to enable these scores to be combined into a single value for each public interest.

Safe & Secure

The public interest Safe & Secure comprises three sub-indicators: external safety, cybersecurity/terrorism, and transport safety. Figure 12 illustrates the weighting of these three sub-indicators, which together account for 29.3% of the total weighting.

The participants rated external safety as the most important of these three. This stems from the fact that robust external safety measures lessen the impact of potential cyber attacks or terrorist incidents, because the available safety zones for hydrogen carriers are already constrained. The group views transport safety as playing a less prominent role in this study. They reason that in relation to external safety, major incidents involving hazardous substances might occur, which invariably have a much greater impact than major traffic accidents. Accordingly, the Delphi group feels that external safety is more crucial than transport safety in terms of gaining public support. Transport safety concerns the risk of accidents involving road casualties and material damage, not accidents during the transport of hazardous materials that impact Dutch society.

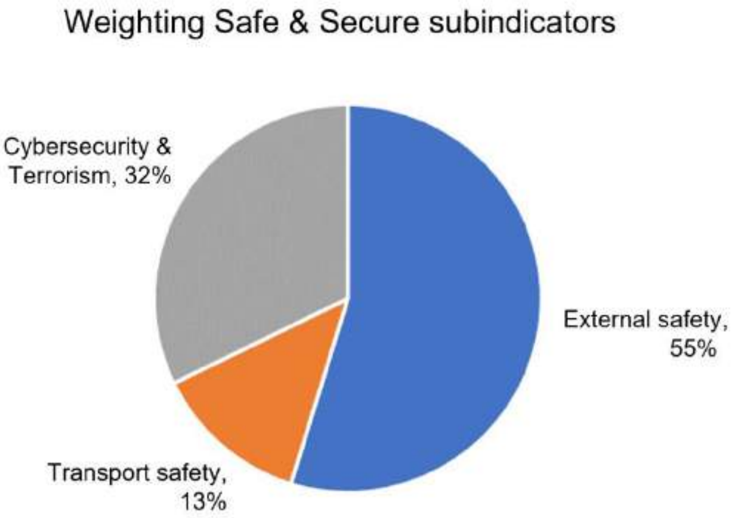


Figure 12: **Breakdown of the weighting of Safe & Secure sub-indicators, based on Delphi scores**

Sustainable

The public interest Sustainable is represented with three sub-indicators: energy losses in the chain, greenhouse gas emissions, and impacts on scarce materials. Figure 13 illustrates the weighting of these three sub-indicators, which together account for 23.6% of the total weighting.

The Delphi group ranks greenhouse gas emissions far above the other two sub-indicators, since reducing these emissions is the main driver behind the Netherlands’ interest in importing green hydrogen.

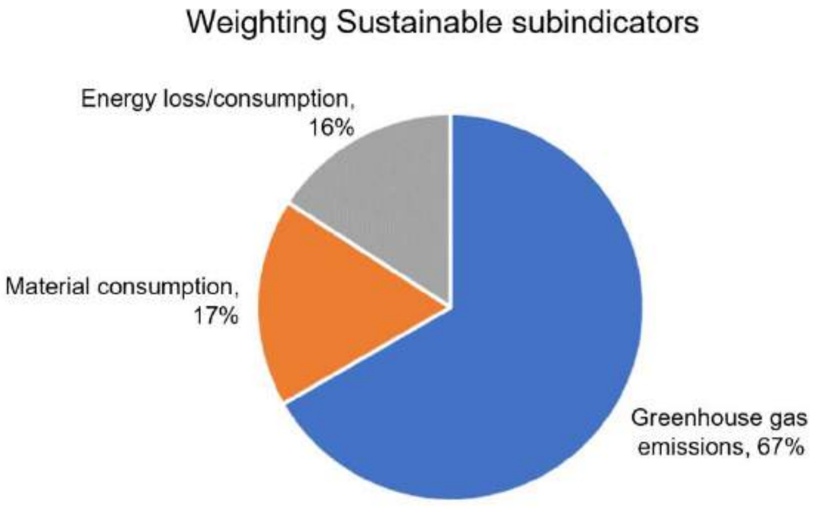


Figure 13: **Breakdown of the weighting of Sustainable sub-indicators, based on Delphi scores**

Fair

The public interest Fair comprises two sub-indicators: an equitable distribution of benefits and burdens at international level, and an equitable distribution in the case of transport within and through the Netherlands. Figure 14 illustrates the resultant weighting between these two sub-indicators, which together account for 3.8% of the total weighting.

In the Delphi process, a slightly higher weighting is given to fair distribution in relation to producer countries, reflecting the participants' view that the Netherlands ought to accept responsibility rather than passing negative externalities on to other nations. However, some participants questioned whether, if the Netherlands pays a higher and fairer price to exporting countries, that money would be well spent, or whether it would just be a drop in the ocean, and could harm the Netherlands economically more than it helps the exporting countries.

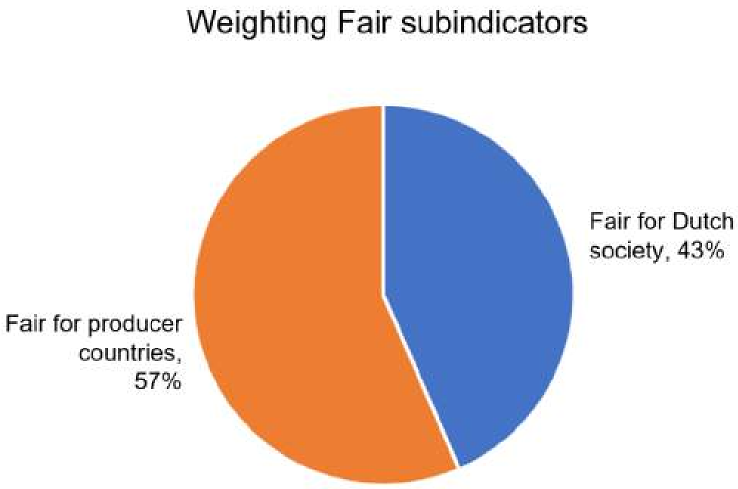


Figure 14: Breakdown of the weighting of Fair sub-indicators, based on Delphi scores

Accessible

The public interest Accessible comprises two sub-indicators: proximity of the hydrogen (carrier) chain for Dutch businesses, and the degree of cost parity in the Netherlands. Figure 15 illustrates the resultant weighting between these two sub-indicators, which together account for 4.2% of the total weighting.

The group assigned the cost parity sub-indicator about three times the weighting assigned to the sub-indicator for proximity of the chain. The rationale put forward for this is that, while greater accessibility of the chain might help to boost hydrogen uptake, the group believes that clustering companies around a limited infrastructure also offers significant advantages: a streamlined market landscape, a reduced need for hydrogen storage, decreased reliance on imports resulting in greater independence, greater electrification efficiency, reduced safety costs (minimal adverse impacts on external safety), and reduced costs for the hydrogen network.

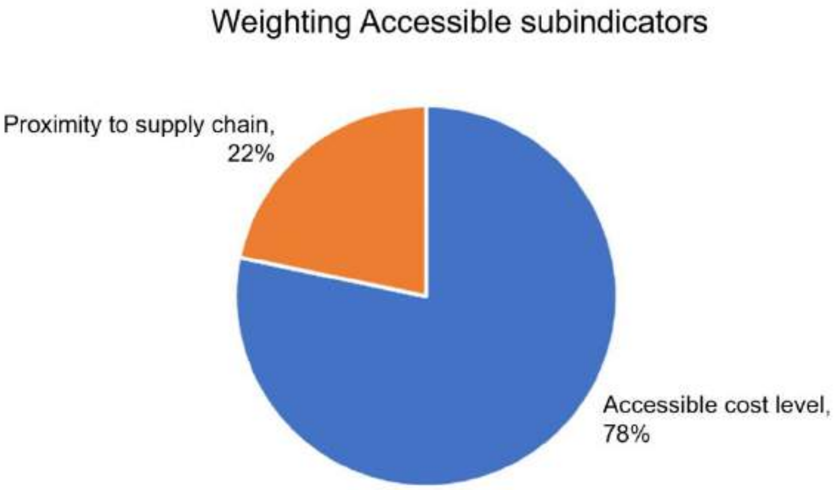


Figure 15: Breakdown of the weighting of Accessible sub-indicators, based on Delphi scores

5.3 COMPARISON WITH 100-POINTS WEIGHTING

In addition to comparing public interests in pairs, the Delphi process participants allocated 100 points to the indicators used to quantify the 10 public interests. The purpose was to verify the consistency of responses in the Delphi survey and AHP analysis.[55]

Comparing the two methods reveals no evidence of inconsistencies in the survey responses based on paired comparisons. The survey results suggest that Safe & Secure and Environment carry a slightly higher weighting in the Delphi results than in the 100-points allocation. This can be attributed to the fact that the public interest Environment was not always taken into account as broadly as intended when allocating the 100 points. It includes not only NO_X emissions but also other environmental emissions such as noise, habitat degradation, particulate matter, and ammonia. Furthermore, the public interest Safe & Secure was weighted more heavily in the Delphi meeting.

---

[55] Typically, a complete AHP analysis for this number of indicators requires respondents to score 120 comparisons (16 indicators, i.e., 15+14+13+…+1=120 paired questions). This enables an internal consistency level to be derived from the responses. However, that number is only realistic in an academic setting. Under the existing arrangement, participants had to set aside 1 to 1.5 days. Consequently, another approach was used to verify consistency.

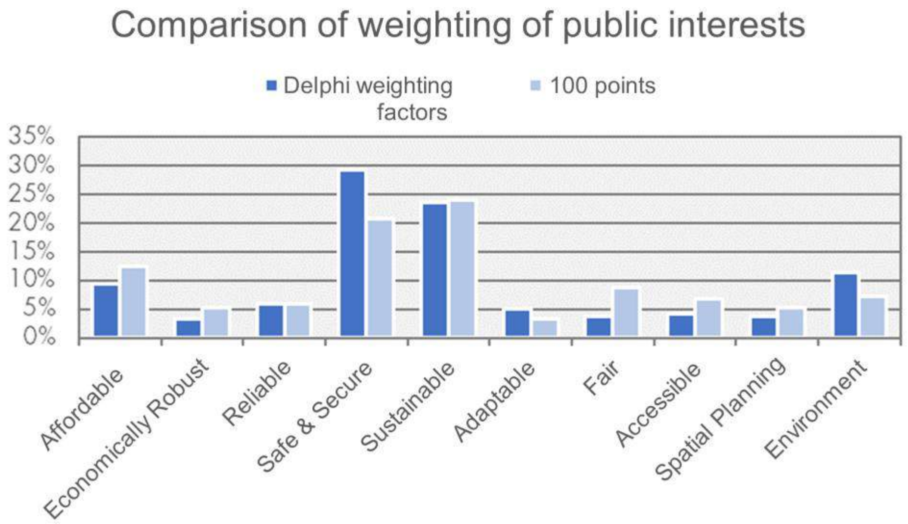


Figure 16: **Comparison of Delphi weighting and 100-points allocation**

5.4 RATIONALE USED IN DELPHI WEIGHTING

Here we summarise the rationale regarding public interests, as presented by participants during the Delphi process.

Affordable

As the participants pointed out, affordability is key to the success of business cases and to garnering support. Cost price is currently the main hurdle to the rollout of hydrogen initiatives. For this reason, a low cost price is of paramount importance. Initiatives are more likely to gain traction if the cost price is low than if it is very high. Without this, sustainable, affordable alternatives to fossil fuels will remain out of reach. Energy costs are projected to increase in the upcoming years. While many businesses and households are already facing high energy costs, there remains a pressing need for significant investment in new technologies and new installations. It is particularly important to keep costs down during the early phases of market development, as this supports end user investment in hydrogen use while providing more security to hydrogen (carrier) importers. Low cost prices can benefit the hydrogen economy and the creation of added value in the chain. If it is to remain a major player in North-Western Europe, the Netherlands needs to retain its status as a central hub for ports and the logistics industry. The Delphi group stated that low costs are critical to this endeavour.

Economically Robust

The participants felt that prioritising hydrogen chains with greater added value (economic value) would unlock opportunities for the Netherlands' future economy. High added value benefits the country as a whole, while a low cost price mainly benefits a select few. Those who back trends with high added values will ultimately recoup their investments. Ensuring sufficient added value in the Netherlands is key to gaining support for the transit of energy carriers to areas further inland in Europe. The Delphi group argued that, since energy is a scarce resource and has environmental impacts, it should mainly be used for high added-value purposes.

Reliable

Companies will only switch to hydrogen use if they can be sure of a stable supply. The Delphi group believes that reliability and security of supply are vital to the success of the energy transition. What the energy transition needs to gain traction is reliable (and affordable) renewable energy. Security of supply and reliability are key economic values. The participants pointed out that, if the reliability of the hydrogen supply chain starts to weaken, additional reserves would be needed, which would inevitably drive up costs.

Safe & Secure

External safety sub-indicator

The participants noted that external safety is crucial, particularly since integrating hydrogen use more widely will inevitably pose challenges. The Delphi group stated that, for this reason, the available safety zones need to be used efficiently. Chains that require larger safety zones per hydrogen equivalent than others tend to be less efficient.

The participants stressed that preventing major incidents is key to gaining acceptance and support for the energy transition, ultimately impacting the pace and implementation of sustainability. Safety should always be the top priority, outweighing any concerns about price. It is essential to take every precaution to prevent not just major incidents with new energy carriers, but also minor ones, especially those involving toxic gas clouds. As far as the participants were concerned, raising risk levels isn't an option, since safety is non-negotiable. Time is a factor here. With initial volumes still limited, there is an opportunity to adapt based on lessons learned. Spending more on costlier modalities or alternatives is a valid way to avoid passing on risks. Robust environmental safeguards lessen the impact of cyber attacks or terrorist incidents. The participants stressed the need to minimise the impact of incidents on those in the surrounding area, regardless of the cause.

Cybersecurity & Terrorism sub-indicator

The Delphi group notes that, for the most part, we should prioritise cybersecurity, as people tend to be overly trusting. The risks from cybersecurity and terrorism outweigh those of external safety, even outside the context of hydrogen carrier use. Dealing with cybersecurity and terrorism is a major challenge. The participants acknowledged that designing measures to lessen the impact and risk of cyber attacks and terrorism is no easy task.

Transport safety sub-indicator

The participants stressed that large-scale movements of hydrogen carriers in the Netherlands must not compromise transport safety in the country. Transport safety matters, and it can be impacted by decisions concerning transport modes.

Adaptable

To reach sustainability quickly, we need to embrace an adaptable option. To minimise the risk of lock-in, the Delphi group stressed the importance of staying focused on the transition.

As adopting new technologies or steps in the chain carries higher risks than participants would ideally like, adaptability is essential. The participants felt that boosting adaptability will make infrastructure investments smoother. This is essential if we are to develop the infrastructure needed for hydrogen distribution.

Sustainable

Greenhouse gas emission sub-indicator

The push for low greenhouse gas emissions is what drives and shapes the energy and raw materials transition. The ultimate goal of green hydrogen (carrier) use is to cut down on CO_2. The

CO_2 emission budget is tight, so hydrogen imports will be counterproductive unless substantial reductions can be achieved. The participants felt that tolerating high greenhouse gas emissions today is just another way of offloading the problem to future generations. The Delphi group stated that it is not a major concern if green hydrogen imports ultimately cost more than imported carriers with a smaller impact on greenhouse gas reduction. It might boost the direct use of electricity, which outperforms hydrogen in terms of energy efficiency, greenhouse gas emissions, *and* spatial footprint, and also requires price incentives. The latter argument, promotes electrification rather than addressing the differences between hydrogen carriers.

Energy loss sub-indicator

The participants noted that the primary focus should be to cut energy consumption, since this offers many benefits. Moreover, reducing energy consumption is still a viable option. Efficient hydrogen chains, with minimal energy losses, help conserve energy for industry, while securing public support by limiting the transport of hazardous substances. Greater energy consumption implies that more energy must be produced to offset losses in the chain, additional transport, and increased material consumption.

Material consumption sub-indicator

The Delphi group predicted that material scarcity will become a major challenge in the future, partly due to geopolitical pressures. Rising pressure on key raw materials will increasingly become a potential constraint for companies. Strengthening strategic autonomy is now a priority for the Dutch and European economies. One core component of the required energy transition is the shift to a circular economy. The participants pointed out that this will safeguard a range of environmental targets, while also strengthening security of supply.

Fair

Impact of transit and chain steps (in the Netherlands) sub-indicator

Support for the transport and use of hydrogen carriers hinges on equitable distribution, particularly when stakeholders experience unequal impacts and benefits. The participants felt that transit operations to foreign countries should not impose substantial external costs on inland regions of the Netherlands. Industrial operations must not impose disproportionately high external costs on Dutch society. If these external costs are not factored into pricing, Dutch taxpayers and the environment will be left to bear the burden of the impacts caused by industry and end users.

Impact on producer countries sub-indicator (activities preceding import into the Netherlands)

The Delphi group felt that more consideration should be given to fairness for producer countries. The Netherlands needs to step up and avoid offloading negative externalities to other nations. In practice, this means choosing carriers with minimal external impacts and being willing to bear the resultant costs. Furthermore, the import of hydrogen carriers should not cause potential exporting countries to defer the greening of their own energy systems in favour of export-driven projects. Some participants questioned whether, if the Netherlands pays a higher and fairer price to exporting countries, that money would be well spent, or whether this might disadvantage the Netherlands more than it helps the countries in question.

Accessible

Proximity sub-indicator

Making hydrogen accessible to as many companies as possible is key for industrial sustainability and helps to ensure fair competition. In addition to industrial clusters, the Delphi group called for assistance for cluster 6 companies, to help them incorporate hydrogen into their sustainability strategies. Without this, there is a risk that the advantages of using hydrogen at scale may go untapped.

Conversely, the participants believed that a limited hydrogen transport network does offer certain advantages: a streamlined market landscape, a reduced need for hydrogen storage, decreased reliance on imports resulting in greater independence, greater efficiency (if the direct electrification option is selected), reduced safety costs (minimal adverse impacts on external safety), and reduced network costs. Businesses, too, can organise themselves into clusters.

The participants noted that the promise of a close-knit hydrogen transport network might also be risky if it causes companies, municipalities, and consumers to delay their sustainability initiatives. A close-knit network incurs greater costs.

Accessible cost level sub-indicator

In any market, it is essential to provide a level playing field. This involves establishing a cost level that is as similar (comparable) as possible. The Delphi group believes that to establish a sufficiently large market for hydrogen carriers, prices must stay affordable for businesses farther from the ports of entry, such as those in cluster 6.

Environment

Hazardous emissions lead to reduced biodiversity, which destabilises ecosystems. The Delphi group warned that this is a risk to everyone's safety and harms the economy. It is important to minimise the environmental impact of energy carriers, (Substances of Very High Concern, particulate matter), given the health risks involved. If energy carriers have a high environmental impact, there is no reason to switch to this new source of energy. An excessive environmental impact will trigger more regulations and rising costs. The Delphi group identified environmental impacts as a key cause of investment delays, suggesting that projects might not be viable without adequate nitrogen allowances. The group emphasised that hydrogen conversion and transport must not add to NO_X emissions, especially given the existing nitrogen deposition surplus.

Spatial Planning

In the Netherlands, physical space for energy transition projects is very tight, and can only be used for one purpose at a time. The participants noted that this also relates to both environmental space and safety zones. Using hydrogen carriers to meet energy demands would take up more scarce space, as they are less energy-dense than most fossil fuels. The Delphi group believes that efficient space utilisation is crucial, enabling the energy transition to achieve the greatest possible climate gains with the space available. A lot hinges on the location of the spatial footprint. Some regions have very limited physical space for economic activities, as well as limited safety zones and environmental space, while other areas still have space available.

COMPARISON OF HYDROGEN CARRIERS
PART C: RESULTS

CHAPTER 6 SCORES FOR PUBLIC INTERESTS

This chapter explains the results for the ten public interests and shows the normalised scores for each public interest for the baseline situation in 2030. This baseline situation concerns the supply of hydrogen or hydrogen carriers to an inland end user in 2030. The results for the baseline situation are followed by the results for the variants: 1) end use in the port of entry, 2) transit and export and 3) finally, the expected situation in 2050. The order in which the public interests are shown reflects the order in the National Energy System Plan (NPE). Further details about the background of the calculations are given in Annex C.

6.1 METHOD OF PRESENTING RESULTS

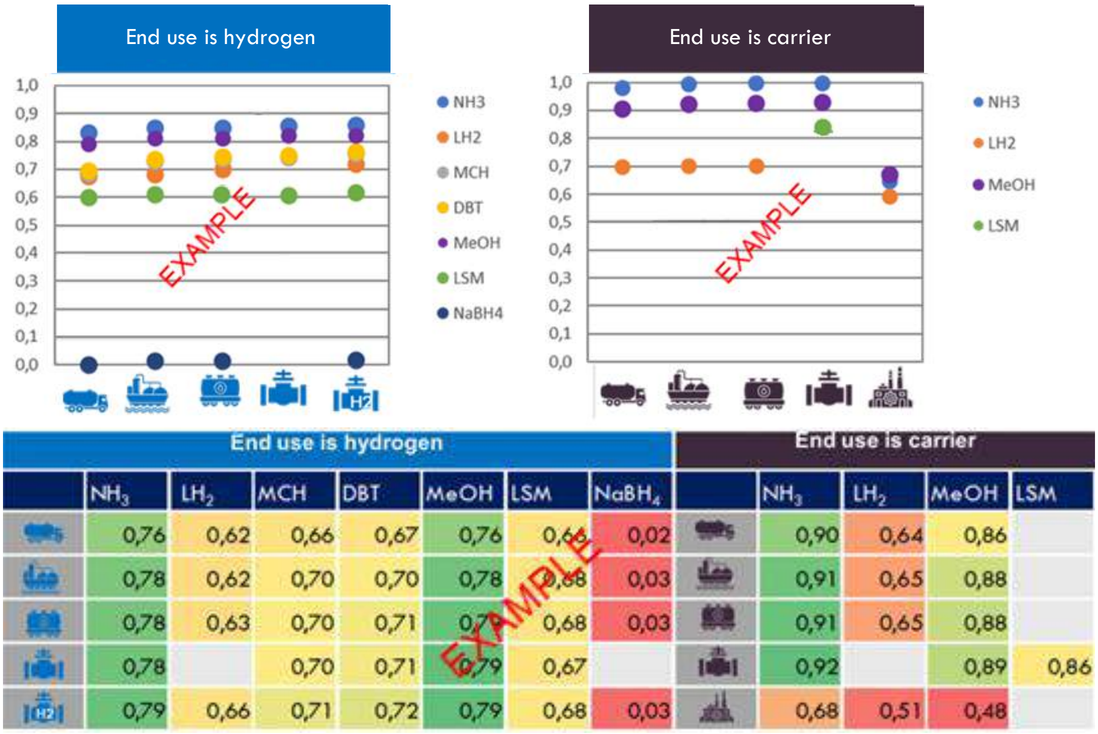
In each case, the results for the supply chains are shown in two separate charts. The charts on the left (see Figure 17, in blue) show all results for end uses that consume *gaseous hydrogen*. The first five supply chain types are shown on the x-axis:

- Type 1: transport by road and conversion to hydrogen at the end user's site;
- Type 2: transport by water and conversion to hydrogen at the end user's site;
- Type 3: transport by rail and conversion to hydrogen at the end user's site;
- Type 4: transport of the carrier by pipeline and converting it to hydrogen gas at the end user's site;
- Type 5: conversion to hydrogen gas in the port of entry and transport through the hydrogen network to the end user.

The charts on the right (see Figure 17, in black) show all supply chains in which the end use consumes a *hydrogen carrier*. The second group of five supply chain types are shown on the x-axis:

- Type 6: transport by road to end user's site (without conversion);
- Type 7: transport by water to end user's site (without conversion);
- Type 8: transport by rail to end user's site (without conversion);
- Type 9: transport of the carrier by pipeline to the end user's site (without conversion);
- Type 10: conversion to hydrogen in the port of entry, transport through the hydrogen network and decentralised synthesis of the same carrier at the end user's site.

Not all hydrogen carriers are suitable for end use. The chart on the right, therefore, shows fewer results.



	End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,76	0,62	0,66	0,67	0,76	0,66	0,02		0,90	0,64	0,86	
	0,78	0,62	0,70	0,70	0,78	0,68	0,03		0,91	0,65	0,88	
	0,78	0,63	0,70	0,71	0,79	0,68	0,03		0,91	0,65	0,88	
	0,78		0,70	0,71	0,79	0,67			0,92		0,89	0,86
	0,79	0,66	0,71	0,72	0,79	0,68	0,03		0,68	0,51	0,48	

Figure 17: Example of visualisation

The highest possible score is represented by 1, the lowest possible score by 0. As some scores for the alternatives are equal, the results (dots) sometimes overlap. A table has therefore been added under the chart to ensure that the results are clear and easy to understand. The layout and icons in the table are the same as in the charts. Various background colours in the table show which supply chains have the highest and lowest scores (from green to red based on ranking). Because the colours vary based on the ranking of the supply chains in the left or right chart, chains with apparently equal scores may nevertheless have different colours. For example: in the left chart, the supply chain that includes DBT transport by road has a score of 71% and is shown in yellow, while the same score (71%) is shown in orange in the right chart. This is because the lowest score in the right chart is 59%, while the lowest score in the left chart is 0%.

6.2 SCORES FOR PUBLIC INTEREST AFFORDABLE

Figure 18 shows the normalised scores for the affordability of hydrogen carriers for the various supply chains for inland use. The higher the score, the lower the cost price per kilogramme of hydrogen equivalent. The bandwidth used is 2.50 euros (score 1) to 12 euros (score 0).

It should be noted that these cost prices are not the same as the market prices, as several costs are not included. These include profit, risk premiums and potential location-specific costs, such as the costs of security measures (see Annex C).

Results for baseline situation (2030, inland end use)

Ammonia and methanol have the highest scores if these substances are used directly (right-hand chart, Figure 18). This is due to the lower import costs. If conversion to hydrogen is necessary (left chart), ammonia and methanol also have the highest score. This is due to the lower import costs and the relatively low conversion costs of both carriers. The losses in the supply chain due to the use of the carrier as fuel in the conversion are included. For hydrogen gas end use, the LOHCs have a slightly lower score, followed by LSM. For direct use, LSM has a similar score to ammonia and methanol. For hydrogen gas end use, liquid hydrogen follows shortly after LSM. For direct use of the carrier, liquid hydrogen follows at a somewhat greater distance due to the higher import, storage and transport costs, which are not partially compensated by the lower conversion costs.

Sodium borohydride has the lowest score. This is primarily because the production of the carrier and recycling of the carrier once the hydrogen has been released are energy intensive. The carrier material, which contains the element boron, is also expensive. This leads to high import costs.

Direct end use of the carrier (right) is cheaper than the supply chains that include conversion (left). The choice of inland transport mode has little effect on the costs.

Because the costs of import and conversion in the literature vary greatly, Chapter 7 includes the results of a sensitivity analysis. This sensitivity analysis shows the impact of using a different dataset for the costs, i.e., the dataset from JRC instead of the dataset from HyDelta.

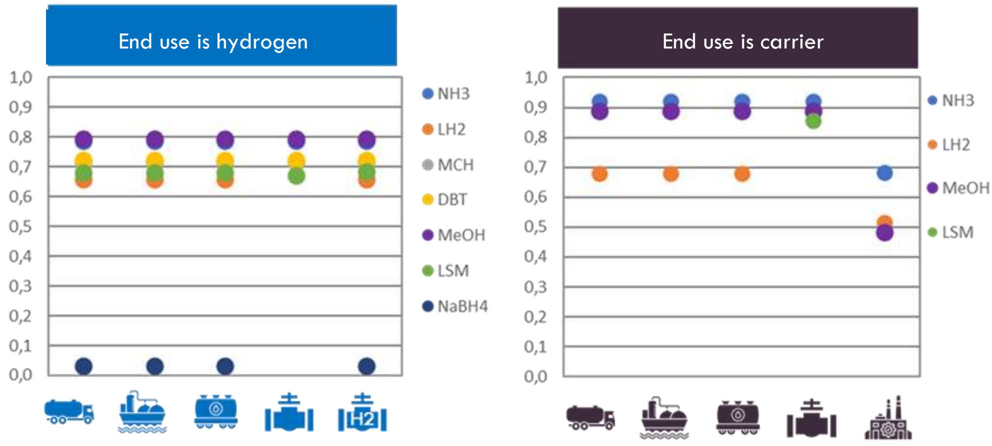
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,76	0,62	0,66	0,67	0,76	0,66	0,02	🚚	0,90	0,64	0,86	
🚢	0,78	0,62	0,70	0,70	0,78	0,68	0,03	🚢	0,91	0,65	0,88	
🚆	0,78	0,63	0,70	0,71	0,79	0,68	0,03	🚆	0,91	0,65	0,88	
	0,78		0,70	0,71	0,79	0,67			0,92		0,89	0,86
H2	0,79	0,66	0,71	0,72	0,79	0,68	0,03	🏭	0,68	0,51	0,48	

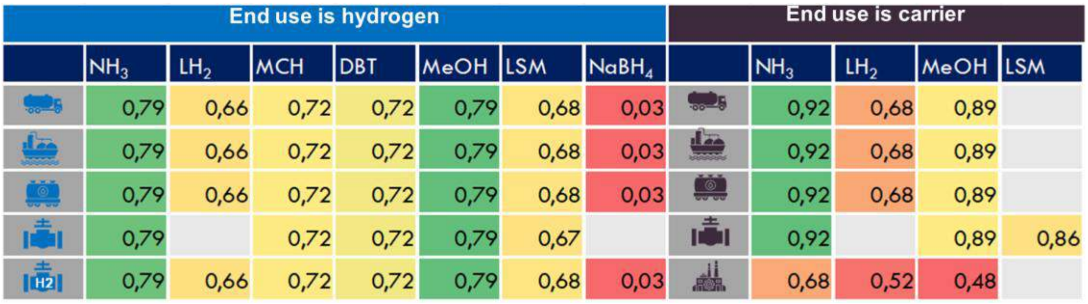
Figure 18: Scores for Affordable for inland supply chains in 2030; hydrogen end use and carrier end use

Results for variants

Port of entry

End use in the port of entry improves the Affordable score compared to the baseline situation, as shown in Figure 19. However, the effect is small, because the inland transport costs are limited compared to the import and conversion costs. There are also no longer any differences between the transport modes, as there are no inland transport costs.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,79	0,66	0,72	0,72	0,79	0,68	0,03	🚚	0,92	0,68	0,89	
🚢	0,79	0,66	0,72	0,72	0,79	0,68	0,03	🚢	0,92	0,68	0,89	
🚆	0,79	0,66	0,72	0,72	0,79	0,68	0,03	🚆	0,92	0,68	0,89	
	0,79		0,72	0,72	0,79	0,67			0,92		0,89	0,86
H2	0,79	0,66	0,72	0,72	0,79	0,68	0,03	🏭	0,68	0,52	0,48	

Figure 19: Scores for Affordable for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use

Transit and export

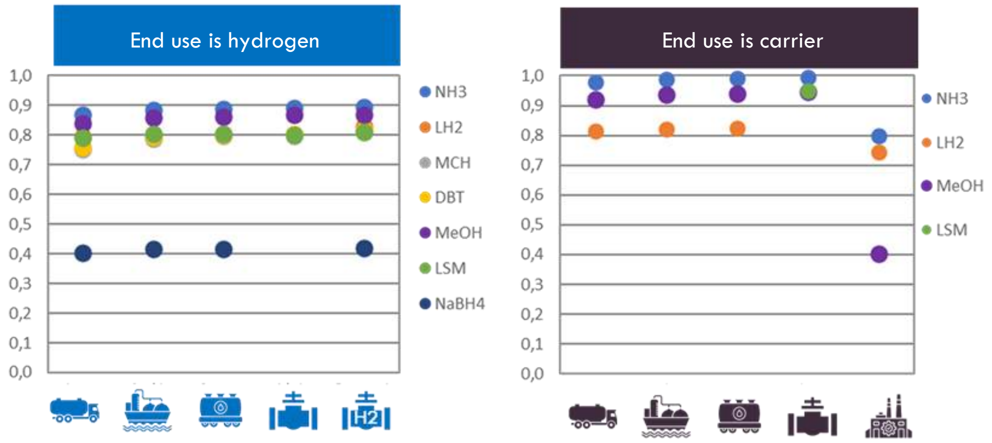
The scores for Affordable for transit to Germany are slightly lower than in the baseline situation, as shown in Figure 20. This is because the costs of storage and conversion at the end user's site do not apply. This conversion is unnecessary where the end use directly consumes the hydrogen carrier or hydrogen from the hydrogen network. This means the score for the fifth supply chain in the left chart is exactly the same, as storage and conversion at the end user's site do not apply. The other differences are often too small to see.

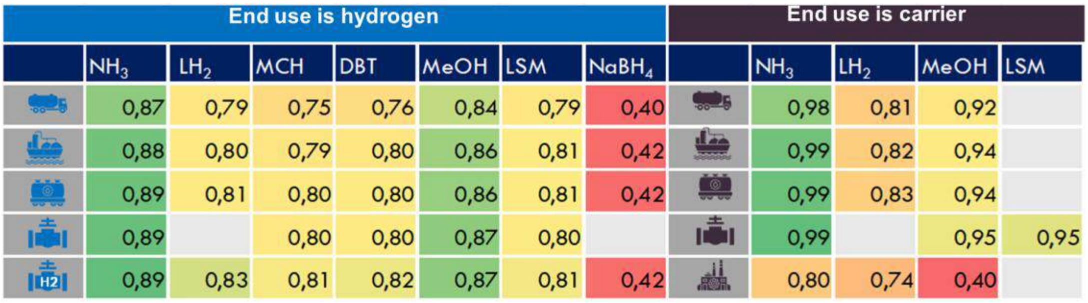
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,76	0,62	0,66	0,67	0,76	0,66	0,02		0,90	0,64	0,86	
	0,78	0,62	0,70	0,70	0,78	0,68	0,03		0,91	0,65	0,88	
	0,78	0,63	0,70	0,71	0,79	0,68	0,03		0,91	0,65	0,88	
	0,78		0,70	0,71	0,79	0,67			0,92		0,89	0,86
H2	0,79	0,66	0,71	0,72	0,79	0,68	0,03		0,68	0,51	0,48	

Figure 20: **Scores for Affordable for transit and export supply chains in 2030; hydrogen end use and carrier end use**

Reference year 2050

In the reference year 2050, the scores for the various alternatives are higher than in the reference year 2030, as all supply chains are expected to improve compared to 2030. Liquid hydrogen and sodium borohydride show the greatest improvement, as the greatest import and conversion cost reductions are expected for these carriers. This means the score for liquid hydrogen is slightly higher than for the LOHCs (Figure 21, left). The exception is the methanol supply chain that includes both conversion and synthesis. Because DAC will be used instead of taking CO_2 from an industrial point source in 2050, more hydrogen will be required as fuel for decentralised DAC, which necessitates greater imports of methanol. The higher import volumes cancel out the cost reduction per kilogramme of methanol.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,87	0,79	0,75	0,76	0,84	0,79	0,40		0,98	0,81	0,92	
	0,88	0,80	0,79	0,80	0,86	0,81	0,42		0,99	0,82	0,94	
	0,89	0,81	0,80	0,80	0,86	0,81	0,42		0,99	0,83	0,94	
	0,89		0,80	0,80	0,87	0,80			0,99		0,95	0,95
H2	0,89	0,83	0,81	0,82	0,87	0,81	0,42		0,80	0,74	0,40	

Figure 21: Scores for Affordable for inland supply chains in 2050; hydrogen end use and carrier end use

6.3 SCORES FOR PUBLIC INTEREST ECONOMICALLY ROBUST

Figure 22 shows the normalised scores for the public interest Economically Robust for the various supply chains for inland use. The higher the score, the higher the added value in the Netherlands. The scores are corrected for congestion and public infrastructure costs. The bandwidth used is 0.20 euros (score 0) to 8.60 euros (score 1) per kilogramme of hydrogen equivalent.

Results for baseline situation (2030, inland end use)

The scores for Economically Robust correlate strongly with those for Affordable, even though the costs of transport in the Netherlands do not apply. These are part of the added value, but they are small compared to other costs, as are the costs of congestion and the use of public infrastructure. The latter two cost types collectively account for less than 1% of the added value and therefore have little effect on the differences between the supply chains.

Ammonia and methanol have the highest scores if these substances are used directly (right-hand chart, Figure 22). If conversion to hydrogen is necessary (left chart), the LOHCs have a comparable score to ammonia and methanol. The higher score for the LOHCs is due to the fact that the higher transport costs in the Netherlands adversely affect the score for the public interest Affordable, but not for the public interest Economically Robust. It is assumed that the expenditure in the Dutch part of the supply chain will make a positive contribution to the Dutch economy.

LSM and liquid hydrogen have a slightly lower score across the board. Sodium borohydride also has the lowest score here. This is due to the higher costs of the imported carrier.

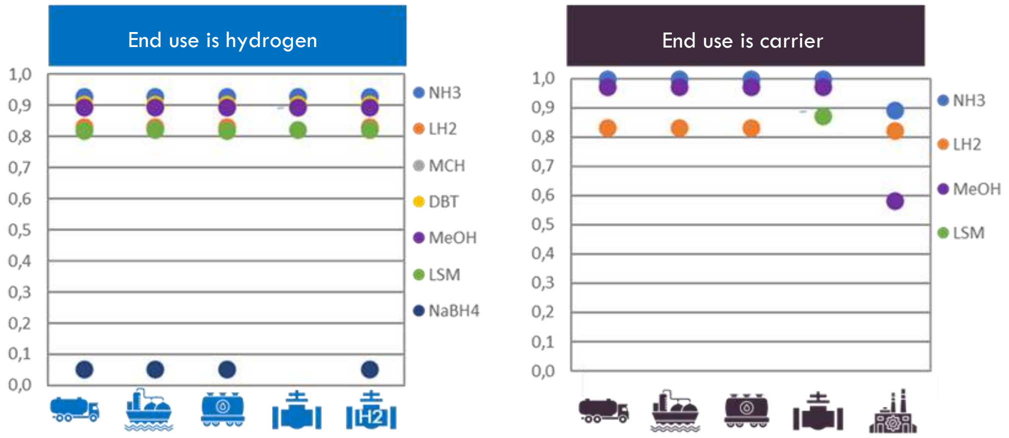
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,93	0,82	0,89	0,90	0,89	0,82	0,05		1,00	0,82	0,97	
	0,93	0,82	0,90	0,90	0,89	0,82	0,05		1,00	0,82	0,97	
	0,93	0,82	0,90	0,90	0,90	0,82	0,05		1,00	0,82	0,97	
	0,93		0,90	0,90	0,90	0,82			1,00		0,97	0,87
H2	0,93	0,83	0,90	0,90	0,90	0,82	0,05		0,89	0,82	0,58	

Figure 22: Scores for Economically Robust for inland supply chains in 2030; hydrogen end use and carrier end use

Results for variants

Port of entry

End use in the port of entry improves the score compared to the baseline situation, except for the supply chains based on pipeline transport, as shown in Figure 23. For end use in the port of entry, there are no differences between the transport modes. This is because the social costs of congestion and use of public infrastructure do not apply. The effect of this is limited and the differences between Figure 23 and Figure 22 are too small to see.



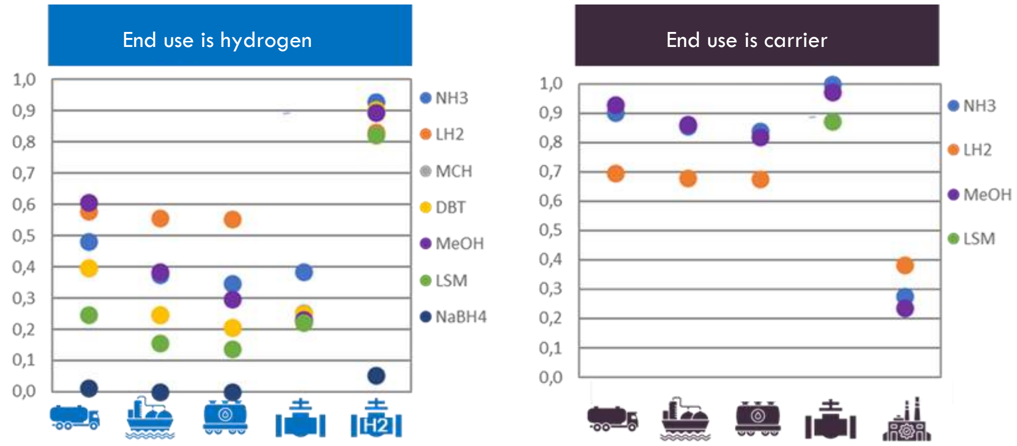
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,93	0,83	0,90	0,90	0,90	0,82	0,05	🚚	1,00	0,83	0,97	
🚢	0,93	0,83	0,90	0,90	0,90	0,82	0,05	🚢	1,00	0,83	0,97	
🚆	0,93	0,83	0,90	0,90	0,90	0,82	0,05	🚆	1,00	0,83	0,97	
	0,93		0,90	0,90	0,90	0,82			1,00		0,97	0,87
H2	0,93	0,83	0,90	0,90	0,90	0,82	0,05	🏭	0,89	0,82	0,58	

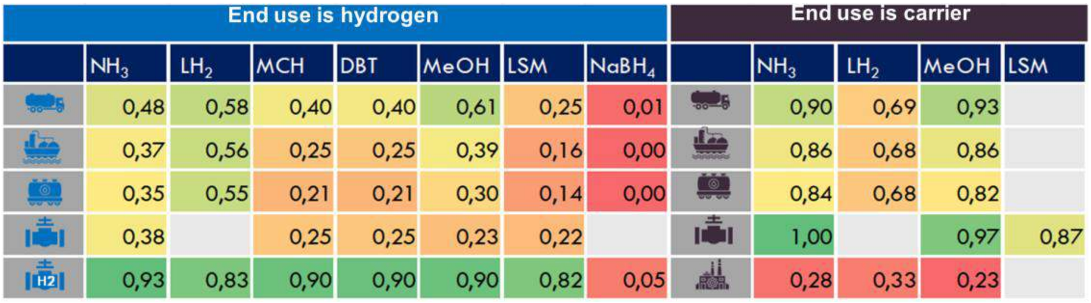
Figure 23: **Scores for Economically Robust for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use**

Transit and export

The scores for transit and export to Germany are lower than in the baseline situation, as shown in Figure 24. This is because the added value of storage and conversion at the end user's site does not apply. The added value is assigned in proportion to the division of costs between the Netherlands and Germany. This means that, if 30% of the costs between import and the end user for transit and export are incurred in Germany, we assume that 30% of the added value between import and the end user will also end up in Germany.

This means that the score for transport by road is higher than the scores for transport by water and rail.



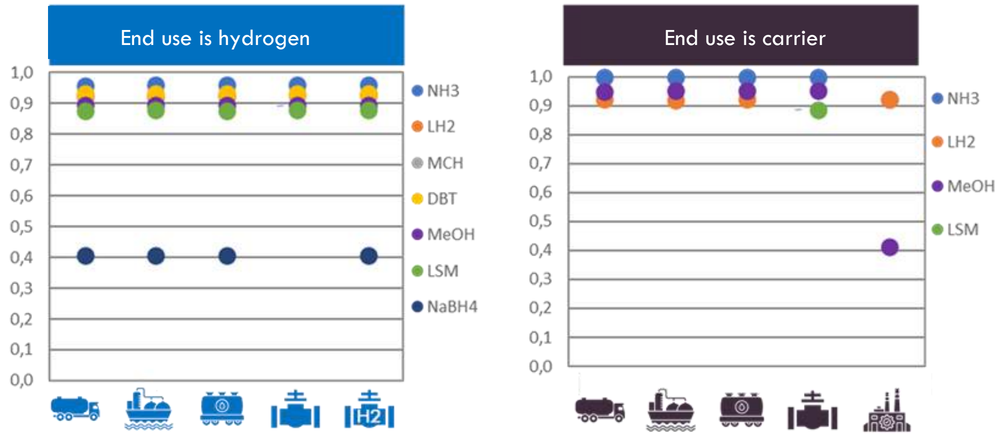


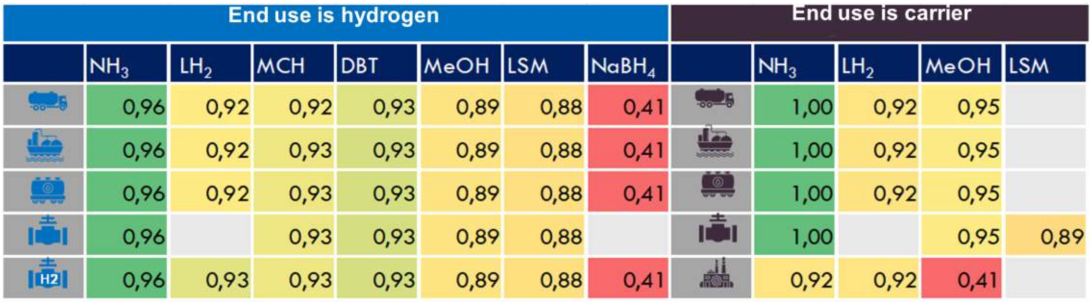
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚛	0,48	0,58	0,40	0,40	0,61	0,25	0,01	🚛	0,90	0,69	0,93	
🚢	0,37	0,56	0,25	0,25	0,39	0,16	0,00	🚢	0,86	0,68	0,86	
🚆	0,35	0,55	0,21	0,21	0,30	0,14	0,00	🚆	0,84	0,68	0,82	
	0,38		0,25	0,25	0,23	0,22			1,00		0,97	0,87
H2	0,93	0,83	0,90	0,90	0,90	0,82	0,05	🏭	0,28	0,33	0,23	

Figure 24: **Scores for Economically Robust for transit and export supply chains in 2030; hydrogen end use and carrier end use**

Reference year 2050

Because of the reductions in the costs of import and conversion due to innovation, all scores improve compared to the baseline situation in 2030. Liquid hydrogen and sodium borohydride improve the most in relatively terms. Liquid hydrogen achieves roughly the same score as the LOHCs (Figure 25, left). Because methanol (and LSM) synthesis using CO_2 from DAC instead of an industrial point source is assumed, the score for the combination of conversion and decentralised synthesis in the Netherlands (rightmost column for carrier end use) is lower, despite the fall in the import costs per kilogramme of methanol. This is because greater volumes are needed, as hydrogen is also needed as fuel for the decentralised DAC process, which means more methanol must first be imported.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,96	0,92	0,92	0,93	0,89	0,88	0,41		1,00	0,92	0,95	
	0,96	0,92	0,93	0,93	0,89	0,88	0,41		1,00	0,92	0,95	
	0,96	0,92	0,93	0,93	0,89	0,88	0,41		1,00	0,92	0,95	
	0,96		0,93	0,93	0,89	0,88			1,00		0,95	0,89
H2	0,96	0,93	0,93	0,93	0,89	0,88	0,41		0,92	0,92	0,41	

Figure 25: Scores for Economically Robust for chains used inland in 2050; hydrogen end use and carrier end use

6.4 SCORES FOR PUBLIC INTEREST RELIABLE

Figure 26 shows the normalised scores for Reliable. The higher the score, the more reliable the supply chain is in the opinion of the consulted experts. The scores are relative. The supply chain assessed as worst is awarded a score of 0. A supply chain that is no less reliable than the existing natural gas network is awarded a score of 1.

Results for baseline situation (2030, inland end use)

The reliability scores for LSM, methanol and ammonia are highest, followed by MCH, DBT, liquid hydrogen and finally sodium borohydride.

LSM, methanol and ammonia were given the highest scores by the experts because large volumes of fossil variants are already transported. No reasons for lower reliability of the supply chains or the necessity of maintaining additional reserves were identified. Ammonia has a slightly lower score than LSM and methanol, as fewer maritime transport vessels are currently available.[56]

The LOHCs have a lower score for Reliable, as the import supply chain has only been demonstrated on a small scale. For the experts, the TRL of the synthesis process in the exporting country was reason enough to give the LOHC chains a lower reliability score. MCH has a higher score than DBT, as there is already a large market for toluene in the chemical industry; the existing

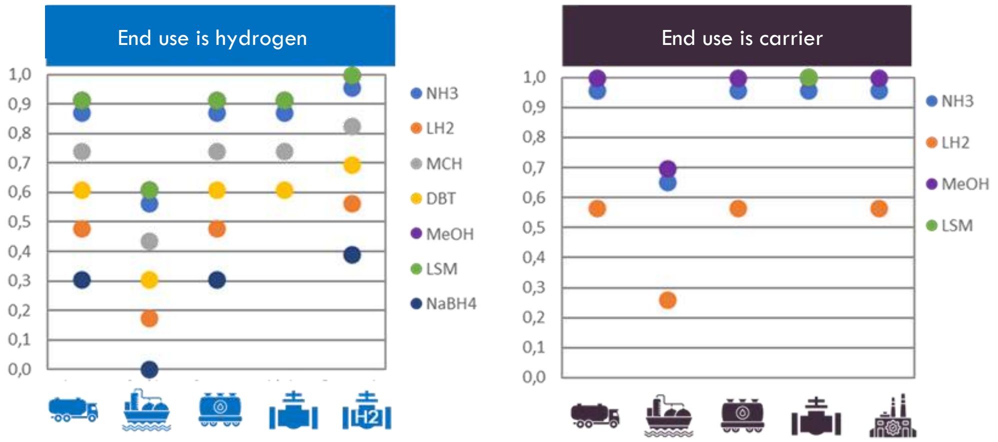
---

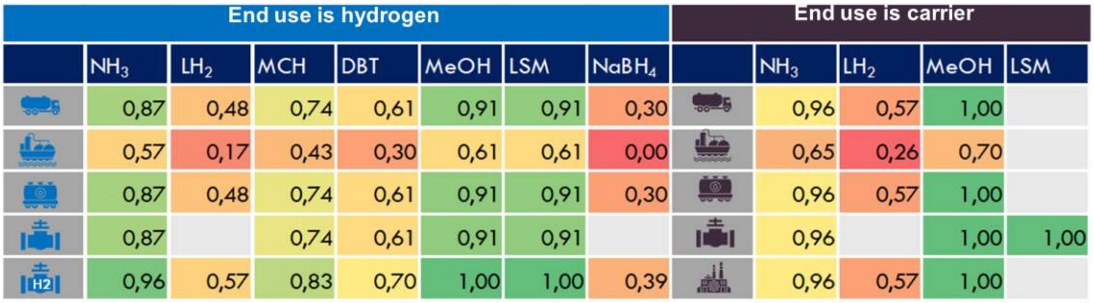
[56] "While the chemical is already traded overseas, the current fleet is extremely small compared to the scale of export-oriented green NH_3 projects expected by 2030." *Hydrogen Insight, 22 August 2023*. The construction of new vessels has since been announced, however.

market for DBT as an industrial heat exchange fluid is much smaller, which results in a slightly lower score for DBT.

The experts gave liquid hydrogen a lower score, as it is not currently used on a large scale and only a single vessel is available for transport between Australia and Japan. The reliability of these supply chains has therefore been assessed as lower for the time being.

The recycling step for sodium borohydride has not yet been demonstrated. Due to the lower TRL and the fact that the storage and transport[57] method must still be developed further, the sodium borohydride supply chains have the lowest score.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,87	0,48	0,74	0,61	0,91	0,91	0,30		0,96	0,57	1,00	
	0,57	0,17	0,43	0,30	0,61	0,61	0,00		0,65	0,26	0,70	
	0,87	0,48	0,74	0,61	0,91	0,91	0,30		0,96	0,57	1,00	
	0,87		0,74	0,61	0,91	0,91			0,96		1,00	1,00
H2	0,96	0,57	0,83	0,70	1,00	1,00	0,39		0,96	0,57	1,00	

Figure 26: Scores for Reliable for inland supply chains in 2030; hydrogen end use and carrier end use

The choice of transport mode sometimes results in a difference in scores for the public interest Reliable. This is not the case between pipeline, road and rail transport, but is the case for transport by water (a lower score) and for transport through the hydrogen network (a higher score).

Inland transport by water was assessed as somewhat less reliable due to the risk of high and low water levels, which can lead to prolonged obstructions. This explains the lower score for the supply chains in which the carrier is transported using inland shipping.

Transport through the hydrogen network has the highest score in the left chart, as decentralised conversion to hydrogen is not required; the conversion takes place in the port of entry. If a supply

---

[57] Bulk transport of sodium borohydride is prohibited in Europe.

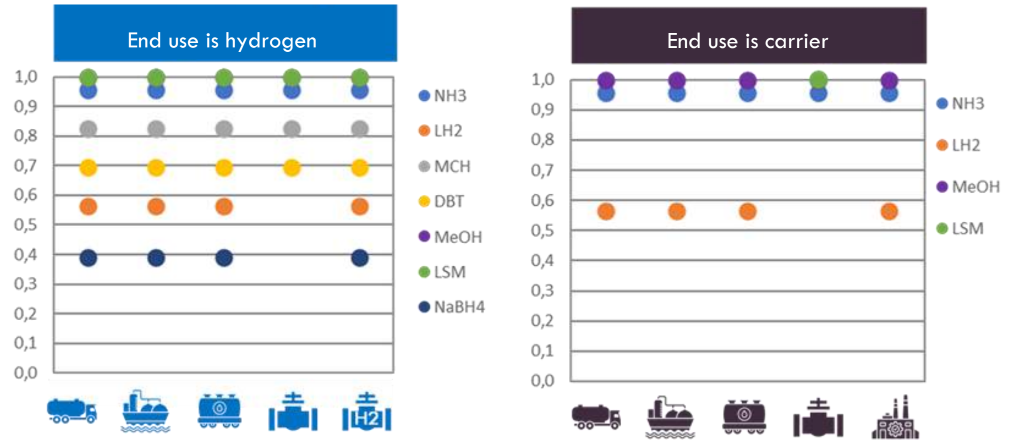
chain includes decentralised conversion, this will result in slightly lower reliability in the opinion of the experts.[58]

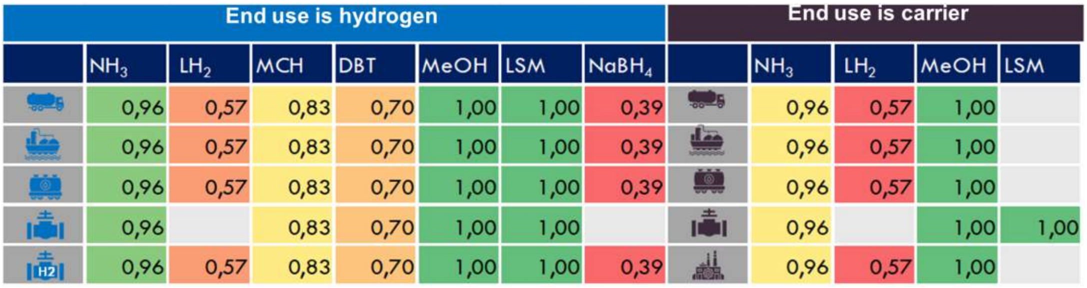
Because decentralised conversion is not required at the site of the end user of the carrier, the average scores in the right chart are slightly higher than in the left chart. According to the experts, decentralised synthesis of ammonia, methanol and liquid hydrogen has no negative effect on reliability. This means that the scores for each hydrogen carrier are the same for the supply chains in the right chart, except for transport by water.

Results for variants

Port of entry

End use in the port of entry improves the reliability of various supply chains compared to the baseline situation.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,96	0,57	0,83	0,70	1,00	1,00	0,39	🚚	0,96	0,57	1,00	
🚢	0,96	0,57	0,83	0,70	1,00	1,00	0,39	🚢	0,96	0,57	1,00	
🚆	0,96	0,57	0,83	0,70	1,00	1,00	0,39	🚆	0,96	0,57	1,00	
	0,96		0,83	0,70	1,00	1,00			0,96		1,00	1,00
H2	0,96	0,57	0,83	0,70	1,00	1,00	0,39	🏭	0,96	0,57	1,00	

Figure 27: **Scores for Reliable for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use**

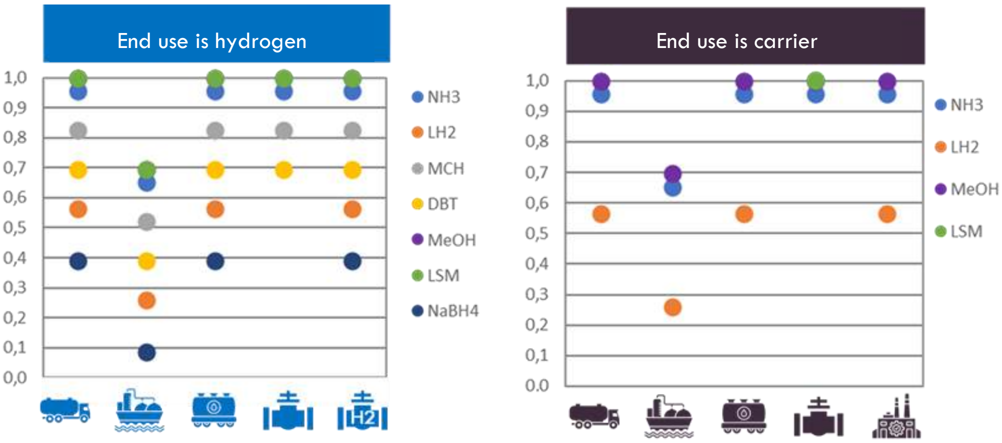
This is particularly the case for transport by inland shipping, as the transport process is no longer affected by high and low water levels. The drawbacks associated with decentralised conversion are also eliminated, as all conversion is centralised.

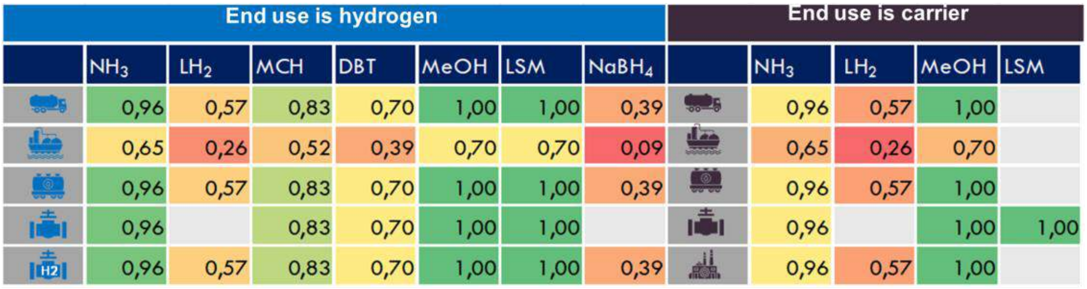
---

[58] The experts indicated that the lower reliability of decentralised conversion applies equally to all carriers. The reliability of evaporating liquid hydrogen could be assessed as higher, due to the relative simplicity of this process compared to conversion of other carriers to hydrogen. However, we have accepted the assessment of the experts.

Transit and export

For end use in Germany or Belgium, the reliability of decentralised storage and conversion is not taken into account. This improves the score for the supply chains that include decentralised conversion (the first four supply chains in the left chart) compared to use in the Netherlands.





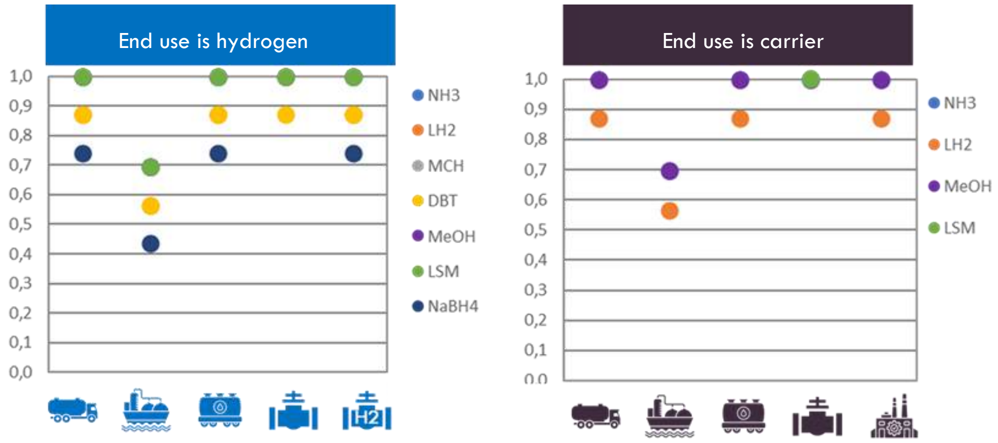
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,96	0,57	0,83	0,70	1,00	1,00	0,39	🚚	0,96	0,57	1,00	
🚢	0,65	0,26	0,52	0,39	0,70	0,70	0,09	🚢	0,65	0,26	0,70	
🚆	0,96	0,57	0,83	0,70	1,00	1,00	0,39	🚆	0,96	0,57	1,00	
	0,96		0,83	0,70	1,00	1,00			0,96		1,00	1,00
H2	0,96	0,57	0,83	0,70	1,00	1,00	0,39	🏭	0,96	0,57	1,00	

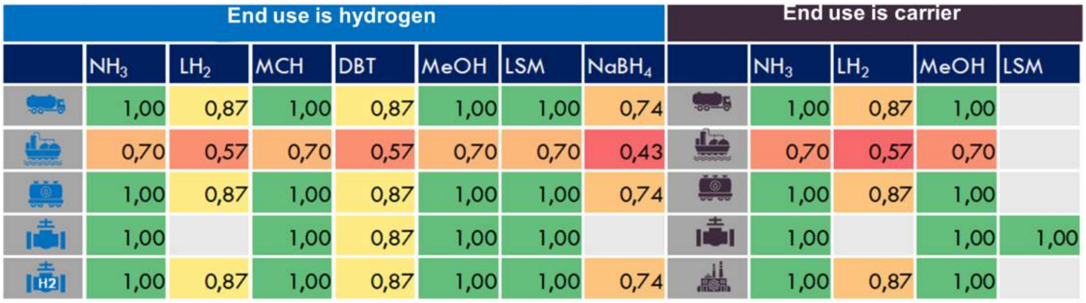
Figure 28: **Scores for Reliable for transit and export supply chains in 2030; hydrogen end use and carrier end use**

Reference year 2050

In 2050, the reliability of various supply chains improves compared to the 2030 baseline situation. This is due to the improved TRLs: the reliability of the carrier and import flows and of decentralised conversion compared to the baseline situation will improve.

The negative effect of the risk of high and low water levels on the reliability of transport by inland vessel remains. According to the experts, sodium borohydride, DBT and liquid hydrogen still achieve a lower score than LSM, ammonia, methanol and MCH, although to a lesser extent than in 2030.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	1,00	0,87	1,00	0,87	1,00	1,00	0,74	🚚	1,00	0,87	1,00	
🚢	0,70	0,57	0,70	0,57	0,70	0,70	0,43	🚢	0,70	0,57	0,70	
🚆	1,00	0,87	1,00	0,87	1,00	1,00	0,74	🚆	1,00	0,87	1,00	
	1,00		1,00	0,87	1,00	1,00			1,00		1,00	1,00
H2	1,00	0,87	1,00	0,87	1,00	1,00	0,74	🏭	1,00	0,87	1,00	

Figure 29: **Scores for Reliable for inland supply chains in 2050; hydrogen end use and carrier end use**

6.5 SCORES FOR PUBLIC INTEREST SAFE & SECURE

We have analysed the public interest Safe & Secure using three indicators: external safety (non-deliberate accidents), protection against cyber attacks and terrorism (deliberate disruptions and incidents) and transport safety. The scores for external safety and cyber attacks and terrorism dominate, due to the high weighting factors assigned by the Delphi group. This chapter begins with a description of the combined and weighted results for the public interest Safe & Secure. The results for each indicator are then explained.

The higher the score, the safer the supply chain is in the opinion of the experts. The scores are relative. The supply chain assessed as least safe is assigned a score of 0. A supply chain without any safety and security risks is assigned a score of 1.

Results for baseline situation (2030, inland end use)

The combined and weighted results for the public interest Safe & Secure[59] are shown in Figure 30. This shows lower scores for ammonia, due to the potential major impact of a toxic gas leak. In accidents involving ammonia, a toxic gas cloud almost always forms immediately[60], while for other carriers, a fire or explosion only occurs following ignition. This therefore has a lower probability (smaller chance). Transport by road has the lowest score, as it has the highest probability

---

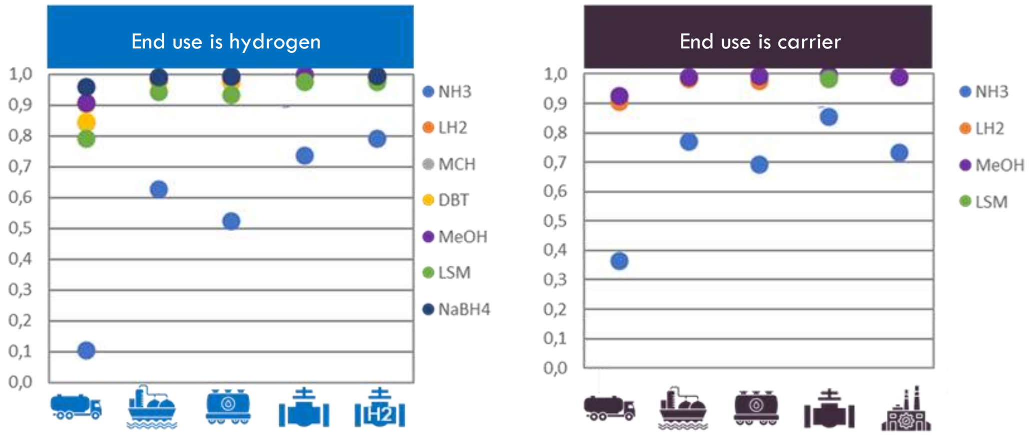
[59] To combine the various indicators, weighting factors for the individual indicators for the public interest Safe & Secure were determined in the Delphi process, see Chapter 5. These were used to determine the score for the public interest Safe & Secure.

[60] A toxic gas cloud forms immediately when ('warm') ammonia liquefied under pressure is released. In the case of cooled liquefied ('cold') ammonia, a pool forms first and it takes longer before a toxic gas cloud forms.

of accidents or incidents, despite the smaller potential effect compared to other transport modes (due to the smaller quantities carried by truck).

The score for transport by rail is higher than for transport by road, but lower than for inland waterways. This is because transport by rail is safer than by road and because the probability of accidents is lower (transport safety) and because the experts assessed the risk to external safety as lower, due to the lower probability of incidents. Inland waterways have a higher score than transport by rail due to the lower estimated probability of an incident affecting external safety.

The score for ammonia is also low for transport modes with a low probability of accidents and a low risk to external safety. This is because there is a higher probability of cyber attacks or terrorist attacks, according to the experts. Plants and pipelines containing ammonia are – more than is the case for other carriers – seen as attractive and more probable targets for cyber attacks and terrorist attacks in the opinion of the experts.



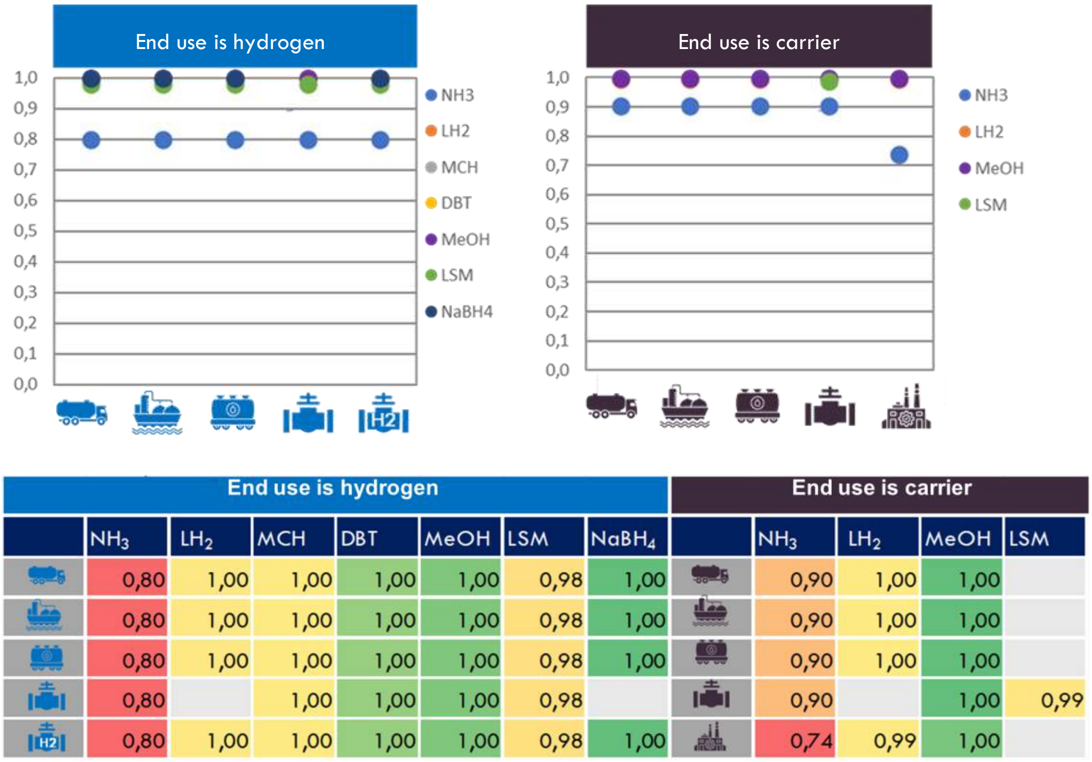
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,10	0,91	0,85	0,85	0,91	0,79	0,96	🚚	0,37	0,91	0,93	
🚢	0,63	0,98	0,98	0,98	0,99	0,94	0,99	🚢	0,77	0,98	0,99	
🚆	0,53	0,98	0,98	0,98	0,99	0,94	1,00	🚆	0,69	0,98	0,99	
	0,74		1,00	1,00	1,00	0,98			0,86		1,00	0,98
H2	0,79	0,99	0,99	1,00	1,00	0,98	1,00	🏭	0,73	0,99	0,99	

Figure 30: Scores for Safe & Secure for inland supply chains in 2030; hydrogen end use and carrier end use

Results for variants

Port of entry

End use in the port of entry improves the safety of various supply chains compared to the baseline situation. This is because the risks to Dutch society of transport through the Netherlands are eliminated (external safety, cyber and terrorism risks and traffic accidents). This also eliminates the differences between the transport modes, see Figure 31.

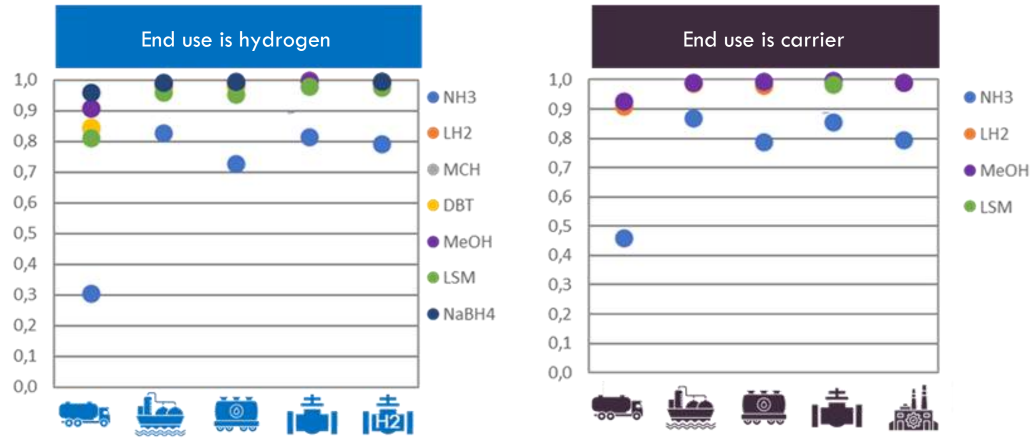


End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,80	1,00	1,00	1,00	1,00	0,98	1,00		0,90	1,00	1,00	
	0,80	1,00	1,00	1,00	1,00	0,98	1,00		0,90	1,00	1,00	
	0,80	1,00	1,00	1,00	1,00	0,98	1,00		0,90	1,00	1,00	
	0,80		1,00	1,00	1,00	0,98			0,90		1,00	0,99
H2	0,80	1,00	1,00	1,00	1,00	0,98	1,00		0,74	0,99	1,00	

Figure 31: Scores for Safe & Secure for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use

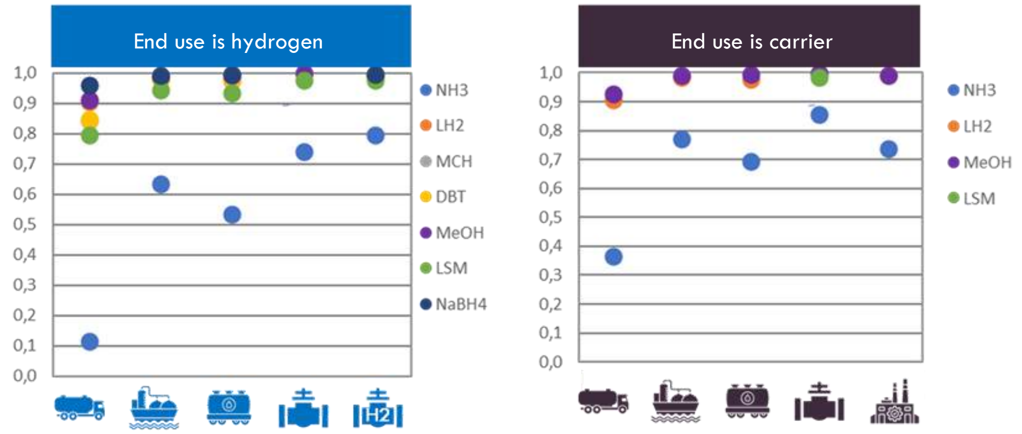
Transit and export

For end use in Germany or Belgium, the safety and security risks (risk to Dutch society and cyber and terrorism risk) of decentralised storage and conversion are not taken into account. This improves the score for the supply chains that include decentralised conversion and/or storage compared to use in the Netherlands. All scores improve, except for the fifth supply chain in the left chart and the fourth supply chain in the right chart.



End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚛	0,31	0,91	0,85	0,85	0,91	0,81	0,96	🚛	0,46	0,91	0,93	
🚢	0,83	0,99	0,98	0,98	0,99	0,96	0,99	🚢	0,87	0,99	0,99	
🚆	0,73	0,98	0,98	0,98	0,99	0,95	1,00	🚆	0,79	0,98	0,99	
	0,82		1,00	1,00	1,00	0,98			0,86		1,00	0,98
H2	0,79	0,99	0,99	1,00	1,00	0,98	1,00	🏭	0,79	0,99	0,99	

Figure 32: Scores for Safe & Secure for transit and export supply chains in 2030; hydrogen end use and carrier end use



End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚛	0,12	0,91	0,85	0,85	0,91	0,80	0,96	🚛	0,37	0,91	0,93	
🚢	0,63	0,98	0,98	0,98	0,99	0,95	0,99	🚢	0,77	0,98	0,99	
🚆	0,53	0,98	0,98	0,98	0,99	0,94	1,00	🚆	0,69	0,98	0,99	
	0,74		1,00	1,00	1,00	0,98			0,86		1,00	0,98
H2	0,80	0,99	0,99	1,00	1,00	0,98	1,00	🏭	0,74	0,99	0,99	

Figure 33: Scores for Safe & Secure for inland supply chains in 2050; hydrogen end use and carrier end use

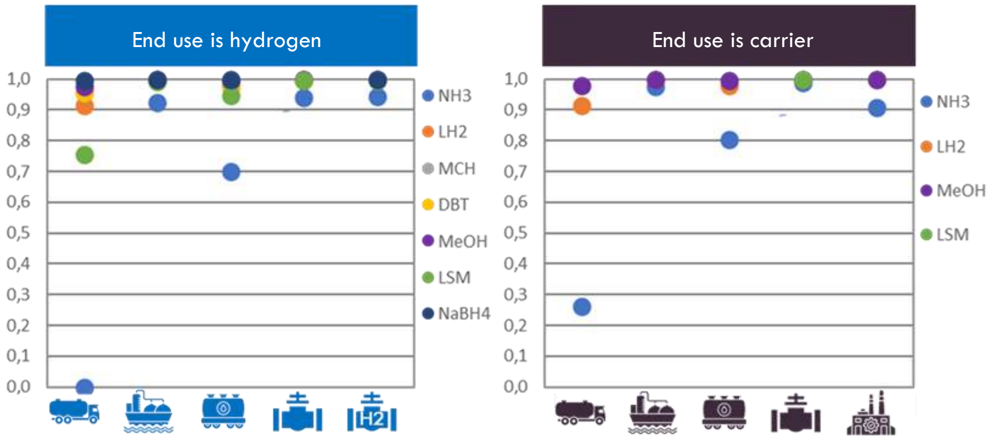
Reference year 2050

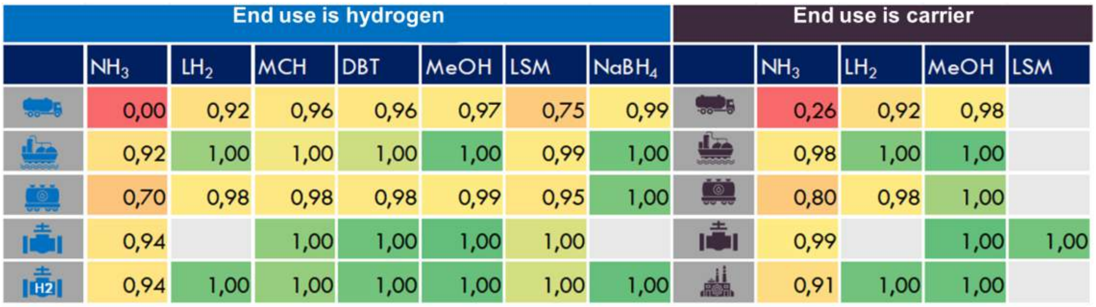
We have not assumed any additional safety measures in 2050 compared to 2030. This means the scores for all supply chains per kilogramme of hydrogen equivalent are practically equal to the scores for the baseline situation. A small improvement can be seen for ammonia in some cases, due to the slightly lower volumes transported as a result of increased conversion efficiency (cracking).

External safety (sub-indicator)

The experts assigned the lowest score for external safety to ammonia. Transport by road and rail in particular have the highest risk. This risk is highest because a toxic gas cloud forms immediately in the event of an incident (breach, leak) (for pressurised transport) or following evaporation (for liquid transport; liquid transport of ammonia by road and rail is however prohibited). With other hydrogen carriers, a breach or leak can lead to fire or explosion, but only if the carrier is ignited. In addition, such incidents result in fewer victims than toxic gas clouds. Road and rail have a lower score than other transport modes, due to the higher probability of incidents and the resulting increased risk.

LSM is associated with the risk of flash fires and jet fires. These result in more victims than pool fires. Due to the explosion hazard, liquid hydrogen also has a lower score than other hydrogen carriers. Although sodium borohydride can also cause explosions if it comes into contact with water, this is less probable, because contact with water must first occur, followed by ignition of the released hydrogen.



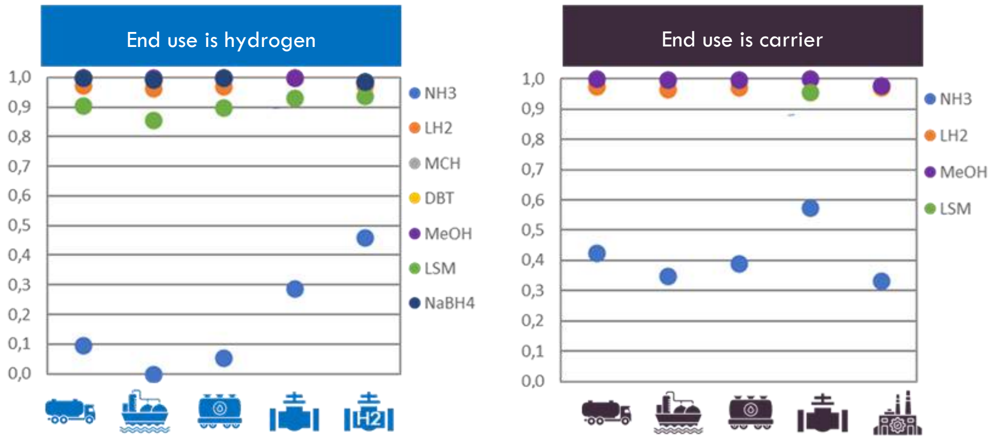


End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,00	0,92	0,96	0,96	0,97	0,75	0,99	🚚	0,26	0,92	0,98	
🚢	0,92	1,00	1,00	1,00	1,00	0,99	1,00	🚢	0,98	1,00	1,00	
🚆	0,70	0,98	0,98	0,98	0,99	0,95	1,00	🚆	0,80	0,98	1,00	
	0,94		1,00	1,00	1,00	1,00			0,99		1,00	1,00
H2	0,94	1,00	1,00	1,00	1,00	1,00	1,00	🏭	0,91	1,00	1,00	

Figure 34: Scores for external safety for inland supply chains in 2030; hydrogen end use and carrier end use

Cybersecurity and terrorism (sub-indicator)

Ammonia also has the lowest score in all supply chains for cybersecurity and terrorism, and lower than for external safety. This is because the experts expect that any attacks will probably be targeted at supply chain assets and substances with the greatest negative impact, rather than on supply chain assets and substances with less catastrophic effects. This also results in a lower score for LSM. However, the difference compared to other carriers is significantly smaller than for ammonia. The scores for the other carriers and supply chains are very similar.



	End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,10	0,97	1,00	1,00	1,00	0,90	1,00	🚚	0,42	0,97	1,00	
🚢	0,00	0,96	0,99	1,00	1,00	0,85	0,99	🚢	0,35	0,97	1,00	
🚆	0,05	0,97	1,00	1,00	1,00	0,90	1,00	🚆	0,39	0,97	1,00	
	0,29		1,00	1,00	1,00	0,93			0,57		1,00	0,95
H2	0,46	0,97	0,99	0,99	0,99	0,94	0,99	🏭	0,33	0,97	0,98	

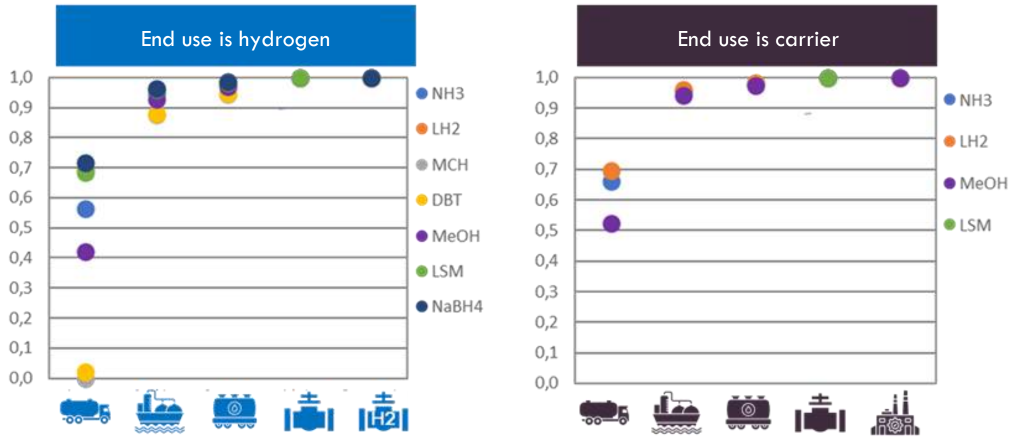
Figure 35: Scores for cybersecurity and terrorism for inland supply chains in 2030; hydrogen end use and carrier end use

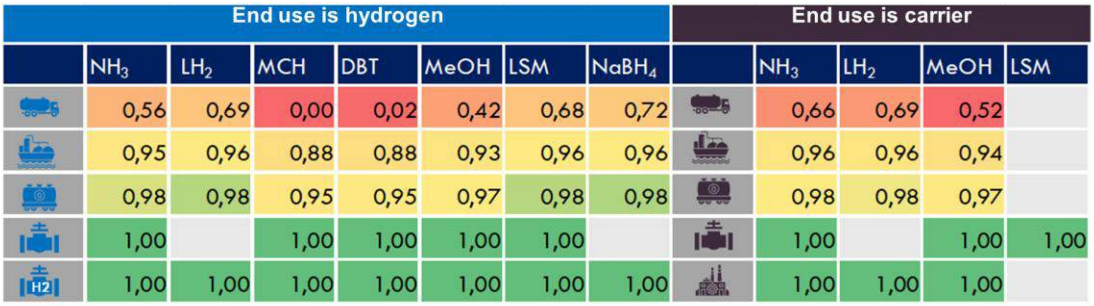
Transport safety (sub-indicator)

Transport by road runs the highest risk of traffic accidents, followed by transport by water and then by rail. Pipeline transport does not cause traffic accidents, which means there is no such risk associated with this transport mode. Of the alternatives that are transported by road, the LOHCs have a relatively low score, as they require the most logistical movements.

The right chart shows slightly higher scores than the left chart, as smaller volumes are transported due to the absence of a conversion step for the first four supply chain groups in the right chart. During conversion of ammonia, methanol and LSM to hydrogen, part of the carrier is used to generate process heat, which means larger volumes of the carrier must be supplied to compensate for conversion losses.

The supply chains that include both conversion and decentralised synthesis in the Netherlands might result in higher transport security costs if the volumes were transported by road, water or rail. However, because these alternatives assume transport through the hydrogen network, the transport safety costs are zero.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,56	0,69	0,00	0,02	0,42	0,68	0,72	🚚	0,66	0,69	0,52	
🚢	0,95	0,96	0,88	0,88	0,93	0,96	0,96	🚢	0,96	0,96	0,94	
🚆	0,98	0,98	0,95	0,95	0,97	0,98	0,98	🚆	0,98	0,98	0,97	
	1,00		1,00	1,00	1,00	1,00			1,00		1,00	1,00
H2	1,00	1,00	1,00	1,00	1,00	1,00	1,00	🏭	1,00	1,00	1,00	

Figure 36: **Scores for transport safety for inland supply chains in 2030; hydrogen end use and carrier end use**

6.6 SCORES FOR PUBLIC INTEREST SUSTAINABLE

The public interest Sustainable has been quantified using three indicators: greenhouse gas emissions, energy losses and material consumption. Greenhouse gas emissions were assigned the highest weighting in this analysis. This chapter begins with a description of the combined and weighted results for the public interest Sustainable. The results for each indicator are then explained.

The score for Sustainable is a combination of three quantitative scores. The supply chain assessed as least sustainable is assigned a score of 0. A theoretical supply chain that does not require any critical materials, that does not produce greenhouse gas emissions and that does not require any additional energy to produce a kilogramme of hydrogen would have a score of 1.

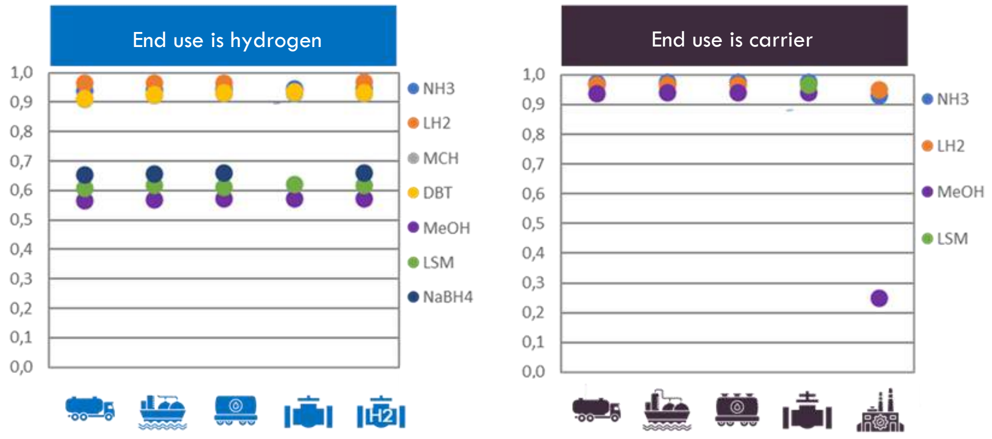
Results for baseline situation (2030, inland end use)

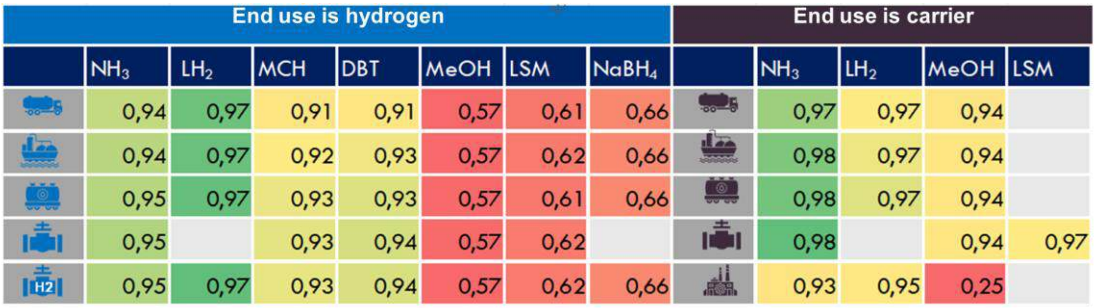
The weighted results for the public interest Sustainable are shown in Figure 37. Most carriers have a high score. Greenhouse gas emissions are largely responsible for the differences. Material consumption and energy losses also have a major effect on the position of sodium borohydride.

CO_2 emissions during the conversion of methanol and LSM have a major effect on the (component) score for greenhouse gas emissions. As a result, these carriers have a lower score. It is assumed that CO_2 of fossil origin from an industrial point source will be used to synthesise LSM and methanol in 2030. If this CO_2 is stored in the exporting country as methane or methanol, and is released again in the Netherlands through steam reforming, this represents a net emission of CO_2 that is assigned to the supply chain.[61] Some CO_2 also escapes during synthesis. We assume that CO_2 from direct air capture will be used in 2050. In this case, the CO_2 released during steam reforming (and also the CO_2 that escapes during synthesis) is not assigned to the supply chain.

Sodium borohydride has a lower score, due to the need for large volumes of boron, a critical material, and the high energy losses during production and recycling.

The differences between the other supply chains are small. The effects of greenhouse gas emissions during transport and boil-off and leakage of liquid hydrogen make little difference. The slightly lower scores for MCH and DBT for transport by road and water are the result of increased CO_2 emissions, due to the larger number of logistical movements resulting from the lower hydrogen concentration released during conversion, the higher loads of the vehicles due to the return flow and the increased CO_2 emissions due to the consumption of electricity in the Netherlands. Other carriers consume less electricity in the Netherlands because 1) some of the carrier itself is used to supply the required energy (methanol, LSM, ammonia), 2) little energy is required for conversion in the Netherlands (liquid hydrogen) or 3) the energy for conversion is primarily required for production abroad (sodium borohydride). We assume that, by 2050, the shift to zero emission transport will eliminate emissions due to logistical movements.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,94	0,97	0,91	0,91	0,57	0,61	0,66	🚚	0,97	0,97	0,94	
🚢	0,94	0,97	0,92	0,93	0,57	0,62	0,66	🚢	0,98	0,97	0,94	
🚆	0,95	0,97	0,93	0,93	0,57	0,61	0,66	🚆	0,98	0,97	0,94	
	0,95		0,93	0,94	0,57	0,62			0,98		0,94	0,97
H2	0,95	0,97	0,93	0,94	0,57	0,62	0,66	🏭	0,93	0,95	0,25	

Figure 37: Scores for Sustainable for inland supply chains in 2030; hydrogen end use and carrier end use

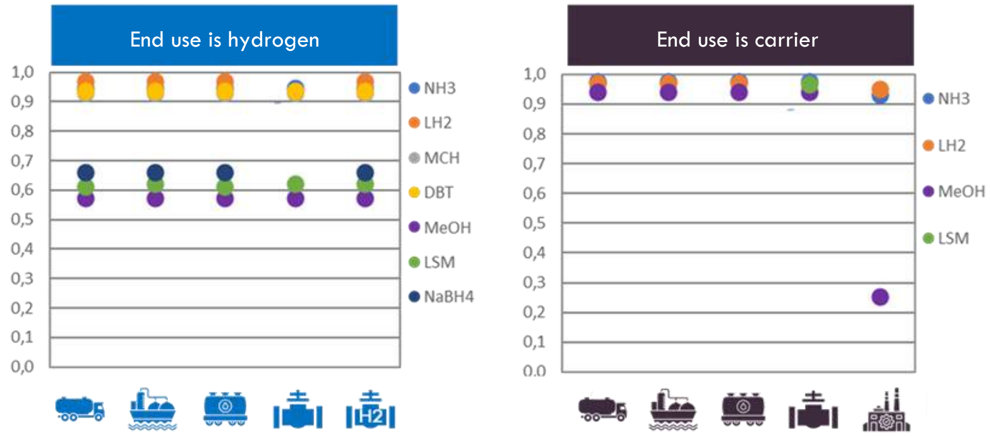
---

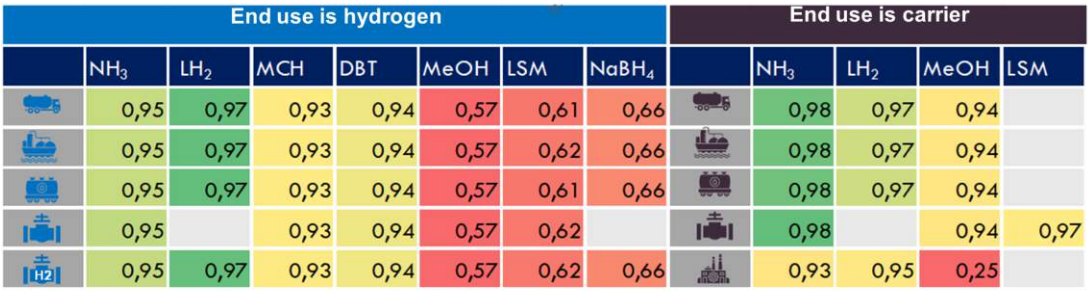
[61] In the baseline situation and the variants – use in the port of entry, transit and export to neighbouring countries and in 2050 – we assume that the CO_2 released during steam reforming is not captured. A sensitivity analysis of the effect of CCS was however carried out, see Chapter 7.

Results for variants

Port of entry

End use in the port of entry slightly improves the score for Sustainable for various supply chains compared to the baseline situation. The effects of inland transport and the difference between the transport modes do not apply, as shown in Figure 38. However, these effects are small compared to the other supply chain steps, which means that the overall effect on the scores is minor.



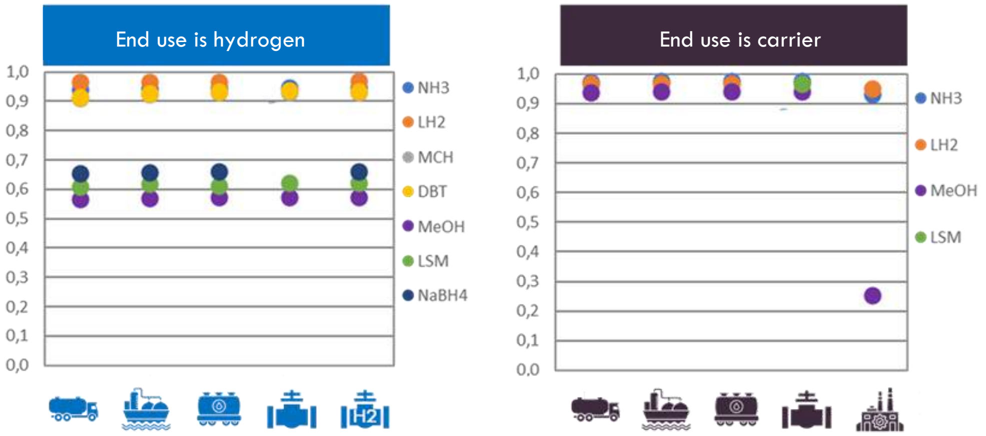


End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,95	0,97	0,93	0,94	0,57	0,61	0,66		0,98	0,97	0,94	
	0,95	0,97	0,93	0,94	0,57	0,62	0,66		0,98	0,97	0,94	
	0,95	0,97	0,93	0,94	0,57	0,61	0,66		0,98	0,97	0,94	
	0,95		0,93	0,94	0,57	0,62			0,98		0,94	0,97
H2	0,95	0,97	0,93	0,94	0,57	0,62	0,66		0,93	0,95	0,25	

Figure 38: **Scores for Sustainable for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use**

Transit and export

For end use in Germany or Belgium, the scores for Sustainable are exactly equal to the baseline situation. This is because we count the sustainability aspects (greenhouse gas emissions, energy losses and material consumption) across the entire supply chain, while we only consider the impact in the Netherlands for the other public interests.

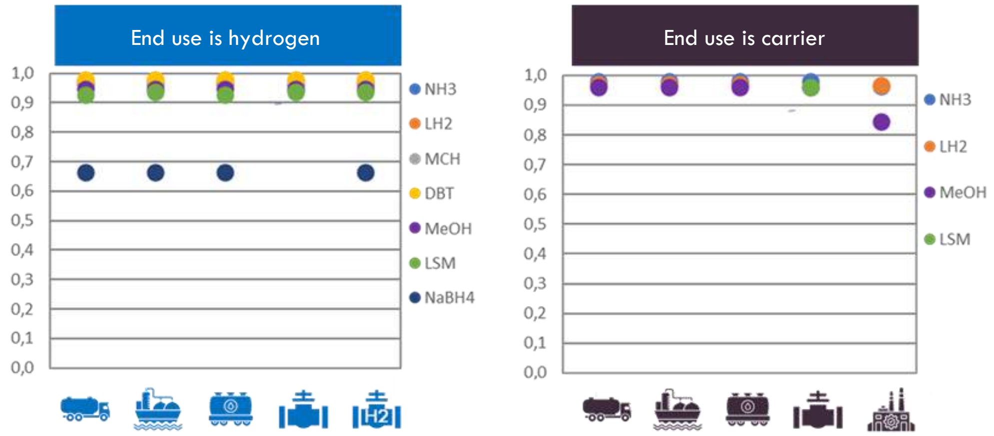


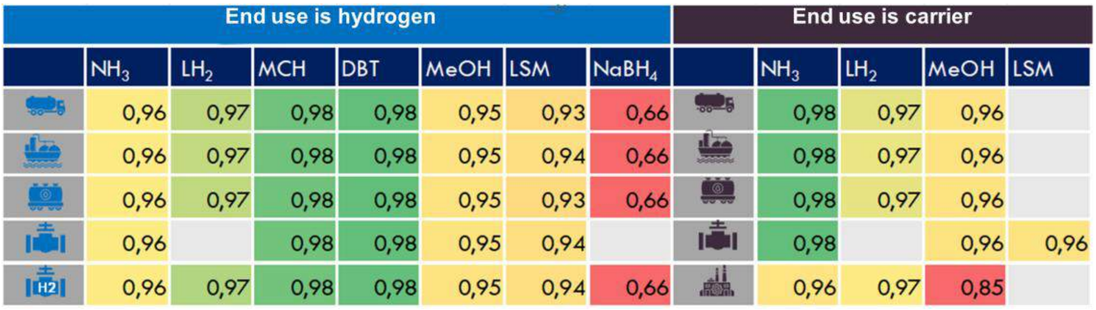
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,94	0,97	0,91	0,91	0,57	0,61	0,66	🚚	0,97	0,97	0,94	
🚢	0,94	0,97	0,92	0,93	0,57	0,62	0,66	🚢	0,98	0,97	0,94	
🚆	0,95	0,97	0,93	0,93	0,57	0,61	0,66	🚆	0,98	0,97	0,94	
	0,95		0,93	0,94	0,57	0,62			0,98		0,94	0,97
H2	0,95	0,97	0,93	0,94	0,57	0,62	0,66	🏭	0,93	0,95	0,25	

Figure 39: **Scores for Sustainable for transit and export supply chains in 2030; hydrogen end use and carrier end use (identical to Figure 37)**

Reference year 2050

In 2050, the scores for Sustainable improve compared to the baseline situation in 2030, but not to the same extent for all supply chains. The LSM and methanol supply chains improve considerably, because the CO_2 emissions in 2050 are climate neutral due to the use of CO_2 from DAC rather than from industrial point sources, as is the case in the baseline situation. Most supply chains benefit from improved energy efficiency and climate neutral transport to some extent. This results in a higher score for the LOHCs in particular. Liquid hydrogen does not have a visibly higher score, as the hydrogen losses in 2050 are assumed to be equal to the baseline situation. The material consumption of the supply chains in 2050 is assumed to be equal to the baseline situation.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,96	0,97	0,98	0,98	0,95	0,93	0,66	🚚	0,98	0,97	0,96	
🚢	0,96	0,97	0,98	0,98	0,95	0,94	0,66	🚢	0,98	0,97	0,96	
🚆	0,96	0,97	0,98	0,98	0,95	0,93	0,66	🚆	0,98	0,97	0,96	
	0,96		0,98	0,98	0,95	0,94			0,98		0,96	0,96
H2	0,96	0,97	0,98	0,98	0,95	0,94	0,66	🏭	0,96	0,97	0,85	

Figure 40: **Scores for Sustainable for inland supply chains in 2050; hydrogen end use and carrier end use**

Greenhouse gas emissions (sub-indicator)

The supply chains with the highest score for greenhouse gas emissions are those without CO_2 emissions and losses during synthesis and conversion. The LSM and methanol supply chains do involve CO_2 emissions and losses, as described above (in the absence of additional measures such as CC(U)S). The supply chain that includes methanol with both conversion and decentralised synthesis in the Netherlands has the lowest score for greenhouse gas emissions, with CO_2 emissions of 18-19 kilogrammes of CO_2 per kilogramme of hydrogen equivalent. In comparison: this is a higher emission level than for steam reforming of fossil natural gas (9 kg CO_2 per kg H_2 equivalent).

Compared to LSM and methanol with conversion to hydrogen gas (left chart), the greenhouse gas emissions from the other alternatives are ‘minor’. These amount to a total of around 0.2 to 2 kilogrammes of CO_2 equivalent per kilogramme of hydrogen. These greenhouse gases are released due to leaks and ventilation of hydrogen and methane vapours and consist of CO_2 emissions from the logistical movements and electricity consumption. This means that the LOHCs have a slightly lower score than the supply chains based on ammonia and liquid hydrogen. Nitrous oxide emissions in the ammonia supply chains have a minor impact.

End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,95	0,97	0,89	0,90	0,41	0,48	0,98		0,98	0,97	0,94	
	0,96	0,97	0,91	0,92	0,41	0,49	0,99		0,98	0,97	0,95	
	0,96	0,97	0,92	0,93	0,41	0,48	0,99		0,98	0,97	0,95	
	0,96		0,92	0,93	0,41	0,50			0,98		0,95	0,99
H2	0,96	0,97	0,92	0,93	0,41	0,50	0,99	🏭	0,94	0,95	0,00	

Figure 41: **Scores for greenhouse gas emissions for inland supply chains in 2030; hydrogen end use and carrier end use**

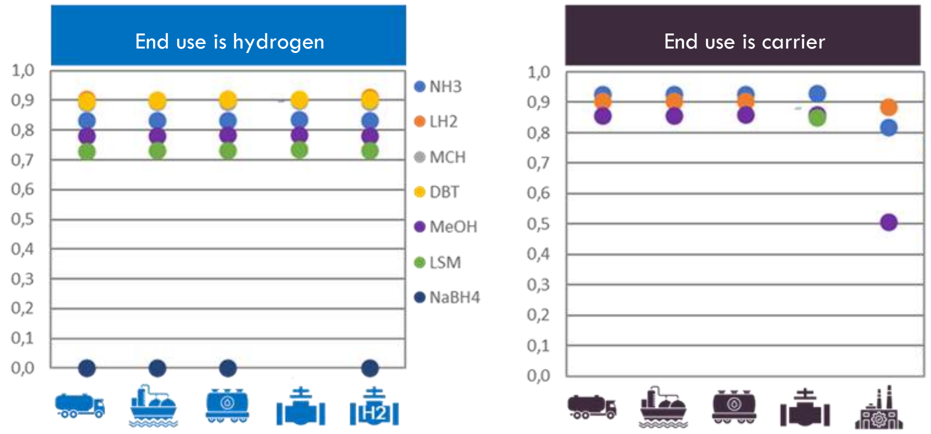
Energy losses (sub-indicator)

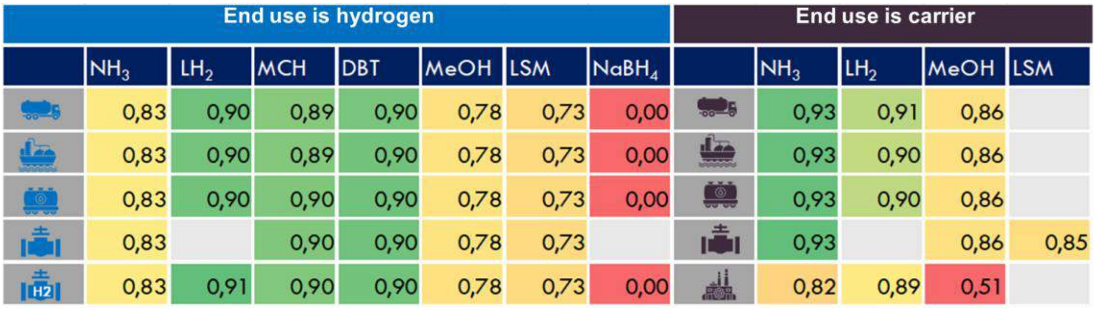
The energy losses per kilogramme of hydrogen equivalent include energy for electrolysis, conversions, transport and losses due to leakage and boil-off. With LSM and methanol, there are also energy losses from CO_2 capture and making CO_2 available to synthesise the carrier. This energy may consist of added electricity or heat, or the consumption or loss of the carrier itself. The theoretically most efficient supply chain, in which the total energy losses are exactly equal to the energy content of a kilogramme of hydrogen, is assigned a score of 1. The supply chain with the highest energy losses per kilogramme of hydrogen is assigned a score of 0.

A supply chain that includes the transport of sodium borohydride by road has the highest energy losses. In this case, the total energy input across the supply chain is around 10 times higher than the energy contained in a kilogramme of hydrogen; however, the share of the total from transport is very small. A great deal of energy is required to produce sodium borohydride and recycle it after the hydrogen is released (‘spent fuel’). A small portion of this energy is released as heat during conversion to hydrogen. This relatively small energy generation (3%) has not been deducted from the energy losses.

The conversion losses also have the greatest impact on this public interest: supply chains with the fewest conversions from hydrogen to hydrogen carrier and vice versa have the highest score, see ammonia in Figure 42 on the right.

Use of the carrier to fuel the conversion process results in lower scores. Some of the hydrogen carrier is consumed during cracking of Ammonia and reforming of LSM and methanol. This contributes to the energy losses for these supply chains, as larger volumes of the carrier must be produced in the exporting countries to supply comparable quantities for end use. Supply chains in which the carrier is not used as fuel are not affected by this. These are the supply chains in which the conversion produces heat (sodium borohydride, liquid hydrogen), or in which the use of electricity for conversion is feasible (DBT and MCH). These consequently have a higher score in Figure 42.





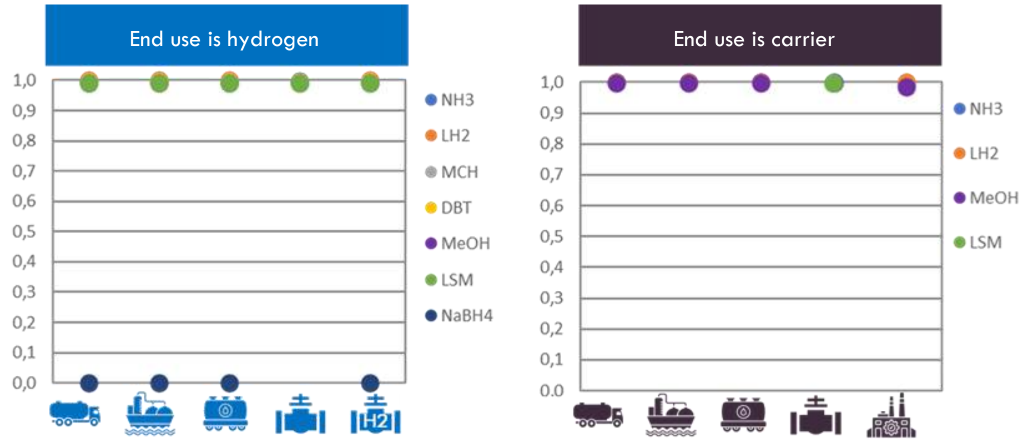
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,83	0,90	0,89	0,90	0,78	0,73	0,00		0,93	0,91	0,86	
	0,83	0,90	0,89	0,90	0,78	0,73	0,00		0,93	0,90	0,86	
	0,83	0,90	0,90	0,90	0,78	0,73	0,00		0,93	0,90	0,86	
	0,83		0,90	0,90	0,78	0,73			0,93		0,86	0,85
H2	0,83	0,91	0,90	0,90	0,78	0,73	0,00		0,82	0,89	0,51	

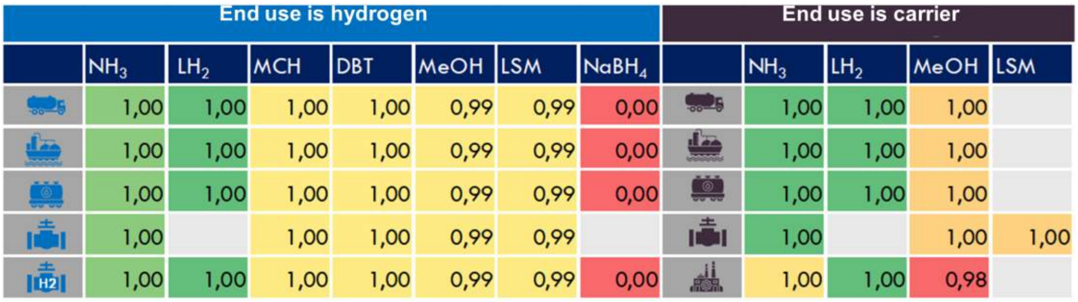
Figure 42: Scores for energy losses for inland supply chains in 2030; hydrogen end use and carrier end use

Material consumption (sub-indicator)

The score for material consumption reflects the extent to which scarce materials are required in each hydrogen supply chain, either as catalysts or as carrier materials. Supply chains that do not use scarce materials are assigned a score of 1. Supply chains with the highest material consumption are assigned a score of 0, i.e., supply chains based on sodium borohydride, due to the use of boron as a component (28wt%). These supply chains require the largest quantities of critical materials, expressed in terms of the current market price of these materials. Around 1.33 kilogrammes of boron are required for each kilogramme of hydrogen equivalent. While this can be reused and used in multiple 'cycles' each year, it requires a substantial investment and will still have to be replaced or replenished in time. We have budgeted the value at more than 1.30 euros per kilogramme of hydrogen.

The material consumption for the other supply chains (€0.00 - €0.02 per kg hydrogen), which consists of various precious metals used as catalysts, is negligible by comparison.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	1,00	1,00	1,00	1,00	0,99	0,99	0,00		1,00	1,00	1,00	
	1,00	1,00	1,00	1,00	0,99	0,99	0,00		1,00	1,00	1,00	
	1,00	1,00	1,00	1,00	0,99	0,99	0,00		1,00	1,00	1,00	
	1,00		1,00	1,00	0,99	0,99			1,00		1,00	1,00
H2	1,00	1,00	1,00	1,00	0,99	0,99	0,00		1,00	1,00	0,98	

Figure 43: **Scores for material consumption for inland supply chains in 2030; hydrogen end use and carrier end use**

6.7 SCORES FOR PUBLIC INTEREST ADAPTABLE

Figure 44 shows the normalised scores for the public interest Adaptable for the various supply chains for inland use that resulted from the expert session. Supply chains that require fewer high-risk investments are assigned a higher score. The bandwidth used is 26 euros (score 0) to 0 euros (score 1) of high-risk investments per kilogramme of hydrogen equivalent. High-risk means that additional investments must be made and that these have no other applications if the supply chain for the hydrogen (carrier) is not successful.

Results for baseline situation (2030, inland end use)

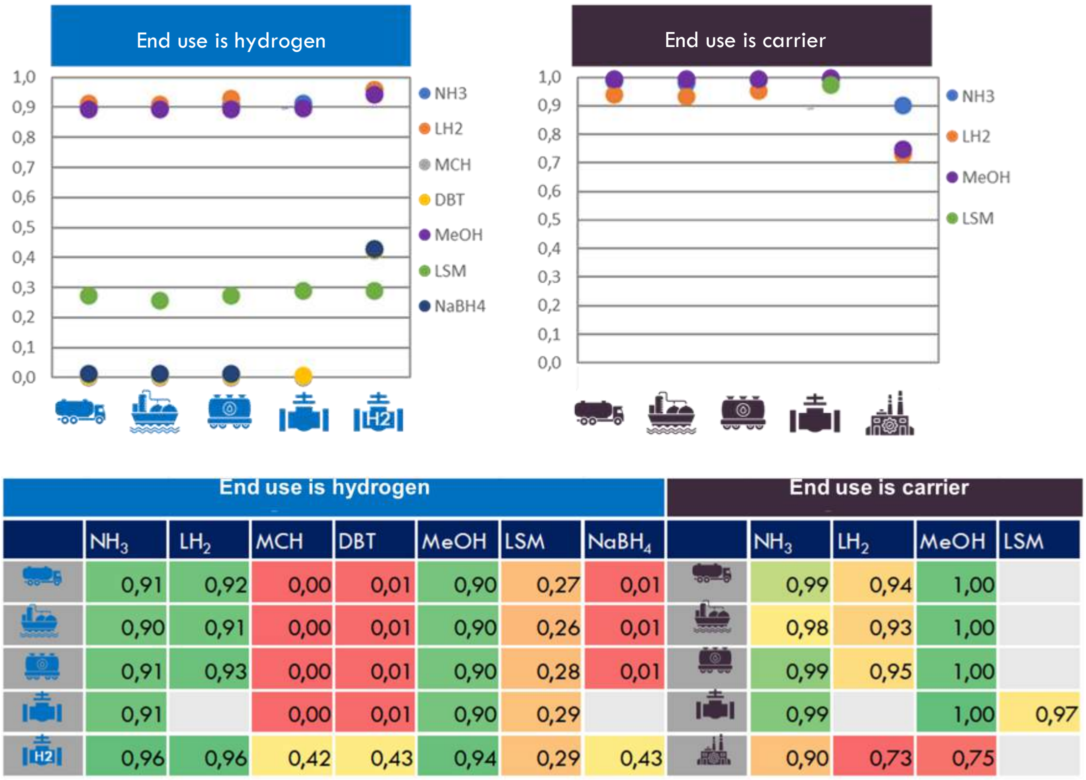
The investments in conversion have the greatest effect on the scores. Supply chains with one or more conversion steps have the lowest score, as conversion plants cannot generally be reused for other processes. Neither are there existing facilities available for use (they do not exist or they are already in use, for example steam methane reforming plants).

No substantial part of the ‘installed base’ will become available in the short term. Substantial additional investments will therefore be required. This may change as fossil fuels are actually phased out. The required investments in conversion facilities are much greater than the investments required in means of transport or storage facilities.

The LOHCs and sodium borohydride have an advantage as regards storage tanks and means of transport, as these assets can be reused for other substances more than is the case for other carriers. Nevertheless, these supply chains have a lower score, as the investments in non-reusable conversion plants per kilogramme of hydrogen are much greater than this advantage and the investments in conversion plants for other carriers, such as ammonia, liquid hydrogen and methanol. LSM plants are also expensive, particularly due to the relatively high additional investments in conversion plants (centralised and decentralised). While there is a large installed base of steam methane reforming plants in the Netherlands, we have assumed that new plants must be built to ensure a fair comparison with other supply chains.

The existing natural gas network is already available and has sufficient capacity. This has a positive effect on the score for the direct use of methane gas from LSM supplied through the natural gas network (see Figure 44 on the right). However, if hydrogen is used following conversion from LSM, the expensive cryogenic LSM installations in fact have a negative effect on the score (see Figure 44 on the left).

In relation to the scores for Adaptable, it is important to note that the extent to which the investments are reusable is based on an expert judgement and that the values for the required investments in the literature are uncertain. We could not find any usable data for the conversion of sodium borohydride; we have assumed the same investments per kilogramme of hydrogen equivalent as for DBT.



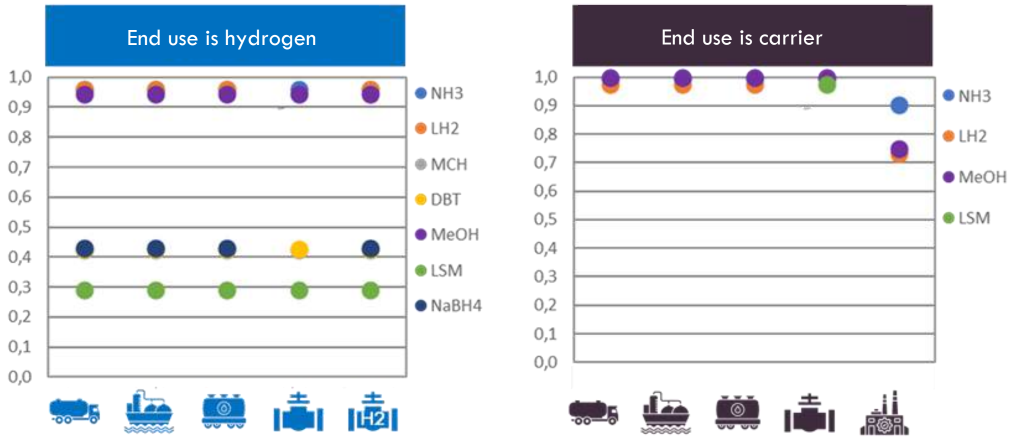
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,91	0,92	0,00	0,01	0,90	0,27	0,01	🚚	0,99	0,94	1,00	
🚢	0,90	0,91	0,00	0,01	0,90	0,26	0,01	🚢	0,98	0,93	1,00	
🚆	0,91	0,93	0,00	0,01	0,90	0,28	0,01	🚆	0,99	0,95	1,00	
	0,91		0,00	0,01	0,90	0,29			0,99		1,00	0,97
H2	0,96	0,96	0,42	0,43	0,94	0,29	0,43	🏭	0,90	0,73	0,75	

Figure 44: Scores for Adaptable for inland supply chains in 2030; hydrogen end use and carrier end use

Results for variants

Port of entry

End use in the port of entry slightly improves the score for Adaptable compared to the baseline situation. This is because no high-risk investments in means of inland transport are required, and because decentralised high-risk investments in conversion are generally estimated to be higher than if a centralised conversion plant is built in the port, which results in economies of scale. The effect is greatest for the LOHCs and sodium borohydride. For LSM plants, no distinction is made between the presumed investments between centralised and decentralised. This means that the score for LSM changes less (only investments in means of transport required).

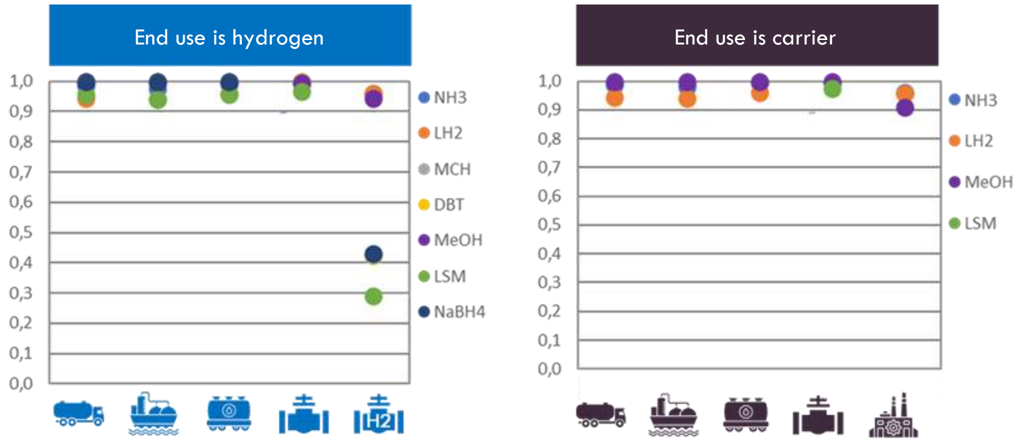


End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,96	0,96	0,42	0,43	0,94	0,29	0,43	🚚	1,00	0,98	1,00	
🚢	0,96	0,96	0,42	0,43	0,94	0,29	0,43	🚢	1,00	0,98	1,00	
🚆	0,96	0,96	0,42	0,43	0,94	0,29	0,43	🚆	1,00	0,98	1,00	
	0,96		0,42	0,43	0,94	0,29			1,00		1,00	0,97
H2	0,96	0,96	0,42	0,43	0,94	0,29	0,43	🏭	0,90	0,73	0,75	

Figure 45: Scores for Adaptable for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use

Transit and export

For end use in Germany or Belgium, the high-risk investments in conversion and storage are not taken into account. This improves the score for the supply chains with decentralised conversion or storage compared to end use in the Netherlands. This applies to all supply chains except the fifth in the left chart and the fourth in the right chart.

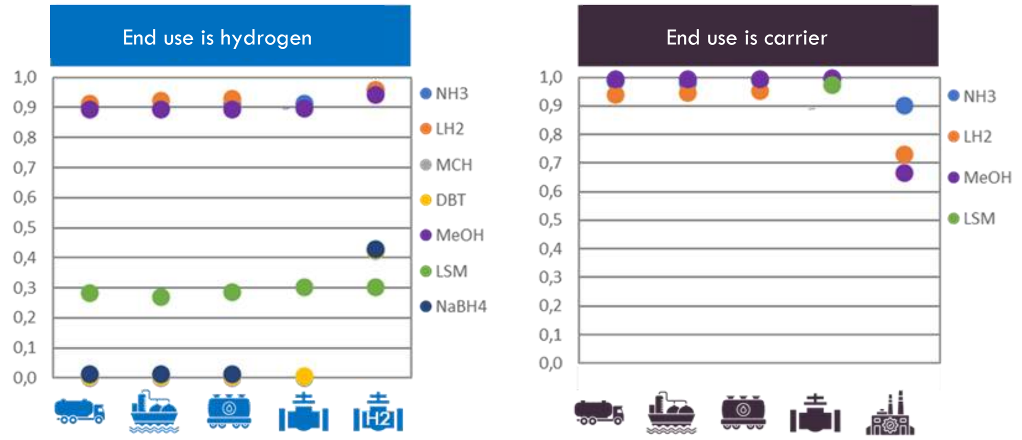


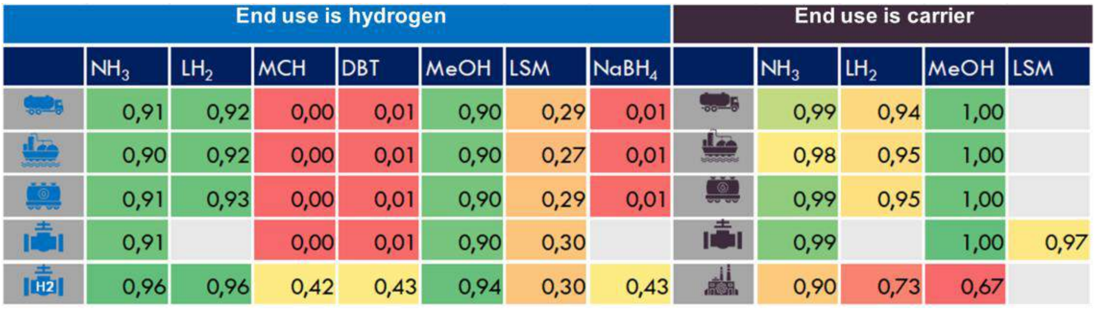
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,99	0,94	1,00	1,00	1,00	0,96	1,00		0,99	0,94	1,00	
	0,98	0,94	1,00	1,00	1,00	0,94	1,00		0,98	0,94	1,00	
	0,99	0,96	1,00	1,00	1,00	0,96	1,00		0,99	0,96	1,00	
	0,99		1,00	1,00	1,00	0,97			0,99		1,00	0,97
H2	0,96	0,96	0,42	0,43	0,94	0,29	0,43		0,96	0,96	0,91	

Figure 46: **Scores for Adaptable for transit and export supply chains in 2030; hydrogen end use and carrier end use**

Reference year 2050

The scores for Adaptable in 2050 are almost equal to the scores in the 2030 baseline situation. This is because the investments in conversion plants have the largest effect on the score. In 2050, these plants will also be unavailable to fulfil the growing demand for hydrogen and hydrogen carriers, neither are they reusable. However, there are small differences due to the reduced investment costs of inland vessels for the transport of liquid hydrogen, lower volumes for use as fuel for the improved conversion process and the use of CO_2 from DAC instead of industrial point sources to synthesise methanol and LSM. This requires larger volumes of the carriers, and thus more plants. This results in a lower score for the supply chain that includes methanol synthesis in the Netherlands (conversion and decentralised synthesis in the Netherlands, column 5 on the right).





	End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,91	0,92	0,00	0,01	0,90	0,29	0,01	🚚	0,99	0,94	1,00	
🚢	0,90	0,92	0,00	0,01	0,90	0,27	0,01	🚢	0,98	0,95	1,00	
🚆	0,91	0,93	0,00	0,01	0,90	0,29	0,01	🚆	0,99	0,95	1,00	
	0,91		0,00	0,01	0,90	0,30			0,99		1,00	0,97
H2	0,96	0,96	0,42	0,43	0,94	0,30	0,43	🏭	0,90	0,73	0,67	

Figure 47: Scores for Adaptable for inland supply chains in 2050; hydrogen end use and carrier end use

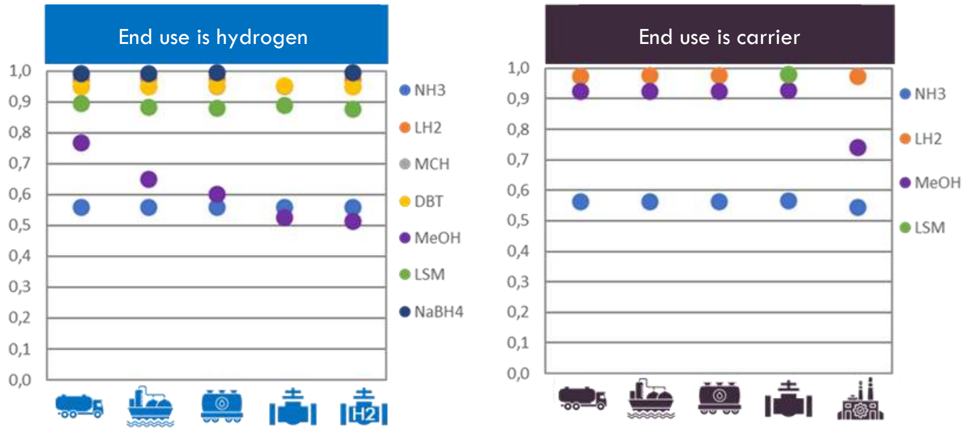
6.8 SCORES FOR PUBLIC INTEREST FAIR

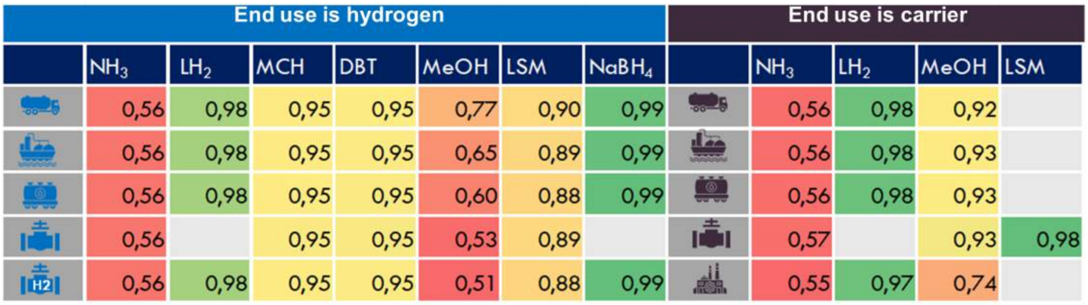
The normalised scores for the public interest Fair are a combination of two indicators: fair for exporting countries and fair for Dutch society. The stakeholders assessed these indicators as roughly equally important. This chapter begins with a description of the combined and weighted results for the public interest Fair. The results for each indicator are then discussed in detail.

The higher the score, the smaller the difference between the ‘true price’ and the costs charged. A supply chain is assigned a score of 1 if there is no difference between the true price and the costs charged; in this case, the true price divided by the costs charged is 100%. The supply chain with the greatest percentage difference is assigned a score of 0.

Results for baseline situation (2030, inland end use)

The weighted results for the public interest Fair are shown in Figure 48. The table shows lower scores for ammonia and methanol. For methanol, this is due to the low import costs. The lower score for ammonia is due to a combination of the low cost price and higher environmental costs, particularly due to ammonia emissions and leaks.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,56	0,98	0,95	0,95	0,77	0,90	0,99		0,56	0,98	0,92	
	0,56	0,98	0,95	0,95	0,65	0,89	0,99		0,56	0,98	0,93	
	0,56	0,98	0,95	0,95	0,60	0,88	0,99		0,56	0,98	0,93	
	0,56		0,95	0,95	0,53	0,89			0,57		0,93	0,98
	0,56	0,98	0,95	0,95	0,51	0,88	0,99		0,55	0,97	0,74	

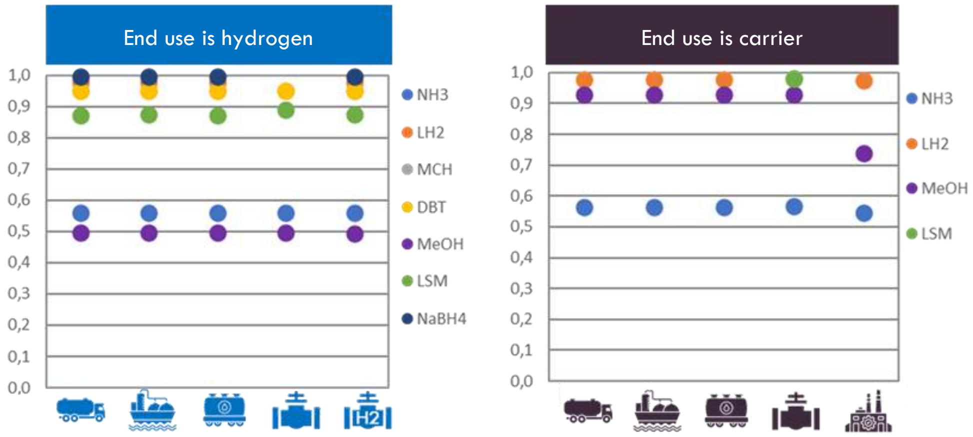
Figure 48: Scores for Fair for inland supply chains in 2030; hydrogen end use and carrier end use

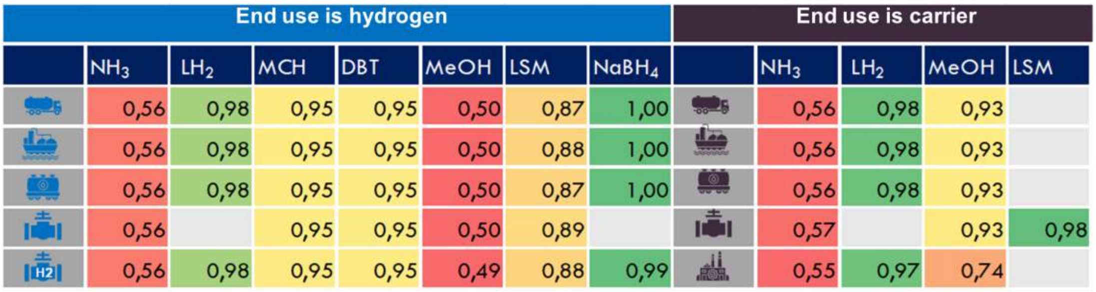
Results for variants

Port of entry

For end use in the port of entry, the difference due to the use of inland transport (fair supply chain in the Netherlands) does not apply. The scores for fairness for the producer countries countries remain the same.

The effect of eliminating the contribution from inland transport varies for each supply chain. Methanol supply chains by road, water, and rail in particular, have lower scores as domestic chain costs decrease more significantly than the externalities.



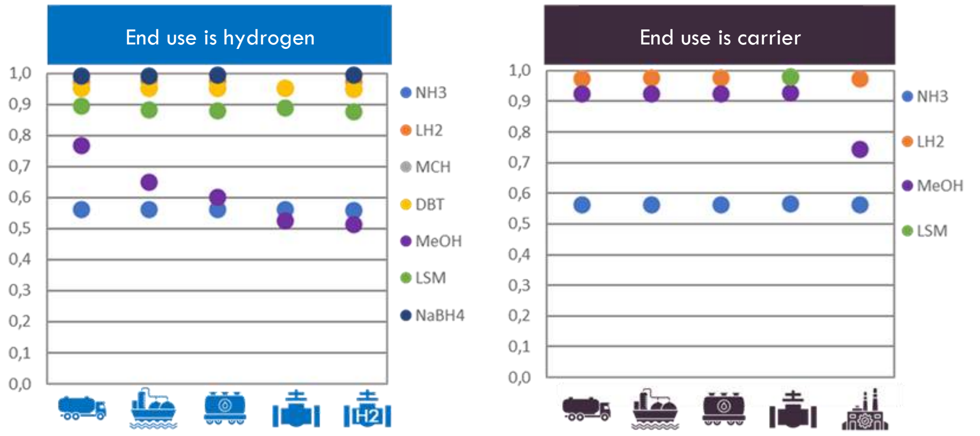


End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,56	0,98	0,95	0,95	0,50	0,87	1,00		0,56	0,98	0,93	
	0,56	0,98	0,95	0,95	0,50	0,88	1,00		0,56	0,98	0,93	
	0,56	0,98	0,95	0,95	0,50	0,87	1,00		0,56	0,98	0,93	
	0,56		0,95	0,95	0,50	0,89			0,57		0,93	0,98
H2	0,56	0,98	0,95	0,95	0,49	0,88	0,99		0,55	0,97	0,74	

Figure 49: **Scores for Fair for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use**

Transit and export

For end use in Germany or Belgium, the contribution from decentralised conversion and storage is not taken into account. This affects the fairness of the supply chain in the Netherlands. As is the case for end use in the port of entry, the fairness of the supply chain in the producing countries remains the same. The effect of eliminating the contributions from decentralised storage and conversion varies for each supply chain. Nothing changes for supply chains without decentralised conversion or storage (use of hydrogen network in the left chart, fifth column and use of pipelines in the right chart, fourth column).

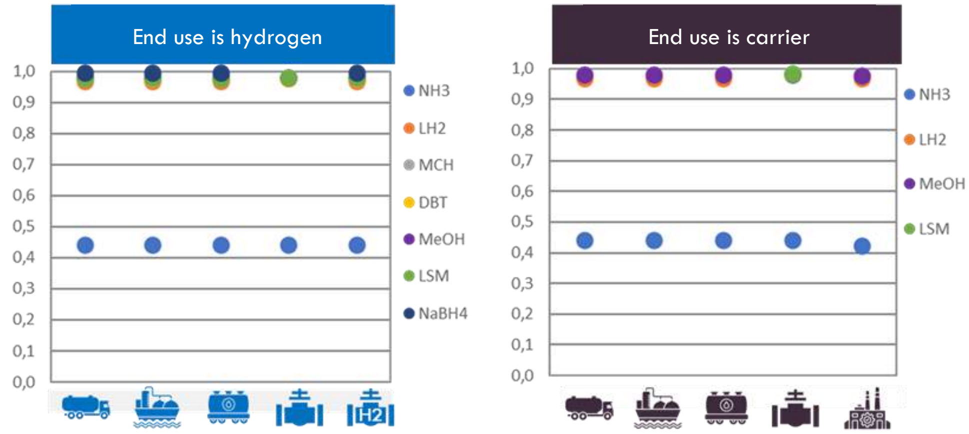


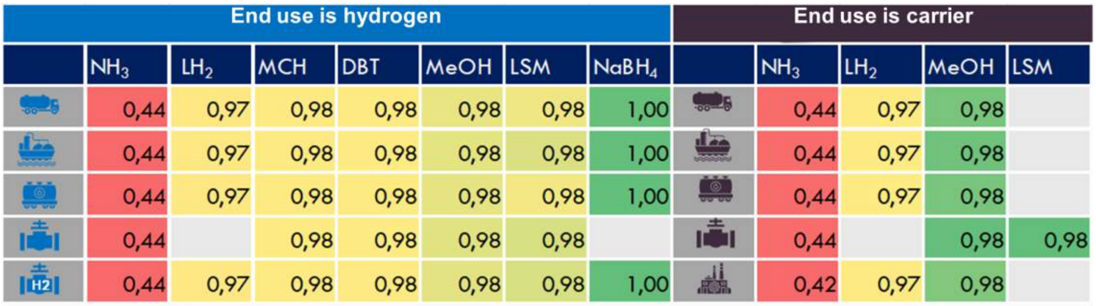
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,56	0,98	0,95	0,95	0,77	0,90	0,99	🚚	0,56	0,98	0,92	
🚢	0,56	0,98	0,95	0,95	0,65	0,89	0,99	🚢	0,56	0,98	0,93	
🚆	0,56	0,98	0,95	0,95	0,60	0,88	0,99	🚆	0,56	0,98	0,93	
	0,56		0,95	0,95	0,53	0,89			0,57		0,93	0,98
H2	0,56	0,98	0,95	0,95	0,51	0,88	0,99	🏭	0,55	0,97	0,74	

Figure 50: Scores for Fair for transit and export supply chains in 2030; hydrogen end use and carrier end use

Reference year 2050

In 2050, some supply chains have a higher score than the 2030 baseline situation, while others have a score that is lower or almost the same. LSM and methanol have a higher score because the external costs (due to greenhouse gases) fall more sharply than the import costs. This reduces the difference between the true price and the actual costs, which results in a higher score. The same applies to the LOHCs and to sodium borohydride to a limited extent. The effects of zero emission transport in 2050 result in a larger fall in the external costs than in the costs charged. This improves the score slightly. However, liquid hydrogen and ammonia in fact have a slightly lower score. This is because the import and conversion cost reductions are greater than the external cost reductions. For liquid hydrogen, the external costs are primarily due to hydrogen leaks. For ammonia, they are due to leakage losses during synthesis and limited NO_X emissions. No changes are anticipated in this respect in 2050.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,44	0,97	0,98	0,98	0,98	0,98	1,00	🚚	0,44	0,97	0,98	
🚢	0,44	0,97	0,98	0,98	0,98	0,98	1,00	🚢	0,44	0,97	0,98	
🚆	0,44	0,97	0,98	0,98	0,98	0,98	1,00	🚆	0,44	0,97	0,98	
	0,44		0,98	0,98	0,98	0,98			0,44		0,98	0,98
H2	0,44	0,97	0,98	0,98	0,98	0,98	1,00	🏭	0,42	0,97	0,98	

Figure 51: Scores for Fair for inland supply chains in 2050; hydrogen end use and carrier end use

External costs passed on to producer countries (sub-indicator)

The import supply chains with the smallest differences between the true price and the calculated cost price have the highest scores: these are the fairest. This is the case for sodium borohydride, as the carrier has a high cost price and causes few externalities. Ammonia, and to a lesser extent methanol, lead to more greenhouse gas emissions and a larger environmental impact abroad, while the import price is in fact lower. This means they have low scores.

End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,24	0,96	0,93	0,93	0,88	0,97	0,99	🚚	0,24	0,96	0,88	
🚢	0,24	0,96	0,93	0,93	0,88	0,97	0,99	🚢	0,24	0,96	0,88	
🚆	0,24	0,96	0,93	0,93	0,88	0,97	0,99	🚆	0,24	0,96	0,88	
	0,24		0,93	0,93	0,88	0,97			0,24		0,88	0,97
H2	0,24	0,96	0,93	0,93	0,88	0,97	0,99	🏭	0,24	0,96	0,88	

Figure 52: Scores for Fair for producing countries for inland supply chains in 2030; hydrogen end use and carrier end use

Passing on the external costs of chains within the Netherlands (sub-indicator)

The score for Fair for Dutch society is determined by the supply chain steps from import and storage up to and including conversion at the end user's site. When combined, the external costs of these steps are highest for LSM and methanol. These are followed by the LOHCs and ammonia, and finally sodium borohydride and liquid hydrogen.

The costs charged are highest for the LOHCs and liquid hydrogen. The middle group consists of LSM and ammonia. The group with the lowest costs charged is made up of the supply chains that include sodium borohydride and methanol.

Methanol has the lowest score here. This is due to the high external costs (the numerator) and the low costs in the supply chain in the Netherlands (the denominator). The costs of sodium borohydride are low in the Netherlands, but the external costs are much lower. LSM also has high external costs, as is the case for methanol, but higher costs charged in the Dutch supply chain than methanol.

The differences between the scores for the various transport modes for methanol stand out. This is because the external costs of the supply chains in the left chart are roughly equal, while the total costs of transport, storage and conversion vary greatly, with road transport the most expensive and transport through the hydrogen network the cheapest mode. The costs also vary for other carriers, although the relative variation is much smaller. For methanol, the transport costs are more than 2.5 times higher for road transport than the lowest costs of transport through the hydrogen network. The costs of road transport for LSM are only 25% higher than the costs of transport through the hydrogen network.

End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,98	1,00	0,98	0,98	0,63	0,80	0,99	🚚	0,99	1,00	0,99	
🚢	0,98	1,00	0,98	0,98	0,36	0,78	1,00	🚢	0,99	1,00	0,99	
🚆	0,98	1,00	0,98	0,98	0,25	0,76	1,00	🚆	0,99	1,00	0,99	
	0,98		0,98	0,98	0,08	0,79			1,00		1,00	0,99
H2	0,98	1,00	0,98	0,98	0,04	0,76	1,00	🏭	0,95	1,00	0,57	

Figure 53: **Scores for Fair for Dutch society for inland supply chains in 2030; hydrogen end use and carrier end use**

6.9 SCORES FOR PUBLIC INTEREST ACCESSIBLE

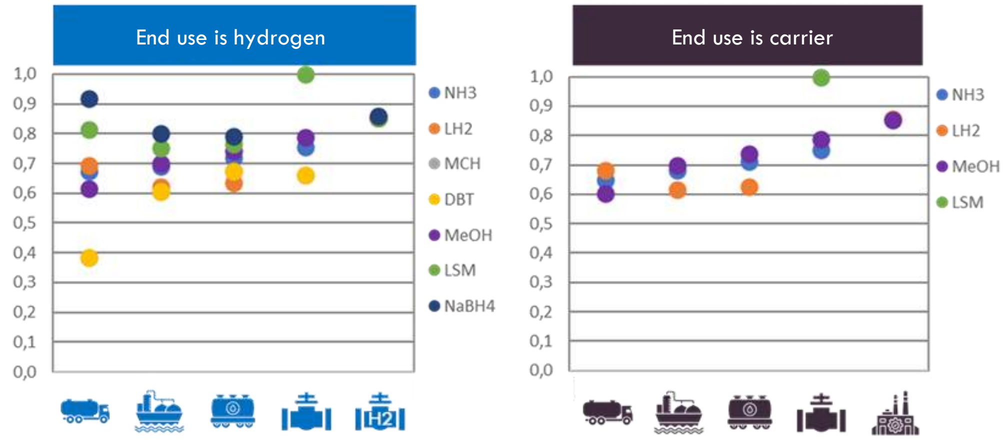
The public interest Accessible consists of two indicators: 1) comparable costs for end users both inland and in the port of entry, and 2) the proximity of the supply chain to inland consumers. Of these two indicators, the Delphi group assigned the highest weighting to an equal, and thus accessible, cost level. This chapter first describes the combined and weighted results for the public interest Accessible. We then explain the results for each indicator.

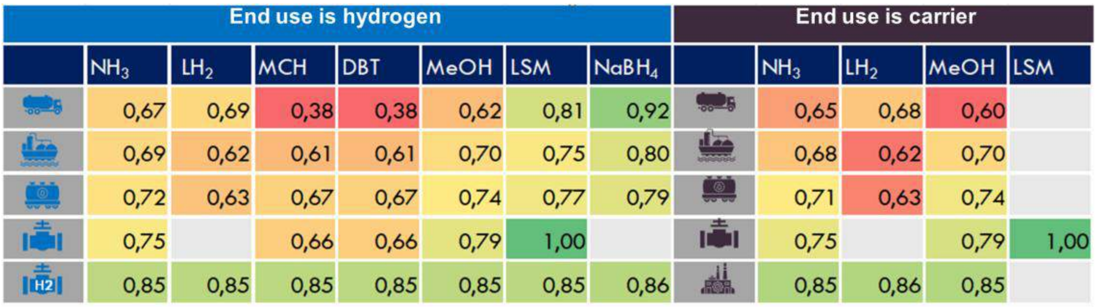
A supply chain that is accessible to all inland companies, with inland costs that are the same as those incurred by companies in the port of entry, is assigned a score of 1. A supply chain is assigned a score of 0 if it is accessible to 0% of inland companies and has the highest additional costs (around 10%) in this analysis compared to companies in the port of entry.

Results for baseline situation (2030, inland end use)

Figure 54 shows the weighted results for the public interest Accessible. Supply through the extensive Dutch natural gas network has the highest score (the fourth column in both the left and right charts). Although road delivery is possible to all industrial estates too, the higher costs result in a lower final score, particularly for DBT and MCH, which have relatively high inland transport costs.

Because of the lower score for the proximity indicator, the combined score for water, rail and pipeline transport is lower than for road transport. The score for sodium borohydride is relatively high. This is because the import costs are relatively high and the additional costs of inland transport result in only a modest cost increase.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,67	0,69	0,38	0,38	0,62	0,81	0,92	🚚	0,65	0,68	0,60	
🚢	0,69	0,62	0,61	0,61	0,70	0,75	0,80	🚢	0,68	0,62	0,70	
🚆	0,72	0,63	0,67	0,67	0,74	0,77	0,79	🚆	0,71	0,63	0,74	
	0,75		0,66	0,66	0,79	1,00			0,75		0,79	1,00
H2	0,85	0,85	0,85	0,85	0,85	0,85	0,86	🏭	0,85	0,86	0,85	

Figure 54: **Scores for Accessible for inland supply chains in 2030; hydrogen end use and carrier end use**

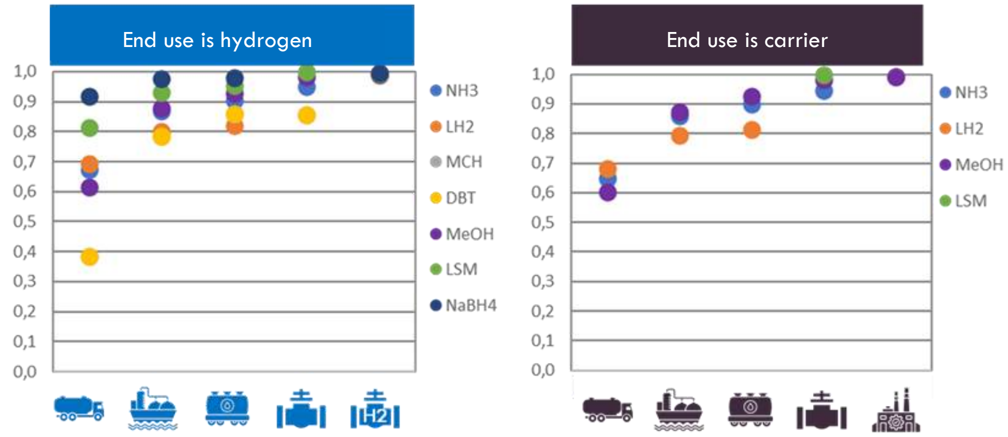
Results for variants

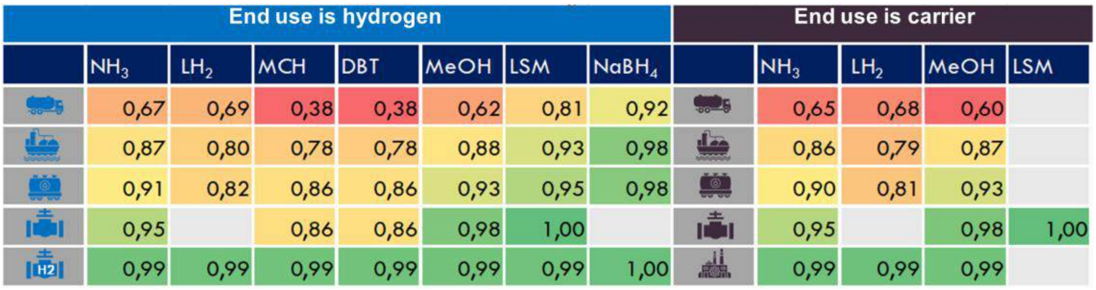
Port of entry

For end use in the port of entry, the inland transport costs no longer apply. In this case, the supply chains have similar scores for the public interest Accessible. The score for all supply chains is the same, i.e., 1. All companies have access to the supply chain and pay the same costs as in the port of entry.

Transit and export

Following discussion with the client, the proximity indicator was deemed to be irrelevant in the case of end use in Germany or Belgium. This is because the indicator concerns the proximity for companies based in the Netherlands, which do not play a role in this variant. We have therefore assigned all supply chains a score of 1 in the model. This results in an improvement to all scores for supply chains with a proximity score below 100% in the baseline situation.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,67	0,69	0,38	0,38	0,62	0,81	0,92		0,65	0,68	0,60	
	0,87	0,80	0,78	0,78	0,88	0,93	0,98		0,86	0,79	0,87	
	0,91	0,82	0,86	0,86	0,93	0,95	0,98		0,90	0,81	0,93	
	0,95		0,86	0,86	0,98	1,00			0,95		0,98	1,00
H2	0,99	0,99	0,99	0,99	0,99	0,99	1,00		0,99	0,99	0,99	

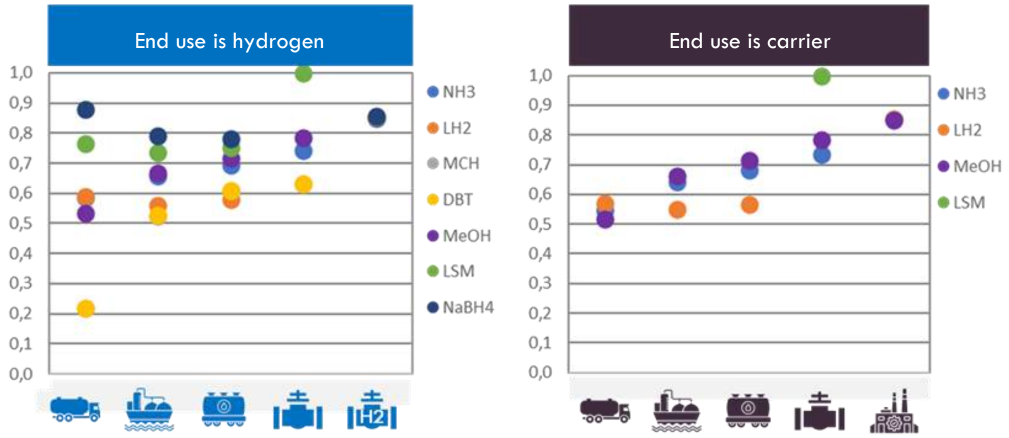
Figure 55: Scores for Accessible for transit and export supply chains in 2030; hydrogen end use and carrier end use

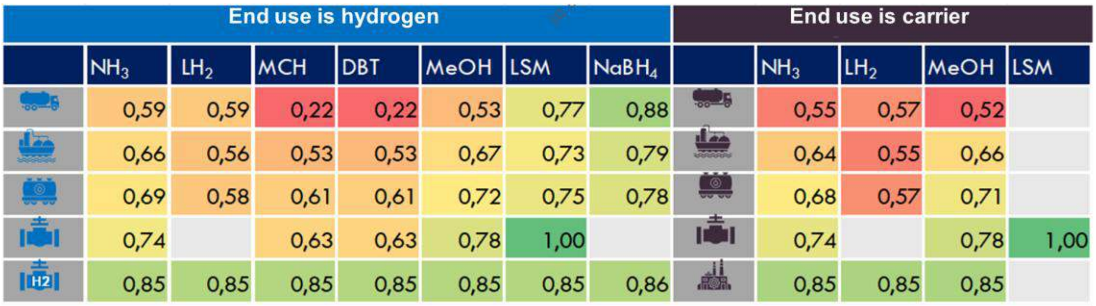
Reference year 2050

In 2050, the scores for Accessible are slightly lower for all supply chains than in the 2030 baseline situation. This is due to the lower scores for the comparable costs indicator. The scores for the proximity indicator remain equal to the baseline situation for all supply chains.

The scores for the comparable costs indicator decrease, because the costs of inland transport do not improve compared to the baseline situation, while the import costs do decrease. This means that the additional inland costs (the costs of inland transport and decentralised storage) increase compared to the costs paid by end users in the port of entry.

The exception is transport through the hydrogen network, as the additional inland costs are so small that they do not have a significant effect on the score.





	End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,59	0,59	0,22	0,22	0,53	0,77	0,88		0,55	0,57	0,52	
	0,66	0,56	0,53	0,53	0,67	0,73	0,79		0,64	0,55	0,66	
	0,69	0,58	0,61	0,61	0,72	0,75	0,78		0,68	0,57	0,71	
	0,74		0,63	0,63	0,78	1,00			0,74		0,78	1,00
H2	0,85	0,85	0,85	0,85	0,85	0,85	0,86		0,85	0,85	0,85	

Figure 56: Scores for Accessible for inland supply chains in 2050; hydrogen end use and carrier end use

Accessible cost level (level playing field sub-indicator)

The supply chains that use a pipeline for transport in the Netherlands have the highest score for this indicator. The supply chains with high additional transport costs have the lowest score. The lower score for the LOHCs is due to the higher costs of transport and decentralised storage. Methanol and ammonia have a somewhat lower score, because the import costs are lower and the costs of transport and decentralised storage result in a greater proportional cost increase. The opposite is true for sodium borohydride. The increase in the import costs due to transport in the Netherlands is smaller, as a result of the high import costs.

End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,58	0,61	0,21	0,21	0,51	0,76	0,90		0,55	0,59	0,49	
	0,83	0,75	0,72	0,72	0,84	0,91	0,97		0,82	0,74	0,84	
	0,88	0,77	0,82	0,82	0,91	0,94	0,97		0,87	0,76	0,91	
	0,94		0,82	0,82	0,98	1,00			0,93		0,98	1,00
H2	0,99	0,99	0,99	0,99	0,99	0,99	1,00		0,99	0,99	0,99	

Figure 57: Scores for Accessible for inland supply chains in 2030; hydrogen end use and carrier end use

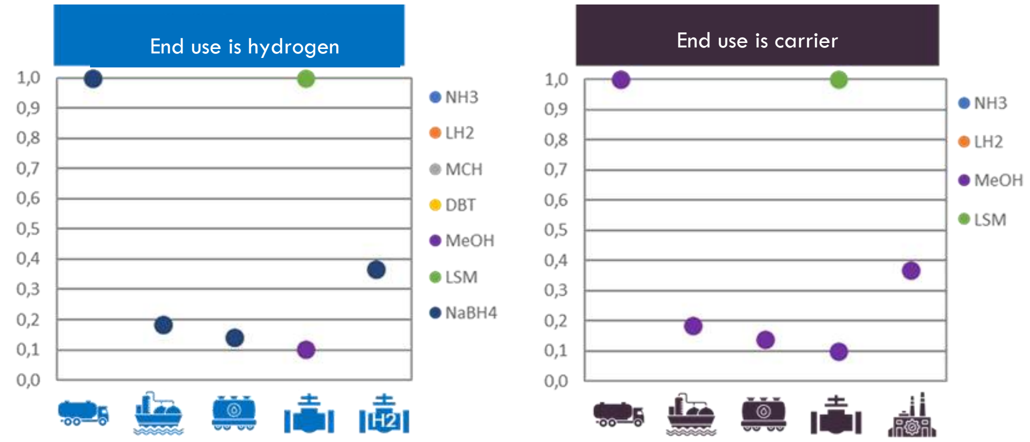
Proximity (sub-indicator)

The scores for this indicator depend only on the transport mode. All supply chains of the same type therefore have the same score in the charts, except for pipeline transport, for which the Delta Rhine Corridor and natural gas network are assigned to the same group. This means that the natural gas network has a better score than the other pipelines for ammonia, the LOHCs and methanol.

The highest scores (1 = 100%) were assigned to supply chains that include inland transport by road and through the natural gas network. This is because every industrial estate in the Netherlands has direct access to these modes.

The lowest score was assigned to a specific pipeline, as is under consideration for ammonia in the Delta Rhine Corridor, or a similar pipeline for methanol or LOHCs. A small percentage of industrial estates in the Netherlands will have direct access to such pipelines. We estimated this to be 10%, see Annex C. If 10% of industrial estates have access, this results in a score of 0.1.

Rail, water transport and the proximity of the national hydrogen network were assigned intermediate scores: 0.14 (=14 percent), 0.18 (=18 percent) and 0.37 (=37 percent) respectively.



	End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	1,00	1,00	1,00	1,00	1,00	1,00	1,00	🚚	1,00	1,00	1,00	
🚢	0,18	0,18	0,18	0,18	0,18	0,18	0,18	🚢	0,18	0,18	0,18	
🚆	0,14	0,14	0,14	0,14	0,14	0,14	0,14	🚆	0,14	0,14	0,14	
	0,10		0,10	0,10	0,10	1,00			0,10		0,10	1,00
H2	0,37	0,37	0,37	0,37	0,37	0,37	0,37	🏭	0,37	0,37	0,37	

Figure 58: Scores for proximity for inland supply chains in 2030; hydrogen end use and carrier end use

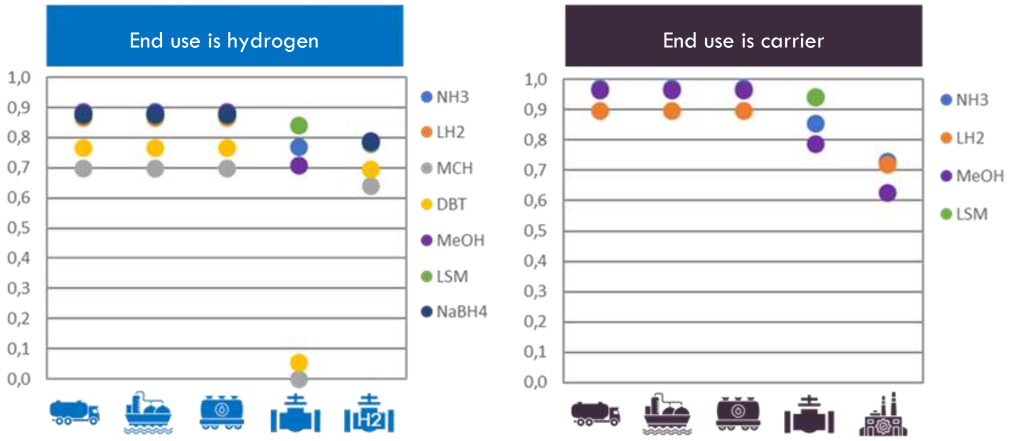
6.10 SCORES FOR PUBLIC INTEREST SPATIAL PLANNING

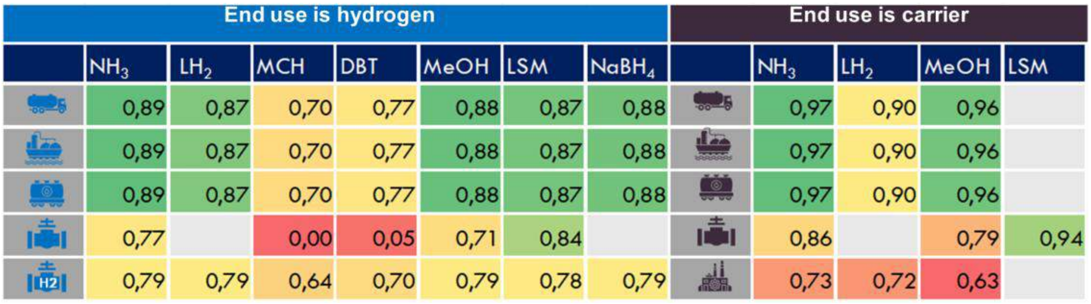
To assign a score for the public interest Spatial Planning, we assessed the physical space that each supply chain occupies. A supply chain with no additional spatial requirements is assigned a score of 1. The supply chain with the largest spatial requirements is assigned a score of 0 in this analysis, i.e., a LOHC supply chain (MCH). The estimated spatial requirements (333 m^2 per kilotonne of hydrogen equivalent) for storage and conversion plants are high for the LOHCs, due to the double storage required. The estimated spatial requirements for the pipelines prove to have the greatest effect on the score. These amount to a strip 61 metres wide and 200 km long for the presumed volumes in 2030, or 7700 square metres per kilotonne for the LOHCs.

Results for baseline situation (2030, inland end use)

The supply chains with the highest scores are those that do not require extensive new pipelines and that have modest spatial requirements for storage facilities. The LOHCs transported through pipelines have the lowest score, as significant pipeline capacity is required to transport the required volumes, as well as a return pipeline. More storage space is also required. The required new pipelines result in slightly lower scores for methanol and ammonia too.

There are no major differences between the supply chains due to the spatial requirements for conversion because, in the absence of data, we have assumed that the spatial requirements for conversion are equal for all hydrogen carriers (equal spatial requirements for each kilotonne of hydrogen equivalent). The only exceptions are LSM and liquid hydrogen, for which we assume that less space is required for each kilotonne of hydrogen equivalent. For the other supply chains, the only differences in the spatial requirements for conversion are due to the differences in volume (expressed in hydrogen equivalent). The space required for storage is largest for the LOHCs, followed by liquid hydrogen; this results in a slightly lower score for liquid hydrogen in the right chart. In the left chart, this disadvantage is compensated by the lower spatial requirements for conversion, which results in a relatively high score for liquid hydrogen.





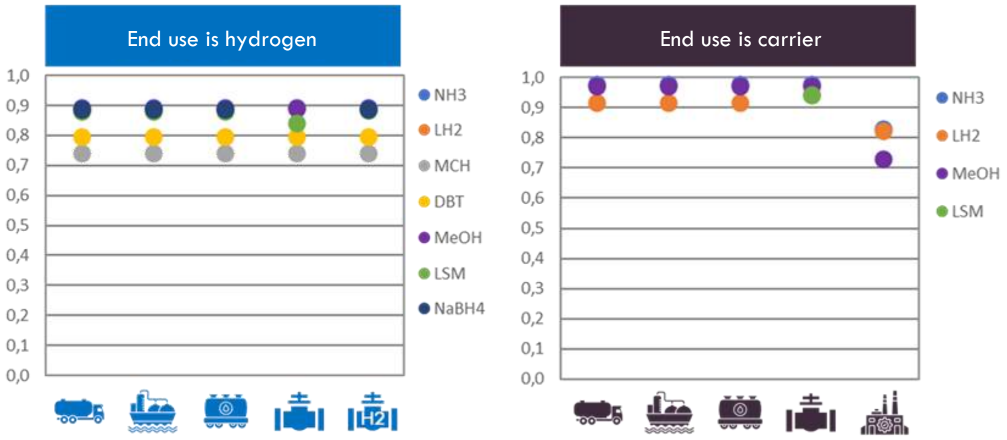
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,89	0,87	0,70	0,77	0,88	0,87	0,88		0,97	0,90	0,96	
	0,89	0,87	0,70	0,77	0,88	0,87	0,88		0,97	0,90	0,96	
	0,89	0,87	0,70	0,77	0,88	0,87	0,88		0,97	0,90	0,96	
	0,77		0,00	0,05	0,71	0,84			0,86		0,79	0,94
H2	0,79	0,79	0,64	0,70	0,79	0,78	0,79		0,73	0,72	0,63	

Figure 59: Scores for Spatial Planning for inland supply chains in 2030; hydrogen end use and carrier end use

Results for variants

Port of entry

For end use in the port of entry, the spatial requirements are lower, as no new pipelines are required for inland transport. Decentralised storage is also not required. In this variant, many supply chains have almost the same score. The differences primarily depend on whether the end user consumes hydrogen or the carrier, and how much storage is required. If the end user consumes the carrier, liquid hydrogen has a lower score due to the increased spatial requirements for storage. The same applies to LSM to a lesser extent. If the end user consumes hydrogen, LSM and the LOHCs have a lower score due to the greater spatial requirements for storage.

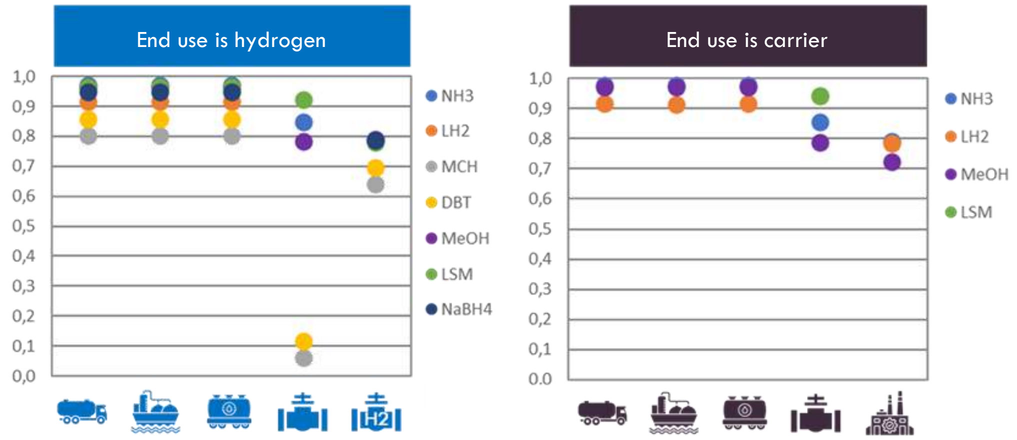


	End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,89	0,89	0,74	0,80	0,89	0,88	0,89	🚚	0,98	0,92	0,97	
🚢	0,89	0,89	0,74	0,80	0,89	0,88	0,89	🚢	0,98	0,92	0,97	
🚆	0,89	0,89	0,74	0,80	0,89	0,88	0,89	🚆	0,98	0,92	0,97	
	0,89		0,74	0,80	0,89	0,84			0,98		0,97	0,94
H2	0,89	0,89	0,74	0,80	0,89	0,88	0,89	🏭	0,83	0,82	0,73	

Figure 60: **Scores for Spatial Planning for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use**

Transit and export

For end use in Germany or Belgium, the space required for decentralised storage and conversion is not taken into account. This slightly improves the score for the supply chains with decentralised conversion compared to end use in the Netherlands. The spatial requirements for pipelines still have a major impact on the score.

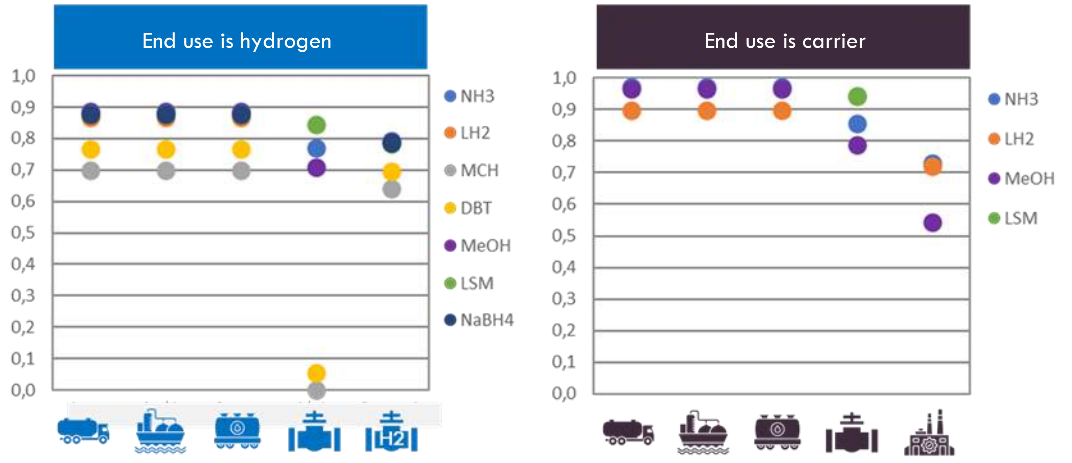


End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,97	0,92	0,80	0,86	0,96	0,96	0,95	🚚	0,98	0,92	0,97	
🚢	0,97	0,92	0,80	0,86	0,96	0,96	0,95	🚢	0,98	0,92	0,97	
🚆	0,97	0,92	0,80	0,86	0,96	0,96	0,95	🚆	0,98	0,92	0,97	
🛢	0,85		0,06	0,12	0,78	0,92		🛢	0,86		0,79	0,94
H2	0,79	0,79	0,64	0,70	0,79	0,78	0,79	🏭	0,79	0,78	0,73	

Figure 61: Scores for Spatial Planning for transit and export supply chains in 2030; hydrogen end use and carrier end use

Reference year 2050

In 2050, the spatial requirements for the various supply chains per kilogramme of hydrogen equivalent change slightly compared to the 2030 baseline situation. For hydrogen carriers that are also used as fuel for the conversion process, the volumes and thus also the spatial requirements are somewhat smaller, due to improvements in the conversion efficiency (LSM, methanol and ammonia for hydrogen gas end use). Despite the improved conversion and synthesis efficiency, the required volume is higher for supply chains with decentralised methanol and LSM synthesis in the Netherlands, as hydrogen is used as an energy source for DAC that provides CO_2 for synthesis in 2050. Additional methanol or LSM must be imported to produce this hydrogen.



End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,89	0,87	0,70	0,77	0,88	0,88	0,88		0,97	0,90	0,96	
	0,89	0,87	0,70	0,77	0,88	0,88	0,88		0,97	0,90	0,96	
	0,89	0,87	0,70	0,77	0,88	0,88	0,88		0,97	0,90	0,96	
	0,77		0,00	0,05	0,71	0,84			0,86		0,79	0,94
	0,79	0,79	0,64	0,70	0,79	0,78	0,79		0,73	0,72	0,54	

Figure 62: **Scores for Spatial Planning for inland supply chains in 2050; hydrogen end use and carrier end use**

6.11 SCORES FOR PUBLIC INTEREST ENVIRONMENT

Various elements are combined to calculate the scores for the public interest Environment. A theoretical supply chain that produces no environmental emissions whatsoever (methane, NO_X, particulate matter, ammonia) and no noise pollution, habitat or environmental damage from emergencies would have a score of 1.

The supply chain with the highest environmental impact is assigned a score of 0 in this analysis. We have monetised this environmental impact using established shadow cost parameters. The various emissions are therefore grouped together. The lowest score equates to environmental costs of around 50 cents per kilogramme of hydrogen equivalent.

Results for baseline situation (2030, inland end use)

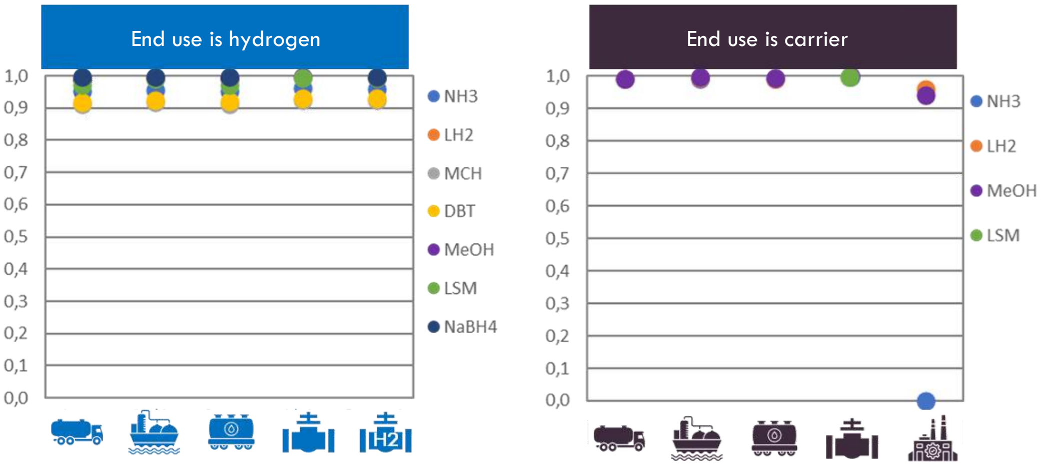
Figure 63 shows the results for the public interest Environment. Ammonia leakage from decentralised synthesis using hydrogen from the national network in the Netherlands proves to have the greatest effect. The leakage from ammonia synthesis is 1.63 grammes per kilogramme of ammonia (JRC). With shadow costs of almost 50 euros per kilogramme of ammonia, this results in an environmental impact of more than 45 cents per kilogramme of hydrogen equivalent for the ammonia chain that includes conversion and decentralised synthesis in the Netherlands (far right in Figure). In addition to these costs, there are some environmental costs of the NO_X emissions: around 2 cents per kilogramme of hydrogen equivalent for conversions (based on the assumed use of $DeNO_X$ plants) and 3 cents for the NO_X emissions due to the electricity consumed in the Netherlands.

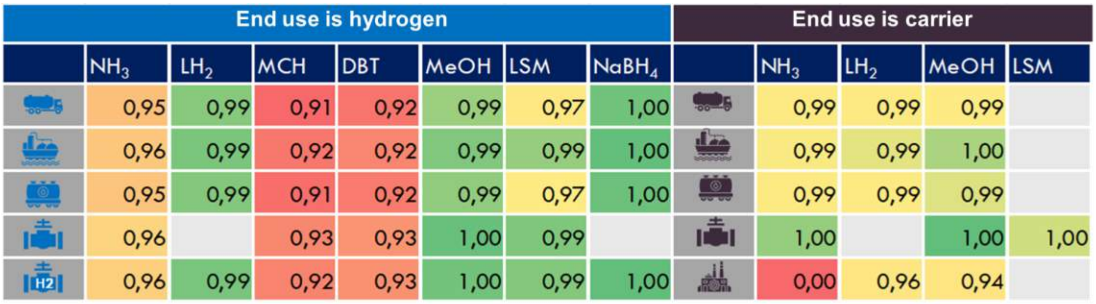
It should however be noted that these emissions already occur during the existing production of ammonia from natural gas, which is used to produce artificial fertiliser. If we assume that equal volumes of fertiliser are produced, emissions will not increase compared to existing production if this production is replaced by ammonia synthesis using hydrogen from the transport network. However, emissions will worsen if ammonia is used for electricity generation.

The minor NO_X emissions from transport are negligible, but the NO_X emissions from the electricity used in the Netherlands do cause distinctive environmental costs. Because we use electric heating instead of hydrogen combustion for LOHC dehydrogenation and the electricity consumption for this is relatively high in the Netherlands, the LOHCs receive a slightly lower score.

The differences between the supply chains due to differences in noise production, particulate matter, habitat degradation and the risk of emergencies are negligible compared to the ammonia emissions during synthesis and the NO_X emissions during conversion to hydrogen gas. These other emissions amount to no more than 1 cent per kilogramme of hydrogen equivalent.

We have assumed that most other hydrogen carriers will also not produce harmful environmental emissions. The LSM supply chains are the exception, as they contribute to smog formation and environmental damage due to methane leakage (maximum 1 cent per kilogramme of hydrogen equivalent). Greenhouse gas emissions are covered by the public interest Sustainable.





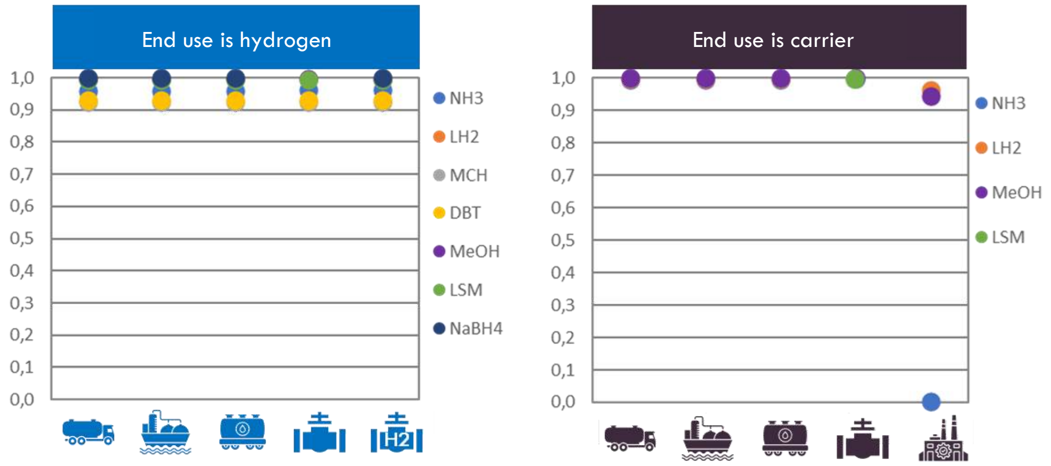
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,95	0,99	0,91	0,92	0,99	0,97	1,00		0,99	0,99	0,99	
	0,96	0,99	0,92	0,92	0,99	0,99	1,00		0,99	0,99	1,00	
	0,95	0,99	0,91	0,92	0,99	0,97	1,00		0,99	0,99	0,99	
	0,96		0,93	0,93	1,00	0,99			1,00		1,00	1,00
	0,96	0,99	0,92	0,93	1,00	0,99	1,00		0,00	0,96	0,94	

Figure 63: Scores for Environment (nature and people) for inland supply chains in 2030; hydrogen end use and carrier end use

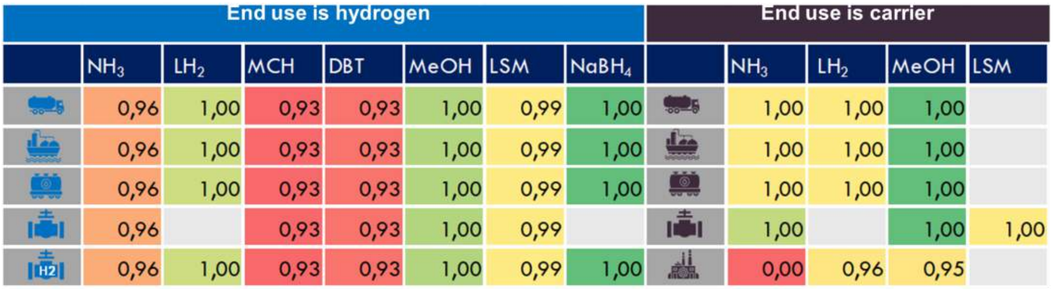
Results for variants

Port of entry

End use in the port of entry results in almost no improvement to the score for Environment compared to the baseline situation. This is because the environmental impact of transport is very small compared to the environmental emissions during conversion and synthesis.


End use is hydrogen

End use is carrier

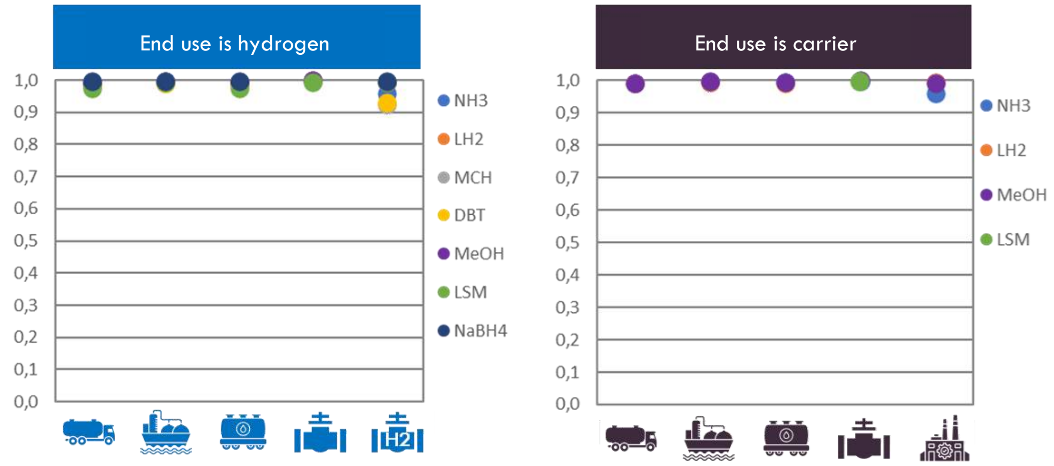


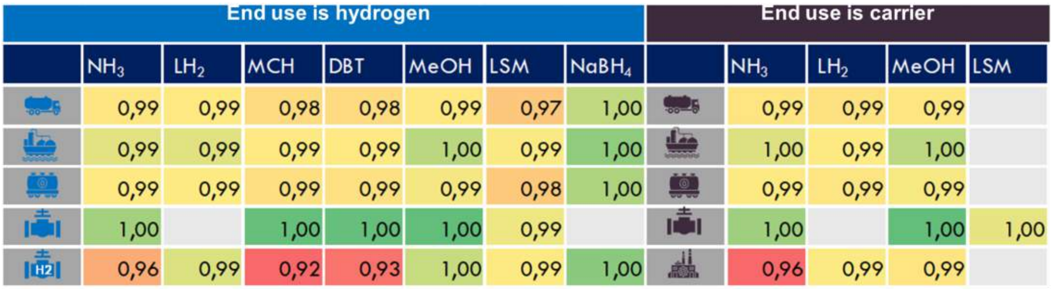
End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,96	1,00	0,93	0,93	1,00	0,99	1,00	🚚	1,00	1,00	1,00	
🚢	0,96	1,00	0,93	0,93	1,00	0,99	1,00	🚢	1,00	1,00	1,00	
🚆	0,96	1,00	0,93	0,93	1,00	0,99	1,00	🚆	1,00	1,00	1,00	
	0,96		0,93	0,93	1,00	0,99			1,00		1,00	1,00
H2	0,96	1,00	0,93	0,93	1,00	0,99	1,00	🏭	0,00	0,96	0,95	

Figure 64: **Scores for Environment for supply chains that involve use in the port of entry in 2030; hydrogen end use and carrier end use**

Transit and export

For end use in Germany or Belgium, the environmental emissions from conversion and storage are not taken into account. This improves the score for the supply chains with decentralised conversion (the first four columns in the left chart and the last column in the right chart) compared to end use in the Netherlands. It results in a higher score for the ammonia supply chain that includes both conversion and decentralised synthesis in particular. This is because the effects of ammonia leakage and NO_X emissions during synthesis are moved abroad. These emissions arise in other countries.



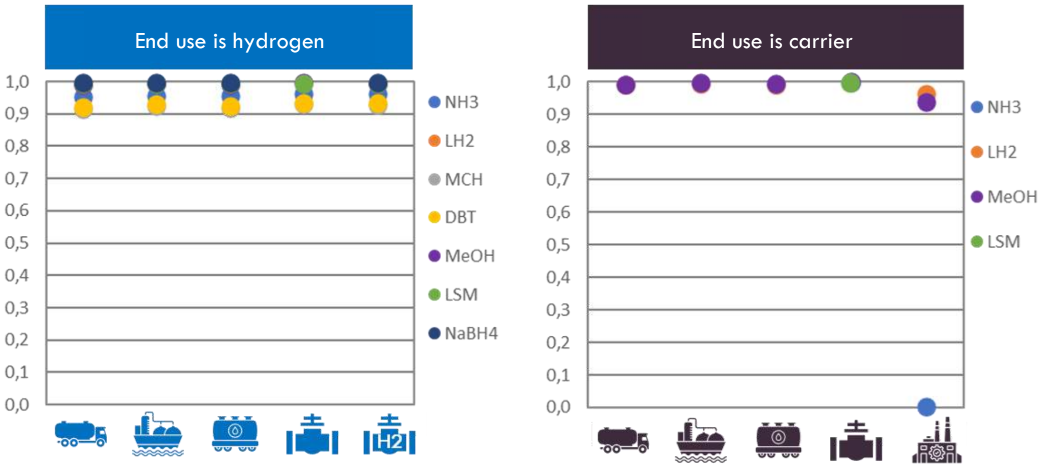


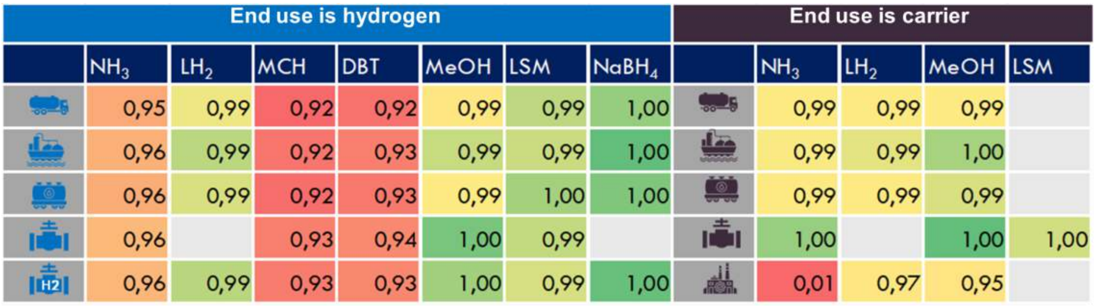
End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$	NH_3	LH_2	MeOH	LSM
🚚	0,99	0,99	0,98	0,98	0,99	0,97	1,00	0,99	0,99	0,99	
🚢	0,99	0,99	0,99	0,99	1,00	0,99	1,00	1,00	0,99	1,00	
🚆	0,99	0,99	0,99	0,99	0,99	0,98	1,00	0,99	0,99	0,99	
	1,00		1,00	1,00	1,00	0,99		1,00		1,00	1,00
H2 / 🏭	0,96	0,99	0,92	0,93	1,00	0,99	1,00	0,96	0,99	0,99	

Figure 65: **Scores for Environment for transit and export supply chains in 2030; hydrogen end use and carrier end use**

Reference year 2050

In 2050, the scores for Environment change very little (they improve slightly) compared to the 2030 baseline situation, even though NO_X and particulate matter emissions during transport and electricity consumption are eliminated. These improvements are almost invisible because the environmental impact of ammonia leakage in the supply chains and NO_X emissions during ammonia synthesis, and to a lesser extent ammonia conversion, remain the same. Compared with the environmental impact of these emissions, the other improvements are minor.





End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,95	0,99	0,92	0,92	0,99	0,99	1,00		0,99	0,99	0,99	
	0,96	0,99	0,92	0,93	0,99	0,99	1,00		0,99	0,99	1,00	
	0,96	0,99	0,92	0,93	0,99	1,00	1,00		0,99	0,99	0,99	
	0,96		0,93	0,94	1,00	0,99			1,00		1,00	1,00
H2	0,96	0,99	0,93	0,93	1,00	0,99	1,00		0,01	0,97	0,95	

Figure 66: Scores for Environment for inland supply chains in 2050; hydrogen end use and carrier end use

CHAPTER 7 FINAL SCORES

This chapter describes the final scores for four situations: firstly the baseline situation in 2030, followed by three variants. Two involve different locations and one concerns a different reference year.

- *Baseline situation:* This concerns the situation for end user groups located inland, at a distance of 200 km from the port of entry (the length of a typical route).
- *Port of entry:* The first variant on the baseline situation location applies to end users who utilise the hydrogen (or hydrogen carrier) directly at the port of entry. In this case, inland transport and decentralised storage are eliminated from the supply chain.
- *Transit and export:* The second variant involves a situation in which the hydrogen (or hydrogen carrier) is routed through the Netherlands for use in Germany or Belgium. In this situation, decentralised storage, conversion, and synthesis are eliminated from the chain.
- *2050:* The final variant involves a projection of the situation in 2050. Some scores of hydrogen carrier supply chains will alter for some public interests, as conditions will change compared to 2030.

This chapter concludes with the results of several sensitivity analyses.

7.1 FINAL SCORES FOR BASELINE SITUATION

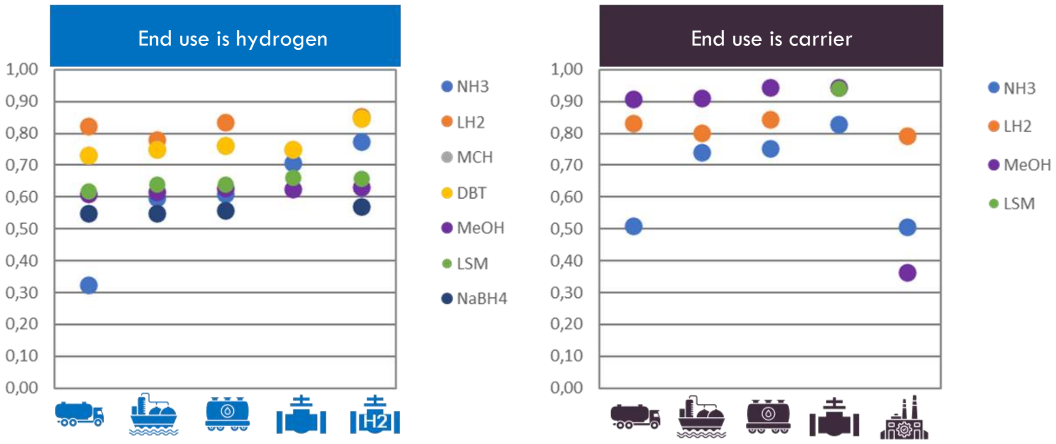
We have combined the results for the public interests (Chapter 6) based on the weighting factors agreed during the Delphi session (Chapter 5). The results are shown in Figure 67, with the supply chains in which the end user consumes hydrogen on the left, and the supply chains in which the end user consumes a hydrogen carrier on the right.

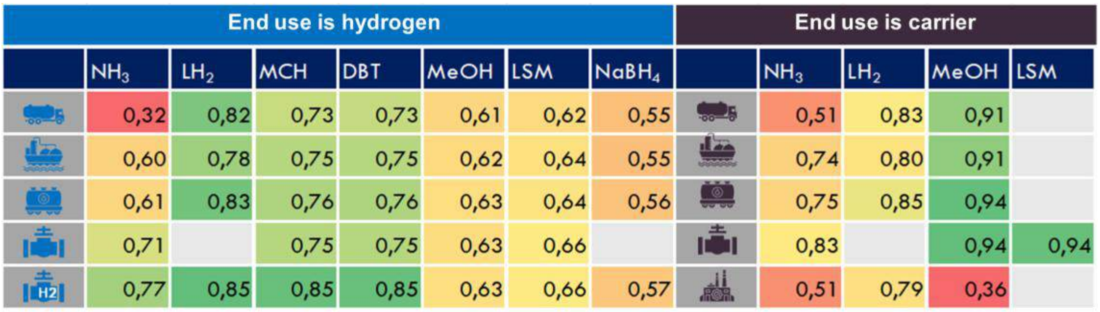
Hydrogen end use (left chart)

The alternatives with the highest scores for hydrogen end use (top 5) are:

1. Liquid hydrogen after evaporation through hydrogen network
2. MCH after dehydrogenation through hydrogen network
3. DBT after dehydrogenation through hydrogen network
4. Liquid hydrogen by rail with decentralised evaporation
5. Liquid hydrogen by road with decentralised evaporation

The differences between the highest scores are small. In general, we see that the supply chains that include liquid hydrogen and the two LOHCs lead the way, followed by the other four carriers, with methanol generally first followed by LSM, ammonia and then sodium borohydride. For supply chains that include pipeline transport combined with decentralised conversion, the carriers have very similar scores.





End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,32	0,82	0,73	0,73	0,61	0,62	0,55		0,51	0,83	0,91	
	0,60	0,78	0,75	0,75	0,62	0,64	0,55		0,74	0,80	0,91	
	0,61	0,83	0,76	0,76	0,63	0,64	0,56		0,75	0,85	0,94	
	0,71		0,75	0,75	0,63	0,66			0,83		0,94	0,94
H2	0,77	0,85	0,85	0,85	0,63	0,66	0,57		0,51	0,79	0,36	

Figure 67: Final scores for inland supply chains in 2030; hydrogen end use and carrier end use

Liquid hydrogen performs well in the comparison as a result of its high score for Sustainable, which is due to the low greenhouse gas emissions and low energy losses, and its high scores for Environment, Adaptable and Fair. These scores compensate for lower scores for the public interests Affordable, Economically Robust, and Reliable. The low energy losses during conversion of liquid hydrogen result in low energy losses across the entire supply chain, despite the additional energy losses due to *boil off* during storage and transport. Of the supply chains that include liquid hydrogen, transport through the hydrogen transport network has the highest score.

The LOHCs also perform well, particularly when supplied through the hydrogen network. The LOHCs have a better score for Affordable, Economically Robust and Reliable than liquid hydrogen. Due to the large volumes that must be transported, stored, and converted, the LOHCs have a lower score for Spatial Planning, Accessible (due to higher transport costs) and Adaptable (due to the required major investments in storage and conversion plants). Figure 67 shows that the differences between DBT and MCH are very small. This is partly due to the necessity of producing a hybrid dataset for the modelling process: in the absence of data about certain aspects for one of the two carriers, we used data for the other LOHC (as is also the case in some of the sources used). As a result, the differences between these two carriers may in fact be greater than can be shown in this report. We therefore present the two LOHCs as one carrier in the conclusions on the results.

LSM and methanol have lower scores than liquid hydrogen and the LOHCs because of their lower score for Sustainable, particularly due to the greenhouse gas emissions indicator (fossil CO_2 used for synthesis in the exporting country is released again in the Netherlands) and the impact of this on Fair.

In 2030, LSM has a high score for the public interest Reliable, and for Accessible when methane gas from LSM is transported through natural gas pipelines. LSM has lower scores than the other supply chains for the public interests Affordable and Economically Robust, Sustainable, Adaptable and Safe & Secure. With the exception of Sustainable (greenhouse gas emissions and energy losses), methanol is one of the carriers with the highest scores. The substance is Affordable and has a higher score for the public interests Safe & Secure, Environment, Reliable and Adaptable. The LSM and methanol supply chains that include conversion in the port of entry and pipeline transport have the highest scores. This is because the supply chains that include use of the hydrogen network and pipeline transport have better scores for the public interests Safe & Secure, Affordable, Environment, Sustainable and Fair than other transport modes (road, rail, inland shipping).

Ammonia has a lower final score due to the low score for the public interests Safe & Secure, Environment and Fair. As Safe & Secure and Environment are heavily weighted, the score for the public interest Affordable cannot compensate for these scores. The supply chain that includes ammonia transport by road has a lower score than all other supply chains. However, the ammonia supply chains are among those with the highest scores – just after liquid hydrogen and the LOHCs – if transport occurs through pipelines and the hydrogen network.

Based on the assumptions used, sodium borohydride generally has the lowest score; only the supply chain that includes ammonia transport by road has a lower score. This is due to the low scores for the public interests Affordable, Reliable and Sustainable (material consumption and energy loss). High scores for Safe & Secure and Fair cannot compensate for these low scores.

Hydrogen carrier end use (right chart)

The alternatives with the highest scores for carrier end use (top 6) are:

1. Methanol by pipeline
2. Methanol by rail
3. Methane gas from LSM through natural gas network
4. Methanol by inland shipping
5. Methanol by road
6. Liquid hydrogen by rail

Methanol performs very well for direct end use, as this carrier has one of the highest scores for all public interests. Direct end use of methanol transported by pipeline or rail has the highest score. Conversion to hydrogen in the port of entry and decentralised synthesis of methanol from hydrogen from the national network has a lower score, due to the additional energy losses and the costs of conversion and synthesis in the supply chain.

Liquid hydrogen also performs well in the analysis. The lower score compared to methanol is primarily the result of the lower score for Affordable due to the higher import costs, for Economically Robust, which is also due to the higher import costs, and for Reliable due to the lower TRL for large-scale conversions, storage, maritime transport, and inland shipping.

In this comparison, synthetic methane is only included in supply chains that involve evaporation in the port of entry and transportation through the natural gas network. Per unit of hydrogen equivalent, it occupies third place after methanol transported by pipeline or rail. This position is the result of a high score for the public interests Reliable (TRL9 for all supply chain steps) and Accessible. All potential end users have access to the supply chain (connection to the natural gas network), and transport through the natural gas network raises the inland costs only slightly compared to the price in the port of entry.

Ammonia has a lower final score in this respect, as it does in the supply chains in which the end use consumes hydrogen, as a result of the lower scores for the public interest Safe & Secure, due to the risk of the formation of a toxic cloud, for Environment, primarily due to ammonia leakage, and for Fair, due to the high external costs compared to the presumed market price. The high score for the public interest Affordable due to the low import costs does not result in a high final score for ammonia supply chains. The exception to the above conclusion is the supply chain that includes ammonia transport by pipeline, which has a similar score to the supply chains that include liquid hydrogen for direct end use. This is because the disadvantage compared to liquid hydrogen for the public interest Safe & Secure is much lower for pipeline transport and without conversion to hydrogen gas, due to the direct use of ammonia. This means that the higher score for Affordable results in a similar score to direct use of liquid hydrogen.

7.2 FINAL SCORES FOR EACH END USER FOR 2030

Table 3 (Chapter 3) presents the 48 studied supply chains. Not every supply chain is relevant for each end user type. We have identified six end user types. In this chapter, we discuss the supply chains with the highest scores for each end user type. The presented scores are not dependent on the end user type. The differences are due to the supply chains that each end user can choose from. The relevant supply chains are discussed for each end user type. The charts from the previous chapters are repeated, with additional outlines to indicate which dots are included in the comparison.

Industrial clusters

Companies in the five industrial clusters that use hydrogen can connect to the national hydrogen network. This option is outlined in column 5 of the left chart in Figure 68. This shows the final scores for the 2030 baseline situation. In terms of the weighted public interests, the preferred order if the hydrogen comes from the hydrogen network is: liquid hydrogen, the LOHCs, ammonia, LSM, methanol and finally sodium borohydride.

For inland industrial clusters located close to pipelines for hydrogen carriers, decentralised conversion to hydrogen is also a realistic option (column 4 in the left chart, circled). In the case of LSM (transported through the natural gas network to an inland steam methane reformer), this results in a minimal advantage compared to conversion of LSM in the port of entry and transport through the hydrogen network. This is because of the higher score for Accessible than for transport through the hydrogen network, due to the low costs of using the natural gas network, and the fact that all end users are already connected to the natural gas network. Decentralised conversion after pipeline transport results in a slightly lower score for ammonia and the LOHCs than for supply chains that use the hydrogen network, and is almost equal for methanol.

Besides situations involving the end use of hydrogen, there could also be a demand within the industrial clusters for the direct end use of specific carriers, either as raw materials or as fuels to comply with specific process requirements. When used as a raw material, the comparison with other carriers is irrelevant, as the choice is dictated by the carrier’s role in the production process. Users do have a certain level of flexibility in deciding which fuel to use – methane, ammonia, or possibly methanol.

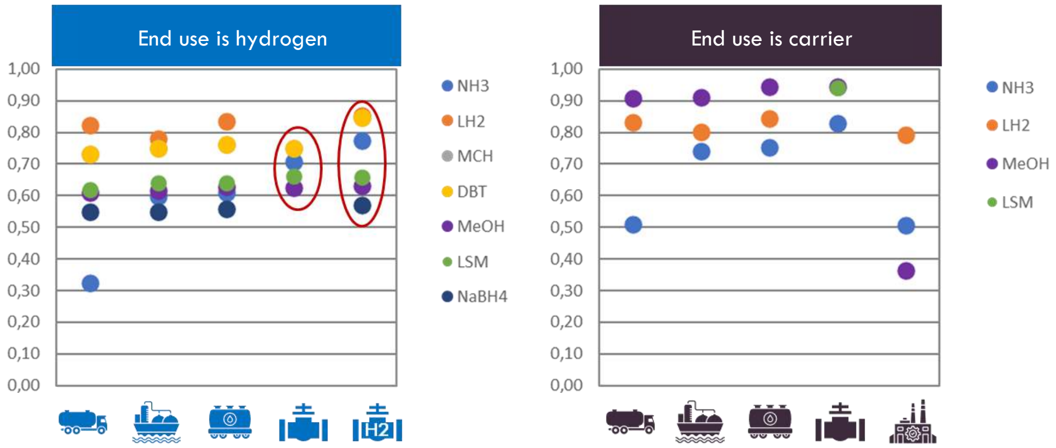


Figure 68: **Final scores for 2030; hydrogen end use and carrier end use**

Fertiliser industry

In principle, fertiliser plants in the Netherlands can choose between three alternatives: import and direct supply of ammonia, decentralised synthesis of ammonia using hydrogen from the hydrogen pipeline network, or ammonia synthesis using hydrogen from steam reforming of methane gas from LSM supplied through the natural gas network. The first two alternatives are circled in columns 9 and 10 in Figure 69. This shows the final scores for the 2030 baseline situation. This reveals that supplying ammonia through a pipeline (without any conversion before it reaches the fertiliser plant) has a higher score for the weighted public interests than ammonia synthesis at the plant with hydrogen sourced from the hydrogen network (with both conversion and decentralised synthesis in the supply chain). The conversion and synthesis processes drive up costs, amplify energy losses, increase emissions, require more space, and exacerbate environmental risks in the supply chain.

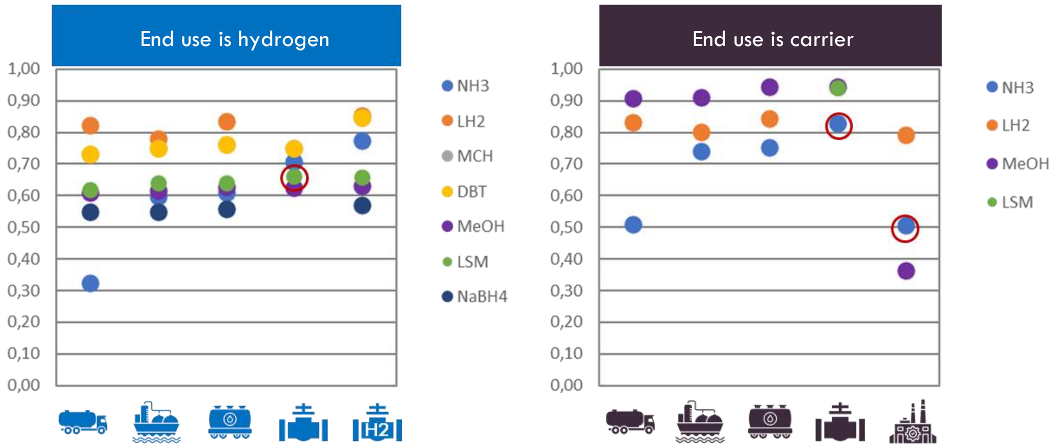


Figure 69: **Final scores for alternatives for the fertiliser industry in 2030; hydrogen end use and carrier end use**

The option involving ammonia synthesis with hydrogen from steam reforming of LSM is not shown in Figure 69. Although the fourth column in the left chart does show the supply chain that includes hydrogen from steam reforming of methane gas from LSM sourced from the natural gas network, the effect of ammonia synthesis should be added to this. Even without this decentralised synthesis, hydrogen gas from methane has a lower score than the supply of ammonia by ship, rail or pipeline (right chart). The extra synthesis step will lower the score even further.

Power stations

We have considered three options to develop CO_2-free dispatchable generation capacity: use of synthetic methane in power plants, use of hydrogen in adapted power plants and use of ammonia in existing or adapted plants. These alternatives are circled in columns 5 and 9 in Figure 70. This shows the final scores for the 2030 baseline situation.

Direct use of methane gas from LSM from the natural gas network has the highest score, followed by the use of hydrogen from the hydrogen network, provided that this hydrogen is produced using centralised conversion of liquid hydrogen or LOHCs. As described for the industrial clusters, the preferred order for the hydrogen carriers from the perspective of the weighted public interests is: liquid hydrogen, the LOHCs, ammonia (provided that it is supplied by pipeline or through the hydrogen network), LSM, methanol and sodium borohydride. Direct use of ammonia supplied by pipeline has a higher score than use of hydrogen derived from a centralised ammonia conversion process, although it scores lower than hydrogen sourced from centrally converted liquid hydrogen and the LOHCs. The use of LSM supplied through the natural gas network to an inland steam reformer results in a minimal advantage compared to conversion of LSM in the port of entry and transport through the hydrogen network.

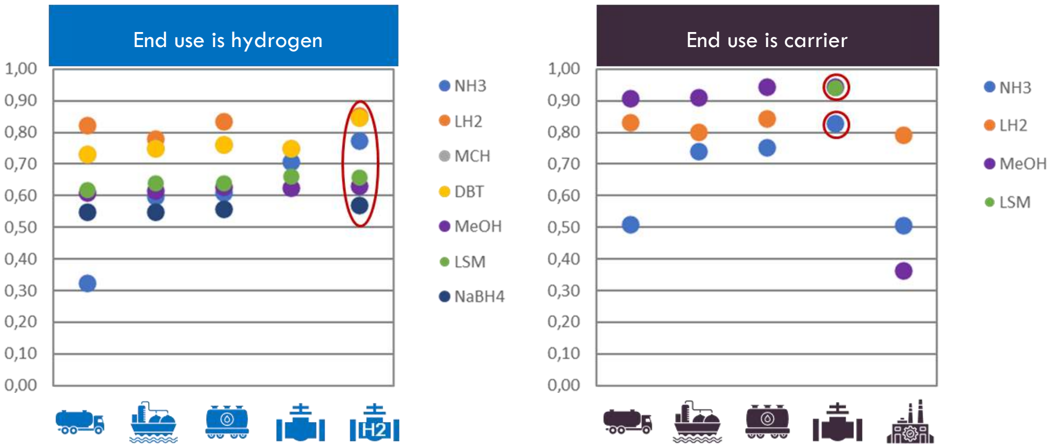


Figure 70: Final scores for alternatives for power stations in 2030; hydrogen end use and carrier end use

Cluster 6 industry

Cluster 6 companies situated near the national hydrogen network will be able to connect to it, in which case the comparison outlined for industrial clusters becomes applicable. The remaining cluster 6 companies will have to be supplied with hydrogen carriers by road, water, rail, or pipeline. In Figure 71, the potential alternatives are circled in columns 1 to 4 in the left chart (for companies that require hydrogen for end use) and in columns 1 to 4 in the right chart (for companies that require the carrier itself for end use). This shows the final scores for the 2030 baseline situation.

In nearly every case, centralised conversion and transport through the hydrogen network has a higher score, provided that the companies have that option. The extent of this advantage varies for each carrier. The differences are relatively large for ammonia and the LOHCs and smaller for the other carriers. Consequently, having no access to the hydrogen network is a disadvantage from the perspective of the weighted public interests. Liquid hydrogen and both LOHCs are the top choices for cluster 6 companies without access to the hydrogen network, with LSM and methanol, ammonia and sodium borohydride trailing quite some distance behind.

When it comes to the direct end use of a carrier, comparisons with other carriers are irrelevant in raw material applications, as that choice is dictated by the carrier's role in the production process (see Industrial clusters).

It should be noted that the supply of liquid hydrogen by road and rail has a slightly higher score than supply by inland vessels. This is due to the expected high CAPEX for the (yet to be constructed) transport vessels and the lower score for Reliable. Costs can be expected to fall as experience is gained. However, the negative impact of high and low water levels on the public interest Reliable remains.

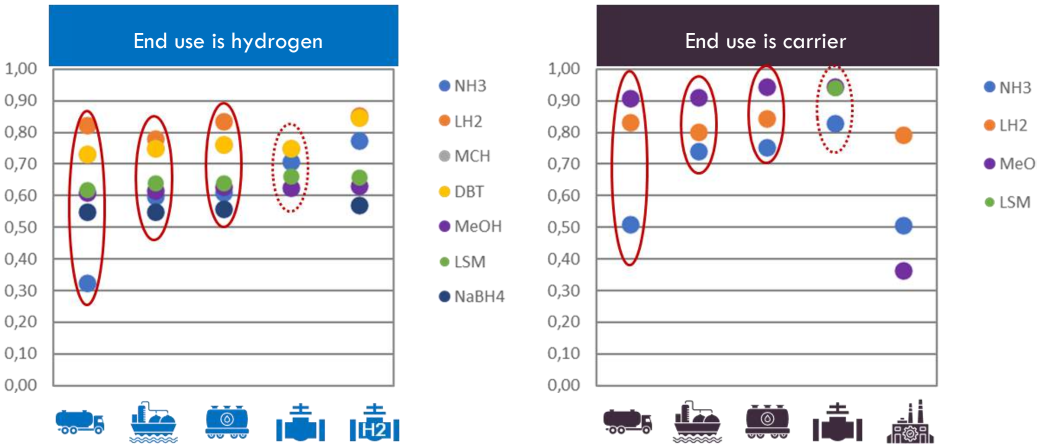


Figure 71: Final scores for alternatives for cluster 6 in 2030; hydrogen end use and carrier end use

Roadside fuelling stations

Within the scope of this study, hydrogen fuelling stations may be supplied by delivering liquid hydrogen to the fuelling stations in tank trucks by road, or by connecting the fuelling station to the hydrogen network (as is the case for the fuelling station in Rhoon). These alternatives are circled in Figure 72. This shows the final scores for the 2030 baseline situation. If vehicles are refuelled with liquid hydrogen, column 1 on the right side of Figure 72 applies. If liquid hydrogen is first converted to a compressed state (350-700 bar) at the fuelling station itself by evaporation, column 1 on the left side applies. Both variants may be combined at a single fuelling station.

If a fuelling station is connected to the hydrogen network, a local purification step will be required to supply hydrogen of the required quality for fuel cells. If we add this step using data from JRC, the scores in column 5 on the left decrease by a maximum of a hundredth of a point.[62] No additional purification is required if liquid hydrogen is supplied.

The comparison reveals that, when we factor in the additional purification step, the hydrogen network route is only superior to transporting liquid hydrogen by road if the hydrogen in the network is sourced from either liquid hydrogen or LOHCs. It has a lower score if the hydrogen

---

[62] JRC1 states that the additional costs amount to an investment of 500,000 euros in PSA purification for a fuelling station with a daily capacity of 1 tonne of H_2. The write-off of this investment over a period of 20 years amounts to 0.068 euros per kgH_2. The additional energy consumption is 3.6 MJ/kg H_2 and the purification step increases hydrogen losses (emissions) by 1%.

from the network comes from LSM, methanol, ammonia or sodium borohydride. In many parts of the Netherlands, this option will not be possible, as the hydrogen network will be too distant from fuelling stations for connections to be feasible. Even when it is nearby, the connection costs involved will be prohibitive in many cases. Consequently, supplying hydrogen in its liquid state is generally the better option in most situations.

Fuelling stations could also supply hydrogen from local dehydrogenation of LOHCs or sodium borohydride, from decentralised steam reforming of LSM or methanol or decentralised cracking of ammonia. However, as can be seen in Figure 72, this does not result in a higher score than supplying liquid hydrogen and is also much more technically complex, requires more space at or near the fuelling station and does not serve the needs of customers who wish to refuel with liquid hydrogen. The latter problem also applies to fuelling stations that are connected to the hydrogen network.

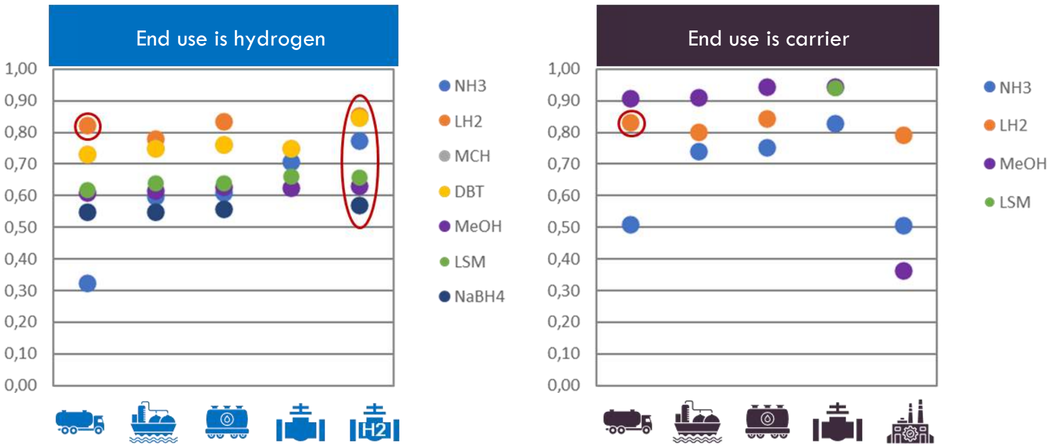


Figure 72: Final scores for alternatives for roadside fuelling stations in 2030; hydrogen end use and carrier end use

Bunkering stations for shipping

The shipping sector is exploring various sustainable alternatives to existing fuels, including liquid hydrogen, methanol, ammonia, LSM, and sodium borohydride. These energy carriers can be supplied to vessels from tank trucks, bunker vessels, or landside bunkering stations. As the landside bunkering stations are supplied by vessels, we have compared only two supply chain groups: by road and inland shipping. These alternatives are circled in columns 1 and 2 on the right side of Figure 73.

This shows that supplying methanol and liquid hydrogen with tank trucks or bunker vessels has a higher score in terms of the weighted public interests than supplying ammonia with tank trucks or bunker vessels. Methanol has a clear advantage as regards the permitting process: in a study for Port of Amsterdam, DNV concluded that for ship-to-ship bunkering the safety distances for methanol can be 3-5 times smaller than for LNG, and that the safety distances for ammonia and liquid hydrogen are comparable to those for LNG.[63] Although the study did not consider bunkering from bunkering stations, this situation is theoretically comparable.

---

[63] "The results for the location-specific individual risk show that the external safety distances (10-6/year) for bunkering of methanol and gaseous hydrogen are much smaller (a factor of 3-5) than those for LNG. For refrigerated ammonia and liquid hydrogen, the safety distances are similar to those for LNG. (…)." DNV (2021), Study of external safety of bunkering alternative fuels for sea shipping.

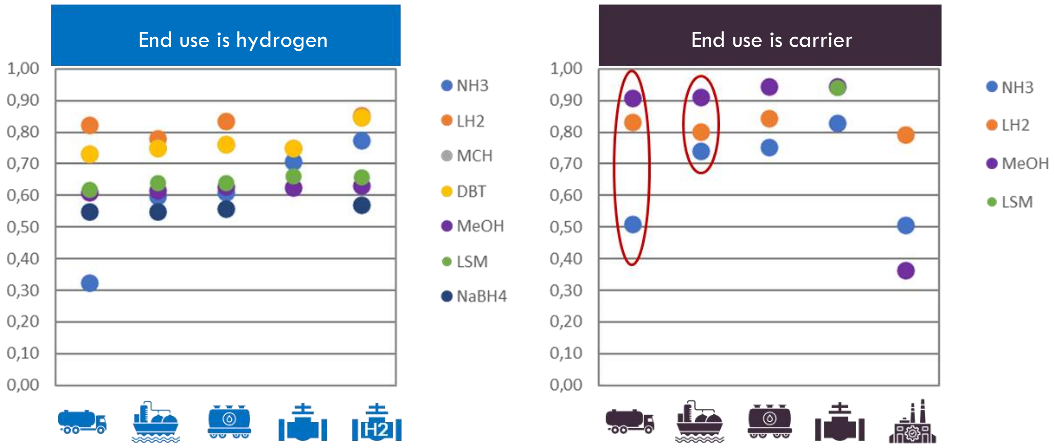


Figure 73: Final scores for alternatives for bunkering stations in 2030; hydrogen end use and carrier end use

7.3 END USE IN PORTS OF ENTRY IN 2030

One of the variants considered is the situation in which the end use of hydrogen and hydrogen carriers occurs in the ports of entry. This means that, in the 2030 baseline situation, the effects of the supply chain steps involving inland transport and decentralised conversion and storage do not apply.

This negates the differences between transport modes. The final scores are slightly higher due to the eliminated costs, energy losses and investments in means of transport, as well as transport-related externalities. Liquid hydrogen and the LOHCs (DBT and MCH) continue to have the highest scores for hydrogen gas end use, and methanol for carrier end use. In this variant, ammonia has a markedly higher score than in the baseline situation.

While the supply chains that include both conversion and synthesis in the Netherlands are shown in Figure 74, these are generally not realistic in a port of entry where the hydrogen carrier itself can easily be supplied. A possible exception is the import of a hydrogen carrier, followed by conversion to hydrogen, which is then liquefied to produce liquid hydrogen for end users in the transport sector (trucks, shipping). Nevertheless, from the perspective of the public interests, direct distribution of imported liquid hydrogen is more attractive.

End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,78	0,86	0,85	0,85	0,64	0,66	0,58		0,89	0,87	0,95	
	0,78	0,86	0,85	0,85	0,64	0,66	0,58		0,89	0,87	0,95	
	0,78	0,86	0,85	0,85	0,64	0,66	0,58		0,89	0,87	0,95	
	0,78		0,85	0,85	0,64	0,66			0,89		0,95	0,94
H2	0,78	0,86	0,85	0,85	0,64	0,66	0,58		0,51	0,80	0,37	

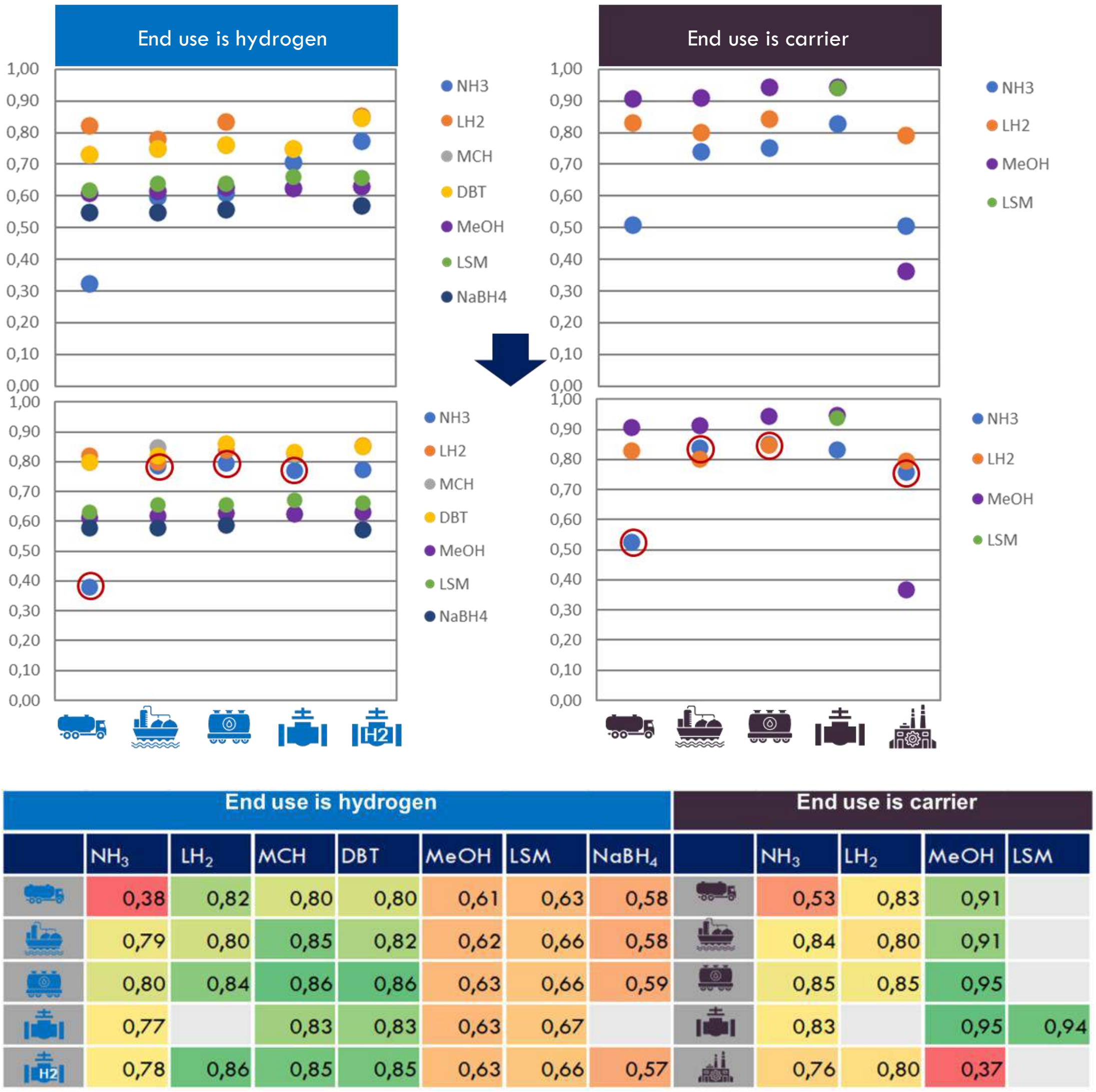
Figure 74: **Change in final scores for variant with end use in the port of entry in 2030; hydrogen end use and carrier end use**

7.4 TRANSIT AND EXPORT IN 2030

The next variant to be assessed is the situation in which hydrogen and hydrogen carriers are forwarded to other countries, where the end use occurs. In the case of transit to other countries, the effects of the supply chain steps that consist of decentralised conversion and storage at the end user's site compared to the 2030 baseline situation no longer apply.

This results in fewer environmental impacts, reduced spatial requirements, and fewer safety and security risks in the Netherlands. In addition, fewer high-risk investments are required in the Netherlands (public interest Adaptable). The added value for the Netherlands decreases (public interest Economically Robust).

As a result, the score for ammonia improves in supply chains in which the safety and security risk and environmental emissions partly shift to other countries (all columns except column 5 in the left chart and column 4 in the right chart). For the other carriers, there is little change from the baseline situation.



End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,38	0,82	0,80	0,80	0,61	0,63	0,58		0,53	0,83	0,91	
	0,79	0,80	0,85	0,82	0,62	0,66	0,58		0,84	0,80	0,91	
	0,80	0,84	0,86	0,86	0,63	0,66	0,59		0,85	0,85	0,95	
	0,77		0,83	0,83	0,63	0,67			0,83		0,95	0,94
	0,78	0,86	0,85	0,85	0,63	0,66	0,57		0,76	0,80	0,37	

Figure 75: Change in final scores for variant with end use abroad in 2030; hydrogen end use and carrier end use

7.5 SITUATION IN 2050

The third variant involves a comparison of the potential situation in 2050. Several entries in the dataset for 2030 were modified to reflect the expected situation in 2050. We have assumed conservative improvements resulting from innovation, including by using cost estimations for 2040 from HyDelta (as HyDelta does not focus on 2050).

Modifications to input for situation in 2050

- Use of CO_2: direct air capture instead of industrial point sources for the synthesis of methanol and LSM in the Netherlands and the exporting country.
- Volume: a quadrupling compared to 2030, based on the high variant (for 2030) in the volume study carried out by Berenschot, Arcadis and TNO, adjusted for efficiency improvements in conversions.
- Affordable: HyDelta dataset for imports from Morocco in 2040 (lower import costs than in 2030). Electricity price in the Netherlands, according to the Climate and Energy Outlook (KEV), is projected to be 98 euros per MWh in 2050; CO_2 price in 2050, 176 euros per tonne.
- Reliable: technologies with lower TRLs in 2030 will achieve higher TRLs in 2050, typically 9.
- Emissions: maritime transport net-zero[64] CO_2 in 2050 in accordance with the International Maritime Organisation (IMO) targets (mix of methanol, ammonia and liquid hydrogen-powered vessels); domestic transport zero-emission (electric or hydrogen).
- Energy loss: for some conversions an improvement in efficiency of the order of 5-7% has been assumed; domestic transport is more economical due to electric propulsion, maritime transport unchanged.

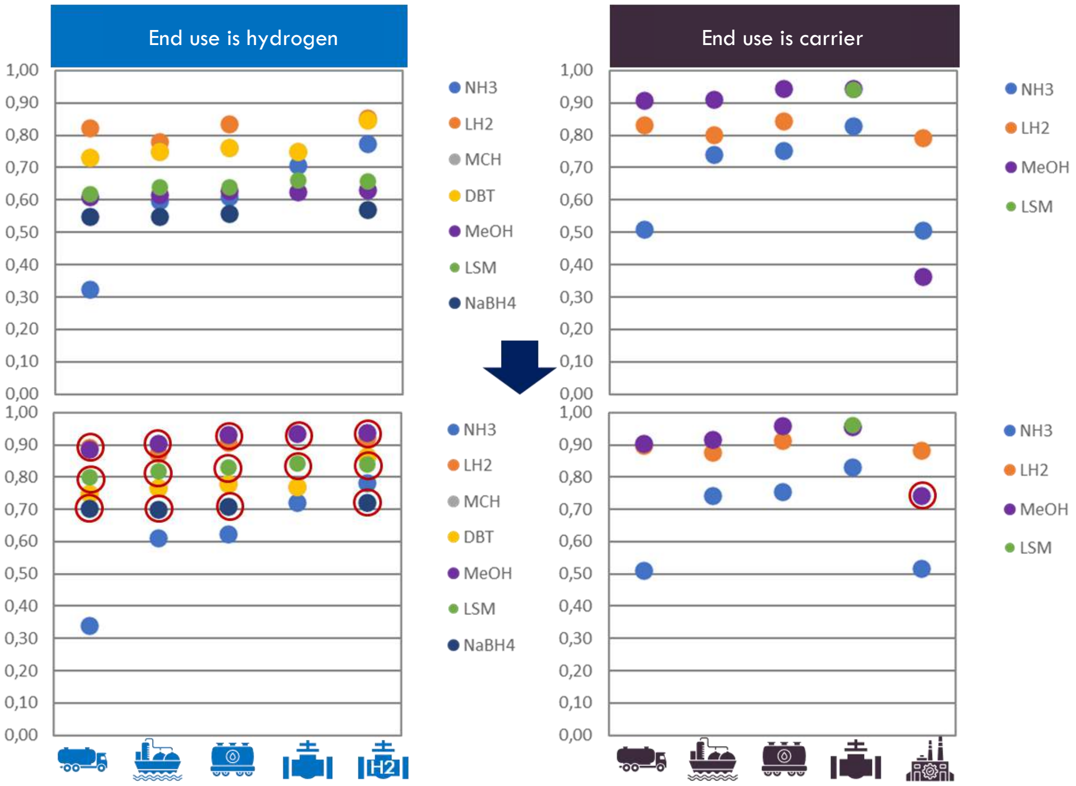
See Annex D for a detailed overview of the revised assumptions, covering both the 2050 variant with conservative assumptions and the sensitivity analysis for 2050 with progressive assumptions.

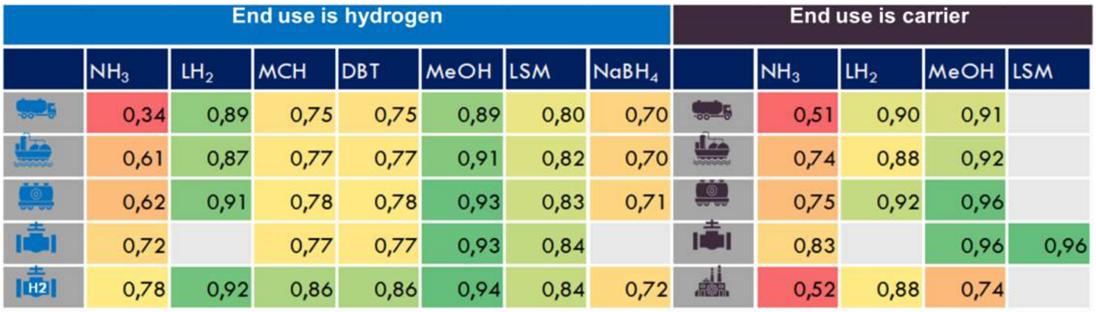
Synthesis using CO_2 from direct air capture instead of industrial point sources results in a large improvement in the scores for methanol and LSM. If the CO_2 emissions from these carriers are eliminated, methanol, which has a relatively low final score in the baseline situation, becomes the carrier with the highest score. LSM rises to third place after liquid hydrogen for hydrogen gas end use, and to second place for direct end use. Methanol has an average or relatively high score for all public interests in 2050. The same is generally true for LSM, although the scores are slightly lower than for the methanol supply chains.

Process improvements (energy efficiency, cost levels) affect the scores for most carriers. This does not result in significant changes to the ranking. The increased volume in 2050 does not affect the final score. The score for sodium borohydride improves, due to the presumed lower energy price in the exporting country in 2050. The emissions from maritime transport and inland shipping decrease but the transport costs do not. This has a limited effect on the scores for the Morocco-Netherlands route.

---

[64] Net-zero refers to a situation in which greenhouse gas emissions are balanced by reductions in emissions. Even though CO_2 emissions may occur during transport, the same quantity of CO_2 is removed from the atmosphere as is emitted.





End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,34	0,89	0,75	0,75	0,89	0,80	0,70		0,51	0,90	0,91	
	0,61	0,87	0,77	0,77	0,91	0,82	0,70		0,74	0,88	0,92	
	0,62	0,91	0,78	0,78	0,93	0,83	0,71		0,75	0,92	0,96	
	0,72		0,77	0,77	0,93	0,84			0,83		0,96	0,96
H2	0,78	0,92	0,86	0,86	0,94	0,84	0,72		0,52	0,88	0,74	

Figure 76: **Change in final scores for alternatives for inland supply chains in 2050; hydrogen end use and carrier end use**

7.6 SENSITIVITY ANALYSES OF WEIGHTING FACTORS

To study the influence of the weighting factors on the final scores, sensitivity analyses were carried out with three sets of weighting factors other than the set determined during the Delphi session:

- Neutral weighting: all public interests equally important (each 10%).
- Affordable weighted higher: the result of the Delphi session was adjusted by doubling the weighting for Affordable, halving the weightings for Safe & Secure and Environment and distributing the remaining percentages proportionally;
- 100-points assignment: participants in the Delphi session each assigned a total of 100 points to the public interests that they considered most important (see Chapter 5.3).

7.6.1 *Neutral weighting*

The pie chart in Figure 77 shows the distribution of the weighting factors if neutral weighting is applied. The neutral weighting differs from the Delphi weighting as follows: Economically Robust, Reliable, Adaptable, Fair, Accessible and Spatial Planning are weighted higher, Environment, Safe & Secure and Sustainable are weighted lower and Affordable is weighted almost the same.

End use is hydrogen

The results are shown in Figure 78. Liquid hydrogen falls from first to third place (except for transport by water, in which case it falls to fourth place). The lower final score for liquid hydrogen compared to the Delphi weighting is primarily due to the higher weighting for Reliable and Spatial Planning and the lower weighting for Sustainable and Environment. Liquid hydrogen has a lower than average score for the first two public interests because the TRL is not estimated to reach 9 for all supply chain steps by 2030, and because storage and transfer require a great deal of space. Liquid hydrogen has a higher than average score for Sustainable and Environment due to the low energy losses in the supply chain and low emissions. Transport by inland shipping scores lower due to the lower score for Reliable. This is due to the risk of high and low water levels.

With this neutral weighting, the LOHCs have a lower score. They fall from second/third in the ranking for the Delphi weighting to fifth/sixth place for the neutral weighting. The lower score is primarily the result of the higher weighting assigned to Reliable, Adaptable and Spatial Planning. The LOHCs require a great deal of space due to the low hydrogen concentration for conversion and the return flows by pipeline, which necessitate more high-risk investments (double storage and more pipelines). The TRL for some supply chain steps is also lower (Reliable).

Methanol has a higher score for hydrogen end use and occupies first place. It has a slightly better score than ammonia, which occupies second place if neutral weighting is applied. The high score for methanol is due to the relatively high final score for all public interests except Sustainable (greenhouse gas emissions and energy losses). If the Delphi weighting is applied, the low score for Sustainable has a major effect on the final score. With neutral weighting, this low score is more than compensated by the scores for the other public interests.

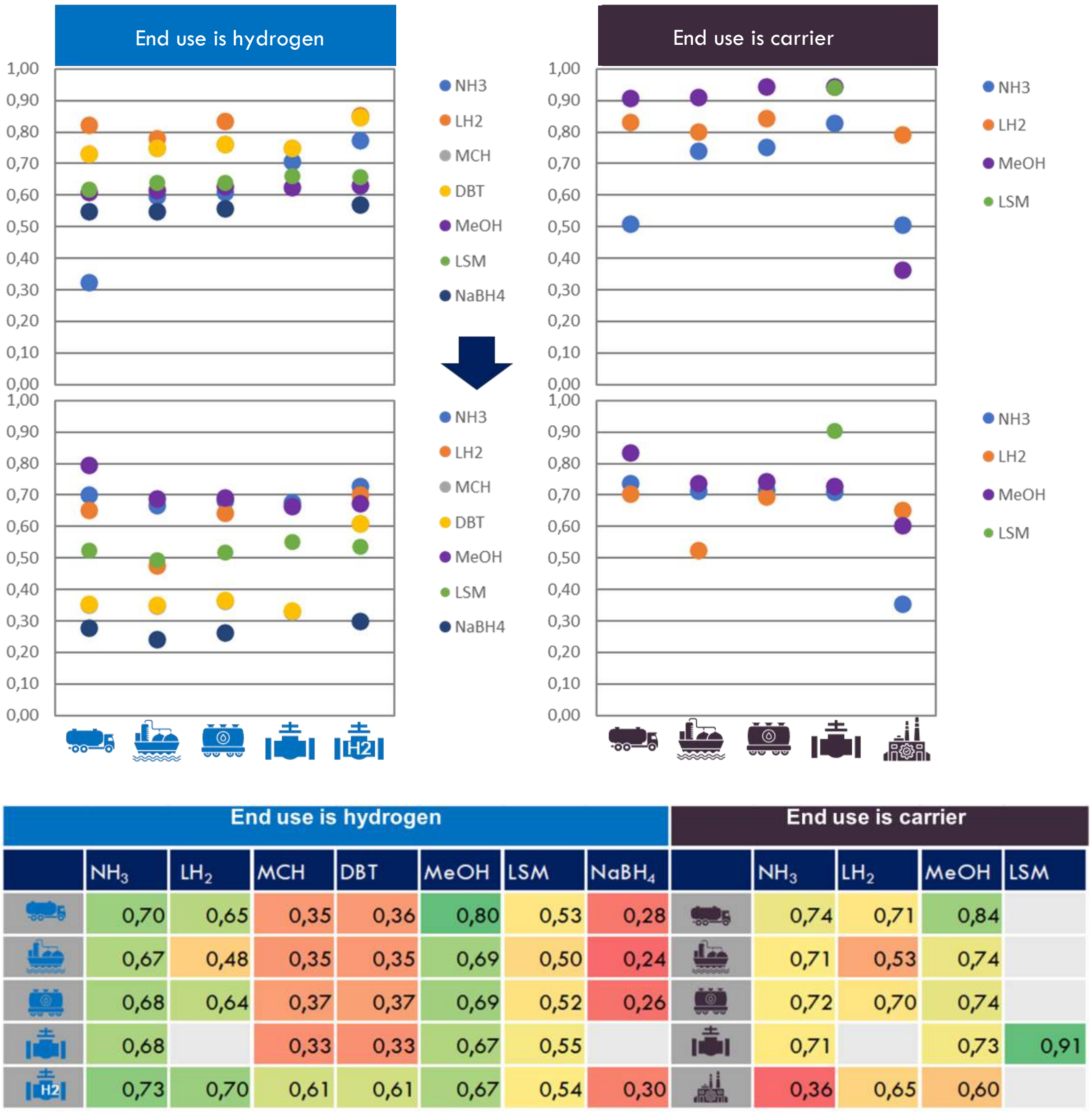
Ammonia also has a high score because the low scores for Safe & Secure (toxic cloud) and Environment (ammonia leak) are less heavily weighted. Sodium borohydride still has the lowest score.

End use is carrier

Where the end use consumes the carrier, LSM supplied as methane gas through the natural gas network has a slightly higher score than methanol and occupies first place, due to the higher weighting assigned to Fair and Accessible. The extensive natural gas network is more accessible than methanol supplied by pipeline and the external costs compared to the cost price are also lower (Fair).

Methanol and liquid hydrogen have a slightly lower score if neutral weighting is applied. Ammonia transport by road has a slightly higher score, primarily because Accessible is weighted higher and Safe & Secure is weighted lower.

Figure 77: **Visual representation of the weighting change; the Delphi weighting of the baseline situation is shown on the left, the neutral weighting on the right**



End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,70	0,65	0,35	0,36	0,80	0,53	0,28		0,74	0,71	0,84	
	0,67	0,48	0,35	0,35	0,69	0,50	0,24		0,71	0,53	0,74	
	0,68	0,64	0,37	0,37	0,69	0,52	0,26		0,72	0,70	0,74	
	0,68		0,33	0,33	0,67	0,55			0,71		0,73	0,91
H2	0,73	0,70	0,61	0,61	0,67	0,54	0,30		0,36	0,65	0,60	

Figure 78: **Sensitivity analysis of neutral weighting factors; hydrogen end use and carrier end use (below) compared to the 2030 baseline situation (above)**

7.6.2 *Adjusted weighting factors: Affordable weighted higher*

In the following sensitivity analysis, we calculated a series of weighting factors in which the public interest Affordable is assigned a much higher weighting. The chosen distribution of weighting factors is shown in the pie chart in Figure 79. The weighting assigned to Affordable is doubled, the weightings assigned to Safe & Secure and Sustainable are halved, with the remaining percentage points distributed proportional across the other public interests.

Figure 79: Visual representation of the changed weighting; the Delphi baseline situation weighting is on the left, and the adjusted weighting is on the right

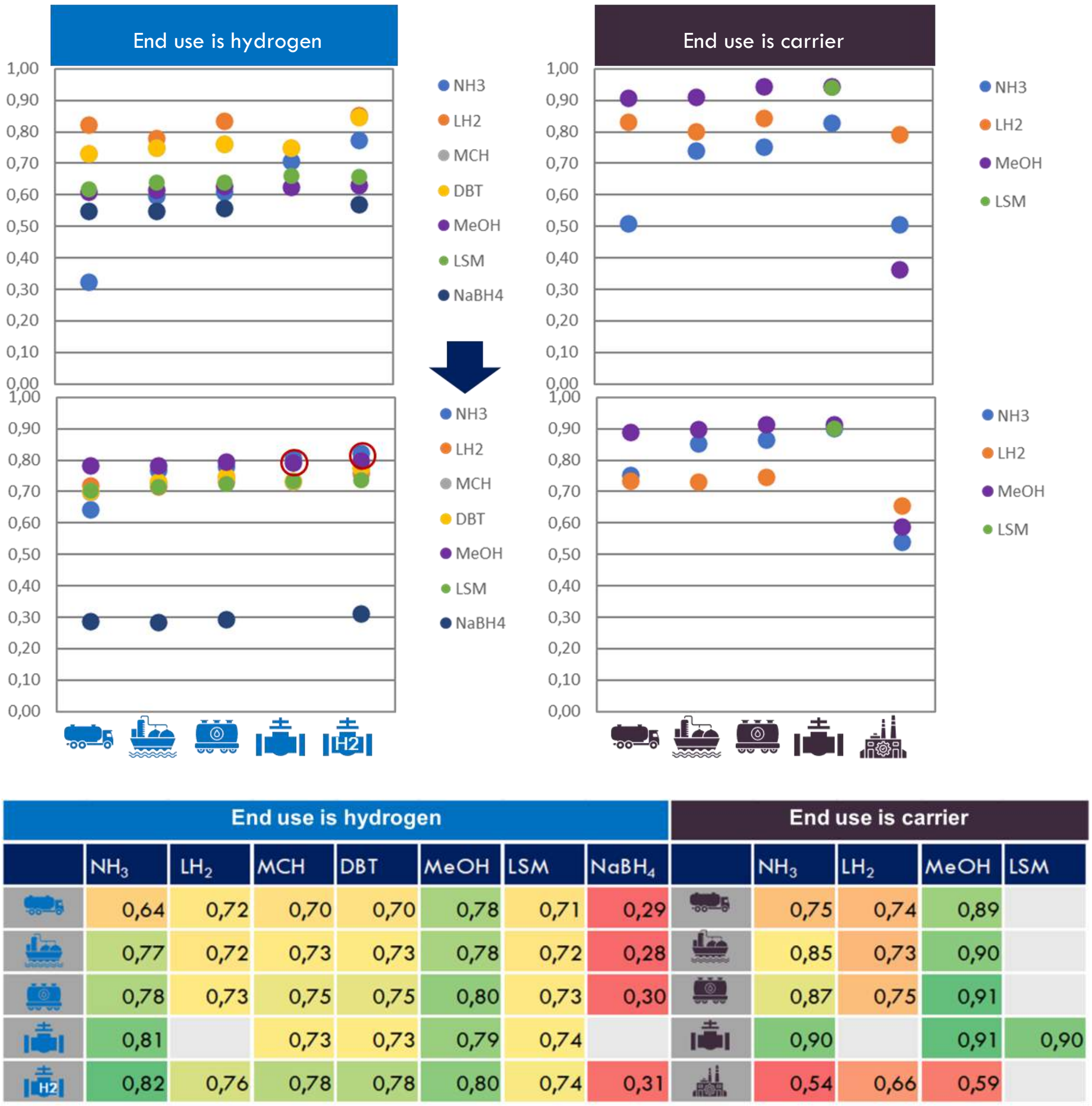
End use is hydrogen

The result is that the scores for most of the carriers converge. With hydrogen end use, ammonia in fact has the highest score if the supply chain includes pipeline transport, or following conversion and transport through the hydrogen network. The higher weighting for Affordable and the lower weighting for Safe & Secure result in a much higher final score for ammonia than in the baseline situation. This is because ammonia has a high score for Affordable, due to the low import costs, and a low score for Safe & Secure due to the risk of the formation of a toxic cloud. The safety and security risk is lowest for pipeline transport or following centralised conversion. In these cases, ammonia scores highest.

Methanol has a slightly better score for other transport modes and direct use. This is due to the larger difference between methanol and ammonia in the score for Safe & Secure for transport by road, water or rail. The estimated safety and security risks of these transport modes for ammonia are much higher than for methanol compared to pipeline transport of the carrier and transport of hydrogen gas through the hydrogen network. This increases the disadvantage of ammonia compared to methanol for the public interest Safe & Secure, while the advantage for the Sustainable (greenhouse gas emissions) public interest remains almost equal.

End use is carrier

For carrier end use, methanol still has the highest score, except in the case of decentralised synthesis: in this case, ammonia synthesis using hydrogen from the hydrogen network scores higher than methanol synthesis. The reason for the high score for methanol is that when used directly, there is no disadvantage for methanol for the public interest Sustainable (greenhouse gas emissions): because no conversion occurs, there are no CO_2 emissions. The rightmost column shows the results for conversion combined with synthesis. In this case, the CO_2 emissions are in fact high, which results in a much lower score for methanol. Liquid hydrogen has the highest score in this column. The slightly higher import costs of liquid hydrogen (Affordable) are compensated here by the higher score than ammonia for Safe & Secure (risk of toxic cloud), Fair (higher import costs and fewer external costs) and Environment (ammonia emissions) and the higher score than methanol for Sustainable (CO_2 emissions) and Fair (far fewer externalities abroad and in the Netherlands, while the costs are not lower).



	End use is hydrogen							End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,64	0,72	0,70	0,70	0,78	0,71	0,29	🚚	0,75	0,74	0,89	
🚢	0,77	0,72	0,73	0,73	0,78	0,72	0,28	🚢	0,85	0,73	0,90	
🚆	0,78	0,73	0,75	0,75	0,80	0,73	0,30	🚆	0,87	0,75	0,91	
	0,81		0,73	0,73	0,79	0,74			0,90		0,91	0,90
H2	0,82	0,76	0,78	0,78	0,80	0,74	0,31	🏭	0,54	0,66	0,59	

Figure 80: Sensitivity analysis of other weighting factors; hydrogen end use and carrier end use (below) compared to the 2030 baseline situation (above)

7.6.3 *Adjusted weighting factors: 100-points assignment*

To examine the effect of weighting on the final score, we also employed a weighting based on the assignment of 100 points. The points were assigned by participants in the Delphi session (see 5.3) to the public interests they considered most important. The differences between this weighting and the results of the Delphi process are that the 100-points assignment gave a slightly higher weighting to Affordable (+3 percentage points), Fair (+5 percentage points) and Accessible (+3 percentage points) and a lower weighting to Environment (-4 percentage points) and Safe & Secure (-9 percentage points). The weighting for Sustainable remains almost equal (<2 percentage points difference).

End use is hydrogen

The adjusted weighting results in higher scores for ammonia and lower scores for sodium borohydride, due to the slightly higher weighting assigned to Affordable and the lower weighting assigned to Safe & Secure and Environment compared to the Delphi weighting factors. Liquid hydrogen, methanol and LSM also have a slightly lower score. The scores for the LOHCs depend on the transport mode.

For hydrogen end use, ammonia and the LOHCs have the highest scores. This is the case for decentralised conversion and transport through the hydrogen network. The shared first place for hydrogen end use is due in part to the slightly higher weighting assigned to Affordable, and to a greater extent to the much lower weighting assigned to Safe & Secure and Environment. Ammonia has the lowest scores for both public interests and consequently, due to the method used, a very low score in the baseline situation. Only the score for ammonia for road transport remains low. The scores for ammonia for water and rail transport are close to those of the supply chains with the highest scores.

For hydrogen end use, the LOHCs have a slightly higher score than liquid hydrogen for water and rail transport and if the hydrogen network is used. This is primarily due to the lower score for liquid hydrogen. This lower score is the result of the higher weighting assigned to Affordable and the higher import costs of liquid hydrogen. The LOHCs have a slightly lower score for road transport due to the higher weighting assigned to the transport safety sub-indicator (Safe & Secure) and the many logistical movements required for the LOHCs due to the lower hydrogen concentration for conversion, and due to the higher weighting assigned to Fair. Pipeline transport of the LOHCs has a lower score because the pipeline network requires a great deal of space, due to the number of pipelines, and because this option has a low score for Accessible.

End use is carrier

LSM has a higher score than methanol for carrier end use for this 100-points assignment because LSM has a higher score than methanol for Accessible in particular. The natural gas network is more accessible than a methanol pipeline and does not significantly increase the inland costs. In addition, due to the lower costs of the natural gas network in the Netherlands, a disadvantage in import costs compared to methanol (Affordable) also disappears. Methanol has a slightly lower score than in the baseline situation due to the lower weighting assigned to Safe & Secure and Environment, combined with its relatively high score for Safe & Secure and Environment, and the higher weighting assigned to Fair and Accessible. Methanol has a low score for Fair due to the high external costs (CO_2 emissions - Sustainable) and the low cost price.

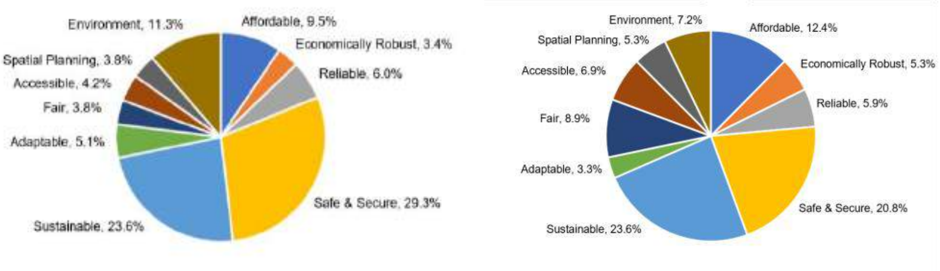
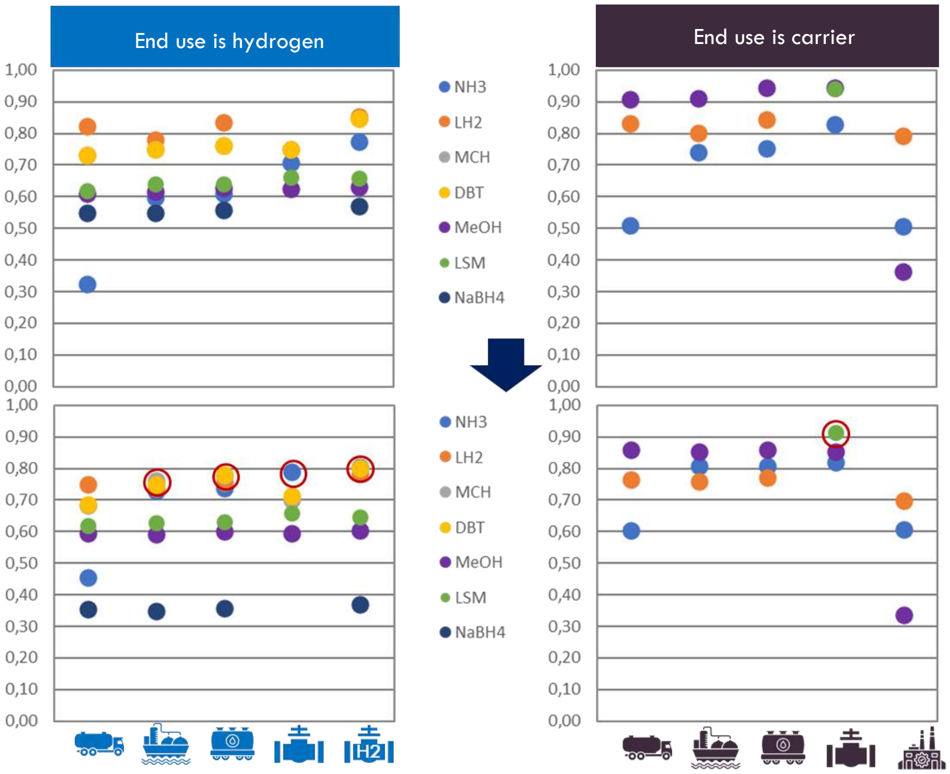


Figure 81: Visual representation of the changed weighting; the Delphi baseline situation weighting is on the left, and the 100-points assignment weighting is on the right



End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚛	0,45	0,75	0,68	0,69	0,59	0,62	0,36	🚛	0,60	0,76	0,86	
🚢	0,73	0,74	0,76	0,75	0,59	0,63	0,35	🚢	0,81	0,76	0,85	
🚆	0,74	0,76	0,78	0,78	0,60	0,63	0,36	🚆	0,81	0,77	0,86	
	0,79		0,70	0,71	0,60	0,66			0,82		0,85	0,91
H2	0,80	0,78	0,80	0,80	0,60	0,65	0,37	🏭	0,61	0,70	0,34	

Figure 82: **Sensitivity analysis of the weighting factors for the 100-points assignment (below) compared to the 2030 baseline situation (above)**

7.7 OTHER SENSITIVITY ANALYSES

7.7.1 *2050 progressive assumptions*

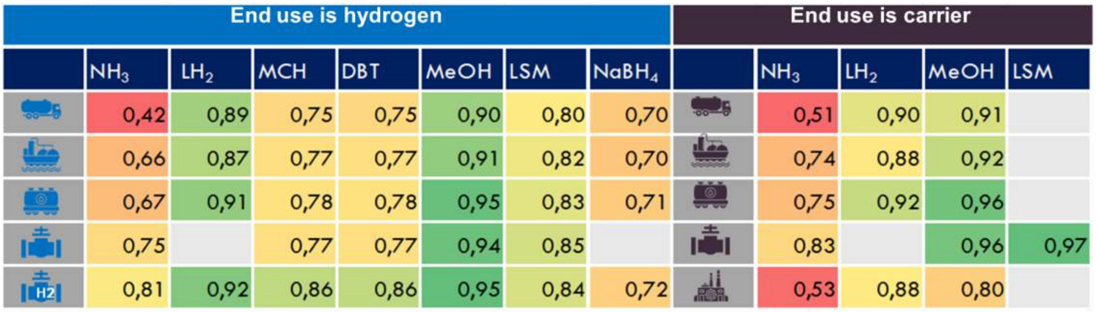
The potential situation in 2050 as calculated with conservative assumptions is presented in chapter 7.5. Several entries in the dataset for 2030 were modified to reflect the expected situation in 2050. Calculations were also carried out for a variant with progressive assumptions for the sensitivity analysis.

Modifications to input for situation in 2050: progressive

- Assumptions for Volume, Affordable, Reliable, Energy Use for Transport, and Emissions are the same as in the conservative calculation, except for a sharper cost reduction in liquid hydrogen tanker vessels.
- Energy loss: for most conversions (see Table 51 in the annex), significantly greater efficiency improvements have been assumed, in the order of tens of percentage points. This is included in the correction of the volume to be imported.

See Annex D for a detailed overview of the revised assumptions, covering both the 2050 variant with conservative assumptions and the sensitivity analysis for 2050 with progressive assumptions.

When these changes are applied, improvements can be seen where the carrier is used as a fuel. This applies to ammonia, methanol and LSM. The imported volumes fall due to the more efficient energy consumption, which results in a slightly higher score for these supply chains for most public interests. Lower volumes lead to lower costs for storage, conversion and transport and fewer externalities. While the energy consumption (electricity) for the other carriers also falls, this does not reduce the volumes that must be transported. Because the energy loss sub-indicator that contributes to the score for Sustainable is not weighted very highly, the effect of lower energy losses in the supply chain is too small to visibly affect the scores (less than 0.01).



End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,42	0,89	0,75	0,75	0,90	0,80	0,70		0,51	0,90	0,91	
	0,66	0,87	0,77	0,77	0,91	0,82	0,70		0,74	0,88	0,92	
	0,67	0,91	0,78	0,78	0,95	0,83	0,71		0,75	0,92	0,96	
	0,75		0,77	0,77	0,94	0,85			0,83		0,96	0,97
H2	0,81	0,92	0,86	0,86	0,95	0,84	0,72		0,53	0,88	0,80	

Figure 83: Sensitivity analysis for progressive assumptions in 2050 (below) vs. conservative assumptions (above); hydrogen end use and carrier end use

7.7.2 Storage and offshore conversion

Offshore storage and conversion reduce the safety and security risks and environmental impacts. We therefore studied the effect of conversion and storage on a decommissioned oil or gas platform, a newly constructed energy island or a floating production, storage and offloading (*FPSO)*[65] facility in the North Sea, rather than in the port of entry.

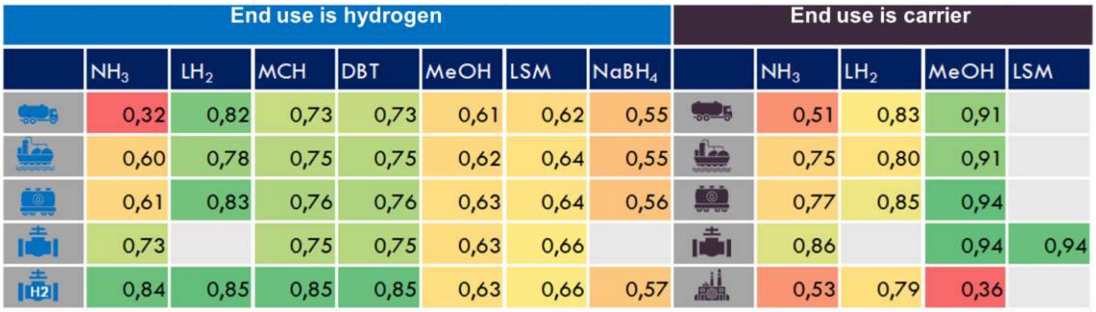
Modifications for the sensitivity analysis of offshore conversion and storage

- Halving the impact of incidents compared to the baseline situation, with the same probability of occurrence.
- Lower environmental impacts: the NO_X shadow price at sea is lower than on land; it is assumed that the NH_3 shadow price and the shadow price of methane's environmental impacts are also lower.
- The carrier (or hydrogen) is transported to land through a pipeline, with no additional route length assumed.
- No changes are made to the cost assumptions within the chain (no costs for the platform, island, or FPSO).
- No adjustments are made for the potential reduction in operational synergy when splitting operations between offshore and onshore sites.

These changes have a limited effect on the results. However, there is a visibly positive effect on the ammonia supply chains that include centralised conversion. The scores for the supply chains in which the risk of centralised storage is significant also improve.

---

[65] In Lublin, Germany, plans are being developed for a hydrogen import terminal, where a floating cracking plant will convert imported ammonia into 30 kilotonne/year of hydrogen. Habibic, Ajsa (2024), Höegh LNG and Deutsche ReGas join forces for world's first floating hydrogen import terminal, *Offshore Energy*, July 1.



	End use is hydrogen							End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
🚚	0,32	0,82	0,73	0,73	0,61	0,62	0,55	🚚	0,51	0,83	0,91	
🚢	0,60	0,78	0,75	0,75	0,62	0,64	0,55	🚢	0,75	0,80	0,91	
🚆	0,61	0,83	0,76	0,76	0,63	0,64	0,56	🚆	0,77	0,85	0,94	
	0,73		0,75	0,75	0,63	0,66			0,86		0,94	0,94
H2	0,84	0,85	0,85	0,85	0,63	0,66	0,57	🏭	0,53	0,79	0,36	

Figure 84: Sensitivity analysis of offshore conversion and storage instead of in the port of entry; hydrogen end use and carrier end use (below) compared to the 2030 baseline situation (above)

7.7.3 *Longer shipping routes*

To study the effect of a longer transport distance from the exporting countries, we assumed that the carrier is produced in Argentina instead of in Morocco.

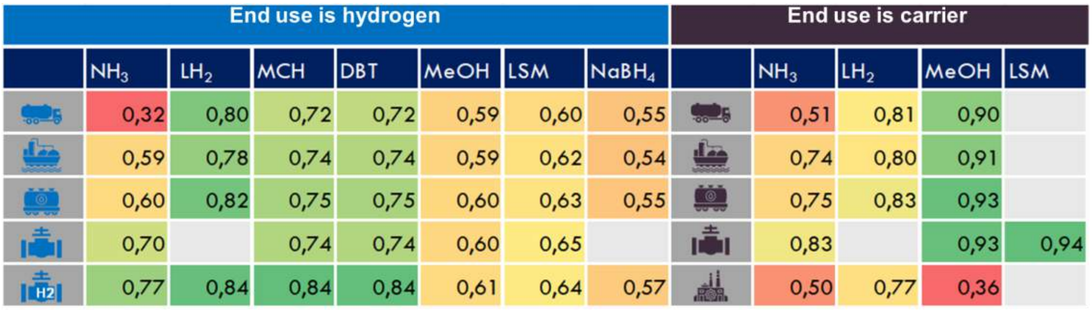
Model adjustments for the sensitivity analysis of shipping routes

- Adjustment of transport distance from 3000 km to 15,000 km.
- Sea transport costs increase; shipping costs based on HyDelta data for the Argentina-Netherlands route rather than the Morocco-Netherlands route.
- The emissions of CO_2, NO_X and particulate matter during maritime transport increase (scaled according to distance).
- Energy losses and boil-off losses during maritime transport increase (scaled according to distance).
- Vessels spend more time at sea, reducing the number of LOHC or sodium borohydride cycles per year; this increases the demand for carrier material, leading to higher material consumption.

The higher costs and emissions associated with longer shipping routes lead to a slight decline in most scores. The scores for Fair are also lower. Liquid hydrogen and the LOHCs are affected most, as a result of the greater increase in the transport costs due to the low energy density (liquid hydrogen) and low hydrogen concentration (hydrogen stored in the LOHCs for conversion) respectively.

The additional CO_2 emissions from seagoing vessels due to the longer transport distances reduce the scores for all carriers, particularly for the methanol and LSM supply chains. This is because these supply chains have the lowest scores for the greenhouse gas emissions indicator and because the weighting method amplifies the effect of this for these supply chains (see Annex G). The scores for the methanol supply chains also fall slightly more, as the score for Fair is already low and all supply chains have a lower score for this public interest. The relative increase in the external costs (due to emissions) is greater than the relative increase in costs. This slightly reduces the score for Fair (costs incurred outside the Netherlands) for the methanol and LSM supply chains.

The adjustments have a minimal impact on the rankings of the various chains. The changes are small.



End use is hydrogen								End use is carrier				
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,32	0,80	0,72	0,72	0,59	0,60	0,55		0,51	0,81	0,90	
	0,59	0,78	0,74	0,74	0,59	0,62	0,54		0,74	0,80	0,91	
	0,60	0,82	0,75	0,75	0,60	0,63	0,55		0,75	0,83	0,93	
	0,70		0,74	0,74	0,60	0,65			0,83		0,93	0,94
H2	0,77	0,84	0,84	0,84	0,61	0,64	0,57		0,50	0,77	0,36	

Figure 85: **Sensitivity analysis for longer transport distance; hydrogen end use and carrier end use (below) compared to the 2030 baseline situation (above)**

7.7.4 CCS

In this sensitivity analysis, we considered the effect of CCS on the supply chains that include conversion of carbon-based hydrogen carriers, i.e., methanol and LSM (methane). In the steam reforming process, the carrier and steam are converted into hydrogen and CO_2. This sensitivity analysis assumes that CO_2 is captured, which is not the case in the baseline situation.

Modifications for the sensitivity analysis of CCS:

- In the Netherlands, we assume CO_2 capture at conversion plants (methanol reforming and LSM).
- Assumed effectiveness of CO_2 capture: 90%.
- Costs for capture facility, transport, and underground storage: 110 euros per tonne of CO_2.
- Energy loss for compression of CO_2 (175 kWh per tonne CO_2) and for heat (300 kWh per tonne CO_2).
- Assumption: CCS plant uses electrical energy for compression and heat.

We assume that the CO_2 used to synthesise methanol and LSM comes from industrial point sources, as is the case in the baseline situation. In the 2050 variant, this CO_2 comes from direct air capture. The effect of CCS combined with CO_2 from an industrial point source is comparable to the effect of using DAC as assumed in the 2050 variant (chapter 7.5). In the latter case, all CO_2 that is lost is climate neutral, while 90% is captured with CCS. We also assume that the synthesis process does not use CCS. The minor CO_2 losses that occur during this process are added to the losses associated with CCS. This means that CCS is not entirely free of CO_2 emissions. If DAC is used, conversion and synthesis will not result in CO_2 emissions.

End use is hydrogen								End use is carrier			
	NH_3	LH_2	MCH	DBT	MeOH	LSM	$NaBH_4$		NH_3	LH_2	MeOH	LSM
	0,32	0,82	0,73	0,73	0,83	0,77	0,55		0,51	0,83	0,90	
	0,60	0,78	0,75	0,75	0,84	0,79	0,55		0,74	0,80	0,91	
	0,61	0,83	0,76	0,76	0,86	0,80	0,56		0,75	0,85	0,94	
	0,71		0,75	0,75	0,86	0,83			0,83		0,94	0,94
	0,77	0,85	0,85	0,85	0,86	0,81	0,57		0,51	0,79	0,69	

Figure 86: Sensitivity analysis for the use of CCS in steam reforming plants; hydrogen end use and carrier end use (below) compared to the 2030 baseline situation (above)

Capture and underground storage of CO_2 greatly improves the scores for methanol and LSM for supply chains that include hydrogen end use. The higher costs and additional energy losses are more than compensated in the scores by the lower CO_2 emissions. The other scores do not change relative to the baseline situation. If CCS is used, methanol obtains first place in the ranking, just ahead of liquid hydrogen. These are followed by LSM, ahead of the LOHCs, except in the case of centralised conversion, where the LOHCs have a higher score. These are followed by ammonia and sodium borohydride.

In the supply chains that include carrier end use, the use of CCS only has an effect for the combination of conversion and decentralised synthesis of methanol. This is the only supply chain that includes steam reforming.

7.7.5 *Alternative cost data (JRC1)*

For the baseline situation, the HyDelta dataset was chosen. This deviates from the cost dataset from JRC1, which consists of high and a low variants. The difference between the JRC variants is due to the energy price used for calculations. The differences between the HyDelta and JRC datasets are discussed in the Affordable section in Annex C. The values from HyDelta and the JRC 'high' variant deviate the most. We therefore carried out a sensitivity analysis using the costs in the JRC1 'high' variant.

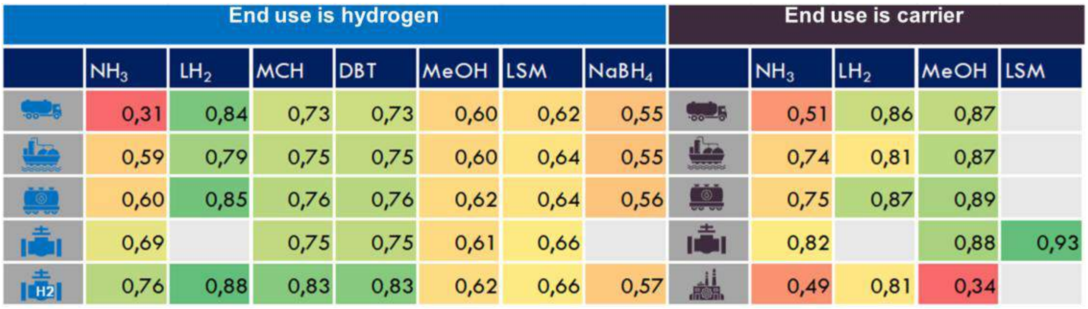
Modifications for the sensitivity analysis of costs

- Rather than relying on HyDelta's cost data for import and conversion, we adopted the high variant figures from JRC1 for liquid hydrogen, ammonia, methanol, and LOHCs.
- We have corrected the methanol data in line with the costs associated with DAC. For the purposes of the 2030 synthesis, the CO_2 is expected to come from an industrial point source.
- We have not adjusted the cost figures for LSM and sodium borohydride.
- JRC's carrier costs are significantly higher for methanol (around 90%) and ammonia (over 60%), slightly higher for LOHC (about 15%), and more than 10% lower for liquid hydrogen.

The effect of the change in costs on the overall score is fairly limited. Liquid hydrogen has a slightly higher score and the LOHCs, methanol and ammonia slightly lower scores, due to the lower and higher cost prices respectively. The scores for LSM and sodium borohydride remain the same.

For hydrogen end use, the scores for the supply chains that include the LOHCs fall due to the higher cost price. This means that they are no longer equal to liquid hydrogen in the case of centralised conversion (column 5 left chart). Liquid hydrogen obtains a higher position in all situations due to the presumed 10% reduction in the cost price.

For carrier end use, LSM obtains the highest score, rather than methanol transported through pipelines, as the cost price of methanol increases, while that of LSM is the same. Liquid hydrogen also rises and methanol falls due to changes in the cost price. With road and rail transport, liquid hydrogen and methanol now have roughly the same score.



End use is hydrogen								End use is carrier				
	NH$_3$	LH$_2$	MCH	DBT	MeOH	LSM	NaBH$_4$		NH$_3$	LH$_2$	MeOH	LSM
🚚	0,31	0,84	0,73	0,73	0,60	0,62	0,55	🚚	0,51	0,86	0,87	
🚢	0,59	0,79	0,75	0,75	0,60	0,64	0,55	🚢	0,74	0,81	0,87	
🚆	0,60	0,85	0,76	0,76	0,62	0,64	0,56	🚆	0,75	0,87	0,89	
	0,69		0,75	0,75	0,61	0,66			0,82		0,88	0,93
H2	0,76	0,88	0,83	0,83	0,62	0,66	0,57	🏭	0,49	0,81	0,34	

Figure 87: **Sensitivity analysis for alternative cost data; hydrogen end use and carrier end use (below) compared to the 2030 baseline situation (above)**

COMPARISON OF HYDROGEN CARRIERS
PART D: CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, we draw conclusions about the results presented in the previous chapter for the baseline situation, the variants – end use in the port of entry, transit and export to neighbouring countries and the 2050 baseline situation – and the sensitivity analyses. We also draw conclusions for the distinct user types and consider potential bottlenecks affecting implementation of the supply chains in the Netherlands. This chapter concludes with recommendations for follow-up studies.

8.1 CONCLUSIONS

The results show that several supply chains have good final scores. The differences are often minimal (hundredths on a scale of 0 to 1) and are shaped by the weighting of public interests, by modelling assumptions, and by uncertainties present in the datasets – despite an extensive analysis of the literature. Over time, the final scores and rankings could change due to innovations and other factors. The highest scoring alternative will also vary, depending on the intended type of end use and on the end user's location. Therefore, if a diverse hydrogen market should develop, it seems likely that opportunities will arise for various hydrogen carriers and diverse supply chains.

8.1.1 *Conclusions concerning the use of hydrogen gas or the direct use of carriers*

The direct end use of hydrogen carriers is typically awarded a higher score than hydrogen use after conversion of the carrier. This applies particularly to methanol and LSM, because when used as a carrier no steam methane reformer is involved and, therefore, no greenhouse gas emissions occur. Note: the out of scope end use may still lead to greenhouse gas emissions.

Direct use of a hydrogen carrier, involving decentralised synthesis at the end user's site using hydrogen from the national hydrogen network, results in a lower score compared to other direct end use supply chains.

8.1.2 *Conclusions regarding the location of conversion*

Centralised conversion at the port of entry offers an advantage over decentralised conversion inland. Centralised conversion avoids costs, energy losses, and transport emissions, as well as the environmental risks that transportation entails. As a result, converting carriers to hydrogen centrally at the port of entry and transporting it through the hydrogen network achieves a higher score than supply chains that involve decentralised conversion inland.

Supply chains relying on decentralised synthesis using hydrogen from the hydrogen network have the lowest final scores, except in the case of liquid hydrogen. The low final score is due to the costs and externalities associated with the extra synthesis step in the supply chain. These costs and externalities are limited in the case of liquid hydrogen.

8.1.3 *Conclusions regarding the location of end use*

Comparison of the baseline situation with the port of entry variant, the transit and export variant and the sensitivity analysis for offshore storage and conversion reveals that the end use location affects the score and ranking. The scores for end use in the port and end use abroad exceed those for use in the Netherlands, 200 km from the port of entry (the baseline situation). This results from partial avoidance of the negative effects associated with the supply chain (transport and decentralised conversion). With offshore storage and conversion, some ammonia chains achieve higher scores than in the baseline situation, due to reduced exposure to safety and security risks.

The ranking of the various carriers remains largely unchanged, whether the end user is situated at the port, 200 km away, or in neighbouring countries. The top-scoring carriers remain liquid hydrogen and the two LOHCs for hydrogen gas end use, along with methanol and LSM for carrier end use.

Port of entry

End use in the port has the highest scores as it (almost) entirely avoids the costs and externalities of inland transport. Distribution to end users in the port involves such short distances that it has a negligible impact (rounded down to zero in the evaluation model) on the scores.

The transport mode used has a limited impact on the scores for the various carriers. Consequently, eliminating the impact of inland transport on end use in the port does not result in a substantial shift. There are two exceptions:

- The Safe & Secure score is heavily influenced by inland transport. Consequently, ammonia supply chains that involve inland transport are assigned a lower score, due to the associated risk of a toxic gas leak. Eliminating this supply chain step improves the score for ammonia more than the scores of other carriers.
- The second exception concerns the two LOHCs. Because of the large number of logistical movements due to the low hydrogen content before conversion, and the need for a double set of pipelines due to the return flow, the impact of domestic transport is bigger. The elimination of this factor leads to a relatively large improvement for transport by pipeline, rail, road, and water.

Transit and export to Germany

Following transit and export, end use in neighbouring countries eliminates the impact of two chain steps – decentralised storage at the end user's site and conversion in the Netherlands (where applicable). As a result, several supply chains achieve a marginally higher score. This mainly affects the ammonia chains and the LOHCs. Ammonia achieves a higher score as the safety and security risks, environmental emissions, and spatial footprint decrease (since decentralised storage and conversion take place abroad).

In addition, fewer high-risk investments (Adaptable) are required in the Netherlands than in the baseline situation and the added value (Economically Robust) for the Netherlands decreases. The lower added value has a negative impact on the score. However, the higher score for the other public interests results in a higher net score than in the baseline situation. For the transit and export variant, the LOHCs also have a higher score than for end use in the Netherlands. This is primarily due to the reduced spatial requirements (Spatial Planning) in the Netherlands and lower high-risk investments (Adaptable).

The scores for supply chains that do not involve decentralised conversion and storage are virtually[66] the same as in the baseline situation. This applies to supply chains with centralised conversion for hydrogen end use, and also to the direct end use of the carrier after pipeline transport.

Storage and offshore conversion

The final score for the ammonia chains improves if storage and conversion take place offshore on an oil or gas platform, energy island, or floating installation in the North Sea. The score for the ammonia chain with offshore conversion is nearly as high as that for liquid hydrogen chains and LOHCs with centralised conversion. This is due to the reduced impact of incidents (external safety, cybersecurity, and terrorism) and environmental emissions. There is no meaningful net effect on the results for the

---

[66] There is still a small visible improvement for ammonia and liquid hydrogen due to the higher score for the proximity indicator (Accessible). Following consultation with the client, it was decided that this indicator is irrelevant for transit and export to Germany. All supply chains were therefore assigned a score of 1 in the model. This resulted in a minimal increase in the final scores.

other carriers, given the minimal impact on their scores. In conclusion, offshore storage and conversion could be advantageous for carriers with high safety and security risks.

8.1.4 *Conclusions regarding the choice of modality*

The results show that supply chains that use the hydrogen network after conversion at the port of entry have an advantage. The ranking of transport modes for each hydrogen carrier typically shows that supply chains that use the hydrogen network achieve the highest scores, followed by those in which the carrier is transported through pipelines. Rail or shipping chains usually come next, followed by road transport.[67] The same ranking holds for chains involving end use of the carrier.

The impact of the chosen modality on the results is minimal, except when it comes to the public interests Safe & Secure, Reliable, and Accessible. As a result, ammonia benefits substantially from pipeline transport (for end use as a carrier) or from the hydrogen network (for end use as hydrogen). In terms of the public interest Reliable, water transport achieves a lower score due to the risk of disruptions caused by high or low water levels. When it comes to the public interest Accessible, the transport of methane gas from LSM through the natural gas network achieves a higher score than the transport of carriers through other pipelines or the hydrogen network, due to the former network's wide coverage and low transport costs.

8.1.5 *Conclusions regarding the various types of end user*

For each type of end user, only the relevant supply chains are compared.

Industrial clusters

Over the next few years, businesses in the ports of entry, inland at Chemelot, and in industrial clusters in Germany will be connected to the hydrogen network. This will ensure that all supply chains relying on the hydrogen network can be used. In terms of the source of the (imported) hydrogen in the hydrogen network, the preferred ranking from the perspective of the weighted public interests is: liquid hydrogen, the LOHCs, ammonia, LSM, methanol, and sodium borohydride.

Decentralised conversion to hydrogen is also a viable option for industrial clusters inland, or in Germany, that are located near a carrier pipeline. This results in a score for imported methanol and LSM that is comparable to conversion in the port of entry followed by transport through the hydrogen network. The scores for LSM and methanol, however, are significantly lower than those for the centralised conversion of liquid hydrogen and the LOHCs, followed by transport through the hydrogen network. The main factors behind this are the greenhouse gas emissions linked to the methanol and LSM chains. Mitigating the CO_2 emissions problem by means of direct air capture (DAC, capturing CO_2 from the atmosphere) or carbon capture and storage (CCS, CO_2 capture and storage) could potentially alter this situation. Decentralised conversion after pipeline transport results in a lower score for ammonia and the LOHCs than for supply chains that use the hydrogen network.

The end user's process specifications may necessitate the direct end use of carriers (e.g. as raw material or to obtain certain flame properties). The degree of flexibility shown when selecting from a range of carriers varies from one end user to another. Users do have a certain level of flexibility in deciding which fuel to use – methane, ammonia, or possibly methanol.

---

[67] For liquid hydrogen, water transport has a lower score than road transport. This is due to the lower score for Reliable as a result of the risk of high and low water levels, the lower score due to the higher investments per inland vessel (Adaptable) and the lower score for Accessible, as road transport is possible for more end users than transport by inland shipping. For other hydrogen carriers, the score for Reliable is generally higher. This reduces the impact of the lower score.

Cluster 6 industry

In general, unlike the industrial clusters, cluster 6 companies are unlikely to connect to the hydrogen network in the near future. These companies will require carriers to be delivered by road, water, rail, or pipeline.

In nearly every case, centralised conversion and transport through the hydrogen network will achieve a higher score, provided that cluster 6 companies have that option. Consequently, having no access to the hydrogen network is a disadvantage from the perspective of the weighted public interests. Liquid hydrogen and both LOHCs are the top choices for cluster 6 companies without access to the hydrogen network, with LSM and methanol, ammonia and sodium borohydride trailing quite some distance behind. After the hydrogen network, the carrier pipeline (which typically has equally limited availability) usually ranks as the second highest scoring mode, followed by rail, water, and road transport.

When it comes to the direct end use of a carrier, comparisons with other carriers are irrelevant in raw material applications, as that choice is dictated by the carrier's role in the production process (see Industrial clusters).

Fertiliser industry

In the ammonia-dependent fertiliser industry, direct use in the port, supplying ammonia by pipeline, and inland waterway transport (without any conversion before the raw material reaches the factory) has a higher score in terms of the weighted public interests than ammonia synthesis sourced from the hydrogen network (with both conversion and decentralised synthesis in the Netherlands). The conversion processes drive up costs, amplify energy losses, increase emissions, require more space and exacerbate environmental risks in the supply chain. The process of synthesising ammonia from hydrogen obtained through the steam reforming of methane gas sourced from LSM is likely to achieve a lower score because it includes several conversion steps (although it has not been specifically studied as a composite chain).

Power stations

With CO_2-free, flexible electricity generation, the highest score for the weighted public interests goes to the direct use of methane from LSM (transported through the natural gas network) in a power station, followed by hydrogen sourced from liquid hydrogen and the two LOHCs through the hydrogen network.

When used in a power station, the direct use of ammonia after pipeline transport has a higher score than the use of hydrogen derived from a centralised ammonia cracking process, although it achieves a lower score than hydrogen sourced from centrally vaporised liquid hydrogen and centrally dehydrogenated LOHCs. Transporting ammonia by inland shipping has a lower score than using hydrogen sourced from ammonia following centralised conversion. Our analysis is based on the premise that hydrogen, methane, and ammonia exhibit similar energy yields during combustion. Following transport by road, water, or rail, the decentralised end use of ammonia achieves notably lower scores than its direct use after pipeline transport, primarily because these modalities are rated lower in terms of the public interest Safe & Secure (due to the risk of toxic gas leaks and traffic accidents).

Roadside fuelling stations

For roadside fuelling stations, liquid hydrogen delivered by tank truck for customers of both liquid and compressed hydrogen typically earns the highest score. When we factor in an additional purification step, the supply of hydrogen to a fuelling station connected to the hydrogen network is only superior to transporting liquid hydrogen by road if the hydrogen in the network is sourced from either liquid hydrogen or the LOHCs. In many parts of the Netherlands, the hydrogen network will be too distant from fuelling stations for connections to be feasible. Even when it is nearby, the connection costs involved will often be prohibitive. Consequently, supplying hydrogen in its liquid state is generally the better option in most situations.

Bunkering stations

In the context of bunkering for the shipping industry, the conclusion is that supplying methanol and liquid hydrogen with tank trucks or bunker vessels (possibly to dedicated bunkering stations) scores higher for the weighted public interests than equivalent deliveries of ammonia.

8.1.6 *Conclusions for various reference years*

In the 2050 variant, LSM and methanol benefit greatly from the reduced CO_2 emissions achieved by sourcing CO_2 from DAC, instead of using an industrial point source for the synthesis process. As a consequence, the 2050 ranking deviates from the 2030 baseline situation. Methanol chains maintain top scores in hydrogen end use situations, while LSM chains now achieve scores similar to those of the LOHCs. The scores are marginally higher across the board (for all hydrogen carriers). This is a result of anticipated process improvements (energy efficiency and cost levels), alongside further advancements in technology readiness levels. The move to net-zero emission maritime transport strengthens the position of all chains. The greatest impact is seen in high transport volume chains, such as those involving the LOHCs. Sodium borohydride supply chains achieve a higher score as a result of reduced energy costs relative to the baseline situation.

While the projected increase in volume (or import volume) does not alter the rankings, it does have implications for the real-world living environment due to capacity constraints on roads, rail, inland waterways, and available space. However, this aspect falls outside the scope of this study.

8.1.7 *Conclusions regarding the dominant factors affecting final scores*

Key factors determining the final scores include material properties, the carrier's import costs, weighting factors, and for LSM and methanol whether to apply CCS or DAC. The selection of transport mode and the costs of the chain steps within the Netherlands have less impact on the overall score, as does sea transport distance and the use of more progressive assumptions regarding energy efficiency improvements in conversion and synthesis processes.

The impact of material properties

The key carrier properties that largely determine the final scores include the level of safety and security risk (public interest Safe & Secure), greenhouse gas (Sustainable) and other emissions (Environment), the energy intensity (Sustainable) of conversion, and how the requisite energy is sourced (electrical, use of the carrier, waste heat). The specific gravity and hydrogen content of the carriers used in conversion contribute to the import volume, a factor which, in turn, impacts all (or almost all) public interests.

- *Safe & Secure and Environment:* Ammonia ranks lower because of its low score for the public interests Safe & Secure and Environment, which the Delphi group weighted heavily, while at the same time its low score for Fair was assigned little weight. The top scores for ammonia chains are achieved in the case of direct end use after transport by pipeline, or when hydrogen gas is used following centralised conversion and transport through the hydrogen network. Experts rank chains involving ammonia transport through pipelines as the safest option. If hydrogen gas is needed, transporting it through the hydrogen network after centralised ammonia conversion is the safer option. On the other hand, transporting ammonia by road has a very low score.
- *Sustainable (greenhouse gases):* The carbon-based hydrogen carriers methanol and LSM achieve lower scores for hydrogen end use, because steam reforming produces CO_2 emissions.[68]

---

[68] If the end use of methanol or methane involves combustion, then CO_2 will still be released into the atmosphere. When methanol and methane are used as raw materials, the carbon remains sequestered for a longer period, depending on the product.

- *Sustainable (energy loss and material consumption):* For the public interest Sustainable, sodium borohydride is heavily impacted by the substantial energy losses incurred during production and recovery of the carrier material (in the exporting country), along with the high value of carrier material required in the supply chain.

See also Chapter 8.1.8 for the individual hydrogen carriers.

The effect of import costs

Import costs are strongly determinant on total expenses and the score for the public interest Affordable. Any chain steps that take place in the Netherlands contribute far less to the costs. Ammonia and methanol benefit from this situation, as the selected source data (from HyDelta) shows they incur the lowest import costs. The benefit of these low import costs outweighs the drawback that some of these carriers are used to generate process heat during the conversion process. Sodium borohydride chains are particularly impacted by the high import costs involved.

The costs cited in the literature show considerable differences. That is why a sensitivity analysis was conducted using an alternative source of cost data. If the JRC cost data (high variant) is used, this leads to minor adjustments in the scores. Chains using ammonia and methanol (both priced higher in JRC than in HyDelta) achieve slightly lower scores, whereas those using liquid hydrogen (which is more expensive in HyDelta than in JRC) achieve slightly higher scores. While the top scoring chains for hydrogen gas and hydrogen carrier end use remain the same, there is a change in their relative rankings. Liquid hydrogen (hydrogen end use) and LSM (carrier end use) chains move up, while the LOHCs (hydrogen end use) and methanol (carrier end use) fall slightly.

Effect of weighting factors

The weighting of the public interests plays a key part in determining the final scores. This weighting effect is highlighted by three sensitivity analyses conducted using variations of the weighting factors derived from the Delphi process. Some of the highlights from the results of this comparison include:

- *Neutral weighting:* When all public interests are assigned the same weighting, methanol transported by road has the highest score for hydrogen end use (instead of liquid hydrogen following centralised conversion). LSM supplied through the natural gas network continues to score highest for carrier end use.

- *Affordable prioritised:* Relative to the weighting factors derived from the Delphi process, weighting of the public interest Affordable was doubled. In the cases of the public interests Safe & Secure and Sustainable it was halved. As a result, ammonia has moved closer to the top-scoring alternatives. Whether cracking is centralised or decentralised after transport by pipeline, ammonia now achieves the top score for hydrogen end use.

- *100-points assignment:* A weighting based on the assignment of 100 points primarily improves the score for ammonia. For hydrogen end use, ammonia achieves one of the highest scores, except for road transport. For carrier end use, methanol and LSM still have the highest scores.

The impact of CO_2 capture and storage (CCS)

The final scores for the carbon-based carriers are especially sensitive to the inclusion or exclusion of CCS. The process of capturing and storing CO_2 during conversion to hydrogen is, overall, very advantageous for methanol and LSM. The score for hydrogen supplied from methanol through the hydrogen network when CCS is applied matches that of hydrogen from liquid hydrogen supplied through that same network. It has a higher score than liquid hydrogen transported by road, rail, or water, following decentralised conversion. LSM also achieves a high score when CCS is used. A similar effect on the scores becomes apparent over time if DAC is involved in the synthesis of these carriers in the exporting country.

In conclusion, importing methanol and LSM for end use as hydrogen will only be relevant from a public interest perspective if CCS is introduced into the chain or if DAC becomes a viable option (by 2050). This probably also applies to the capture of CO_2, for example for use as a chemical feedstock (CCU), but that falls outside the scope of this study.

The effect of transport distance

Importing carriers from further afield (such as Argentina rather than Morocco) has very little impact on the final scores. The higher costs and emissions associated with longer shipping routes lead to a slight decline in most scores. The adjustments have a minimal impact on the rankings of the various chains. In conclusion, extending the transport distance has a negligible effect on the scores and rankings.

Progressive assumptions for 2050

More progressive assumptions about energy loss reductions in conversion processes have a minimal impact on the relative positions of these chains. While using the carrier as fuel in conversion processes (specifically, for ammonia, methanol, and LSM) does result in marginally higher scores, it does not affect the overall ranking. In conclusion, the more progressive assumptions have little impact on the final scores.

8.1.8 *Conclusions for individual carriers*

Building on the previous conclusions, the multi-criteria analysis allows us to reach specific conclusions regarding the various carriers.

Liquid hydrogen

In the various variants, liquid hydrogen consistently achieves the best score (or at least a high score), which means it effectively satisfies the various public interests. However, liquid hydrogen needs to be available in adequate quantities, which is not yet the case. The current technology readiness level of the various chain steps represents an ongoing challenge. Until such time as adequate import and distribution options become available, it will be necessary to seek alternative solutions. There is a risk of hydrogen emissions from the process steps and leakage. If these are much higher in practice than we currently assume, the scores may fall.

LOHCs

Like liquid hydrogen, the LOHCs considered here achieve high scores and fit seamlessly into existing and freed-up infrastructure. Nonetheless, the hydrogen-lean variant involves a return flow, and the hydrogen content per unit of mass in conversion is low. This effectively doubles the storage requirement and makes transportation less efficient. Pipeline transport is particularly affected, as the standard diameter of existing pipelines that may be suitable for LOHCs is smaller than those used for other carriers. There must also be a return pipeline. Consequently, LOHCs achieve a substantially higher score when converted centrally at the port of entry than when transported as carriers.

Methanol

Methanol has an average score for hydrogen conversion in the baseline situation, but it actually achieves the highest score when used directly as a carrier, if CCS is applied, and for the 2050 variant (when DAC is applied). In conclusion, importing methanol for end use as hydrogen will only be relevant from a public interest perspective if CCS is introduced into the chain or if the CO_2 is sourced through DAC. This probably also applies to the capture of CO_2, for example for use as a chemical feedstock (CCU), but that falls outside the scope of this study. A combination of CCS and DAC is also theoretically possible, but has not been studied.

Methanol for direct end use achieves the highest score when transported by either pipeline or rail. This results from marginally reduced transport risks (Safe & Secure) plus slightly lower costs per tonne inland (Affordable and Accessible). The challenges posed by periods of high and low water levels impact transport by inland shipping (Reliable). Methanol can be swiftly integrated into the system as a hydrogen carrier.

LSM

Like methanol, LSM has an average score for conversion to hydrogen in the baseline situation, but it achieves a much higher score when used directly as a carrier, if CCS is applied, and in the 2050 variant. In conclusion, the import of LSM for end use as hydrogen will be worth considering if the CO_2 problem can be resolved. Under these circumstances, LSM would be a viable option for use in the near future (provided that CCS is available) and would achieve high scores for Reliable (minimal risks as there is an established fossil supply chain) and Accessible (limited extra costs inland compared to the port of entry). For the other public interests, LSM has a similar score to the other carriers with a high final score.

Ammonia

Green ammonia is set to become available in the near future. It can be integrated seamlessly into the infrastructure created for grey ammonia. It has a low score for Safe & Secure, a public interest that carries considerable weight in the Delphi weighting process. Consequently, ammonia has a low final score, notwithstanding the high scores it achieves for other public interests. Because of its low score for Safe & Secure, centralised conversion – possibly conducted offshore – and transport through the hydrogen network are strongly favoured for hydrogen end use. When using ammonia directly, the hydrogen network option, combined with decentralised synthesis at the end user's site, is less appealing from the public interest perspective. To mitigate the risks of potential toxic gas leaks as much as possible, the preferred option is to use ammonia at the port of entry followed by transport inland by pipeline. In the absence of an ammonia pipeline (at present), the highest-scoring supply chains for direct end use are those involving transportation by rail or inland shipping.

Sodium borohydride

Sodium borohydride achieves high scores for Environment (negligible emissions to the environment), Safe & Secure (with dry storage there is only a minor explosion hazard), and Fair (since external costs represent only a fraction of the overall cost price). Even so, due to elevated costs, substantial energy loss, and high levels of costly carrier material use, it achieves a low final score. Sodium borohydride's specific properties mean that this carrier is potentially very well suited to niche applications. For instance, it is a solid, which makes it suitable for long-term energy storage. Nonetheless, as long as energy in the exporting country is not free, and boron is deemed to be a critical raw material, sodium borohydride's relatively low score is unlikely to improve. There is also another issue to be addressed: the recycling step has not yet been demonstrated on a large scale. Bulk transportation of sodium borohydride is also prohibited in the EU.

8.1.9 *Conclusions regarding bottlenecks affecting implementation*

These final scores reflect the extent to which the various supply chains align with the ten public interests. This study does not address the issue of whether the requisite volumes and infrastructure can be achieved or permitted within the specified time frame (except for the contribution of technical maturity to the Reliable score). For the supply chains to be successfully integrated, it may be necessary to resolve bottlenecks in areas such as:

- *Network congestion:* Options that require the use of large amounts of (electrical) energy in the Netherlands (principally for conversions) are at a disadvantage, particularly if the electricity is required inland, where the capacity of the electricity grid is often limited. This affects dehydrogenation of the LOHCs, cracking of ammonia, inland synthesis of ammonia and methanol and liquefaction of hydrogen. These processes rely wholly or partly on electricity.
- *Transport capacities of various infrastructure types:* Carriers that must be transported in substantial volumes over roads, railways and waterways with limited capacities are at a disadvantage (physical capacity and capacity of the basic network).

- *Spatial footprint:* Supply chains with major spatial requirements are at a disadvantage. This includes both physical space for pipelines and storage and environmental space (nitrogen deposition) and safety zones (risk contours). This particularly applies to the two LOHCs.
- *Transition path for pipelines:* There is a risk of overcapacity if the predicted volumes fail to materialise; once installed, a pipeline is not scalable in the same way as other transport modes. Supply chains that use the natural gas network or hydrogen network no longer have this disadvantage, as the investments have already been made (for natural gas) and the decision to invest has already been taken (for hydrogen).
- *Synergy with existing assets:* This aspect was not explicitly studied. Possible synergies include the use of waste heat as process heat for conversions, or the use or sale of released heat or the sharing of port facilities for the import of hydrogen carriers.

The interests and preferences of individual companies and sectors were not studied. It appears probable that companies will assign greater importance to commercial interests – cost price, maximum CO_2 reduction per euro, availability (security of supply) – than other public interests (including Safe & Secure, Environment, and Fair). These commercial interests determine the economic viability of supply chains. If these interests are weighted more heavily in the multi-criteria analysis, the final scores will change.

8.2 RECOMMENDATIONS FOR FOLLOW-UP STUDIES

Various questions and knowledge gaps came to light during the study. While some of these have been addressed, there was insufficient time to resolve all these issues. We have therefore included them as recommendations for follow-up studies.

1. *Further research to arrive at a more accurate estimation of the hydrogen emissions from pipelines:* The bandwidth of the estimated hydrogen emissions from pipelines in the literature is considerable. JRC specifies a figure of 0.4%, some NGOs assume even higher percentages, while the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers uses the value of 0.01% from Gasunie. Gasunie's justification for this low value (based on existing leakage of methane from Gasunie pipelines and the ability to use the best available technology) convinced us to use this value. However, we recommend further investigation of these differences.[69]

2. *New carriers and updating data: repeat every three to four years.* Some stakeholders advocate for the use of formic acid ('hydrozine'). This substance could have a high score for various public interests. However, as there are no plans to import it and, as far as we are aware, there are no hydrogen-producing countries with the ambition to export it, we did not study this carrier. If this situation changes, then this carrier could be added to the set of carriers to be studied. The same applies to new LOHCs, provided that sufficient information is available to assess them.

3. *Assessing/verifying external safety:* The regional risk profile method and the country-wide national security risk analysis can be used to assess the risk of incidents. As this method is very extensive, it was employed in a simplified form in this MCA study, for a limited number of potential incident scenarios in the Dutch supply chain steps except for end use, and for abstract rather than specific geographical locations. We recommend carrying out a more detailed study of the potential safety and security risks without this simplification and for specific geographical locations in partnership with the regional security services and industrial clusters.

4. *Studying differences between the LOHCs:* There are many different LOHCs. We selected DBT and MCH, as these were the types with the most available data, although this information was spread across multiple datasets. HyDelta (costs) carried out calculations for MCH, while JRC

---

[69] This is recommended by the Environmental Defense Fund: "Current hydrogen leak estimates vary by up to 100-fold. We need to know more before betting the farm." (EDF Blogs, 16 August).

assumed the use of DBT (costs, energy losses, lifecycle analysis). In the absence of data for one LOHC, we sometimes used data for the other LOHC due to the lack of a better alternative. Annex H contains a comparison of the data for DBT and MCH. In a future study, it would be desirable to improve the datasets for both selected LOHCs (with the potential addition of new and promising LOHCs) to make it clearer how and to which extent they differ.

BIBLIOGRAPHY

Abdin, Zainul, Chunguang Tang, Yun Liu and Kylie Catchpole (2021), Large-scale stationary hydrogen storage via liquid organic hydrogen carriers, *iScience* 24, 102966, September 24.

Agora Industrie, Technische Universität Hamburg (2023), Wasserstoff-Importoptionen für Deutschland. Analyse mit einer Vertiefung zu Synthetischem Erdgas (SNG) bei nahezu geschlossenem Kohlenkreislauf, September.

Ainee, Ibrahim, Mark Pakevicius and Craig E. Buckley (2023), Chemical compression and transport of hydrogen using sodium borohydride, *Sustainable Energy & Fuels*, 2023, 7, 1196-1203.

Analistennetwerk Nationale Veiligheid (2022), Rijksbrede Risicoanalyse Nationale Veiligheid.

Arcadis, Gemini Consultants, Houdijk Advies, Stichting Werkgemeenschap tussen Techniek en zorg (2009), Handreiking regionaal risicoprofiel.

Arcadis, Berenschot, *Ketenstudie omgevingsveiligheid van duurzame waterstofrijke energiedragers* (Chain study on the external safety of sustainable hydrogen-rich carriers), 65256 October 2021.

Aziz, Muhammad, Takuya Oda, Takao Kashiwagi (2019), Comparison of liquid hydrogen, methylcyclohexane and ammonia on energy efficiency and economy, 10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China, *Energy Procedia* 158 (2019), 4086-4091.

Balcombe, Paul, Dalia A. Heggo and Matthew Harrison (2022), Total Methane and CO_2 Emissions from Liquefied Natural Gas Carrier Ships: The First Primary Measurements, *Environ. Sci. Technol.* 2022 Jul 5; 56(13): 9632–9640, https://doi.org/10.1021/acs.est.2c01383

Bargiacchi, Eleonora, Nils Thonemann, Jutta Geldermann, Marco Antonelli and Umberto Desideri (2020), Life Cycle Assessment of Synthetic Natural Gas Production from Different CO_2 Sources: A Cradle-to-Gate Study, *Energies*, September 2020, 13, 4579.

Basu, Shankar and Schroeder, Roger G. (1977), "Incorporating Judgments in Sales Forecasts: Application of the Delphi Method at American Hoist & Derrick", *Interfaces*, INFORMS, vol. 7(3), pp. 18-27, May.

Berenschot, Arcadis (2024), Social Cost-Benefit Comparison of Hydrogen Carriers *(Maatschappelijke Kosten en Baten Vergelijking (MKBV) Waterstofdragers)*, 23 February.

Besier, Jorick, Marc Marsidi (2020), Decarbonisation options for the Dutch ceramic industry, PBL Netherlands Environmental Assessment Agency and TNO, 21 December.

Busch T. et al. (2023), The role of liquid hydrogen in integrated energy systems. A case study for Germany, *International Journal of Hydrogen Energy*, Vol. 48, Issue 99, 25 December, Pages 39408-39424, https://doi.org/10.1016/j.ijhydene.2023.05.308

CE Delft (2019), Handbook on the external costs of transport.

CE Delft (2021), STREAM Goederenvervoer 2020. Emissies van modaliteiten in het goederenvervoer – Version 2, February

CE Delft (2022), Toekomstverkenning, De prijs van een reis, Verkennende analyse richting 2050, May.

CE Delft (2023), Handboek Milieuprijzen 2023 (Environmental Prices Handbook 2023), Methodische onderbouwing van kengetallen gebruikt voor waardering van emissies en milieu-impacts (Methodological substantiation of benchmark figures used for valuation of emissions and environmental impacts), February.

Clean Hydrogen Partnership (2023a), Study on hydrogen in ports and industrial coastal areas – Report 1, March.

Clean Hydrogen Partnership (2023b), Study on hydrogen in ports and industrial coastal areas – Report 2, September.

Clingendael International Energy Programme (2023), Relaunching Ammonia. From Fertilizer to Energy Carrier in Northwest Europe, December.

Clematis, D., Bellotti, D., Rivarolo, M., Magistri, L., Barbucci, A. (2023), Hydrogen Carriers: Scientific Limits and Challenges for the Supply Chain, and Key Factors for Techno-Economic Analysis, *Energies* 2023, 16, 6035, https://doi.org/10.3390/en16166035

Dalkey. N. and Helmer, O. (1963). An experimental application of the DELPHI Method to the use of experts. *Management Science*, 9, 3: 458-467, https://doi.org/10.1287/mnsc.9.3.458

Decisio (2023), MKBA Delta Rhine Corridor Phase 2, for Ministry of Economic Affairs and Climate Policy, 22 December.

DIW Econ, Wuppertal Institut (2020), Bewertung der Vor- und Nachteile von Wasserstoffimporten im Vergleich zur heimischen Erzeugung, Studie für den Landesverband Erneuerbare Energien NRW e. V. (LEE-NRW), 3. November.

DNV (2020), Study on the Import of Liquid Renewable Energy: Technology Cost Assessment, October.

DNV (2021), Study of external safety of bunkering alternative fuels for sea shipping, Report No: 10246009-1, 19 April.

E4Tech (2021), Decarbonisation potential of synthetic kerosene, Final report, for Ministry of Infrastructure and Water Management, May.

E4Tech (2022), Expansion of hydrogen production pathways analysis – import chains, Report for the UK's Department for Business, Energy & Industrial Strategy (BEIS), July.

ENTEC (2022), The role of renewable H_2 import & storage to scale up the EU deployment of renewable H_2, Fraunhofer Institut, Guidehouse, McKinsey & Company, TNO, Trinomics, Utrecht University, February.

Environmental Defense Fund (2023): 'Known Unknown: Current hydrogen leak estimates vary by up to 100-fold', EDF Blogs, 16 August.

Erasmus Commodity & Trade Centre, TU Delft (2023), CommodipHy. The commodification of ammonia and the role of Rotterdam as a global pricing centre. Research Report, March.

European Commission (2023), COM/2023/160 final, Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020

Fluor (2023), Executive summary pre-feasibility study large-scale industrial ammonia cracking plant.

Fraunhofer ISI (2022), Conversion of LNG Terminals for Liquid Hydrogen or Ammonia. Analysis of Technical Feasibility under Economic Considerations, 3 November.

Fraunhofer ISE (2023), Site-specific, comparative analysis for suitable Power-to-X pathways and products in developing and emerging countries. A cost analysis study on behalf of H2Global, May.

Gas for Climate, Guidehouse (2022), Facilitating hydrogen imports from non-EU countries, October.

Gasunie (2021), HyWay27: Waterstoftransport via het bestaande gasnetwerk? Final report for the Ministry of Economic Affairs and Climate Policy, June.

Genge Lucien, Fabian Scheller, Felix Müsgens (2023), Supply costs of green chemical energy carriers at the European border: A meta-analysis, *International Journal of Hydrogen Energy*, 19 December 2023, Pages 38766-38781, https://doi.org/10.1016/j.ijhydene.2023.06.180

Godinho, João (2021), Maritime transportation of LOHCs. A greenhouse gas footprint and economic assessment of importing renewable H_2 from Portugal to the Netherlands, using liquid organic hydrogen carriers, Master thesis Utrecht University, November.

Habibic, Ajsa (2024), Höegh LNG and Deutsche ReGas join forces for world's first floating hydrogen import terminal, *Offshore Energy*, July 1.

Hampp J., Düren M., Brown T. (2023), Import options for chemical energy carriers from renewable sources to Germany. *PLoS ONE* 18(2): e0262340, https://doi.org/10.1371/journal.pone.0281380

HyDelta (2022), WP7B Technical analysis, D7B.3 – Cost analysis and comparison of different hydrogen carrier import chains and expected cost development, 31 March. With Factsheets D7B.1 and D7B.2 and dashboard in Excel.

Hydrogen Europe (2023), Clean ammonia in the future energy system, March.

IEA (2019), The Future of Hydrogen. Seizing today's opportunities. Report prepared by the IEA for the G20, Japan, June 2019. With separate Assumptions annex, December 2020.

IEA (2021), Is carbon capture too expensive?, 21 July.

IEA (2023), The Role of e-Fuels in Decarbonizing Transport, 23 December.

Incer-Valverde, Jimena Ying Lyu, George Tsatsaronis, Tatiana Morosuk (2023), Economic evaluation of a large-scale liquid hydrogen regasification system, *Gas Science and Engineering* 119 (2023), 205150.

Instituut Fysieke Veiligheid (Event Safety Institute) (2022). Kennisbundel transport van waterstof(dragers). Arnhem: IFV.

IPCC (2021), AR6 Climate Change 2021: The Physical Science Basis.

IPCC (2023), AR6 Synthesis Report Climate Change 2023 for the Sixth Assessment Report during the Panel's 58th Session held in Interlaken, Switzerland from 13-19 March 2023.

IRENA (2022), Global hydrogen trade to meet the 1.5°C climate goal: Part II – Technology review of hydrogen carriers, International Renewable Energy Agency, Abu Dhabi.

Jonkeren, O. and Francke, J. (2023), Netherlands Institute for Transport Policy Analysis | KiM, Kennisbasis Goederenvervoer (Freight transport knowledge base), Memorandum, February.

JRC (2016): Techno-economic and environmental evaluation of CO_2 utilisation for fuel production. Synthesis of methanol and formic acid. JRC Science for Policy Report.

JRC1: Joint Research Centre (2022), Assessment of Hydrogen Delivery Options Feasibility of Transport of Green Hydrogen within Europe. JRC Technical Report.

JRC2: European Commission, Joint Research Centre, Arrigoni, A. et al (2024)*, Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe*, Publications Office of the European Union, Luxembourg, https://data.europa.eu/doi/10.2760/5459, JRC137953.

Letter to Parliament on 'External safety of future flows of hydrogen-rich energy carriers' study, 17 March 2023.

Letter to Parliament on energy diplomacy and hydrogen imports, 2 June 2023.

KiM (2023), Kennisbasis goederenvervoer 2023.

LNG Industry (2016), VTG loads LNG tank car for first time in German port, www.lngindustry.com, 24 January.

Serpell, Oscar, Zakaria Hsain, Amy Chu, and Walter Johnsen (2023), Ammonia's role in a net-zero hydrogen economy, Kleinman Center for Energy Policy, March.

Kroon, Pieter (2023), Waterstofverbranding en stikstofemissies, TNO report R10343 14 April.

MENA Hydrogen Alliance (2024), Bulk Transport options for Green Molecules. Focus Area: Europe and MENA Region. White Paper.

Methanol Institute (2023), Marine Methanol: Future-Proof Shipping Fuel.

Ministry of Economic Affairs and Climate Policy and Ministry of the Interior and Kingdom Relations (2023), Ontwerp-Programma Energiehoofdstructuur, Ruimte voor een klimaatneutraal energiesysteem van nationaal belang, July.

Ministry of Economic Affairs and Climate Policy (2023), National Energy System Plan, December.

Ministry of Infrastructure and Water Management and Witteveen+Bos (2022), Factsheet Veiligheid van waterstof(dragers). Waterstof in de energietransitie en omgevingsveiligheid.

Moritz M. et al., Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities, *International Journal of Hydrogen Energy*, https://doi.org/10.1016/j.ijhydene.2022.12.046.

Nayak-Luke, R.M., C. Forbes, Z. Cesaro, R. Bañares-Alcántara, K.H.R. Rouwenhorst (2021), Techno-Economic Aspects of Production, Storage and Distribution of Ammonia, in: Techno-Economic Challenges of Green Ammonia as an Energy Vector, https://doi.org/10.1016/B978-0-12-820560-0.00008-4

NTA 8036 (2021), Eisen voor de gezamenlijke ligging van buisleidingsystemen in een leidingenstrook, November.

Ocko, Ilissa B. and Steven P. Hamburg (2022), Climate consequences of hydrogen emissions, *Atmos. Chem. Phys.*, 22, 9349–9368, 2022, https://doi.org/10.5194/acp-22-9349-2022

Öko-Institut, ICCT (2020), Decarbonization of on-road freight transport and the role of LNG from a German perspective, Berlin, May.

Öko-Institut (2021): Ammonia as a marine fuel. Risks and perspectives, Berlin.

Oner, Oytun, Kaveh Khalilpour (2022), Evaluation of green hydrogen carriers: A multi-criteria decision analysis tool, *Renewable and Sustainable Energy Reviews* 168 (2022), 112764, https://doi.org/10.1016/j.rser.2022.112764.

Panteia (2023), Cost Figures for Freight Transport – final report, commissioned by the Netherlands Institute for Transport Policy Analysis (KiM), January.

Rijksinstituut voor Volksgezondheid en Milieu (National Institute for Public Health and the Environment) (2022), Verkenning vloeibare organische waterstofdragers (LOHC's) in termen van ZZS-eigenschappen, commissioned by the province of Zuid-Holland, December.

Rizi, Hossein Ali Yousefi, and Donghoon Shin (2022), Green Hydrogen Production Technologies from Ammonia Cracking, *Energies* 2022, 15, 8246. https://doi.org/10.3390/en15218246

Roland Berger (2021), Hydrogen transportation | The key to unlocking the clean hydrogen economy.

Saaty, R.W. (1987), The analytic hierarchy process-what it is and how it is used, *Mat/d Modelling*, Vol. 9, No. 3-5, pp. 161-176.

Saaty, R.W. (2008), Relative Measurement and Its Generalization in Decision Making. Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors, The Analytic Hierarchy/Network Process, vol. 102 (2), 2008, pp. 251–318.

Sand, M., R.B. Skeie, M. Sandstad, S. Krishnan, G. Myhre, H. Bryant, R. Derwent, et al. (2023), 'A Multi-Model Assessment of the Global Warming Potential of Hydrogen', *Communications Earth and Environment*, Vol. 4, No. 1, 2023..

Sharma, Gagan Deep, Mahesh Verma, Babak Taheri, Ritika Chopra, Jaya Singh Parihar (2023), Socio-economic aspects of hydrogen energy: An integrative review, *Technological Forecasting & Social Change* 192 (20230, 122574, https://doi.org/10.1016/j.techfore.2023.122574

Siemens, Engie, Science & Technology Facilities Council, Ecuity (2020), Ammonia to Green Hydrogen Project. Feasibility Study, for UK's Department for Business, Energy and Industrial Strategy (BEIS).

SoeHtet Wai, Yasuyuki Ota, Masakazu Sugiyama, and Kensuke Nishiok (2020), Evaluation of a Sabatier Reaction Utilizing Hydrogen Produced by Concentrator Photovoltaic Modules under Outdoor Conditions, *Appl. Sci.* 2020, 10, 3144; doi:10.3390/app10093144

Spatolisano, Elvira, Laura A. Pellegrini, Alberto R. de Angelis Simone Cattaneo Ernesto Roccaro (2023), Ammonia as a Carbon-Free Energy Carrier: NH_3 Cracking to H_2, *Ind. Eng. Chem. Res.* 2023, 62, 28, 10813–10827.

Straatsma, Renze (2021), Hydrogen import terminals in the Port of Rotterdam: An assessment of uncertainty, Master thesis Delft University of Technology.

Sweco, Ecorys (2022), MKBA Delta Corridor. Summary of the draft report on the Delta Corridor Social Cost-Benefit Comparison (MKBV) given the status of the project on 28 September 2022, Rotterdam.

Tijdgat, J. (2020), Shipping renewable hydrogen carriers. A study on the impact of shipping renewable hydrogen carriers and using those as a fuel on, the ship design, the different powertrain configurations, and the cost of transported hydrogen, Master thesis Delft University of Technology.

TNO, Arcadis and Berenschot (2023), Omgevingskwaliteit van toekomstige stromen waterstofrijke energiedragers, 68008, 26 January.

P. Wammes and M. Weeda (2024) Eigenschappen van waterstofdragers. Een overzicht voor visievorming over import van waterstof, TNO 2024 M10863.

Wai, SoeHtet, Yasuyuki Ota, Masakazu Sugiyama, and Kensuke Nishioka (2020), Evaluation of a Sabatier Reaction Utilizing Hydrogen Produced by Concentrator Photovoltaic Modules under Outdoor Conditions, *Applied Sciences* 10(9):3144, April.

Walison, Patrick, Tom Busking, Nikki Blankerts (2023), De rol van waterstof in havens van nationaal belang, RoyalHaskoningDHV for the Ministry of Infrastructure and Water Management, 24 November.

Wärtsilä (n.d.), Encyclopedia of Marine and Energy Technology, Boil Off Rate, https://www.wartsila.com/encyclopedia

WaterstofNet (2021), Waterstof in de Deltaregio. Troeven, knelpunten, uitdagingen en faciliterende rol van de Vlaams-Nederlandse Delta, 29 October.

Weltenergierat (2023), Ammoniak als Energieträger für die Energiewende, December 2023.

Market information: various companies supplied information during this study. This information was treated and processed confidentially.

ANNEX A: SOURCES AND ASSUMPTIONS USED IN THE MODELLING

This multi-criteria analysis hinges on substantial amounts of baseline data and numerous assumptions. This annex gives a breakdown of the sources and key assumptions underpinning the modelling.

SOURCES

We were tasked with basing the study on the existing body of literature. The topic of hydrogen carrier imports has already been explored in dozens of published studies. Some of these reports and articles were provided by the ministry, while the remainder were sourced by the study team. No individual study covers the full set of hydrogen carriers selected for this particular study for every specified aspect (the public interests set out in the National Energy System Plan). Many studies lack transparency regarding the data selected or how it was processed. The scope is generally limited to imports to the Netherlands or Europe, and occasionally to conversion to hydrogen, but without addressing inland transport, and/or decentralised storage, or decentralised synthesis. Besides differing in focus and scope, the studies also display material inconsistencies, for instance because different studies made different assumptions.

This made it necessary to integrate datasets from a range of different studies. As a result, it became essential to develop a way of managing inconsistencies between the various studies. Examples can be found in:

- import costs (differences between HyDelta and JRC1),
- selected fuel for shipping: HyDelta operates on the assumption that vessels use their cargo (the hydrogen carrier) as fuel, while JRC1 assumes that biodiesel is used for all vessels. For 2030, we adopted the values quoted in the STREAM emissions handbook, determined for a gas oil mix and anticipated the use of climate-neutral fuels in 2050 (in line with IMO targets).
- electricity completely generated from renewable sources or generated with a mix including fossil sources.
- the option of using a hydrogen carrier for process heat or using external heat sources for synthesis and conversion.

After reviewing the available literature, we selected – together with the client – the most complete and transparent studies, as a basis for the following public interests. We resolved any data gaps in these studies by drawing on data from other research or market information sources. If the assumptions were inconsistent, we made corrections to the data wherever feasible.

Affordable, Economically Robust

- We derived the import costs for liquid hydrogen, ammonia, MCH, and methanol from the Dutch HyDelta study (2022). This study examined the costs of importing these carriers from eight different countries, closely analysing the costs of the hydrogen production chain in the exporting country through to centralised conversion in the Netherlands.

- We determined the costs of inland chain steps using data from JRC1 (2022). This study explored the costs and energy losses involved in the import chains for liquid hydrogen, ammonia, DBT, and methanol. This includes the costs from the hydrogen carrier's production chain in the exporting country right through to centralised or decentralised conversion in the importing country.
- Neither study includes liquid synthetic methane. Additionally, we drew on a study by Agora and TU Hamburg (2023) that modelled the LSM import chain to Germany, in relation to other hydrogen carriers.
- No full supply chain studies are available on the use of sodium borohydride. We therefore drew on scientific articles covering parts of the chain, together with market information sources.
- We were unable to locate individual comprehensive datasets for the LOHCs DBT and MCH. HyDelta and JRC opted to use different LOHCs in their modelling but, in some cases, they adopted values from other LOHCs due to a lack of data. We have made every effort to distinguish between the data for DBT and MCH.
- the costs incurred by maritime transport are part of HyDelta. We relied on data from Panteia, CE Delft, the Netherlands Institute for Transport Policy Analysis (KiM), and various market information sources for details of the costs associated with inland transport. We derived the costs of pipelines from JRC1 and verified them against market information sources.
- The figures for electricity costs in the Netherlands and CO_2 prices were sourced from the Climate and Energy Outlook (KEV; 2030 and 2050).
- With regard to the public interest Economically Robust, we used KiM benchmark figures to determine the costs associated with congestion and infrastructure usage.

Sustainable, Environment:

- Most of the data on energy loss, emissions, and material usage was sourced from a lifecycle analysis by JRC, which builds on the cost analysis mentioned above. This LCA study assessed the same energy carriers and supply chains as JRC1, but also included liquid synthetic methane.
- Data on the energy and material usage of sodium borohydride, and the associated emissions, was obtained from the scientific literature and market information sources.
- For 2030, we adopted the KEV emissions factor for electricity production in the Netherlands (0.07 g/kWh). PBL's projections show that, by 2030, the emissions factors for NO_X and particulate matter will be 0.09 g/kWh and almost 0 g/kWh respectively. Looking ahead to 2050, our assumption is that production will be fully renewable, with zero emissions.
- Benchmark figures on transport-related energy losses and emissions, as well as environmental cost factors for monetising emissions, were sourced from studies by CE Delft and KiM.

Safe & Secure, Reliable, Adaptable, Spatial Planning:

- For some public interests, little or no published information was available. For this reason, we sought the insights of experts. As part of this study, five expert sessions were conducted to address the public interests Safe & Secure (covering external safety, cybersecurity, and terrorism, using risk matrices to illustrate the likelihood and impact of various incidents), Reliable (relative security of supply), and Adaptable (additionality and reusability of investments in the supply chains). The sessions drew on expertise from government agencies, public sector organisations, and the market. The resulting assessments were totalled for each step within the individual chains. All chain assessments (both qualitative and quantitative) were then normalised (see Annex D).

- Literature-based assessments of Technology Readiness Levels for various steps in the chain – including production, maritime transport, storage, conversion, and modes of transport – were reviewed during the Reliable expert session (sources included Agora and TU Hamburg). The study looked into the availability of suitable transport options and evaluated modes of transport in terms of their robustness.
- Investment figures from JRC1, plus additional market information, were used in the detailed analysis of the Adaptable expert session.
- Indicators for external safety and vulnerability to cyber attacks and terrorism were determined by multiplying the qualitative scores for probability and impact, as estimated by experts, to produce a risk level for each step of the chain.
- Benchmark figures from KiM and CE Delft were used to derive the transport safety indicator (traffic accidents).
- In addressing the public interest Spatial Planning, we used spatial footprint estimates for each chain step (provided by companies), wherever such data was available. In cases where information was neither found nor supplied, estimates for steps were made by scaling existing data on chain steps, based on the specific gravity differences between hydrogen carriers.

Fair, Accessible

- Scores for the public interest Fair were based on the results in other public interests, specifically Affordable, Safe & Secure, Sustainable (greenhouse gas emissions indicator), and Environment. There was no need for separate data in this instance.
- The indicator for the Accessible public interest cost level inland and in the port of entry was derived from the information required for the Affordable public interest. There was no need for separate data in this instance.
- The Proximity indicator for the public interest Accessible was determined by using the IBIS database to discover how many industrial estates are connected to rail or waterways. Planned routes for the national hydrogen network and Delta Rhine Corridor pipelines were also reviewed to determine how many industrial estates lie in municipalities along these routes.

ASSUMPTIONS USED IN THE MODELLING

Scope

- For the public interests Affordable and Sustainable, the costs, greenhouse gas emissions, and energy losses in the import chain and in the Netherlands are factored in up to the point of delivery to the end user or to a fuelling station. When it comes to other public interests (e.g. Safe & Secure, Spatial Planning, Environment), only the impact within the Netherlands is taken into account (also up to and including the point of delivery). The public interest Fair does take account of the environmental impact in the exporting country.
- The results are expressed per kilogramme of hydrogen equivalent supplied to the end user, wherever feasible. Allowances are made here for conversion and other supply chain losses, which may cause the import volume to exceed the volume that the end user ultimately receives.
- We base our approach on the 2030 mid-range variant from the volume study by Arcadis/Berenschot/TNO, using it as the only situation for 2030. We adopted the high variant from this study for 2050 (although it actually pertains to 2030). This results in a volume that is four times higher.
- Direct end use only involves gaseous and liquid hydrogen, ammonia, and methanol, not LOHCs or sodium borohydride. The direct use of liquid synthetic methane was

also deemed to be out of scope. However, the use of gaseous methane delivered through the natural gas network was factored in. Gaseous hydrogen (and methane) is transported exclusively through the hydrogen network (and natural gas network), not by road, water, or rail.

- Only research into potential hydrogen carrier synthesis to ammonia, methanol, and liquid hydrogen in the Netherlands was assessed, not including methane. The modelling for this synthesis is based on the premise that it uses hydrogen derived from a prior conversion of the same substance. The possible benefits of synthesising an alternative imported carrier were considered, if this approach was deemed to be potentially more beneficial to society.
- With regard to ammonia, the current government position was adopted as the guiding principle for planned safety measures in the chains. As no further measures were assumed to be put in place to enhance safety standards, no additional costs were assumed. The scope of this study does not permit a comprehensive exploration of all possible options in this area.

Geography

- In the baseline situation and other variants, the country of origin of the imported hydrogen is Morocco (a distance of 3000 km). In a sensitivity analysis, we opted for delivery from Argentina (a distance of 15,000 km). The figures for these routes were supplied by HyDelta.
- Allowance was made for a typical 200 km transport route within the Netherlands, based on the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers conducted by Berenschot and Arcadis. The use of typical routes eliminates any discrepancies between the ports of entry and between the distances to various end user sites.
- We did, however, identify six separate types of end users. Large transport flows of hydrogen (or hydrogen carriers) pass from the ports of entry to industrial clusters for fertiliser production (using ammonia and hydrogen as raw materials), power stations (using hydrogen, methane, and ammonia as fuels), or other industries (refineries, steel industry, and chemical industry, using hydrogen as a fuel/raw material). Smaller volumes pass from the ports of entry to sectors outside the clusters (cluster 6: ceramics, metal industry, waste/recycling) and to roadside fuelling stations and riverside bunkering stations. The option of using certain transport modes, combined with the type of end use, dictates which supply chains end users can select. By 2030, many major industrial users will be located close to the national hydrogen network, unlike many fuelling stations. What sets the large and smaller flows apart is less the type of industry involved and more whether or not they are able to access the national hydrogen transport network.
- End use could also occur outside the country. In this case, the chain steps of decentralised storage and conversion will no longer apply.
- End use could also occur in the port of entry. In this case, inland transport and decentralised storage do not apply. Decentralised conversion will then coincide with centralised conversion.

Emissions and energy loss

- Various steps in the chain may be associated with emissions of greenhouse gases and other substances. These are then monetised using environmental cost factors, and totalled for each chain. It is assumed that the electricity used in the exporting country's supply chain for water electrolysis and hydrogen carrier synthesis is emissions-free. In the Netherlands, the KEV electricity mix is assumed to apply to chain steps such as dehydrogenation and transport (including electric transport).
- Emissions are totalled up to the point of delivery to the end user or to a fuelling station. We decided not to include the emissions and energy efficiency associated with the

direct use of carriers by end users, since this encompasses a broad spectrum of technologies (fuel cells, burners, turbines, internal combustion engines, process reactors, etc.).

- By 2030, maritime and domestic transport (road, inland waterways, rail) will still be emitting CO_2, although this is expected to be less than today's levels. We anticipate that by 2050, maritime transport will achieve net-zero emissions in accordance with the International Maritime Organisation (IMO) targets (by using synthetic methane, methanol, ammonia), and that road transport and inland shipping will meet EU zero-emission standards by means of electric propulsion (by using batteries or hydrogen).
- It is assumed that CO_2 of fossil origin from an industrial point source will be used to synthesise LSM and methanol in 2030. If this CO_2 is stored in the exporting country as methane or methanol, and is released again in the Netherlands through steam reforming, this represents a net emission of CO_2 that is assigned to the supply chain. Some CO_2 also escapes during synthesis. We assume that CO_2 from direct air capture will be used in 2050. In this case, the CO_2 released during steam reforming (and also the CO_2 that escapes during synthesis) is not assigned to the supply chain.
- The assumption is that $DeNO_X$ post-treatment will be used at ammonia conversion plants in the Netherlands, but not in the exporting country. This results in a 93% cut in the emissions of NO_X compared to the value listed in the JRC1 dataset.

ANNEX B: VOLUME

This study assumes that the same volume of hydrogen equivalent will be delivered to the end user for all supply chains, at the factory gate or at the fuelling station. This volume is based on the intermediate variant in the volume study carried out by TNO, Berenschot and Arcadis. In this situation, 1578 kilotonnes of hydrogen equivalent (in 2030) is supplied in the form of various hydrogen carriers. The 2030 Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers by Arcadis and Berenschot study also assumes this situation.

The following percentages by weight are used to calculate the volumes of the hydrogen carriers for each supply chain based on the volume of hydrogen equivalent. (Although we in fact calculate the mass of a hydrogen carrier for every supply chain, we follow the terminology used in the research question for this study.)

Table 6: Weight ratio of hydrogen carriers and hydrogen concentration

Hydrogen carrier	mass percentage H_2	H_2 equivalent
NH_3	17.8	5.63
DBT	6.16	16.23
MCH	6.12	16.33
LH_2	100	1.00
MeOH	12.58	7.95
LSM	25.13	3.98
$NaBH_4$	10.6	4.73*

Source NH_3, LOHC: Berenschot, Arcadis (2024); other: Molecular Weight Calculator

*) When sodium borohydride reacts with water, twice as much H_2 is released as is stored in the substance: $NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2$. We therefore use the figure in the right column for the volume calculations.

Because losses arise in the supply chains during conversions and due to storage and transport leakage, more hydrogen carrier must be imported than would be calculated using the figures in Table 6.

Efficiency of conversion steps

We use the figures from JRC2 for conversion losses, except for hydrogenation and dehydrogenation of the LOHCs. We use the figures from JRC1 for DBT. The difference between the two studies is that JRC1 assumes a fully electrified conversion process, while JRC2 assumes the use of hydrogen to generate process heat. A third alternative in JRC1 is the use of industrial waste heat for the conversion process. We chose the electrified conversion process for the modelling, because using electricity will be cheaper and because we assume that the importer of the hydrogen contained in the LOHC will aim to sell as much hydrogen as possible.

To model the conversions of ammonia, methanol and LSM to hydrogen, we assume that some of the hydrogen carrier volume will be used as fuel to generate process heat, as electrified processes will not become available in the foreseeable future. If heating with hydrogen is also used to dehydrogenate LOHCs, 38% more DBT must be imported.

The figures for conversion of MCH and sodium borohydride are based on a team analysis that partly relies on information from the market.

As regards the synthesis of methanol and LSM abroad, JRC2 assumes the use of direct air capture (DAC) to supply the required CO_2, with hydrogen used to produce process energy. However, we assume the use of CO_2 from an industrial point source in 2030 and DAC in 2050. This requires less hydrogen equivalent than if DAC is used.

Table 7: Conversion efficiencies from hydrogen carrier to hydrogen and vice versa

Efficiencies Output						Without DAC*	With DAC*	Without DAC*	With DAC*
Input	**H_2**	**NH_3**	**LH_2**	**MCH**	**DBT**	**MeOH**	**MeOH**	**LSM**	**LSM**
H_2 gas	100%	100%	98%	99%	100%	63%	46%	55%	43%
NH_3	78%	100%							
LH_2	100%		100%						
MCH	98%			100%					
DBT	100%				100%				
MeOH	82%					100%	100%		
LSM	76%							100%	100%
CH_4 gas	76%								
$NaBH_4$	100%								

*) We assume that CO_2 from an industrial point source will be used for methanol and LSM synthesis in exporting countries and the Netherlands in 2030, and from direct air capture (DAC, CO_2 captured from the air) in 2050.

Efficiency of transport, transshipment and storage

Losses may arise during the storage, transfer and transport of imported hydrogen carriers due to leakage and boil-off (evaporation) of carriers. These losses are only significant for liquid hydrogen, and to a limited extent for ammonia. Provided that it remains dry, no hydrogen losses occur with sodium borohydride.

Table 8: **Efficiencies of storage, transsphipment and transport: losses due to leakage and boil-off**

Efficiencies	Mode of transport							
Input	Pipeline	Road	Train	Ship	Natural gas network	H_2 network	Storage	Maritime transport
H_2 gas						100%*		
NH_3	100%	100%	100%	100%			100%**	100%
LH_2		99%	99%	98%			98%	99%
MCH	100%	100%	100%	100%			100%	100%
DBT	100%	100%	100%	100%			100%	100%
MeOH	100%	100%	100%	100%			100%	100%
LSM		100%	100%	100%			100%	100%
$NaBH_4$		100%	100%	100%			100%	100%
CH_4 gas					100%*			

*) Leakage of 0.01% from the H_2 network and natural gas network is assumed (Gasunie).
**) Leakage of 0.02% when NH_3 is stored is assumed (JRC1).

Liquid hydrogen boil-off during maritime transport (0.2% per day, i.e., 1% for the route between Morocco and the Netherlands, and five times as much between Argentina and the Netherlands) is used as fuel for the vessel's engine. Boil-off during transport by tank truck or tank wagon is lost as emissions. Inland vessels can use this boil-off to fuel the engine (1% per day). These daily losses are multiplied by the transport duration:

- Inland shipping: Four days to and from the destination (200 km), 50% of the time with LH_2 cargo: 2 days x 1% per day = 2% loss.
- Tank wagon: Three days by rail to and from the destination, 50% of the time with LH_2 cargo: 1.5 days x 1% per day = 1.5% loss.
- Tank truck: One and a half days by road to and from the destination, 50% of the time with LH_2 cargo: 1 day x 1% per day = 1% loss.
- The assumption is that boiled-off hydrogen during centralised storage is reliquefied, but escapes to the atmosphere when stored decentrally (0.2% per day for 3 days).

Storage

We assume that all import supply chains involve storage in the port of entry for 14 days, and 3 days at the end user's site. We divide the total annual imported volume of hydrogen carrier, either used directly or converted to hydrogen in Netherlands or transited, by 365 days and multiply this by 14 and 3 days respectively. In the supply chains that use the hydrogen network or natural gas network, the storage capacity of the salt caverns or gas fields connected to these pipelines must be considered. This storage capacity is already in use for natural gas and is in development for hydrogen. We do not include the underground storage capacity in the modelling, as we follow the assumption in JRC1 that only 1% of the volume in the supply chain passes through a salt cavern.[70]

Conversion to tonne-kilometres

For several public interest indicators, we employ a calculation based on benchmark figures per tonne-kilometre. The number of tonne-kilometres for each supply chain is determined by multiplying the hydrogen carrier volumes by the route length of 200 km.

Table 9: Summary of indicators depending on tonne-kilometres for which corrections for return trips are, or are not, necessary

Indicators for which full return trips for sodium borohydride and LOHCs do not affect the calculated effects	Indicators for which full return trips for sodium borohydride and LOHCs do affect the calculated effects
• Congestion costs (Economically Robust) • Transport safety (Safe & Secure) • H_2 or CH_4 emissions (Sustainable) during transport of LOHCs or borohydride, as there are no H_2 or CH_4 emissions • Material consumption (loss of H_2eq or material) (Sustainable), as there are no losses during transport • Noise (Environment) • Habitat degradation (Environment) • NH_3 emissions (Environment) during transport of LOHCs or borohydride, as there are no NH_3 emissions • Spatial costs per tonne-kilometre (Spatial Planning)	• Transport costs (Affordable) • CO_2 emissions (Sustainable) • Energy losses (Sustainable) • NO_X (Environment) • Particulate matter (Environment)

The standard assumption in the calculations is that the truck, train or inland vessel travels to the end user fully loaded and returns empty or filled with ballast water (Panteia). There are however return flows if the LOHCs or sodium borohydride are used. These return flows do not increase the number of logistical movements. However, the loading of the return trip is higher. The higher average loading may affect the energy losses, which may lead to various other effects, depending on the indicator. To account for this effect, we assume 40% higher energy losses and emissions for a full trip than for an empty trip for the LOHCs and borohydride.[71] This figure approximates the average additional energy losses and thus also the additional costs and emissions. We do not generically apply this correction to the number of tonne-kilometres in the model. Instead, we apply it to the relevant effect, as the correction varies. Pipelines are only used for one way transport. If a return flow is involved, the required capacity must be doubled. This doubles the effects of:

- Transport costs (Affordable)
- Energy losses (Sustainable)

---

[70] TNO has studied how much underground storage capacity is required in a CO_2-free electricity system in which all gas-fired power stations have been converted to hydrogen and can serve as a flexible backup for wind and solar energy. This amounts to an electricity generation capacity of 15.8 GW. Additional hydrogen production capacity or faster depletion of the underground storage capacity will be required to generate sufficient electricity to meet peak demand during certain periods of the year. Six additional salt caverns would be needed to meet the average shortfall using only gas stored in these caverns. Sander Blom, Berend Hopman, Sebastiaan Hers (2024), *Waterstof-opslagbehoefte 2030-2035*, TNO 2024 R10304, 16 February 2024.

[71] *CE Delft (2021), STREAM Goederenvervoer* 2020. *Emissies van modaliteiten in het goederenvervoer* – Version 2, p. 86.

- Spatial costs (Spatial Planning)

Required transport capacity

For some public interest indicators, it is necessary to know how many logistical movements and means of transport are required for each supply chain to transport the required volume (in fact: mass). To calculate this, the volume is divided by the capacity of the means of transport as shown in Table 10. The required number of each means of transport is then calculated by dividing the number of days in the year by the transport duration as specified in the list above.

For road and rail transport, the regulated axle loads and carrying capacity of the road surface or railway embankment limit the quantities that can be transported. For inland vessels, the volumetric capacity (cargo hold) determines the quantities of material that can be carried. However, we calculate the costs, energy losses and emissions for water transport using benchmark figures per tonne-kilometre. Volume (in terms of its literal meaning in relation to cargo space) is only relevant when determining the number of inland vessels and the required investments (public interest Adaptable). Due to the different specific gravities of the LOHCs, DBT and MCH, the volume (m^3) of transport capacity required to carry the same mass (kilotonnes) of hydrogen is not the same for these carriers. However, we disregard this difference, as it only has a minor effect on the results for Adaptable.

Table 10: Capacities of means of transport in tonnes of hydrogen carrier

Capacity Carrier	Tractor-trailer	Tank wagon	Inland vessel
NH_3	29	55.1	1,850
LH_2	4.3	9	350
MCH / DBT	29	65.4	1,850
MeOH	29	63.2	1,850
LSM	20	45	1,000
$NaBH_4$[72]	29	55	1,850

Sources: Panteia (2023), JRC1 (2022), LNG Industry (2016), Busch et al.[73]

Required volumes of carrier materials for LOHCs and sodium borohydride

The quantity of carrier material required to import a given quantity of hydrogen depends on the throughput, i.e., the number of cycles. A DBT molecule is loaded with hydrogen in the exporting country, is stored, transferred to a ship, travels to the Netherlands, is stored again there for some time, after which dehydrogenation takes place (possibly preceded by another trip inland), after which the DBT returns to the country of origin. The duration of this cycle depends on the transport distance.

Example for Morocco: after hydrogenation, 7 days storage before export, 5 days by sea to the Netherlands, 14 days storage in a Dutch port of entry, followed by dehydrogenation (or possibly first 1-2 days distribution to an end user, where dehydrogenation occurs after 3 days). When the return journey is added, this amounts to a total of around 52-61 days. This results in a total of

---

[72] Due to its reactivity with water, we assume that sodium borohydride is shipped in waterproof big bags inside containers. We assume that the capacity per trip is equal to the standard values for tractor-trailers and dry bulk freight rail wagons.

[73] Busch T. et al. (2023), The role of liquid hydrogen in integrated energy systems. A case study for Germany, *International Journal of Hydrogen Energy*, Vol. 48, Issue 99, 25 December, pp. 39408-39424.

around 6 cycles each year. This means the required quantity of the carrier material can be calculated by dividing the annual quantity of hydrogen equivalent by the percentage of hydrogen by weight, and dividing this by 6.

Example for Argentina (15,000 km): as the transport distance is five times greater, the cycle will take 92-101 days. This results in a rounded total of 3 cycles each year.

The lower the number of cycles per year, the greater the quantity of carrier material needed.

With this low number of cycles, the carrier material will have a long lifespan: a loss of 0.013% per cycle for DBT and 0.7-0.84% for MCH arises because undesired byproducts are created during the dehydrogenation process, which means the material must be purified after each cycle (source: JRC and market information).

ANNEX C: SUBSTANTIATION AND EXPLANATION

This annex explains the underlying assumptions and figures for each public interest. The order in which these are given is identical to that in the National Energy System Plan.

1. AFFORDABLE

This multi-criteria analysis (MCA) study uses existing literature as much as possible. In recent years numerous studies have been published in the Netherlands and elsewhere that compare the costs of imported hydrogen carriers. As these various studies are often characterised by differing assumptions and scopes, it is desirable to employ the same source wherever possible. However, no single study compares all the seven hydrogen carriers that we compare here. We take the Dutch HyDelta study as a basis and explain this choice below Table 12.[74] HyDelta compares the costs of importing four of the seven selected hydrogen carriers - ammonia, liquid hydrogen, methylcyclohexane (MCH), and methanol - from eight exporting countries to the Netherlands in 2030.[75] We have selected Morocco as the country of origin. For dibenzyltoluene (DBT) we assume the same cost basis as for MCH.

The cost calculations in HyDelta employ a different division of supply chain steps than used in this MCA study. We have therefore summed the costs of certain steps according to HyDelta in order to determine the costs of these steps in the MCA.

The HyDelta study assumes that methanol is produced in the country of export using CO_2 obtained through direct air capture. This is not a realistic assumption for 2030, but can be assumed for 2050. For this reason we employ a 2030 correction for the costs of 'additional feedstock'. To use CO_2 derived from an industrial point source, investments must be made in its collection, compression, and possible connection to a CO_2 transport pipeline. These investment costs depend largely on the volume of the gas stream from which the CO_2 is captured, the concentration of CO_2 in the gas stream, the process from which the CO_2 is derived, the technology employed, and whether the factory is purpose-built or adapted. We have assumed fossil-fuel-derived CO_2 purchase costs of 50 euros per tonne from an industrial point source.[76] We have replaced the 952 euros per tonne of hydrogen equivalent amount with 580 euros per tonne of hydrogen equivalent. The import costs of methanol then fall to 4296 euros per tonne of hydrogen equivalent (see Table 11).

Other sources were used to calculate the hydrogen carrier costs of liquid synthetic methane and sodium borohydride, namely Agora/TU Hamburg and confidential data obtained from market parties.

---

[74] HyDelta (2022), WP7B Technical analysis, D7B.3 – *Cost analysis and comparison of different hydrogen carrier import chains and expected cost development*, 31 March 2022.

[75] The countries are: Morocco, Saudi Arabia, Oman, Argentina, the United Kingdom, Iceland, Canada and Australia.

[76] On the basis of the following sources: IEA (2021), *Is carbon capture too expensive?*, 21 July, and IEA (2023), *The Role of e-Fuels in Decarbonizing Transport*, 23 December.

Table 11: The costs of importing hydrogen carriers from Morocco to the Netherlands in 2030, in euros/tonne of hydrogen equivalent delivered to the end user (HyDelta)

Morocco 2030 HyDelta	H_2 in NH_3	H_2 in LH_2	H_2 in MCH	H_2 in MeOH
Local H_2 production	€2691	€2840	€3206	€3193
Compressed H_2 storage	€33	€34	€62	€43
Additional feedstock	€ -	€ -	€ -	€580**
H_2 to carrier conversion	€1047	€876	€323	€378
Carrier export and storage	€216	€780	€266	€43
Transport: shipping	€33	€300	€420	€59
Transport: pipeline	€ -	€ -	€ -	€ -
Carrier import and storage	€187	€704	€192	€35
Carrier to H_2 conversion	€300***	€192	€732	€124
Total import costs *	€4018	€4831	€4277	€4296**

*) Import costs are the sum of costs up to the first horizontal line: excluding storage in the port of entry and conversion to hydrogen.

**) The values by HyDelta are based on direct air capture (DAC). In this table these values are corrected for the use of CO_2 derived from an industrial point source.

***) HyDelta takes no account of the application of $DeNO_X$ post-treatment when cracking ammonia. We do assume the application of this post-treatment in this study. We calculate the costs of $DeNO_X$ on the basis on data from the Rotterdam ammonia cracking feasibility study (the scale of production capacity and its NO_X emissions) and from the Informatiepunt Leefomgeving (General Information on Environment and Planning Laws) (investment and operational costs).[77]

Agora/TU Hamburg calculates an import price for LSM ranging from 6,400 euros to 7,500 euros per tonne of hydrogen equivalent; we assume 7,000 euros.[78] This is minus a reduction of 100 euros for storage in the port of entry and 900 euros for conversion of LSM to hydrogen with CO_2 capture and storage (CCS), resulting in 6,000 euros.[79] Agora assumes methanation using CO_2 derived from direct air capture at a cost of 1100 euros per tonne of hydrogen equivalent. If we correct this for the use of CO_2 from a fossil fuel based industrial point source (€50 per tonne CO_2, or 503 euros per tonne of hydrogen equivalent) we arrive at import costs of 6000 – 1100 + 503 = 5.403 euros per tonne of hydrogen equivalent (excluding transshipment/storage and conversion).

No full supply chain studies have yet been published on sodium borohydride. From the literature[80] and from confidential information provided by market parties it appears that its costs are strongly determined by the energy input into the process of making the carrier material, and the recycling and regeneration of the 'spent fuel', the return flow. Releasing hydrogen from the powder is exothermic (produces energy). CAPEX estimates for the process installations are unknown.

---

[77] According to IPLO, investment in selective catalytic reduction (SCR) is €3-100/Nm^3/per hour. The waste gas stream contains at most 80 mg/m3 of NO_X; this is 140 tonnes/year. The overall waste gas stream is then 200 Nm^3/hour. 1 million tonnes/8760 hours = 114 tonnes/hour of H_2 are produced. This brings the CAPEX costs to €5-18/tonne of H_2. The operational costs of SCR are €150-200 per tonne of removed NO_X for the reagents, plus €0.33/(Nm^3 of flue gases per hour) for the catalyst. These amount to €0.021-0.28 per tonne of H_2 and €0.058 per tonne of H_2 respectively, both of which are negligible compared to the CAPEX costs.

[78] Agora Industrie & Technische Universität Hamburg (2023), *Wasserstoff-Importoptionen für Deutschland. Analyse mit einer Vertiefung zu Synthetischem Erdgas (SNG) bei nahezu geschlossenem Kohlenkreislauf*, September 2023.

[79] By comparison: The International Energy Agency (IEA) assesses these costs as €500 for conversion without CCS and €1000 with CCS, both per tonne of hydrogen equivalent. IEA (2019), The Future of Hydrogen. Seizing today's opportunities. Report prepared by the IEA for the G20, Japan, June 2019.

[80] E.g. Ainee Ibrahim *et al.*, Chemical compression and transport of hydrogen using sodium borohydride, *Sustainable Energy & Fuels*, 2023, 7, 1196-1203.

For this supply chain to be competitive it will need access to cheap energy, e.g. in the Middle East. For the comparison we have chosen a low energy price, which is realistic in the Middle East, for the production of sodium borohydride. Without including the CAPEX and purchase price of the raw materials, we have then set the import price at 11,350 euros/tonne of hydrogen equivalent. This makes it by far the most expensive hydrogen carrier. Another 350 euros per tonne of hydrogen equivalent is required for port of entry storage, distribution, and dehydrogenation.

Certain supply chains also include a synthesis step in the Netherlands in which liquefaction to liquid hydrogen or the synthesis of ammonia or methanol uses hydrogen supplied through the national hydrogen network. We have adopted the costs of these conversion steps in the United Kingdom as estimated by HyDelta, on the assumption that of the countries examined by HyDelta the UK most closely resembles the Netherlands. Table 12 summarises the conversion costs according to HyDelta and the other consulted sources.

The costs of steam reforming methanol into hydrogen appear low, but we have adopted these values for the baseline situation in the interests of keeping the HyDelta dataset as complete as possible.

Table 12: Conversion costs in euros per tonne of hydrogen equivalent, from carrier to hydrogen and vice versa

Conversion cost per tonne of output H_2 equivalent	Output				
Input	**H_2**	**NH_3**	**LH_2**	**MeOH**	**CH_4**
H_2 gas		€1014	€1287	€373	
NH_3	€300				
LH_2	€192				
MCH	€732				
DBT	€732				
MeOH	€124				
LSM	€500				€78
CH_4 gas	€500				
$NaBH_4$	€250				

Explanation of the choice for HyDelta: a comparison with JRC and meta-study

Numerous studies have been carried out into the cost basis of imported hydrogen carriers. We searched for studies that compared the largest number of the hydrogen carriers we were interested in, and which were the most transparent with regard to methodology and data. Two recent studies best met these requirements: HyDelta and JRC.

For the public interest Affordable we adopted the import costs of liquid hydrogen, ammonia, liquid organic hydrogen carriers (LOHC) – specifically methylcyclohexane (MCH) – and methanol in the HyDelta dataset. This dataset offers a number of advantages for our own modelling: the costs are clearly broken down into supply chain steps, the dataset is available for a number of different countries of origin for hydrogen carriers, and it encompasses two reference years. The study was also carried out by Dutch parties.

The JRC study examines the same set of hydrogen carriers (though with dibenzyl toluene (DBT) instead of MCH as the LOHC) and also provides fairly complete explanations. The disadvantages of the JRC study are that the results per supply chain step are presented only as charts, and that no distinction is made between country of origin or reference year. HyDelta therefore represents a better basis for our own study.

We compared the results of the HyDelta and JRC studies, and also considered a meta-study that had evaluated 30 studies on the importing of hydrogen carriers.[81] The meta-study only considered supply chains until their arrival in the EU, and gave no information on chain steps, countries of origin, reference years, or other assumptions. HyDelta and JRC were not included in the 30 studies considered by the meta-study.

We used other sources for LSM and sodium borohydride, as these carriers were not taken into consideration by HyDelta, JRC1, or the meta-study.

Figure 88 compares the costs of hydrogen carriers in the port of entry, including central conversion in the port, according to HyDelta and JRC. HyDelta and JRC do not employ the same supply chain step divisions; we have therefore interpreted and compared these as well as possible. JRC performs calculations for two variants: low and high electricity prices in the country of origin and in the country of use (the Netherlands). The table shows the different assumptions made by JRC and HyDelta.

Figure 88 shows that the costs of methanol are lower according to HyDelta than they are according to JRC (both variants) and that the costs of liquid hydrogen are higher according to HyDelta than they are according to JRC (both variants).

€/MWh(el)	Production site	End use
JRC (high)	50	130
JRC (low)	10	50
HyDelta	34 (Morocco)	50 (Netherlands)

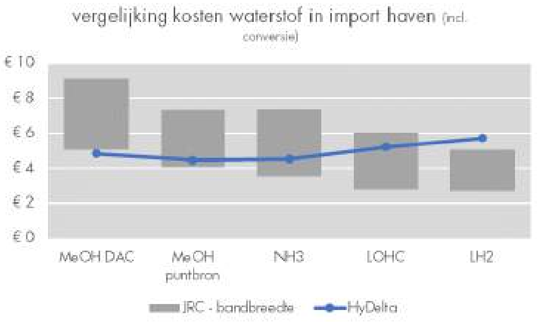


Figure 88: Comparison between HyDelta and JRC (in €/kg of H_2 equivalent)

Not only do the overall figures differ, but differences can also be seen in the cost basis of the supply chain steps (Figure 89).

- The greatest differences between HyDelta and both JRC variants are in hydrogen production. This results mainly from differences in assumed electricity prices, and because more hydrogen has to be generated for supply chains in which hydrogen carriers are used in conversion processes (e.g. ammonia, methanol).
- HyDelta and JRC also display differences between the various conversion processes. These can also be explained in part by differences in the price of electricity. However, without insight into the source data, which are unavailable, we cannot put forward an opinion on which results are the more 'realistic'.
- An example of this is the conversion of methanol to hydrogen. This is notably cheaper in HyDelta than in both JRC variants. Both studies were carried out by reputable institutions and are recent. Both studies give disclaimers on the uncertainties in their calculations. As HyDelta notes: "*It is important to mention that a small capacity of 5.5 kt methanol*

---

[81] Genge L et al., Supply costs of green chemical energy carriers at the European border: A meta-analysis, *International Journal of Hydrogen Energy*, 19 December 2023, pp. 38766-38781.

per year is used as an anchor point for the CAPEX calculation. The annual capacity in the study is 1375 kt methanol per year, 250 times larger, which results in great uncertainty of the cost estimation."[82] JRC1 writes: "*While literature is available on designs for small scale applications targeted especially at fuel cells [140]–[142], it is difficult to find designs and specifications for the production of large amounts of hydrogen [143], [144]. (…) Not much information is available on large–scale methanol reforming installations.*"

- Another example is the liquefaction, storage and transport of liquid hydrogen: according to HyDelta this is considerably more expensive than it is in both JRC variants. A third example is the synthesis of ammonia: this is most expensive in HyDelta, but cracking ammonia is the cheapest in HyDelta.

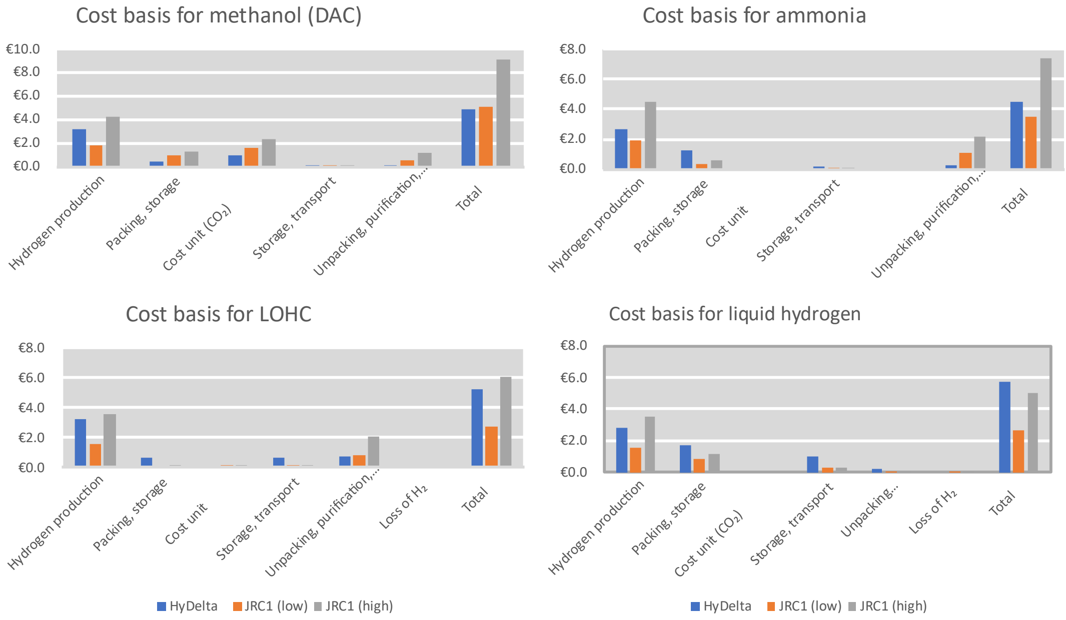


Figure 89: Cost basis of hydrogen carriers according to HyDelta and JRC: comparisons of methanol (with DAC), ammonia, LOHC, and liquid hydrogen (in €/kg of H_2 equivalent)

We also compared HyDelta and JRC with the meta-study. This comparison can only be performed for the part of the supply chain that the meta-study takes into consideration, and therefore excludes conversion in the Netherlands. It is clear that the cost calculations performed by HyDelta, JRC and the meta-study differ. The costs of hydrogen carriers according to HyDelta are generally higher than those given by the meta-study, except for methanol. The costs of most of the carriers given by the meta-study fall within the bandwidth of the JRC variants. For methanol the costs according to the meta-study lie at the lower boundary of this bandwidth, and partly outside it.

---

[82] HyDelta (2022), WP7B Technical analysis, D7B.3 – *Cost analysis and comparison of different hydrogen carrier import chains and expected cost development,* 31 March, 63; JRC1 (2022), *Assessment of Hydrogen Delivery Options. Feasibility of Transport of Green Hydrogen within Europe*, JRC Technical Report, 20.

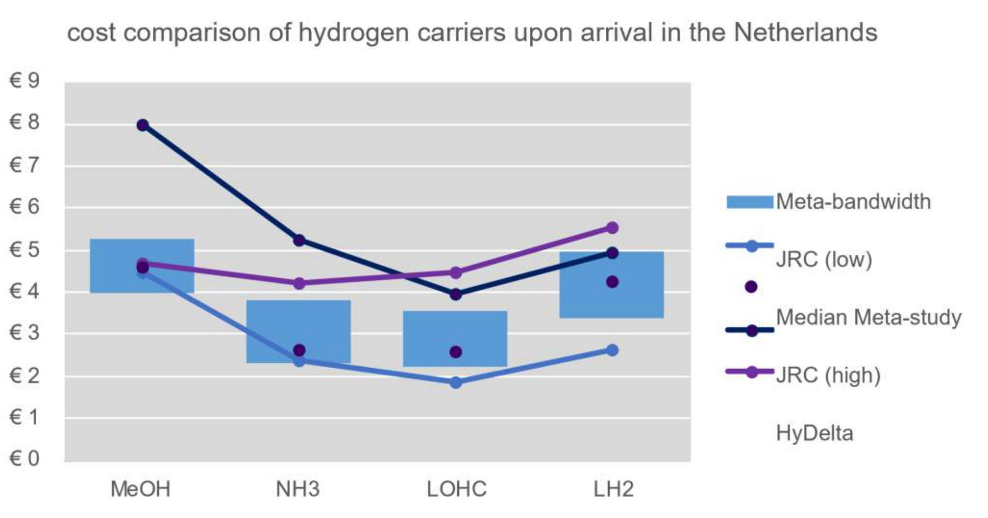


Figure 90: **Comparison between HyDelta and JRC with the meta-study (in €/kg of H_2 equivalent)**

On the basis of the information currently available to us, we cannot judge which of these studies is best. For the baseline situation we decided to use the HyDelta dataset. In order to examine the influence of other costs we performed a sensitivity analysis on the dataset of JRC's 'high' variant. In the sensitivity analysis methanol becomes considerably more expensive, ammonia more expensive, LOHC slightly more expensive, and liquid hydrogen slightly cheaper than in the baseline situation. In the sensitivity analysis LSM and $NaBH_4$ costs remain the same as in the baseline situation. Both in the baseline situation and in the sensitivity analysis we assume that methanol synthesis in 2030 uses CO_2 from an industrial point source rather than direct air capture. The datasets have been corrected accordingly.

Carbon Capture and Storage (CCS) sensitivity analysis of Dutch conversion installations

In the baseline situation, steam reforming installations for methanol and methane emit CO_2 to the air. We carried out sensitivity analysis to determine the effect of CO_2 capture and storage in Dutch installations; we assume that no CCS is employed during synthesis (in Europe and in the country of export). This leads to altered cost assumptions: using the basic costs cited in the Stimuleringsregeling Duurzame Energie++ [Sustainable Energy Incentive Scheme] we can assume additional costs of 110 euro per tonne of CO_2. This includes 15 per tonne of CO_2 for underground storage and 45 euros per tonne of CO_2 for transport to storage.

Transport costs in the Netherlands

In the HyDelta study, the import chain runs up to and includes conversion to hydrogen in the Netherlands. In this MCA study, the supply chains extend up to the point of delivery to the end user. We therefore added the costs of transport in or through the Netherlands to the import costs. These costs are calculated by reference to Panteia figures (the integral costs per tonne-kilometre for transport by road, rail, and inland waterways).[83]

---

[83] Panteia (2023), Cost Figures for Freight Transport – final report, commissioned by the Netherlands Institute for Transport Policy Analysis (KiM), January 2023.

Table 13: Transport costs in euros/tonne of hydrogen equivalent by road, rail, water, and pipeline

Costs of transfer/transshipment and transport in tonnes of H_2eq					Mode of transport		
Carrier	Import	Transshipment/ import	End user storage	Pipeline/natural gas network/H_2 network	Road	Train	Ship
H_2 gas				€7			
NH_3	€3116	€145	€31	€28	€160	€23	€44
LH_2	€4831	€704	€151		€140	€20	€39
MCH*	€4193	€188	€48	€119	€519	€75	€146
DBT*	€4193	€188	€48	€119	€519	€75	€146
MeOH	€3846	€29	€11	€10	€220	€32	€62
LSM	€4531	€76	€16		€110	€16	€31
$NaBH_4$*	€11,350	€100	€21		€135	€20	€21
CH_4 gas				€0			

*) When calculating the costs of LOHCs and sodium borohydride, account was taken of the return flow of spent fuel: double costs for storage, double costs for LOHC transport by pipeline (as return pipes are needed), and additional costs for return flows by road, rail, and water as loading factors are higher than when deliveries return empty.

We calculated the transport costs of hydrogen carriers through pipelines by reference to JRC and Delta Rhine Corridor figures (a team analysis based on public sources and information from market parties).[84]

- For ammonia we follow the data given for the planned Delta Rhine Corridor pipeline. This cost estimate is notably higher than that given by JRC1, principally because the pipeline diameter is larger (24 inch vs. 18 inch) and the fact that the requested market offer will have taken account of higher raw material prices and the associated higher costs per kilometre of pipeline. For OPEX we have followed the JRC1 figures. The capacity of the DRC pipeline is able to transport the full volume of ammonia (1578 kilotonnes (kt) of hydrogen equivalent). The route incorporates 3 pumping stations, each with 2 pumps.
- For methanol we follow the JRC1 data. JRC has derived some of this data from data on ammonia, given the lack of specific data on methanol pipelines; we have adopted their scaling factors. The transport of the full volume of methanol (1578 kt of hydrogen equivalent) requires two 18-inch pipelines, as modelled by JRC1. Each pipeline incorporates 3 pumping stations, each with 2 pumps.
- For LOHC we also take the JRC1 data. JRC1 uses data for DBT transport. We were unable to source specific data for MCH transport, and therefore also adopt the DBT data for MCH. In order to transport the full volume of the LOHCs (1578 kt of hydrogen equivalent), 26 sets of 32-inch (delivery) and 28-inch (return) pipelines are required, as modelled by JRC1. This raises the CAPEX of the pipelines and pumping stations. Each pipeline direction has 2 pumping stations, each with 2 pumps per pipeline.

---

[84] JRC1: JRC, Assessment of Hydrogen Delivery Options Feasibility of Transport of Green Hydrogen within Europe, 2022; and JRC2: European Commission, Joint Research Centre, Arrigoni, A. et al. (2024), Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe, Publications Office of the European Union, Luxembourg. Decisio (2023), MKBA *Delta Rhine Corridor* Phase 2, for the Dutch Ministry of Economic Affairs and Climate Policy, 22 December 2023.

- For the national hydrogen network we take the JRC1 figures as the starting point. The construction of a new pipeline costs between 1.4 and 3.4 million euros per km, and the repurposing of an existing natural gas pipeline costs between 0.2 and 0.6 million euros per km. Since the Social Cost-Benefit Comparison of Hydrogen Carriers (MKBV) by Arcadis and Berenschot assumes that 80% of the route will comprise reused natural gas pipelines, we have chosen the figure of 0.8 million euros per km.[85] The capacity of the pipeline for the representative route is large enough to transport the full volume (1578 kt) of hydrogen. Gasunie (the Dutch national natural gas transport company) expects that no network gas compression will be needed to transport hydrogen; its injection pressure will suffice. For the purposes of supply chain comparability, we have nevertheless assumed the need for this compression. We assume the same conditions as for the national natural gas network, namely one compressor station every 200 km, each containing two compressors. This is consistent with the assumption in JRC1. The OPEX for the pipeline is taken from studies of a national hydrogen pipeline network (1% of CAPEX annually). The compression-related energy loss figures are taken from JRC2.
- For natural gas pipelines, the capacity of the pipeline on the representative route is able transport the full volume (1578 kt of hydrogen equivalent). We assume one compression station for a 200 km route. The compression-related energy loss figures are taken from JRC2. This appears low compared to the compression-related energy loss for hydrogen: according to Gasunie, they should be more similar (factor 3 because of the difference in energy density). For reasons of consistency with the other carriers, we use the JRC2 data. Because the existing natural gas network is capable of transporting these volumes, no costs have been assumed.

---

[85] Gasunie (2021), *HyWay27: Waterstoftransport via het bestaande gasnetwerk?* Final report for the Ministry of Economic Affairs and Climate Policy, June 2021.

Table 14: Transport costs by pipeline for a 200 km route

Transport costs with pipelines	H_2 36"	LOHC 32"/28" (1)	NH_3 24" (DRC)	MeOH 18"	CH_4 36"
Capacity (kilotonne/year)	2,180	1,000	17,164	6,893	12,724 (2)
Route throughput (kt/year)	1,578	25,800	8,884	12,545	6,280
Number of pipes needed	1	26	1	2	1
CAPEX pipe (MEUR/km)	€0.8	€0.32	€4.0	€0.7	€2.2 (3)
CAPEX pipe 200 km (MEUR)	€160	€3328	€800	€280	€440
Service life	50	50	50 (4)	50 (4)	50
OPEX pipe, % of CAPEX per year (5)	1%	0.04%	0.04%	0.04%	1%
Number of compression/pumping stations	1	104	3	6	1
CAPEX compression/pumping stations (MEUR)	€12	€32	€6.6	€7.2	--
Service life	20	20	20	20	20
OPEX compression/pumping stations (5)	1.2%	4%	4%	4%	1.2%
Energy input compr./pumping (MWh/year)	577,548	211,560	122,400	73,440	90,432
Energy costs (MEUR) (6)	€28.9	€10.6	€6.1	€5.6	€4.5
Relative percentage	5%	5%	5%	5%	5%
Annuity per year per kt of carrier	€7269	€7263	€5058	€1301	€4538 (3)
Annuity per year per kt of H_2 equivalent	€7269	€118,745	€28,476	€10,339	€18,062 (3)

(1) There and back.
(2) Balgzand-Bacton pipeline as reference: 36 inch, 230 km, capacity 42 million m^3 of natural gas per day.
(3) Inclusive of compression station costs. With regard to the relevance of pipeline costs to the public interest Affordable we assume that the existing gas network can be used at no cost.
(4) JRC1 and DRC give 40 years, but we assume identical service lives for all pipelines.
(5) JRC1 gives a higher OPEX for gas pipelines than for liquid pipelines.
(6) Calculated using €76/MWh in 2030, following KEV and Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers.

Decentralised storage costs

Decentralised storage costs are calculated as a 3/14th part of the costs of centralised storage (3 days of decentralised storage, 14 days of centralised storage). We did this because the costs of decentralised storage are not available for all carriers, but they are available for centralised storage. For centralised storage a 14-day supply of the average daily end use is assumed, and for decentralised storage a 3-day supply of the average daily end use. If the JRC data indicated a cost difference between centralised and decentralised storage, an appropriate correction was applied.

Non-included costs and potential incomes

A number of costs have not been included in the cost calculation of hydrogen carriers:

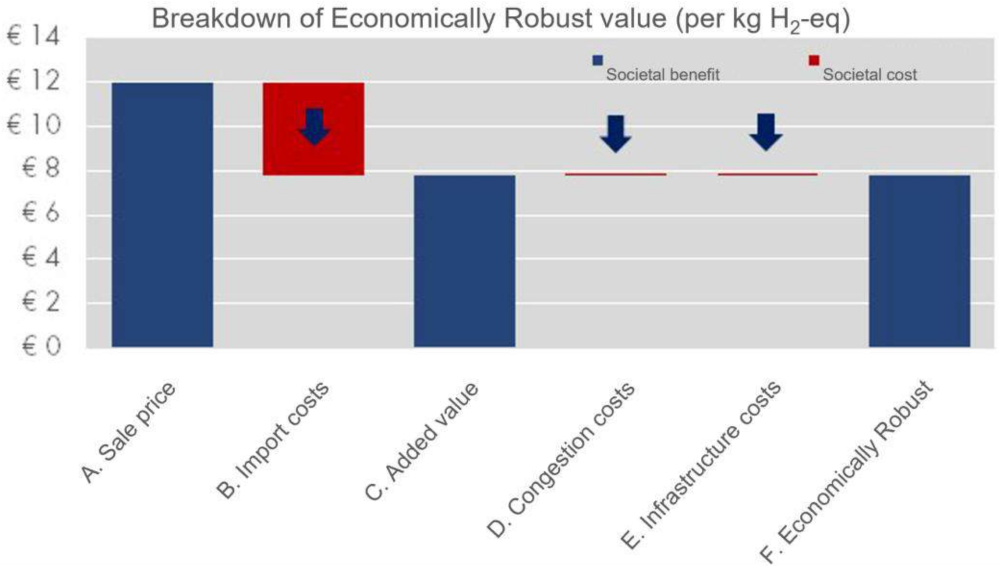
- Any taxes, import duties, licence costs and so on;
- Land acquisition or rental, staffing costs (in import and conversion costs, but these are included in inland transport), and the costs of on-location safety measures;
- Specific infrastructural adaptations to resolve bottlenecks (canal underpasses, etc.);
- Risk assessment and profit margins;
- Revenue from the sale of by-products and heat.

Land costs are considered for the public interest Spatial Planning.

2. ECONOMICALLY ROBUST

For the public interest Economically Robust we decided to use a composite indicator, comprising the added value minus the social costs of congestion and those of public infrastructure, see Figure 91. The most crucial component is the difference between the sale price and the import costs. The congestion and infrastructural costs are negligible in comparison.

As an example, note the composition of the value of various DBT supply chains for the Economically Robust indicator. This example shows that the value of Economically Robust differs between DBT supply chains according to whether or not congestion and infrastructural costs apply. The import costs of the DBT supply chain with centralised conversion are marginally higher than those of the other DBT chains, because of slightly higher hydrogen losses in the chain.



per kg of H_2 equivalent	A. Sale price	B. Import	C. Added value (A-B)	D. Congestion costs	E. Infrastructure costs	Economically Robust value (C-D-E)
DBT (by road)	€12,000	€4214	€7786	€0.017	€0.019	€7750
DBT (by water)	€12,000	€4214	€7786	-	€0.002	€7783
DBT (by rail)	€12,000	€4214	€7786	-	€0.001	€7785
DBT (by pipeline)	€12,000	€4214	€7786	-	-	€7786
DBT (centralised conversion + hydrogen network)	€12,000	€4215	€7785	-	-	€7785

Figure 91: Illustration of breakdown of Economically Robust value for DBT (values in chart for road distribution only)

Added value

Added value is defined as turnover minus purchase costs.

To calculate turnover we assume an indicative sale price per kilogramme for hydrogen at the point of delivery to end users. If the hydrogen is delivered in a different form than as pressurised liquid or gaseous hydrogen, then we use a derived price per hydrogen equivalent.

We do not use the current market prices for ammonia, methanol, etc. These are not representative of the future sale prices of green hydrogen carriers, because these market prices are determined by today's predominantly grey hydrogen production. If we compare the difference in price between grey hydrogen and grey ammonia per hydrogen equivalent, then ammonia is much too expensive to use as a hydrogen carrier; it is cheaper to buy grey hydrogen, while ammonia also requires additional conversion steps, which raise its costs.

If we assume the same price for hydrogen carriers expressed in hydrogen equivalent, and we correct this for the necessary conversion costs per hydrogen equivalent, we then obtain a more logical price comparison. We therefore chose a sale price for hydrogen and subtracted the conversion costs per hydrogen equivalent from that amount in order to determine the retail price of other hydrogen carriers.

The exact amount of the chosen sale price of hydrogen is not important, because our concern is the difference between the purchase price and sale price; this determines the score for this indicator, together with the following cost items. This concerns, incidentally, the pre-tax sale price without upward potential such as the value of renewable energy units (Hernieuwbare Brandstof Eenheden, HBEs).[86]

Table 15: Presumed turnover per tonne for green hydrogen carrier in 2030

	Indicative sale price per tonne	
H_2 gas	€12,000	After conversion of all hydrogen carriers
LH_2	€12,000	
NH_3	€11,700	Corrected for conversion costs to H_2
MeOH	€11,876	Corrected for conversion costs to H_2
CH_4 gas	€10,800	Corrected for conversion costs to H_2

Congestion

No congestion is assumed for transport by rail or waterway[87], only for road transport. Congestion does not apply to pipelines. The costs of congestion are calculated by multiplying the transport volumes (tonne-km) by the CE Delft benchmark figures used by the Netherlands Institute for Transport Policy Analysis (KiM).[88] In contrast to the method CE Delft usually uses, the KiM chooses to determine congestion figures on the basis of 'dead weight' rather than vehicle hours lost.[89] This results in a lower estimate. A correction is applied to these figures for liquid hydrogen because of its low energy density: costs are raised by a factor of 5.

---

[86] HBEs will be termed EREs (Emissie Reductie Eenheden, Emission Reduction Units) from 2026 onwards. Industry will also use HWIs (Hernieuwbare Waterstofeenheden voor de Industrie, Renewable hydrogen units for industry).

[87] Possible congestion resulting from the use of smaller vessels, a narrower navigable channel during periods of low water, or because stricter safety standards apply to vessels carrying ammonia through locks, for instance, have not been taken into consideration.

[88] O. Jonkeren and J. Franke, Netherlands Institute for Transport Policy Analysis | KiM, Kennisbasis Goederenvervoer (Freight transport knowledge base), Memorandum, February 2023. CE Delft, *Toekomstverkenning, De prijs van een reis, Verkennende analyse richting 2050*, May 2022.

[89] Two concepts are commonly used to assess total or average congestion costs: 'delay costs' and 'deadweight loss costs'. With 'delay costs', the costs associated with all the delays that road users experience (compared to a situation of free flow, or a given reference speed) are taken as congestion costs. 'Deadweight loss' costs refer to the costs that arise compared to the optimal congestion level, i.e., the congestion level at which the marginal social congestion costs are equal to the marginal costs of congestion.

Table 16: Valuation figures for the marginal costs of congestion (source CE Delft 2019)

Valuation figures for congestion costs	Average costs per 1000 tonne-km*	Explanatory notes
Road	€5.20	average truck
By rail	€ -	electric freight train
By water	€ -	inland shipping
Pipeline, hydrogen network, natural gas network	€ -	no information available

*) LH_2 correction: costs are raised by a factor of 5.

The costs of using space and public infrastructure

The transportation of hydrogen carriers uses public infrastructure, which takes up space and requires management and maintenance. We calculate the costs of using space and public infrastructure by multiplying the transport volumes (tonne-km) by figures given by KiM/CE Delft.[90] Comparable figures for pipelines are lacking. As the management and maintenance costs of pipelines are incorporated in the transport costs billed to end users, it is not unreasonable to evaluate the costs of this public infrastructure as zero. The spatial footprint of pipelines is considered for the public interest Spatial Planning. We apply a correction to these figures for liquid hydrogen because of its low energy density, which results in more logistical movements: the costs are raised by a factor of 5.

Table 17: Valuation figures for the marginal costs of the use of space and infrastructure (source KiM 2023)

Valuation figures for the marginal costs of space/infrastructure	Average costs per 1000 tonne-km*	Explanatory notes
Road	€5.72	average truck
By rail	€0.31	electric freight train
By water	€0.73	inland shipping
Pipeline (new)	€ - (PM)	benchmark figures unknown, costs paid by users

*) LH_2 correction: costs are raised by a factor of 5.

3. RELIABLE

In this study we take reliability to mean the degree to which hydrogen supply chains offer robustness and security of supply. If delivery is less reliable, this can be handled in the supply chain by incorporating more storage capacity. As the indicator of reliability we therefore take the additional storage capacity that the supply chain would need to install in order to offer the same delivery reliability as today's fossil fuel supply chains.

To determine the scores for Reliable we employ identical assumptions on the need for chain storage capacity in order to yield a comparable baseline situation. Our modelling adopts the assumptions in the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers:

- Storage capacity in ports of entry: 14 days (14/365 of total volume)
- At the end user: three days.

---

[90] O. Jonkeren and J. Franke, Netherlands Institute for Transport Policy Analysis | KiM, Kennisbasis Goederenvervoer (Freight transport knowledge base), Memorandum, February 2023. CE Delft, *Toekomstverkenning, De prijs van een reis, Verkennende analyse richting 2050*, May 2022.

In practice there will be differences between different end user groups and between hydrogen carriers that result in differing supply chain storage capacity requirements.[91] We quantify and sort these requirements by examining the characteristics of each carrier and supply chain on the basis of literature and expert estimates.[92]

The reliability of the supply chain is influenced by numerous factors, including the economic climate, the geopolitical situation, weather conditions, scarcity in the transport market, and so on. We consider only those factors that are directly linked to and distinctive for hydrogen carriers. If it is difficult to allocate sufficient space for a supply chain, this can affect its reliability; we examine this issue in relation to the public interest Spatial Planning. The commodification of a given hydrogen carrier in 2030, its large-scale trading, and its market regulation are also important factors in the reliability of each supply chain.

In the expert session that was held on this topic, a method was proposed that expressed the reliability of the supply chain in terms of the need for additional storage capacity. We estimate the reliability of each supply chain step by comparison with the fossil fuel supply chain. For each supply chain we sum the reliability scores for each chain step (expressed in terms of the extra storage requirements for the end user) to derive an overall value. This is therefore a relative score: the most reliable supply chain has a value of 1, and the least reliable has a value of 0. The assessment of reliability is subject to many uncertainties, but by using a standardised method for all supply chains we assume that the scores will at least be representative with regard to each other.

The supply chain is divided into three parts, each having one or more indicators of reliability (see Figure 92).

- Import of hydrogen carriers: The TRL (technology readiness level) of production of a hydrogen carrier from hydrogen, the TRL of ocean-going vessels and of storage, the stability/storage life of the carrier, the scalability of fleet and storage
- Distribution of hydrogen carriers: The TRL of modes of transport, the availability of modes of transport, and the robustness of modalities
- Conversion installations: The TRL of installations and the availability of back-up

---

[91] The Netherlands maintains a 90-day strategic reserve of fuels. We assume that in 2030 it will not yet be necessary to maintain a 90-day reserve of hydrogen carriers because there will still be a strategic reserve of fossil fuels. We assume that by 2050 an adequate level of strategic reserve will be maintained through the underground storage of hydrogen, for instance (salt caverns, possible gas fields), linked to the national pipeline network, and not in the form of hydrogen carriers. Strategic reserves will, however, be necessary for substances that can serve other immediate purposes besides being a hydrogen carrier.

[92] This is the result of expert judgement on the basis of the best estimates that experts in a structured discussion session could provide. Little experience with many hydrogen carriers has been accumulated to date; that is to say, there is experience with the substance, but not with its function as a hydrogen carrier. A more extensive scientific study is advisable, as is the development and demonstration of supply chain steps that have not yet met TRL 9.

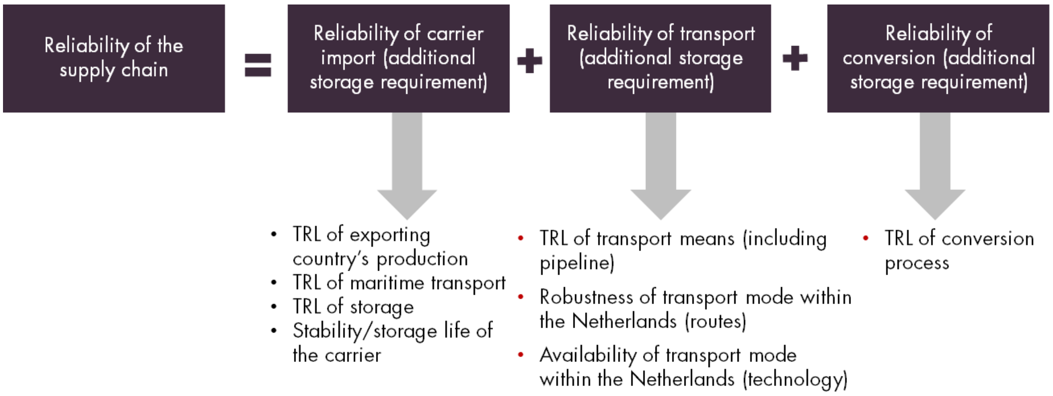


Figure 92: **Assessing the reliability of hydrogen carrier supply chains**

The following table gives a summary of the TRLs of all hydrogen carrier supply chain steps to, within, and through the Netherlands. Most supply chain steps are ranked as TRL 9, but many chains have lower ranked steps. These 'weak spots' are indicated in bold. Following Table 18, our assessment of the different supply chain steps is described separately.

Table 18: **The TRL (Technology Readiness Levels) of hydrogen carrier supply chain steps to and within the Netherlands. The weak spots in the supply chains (TRL <9) are indicated in bold type.**

	TRL of hydrogen carrier production in the exporting country	TRL of maritime transport	TRL of storage	TRL of inland transport (road, rail, water, pipeline)	TRL conversion plants
H_2 gas			TRL9, salt caverns (US):	TRL9, pipeline	
NH_3	TRL9, large-scale production, usually with H_2 from natural gas but also through electrolysis	TRL9, dedicated NH_3 tankers	TRL9, large-scale	TRL9, any except **pipeline TRL7-8**	Cracking: TRL9 small/medium-scaled, **TRL7 large-scale, demonstrations planned** Synthesis from H_2: TRL9
LH_2	TRL9, small/medium-scale **TRL7-8, large-scale**	**TRL7-8, only 1 such ship**	TRL9 small-scale, **TRL5-6 for large-scale**	TRL9, any except **tanker vessel TRL5** Pipeline not applicable.	Evaporation: TRL9 small-scale, **TRL8 large-scale** Liquefaction: TRL9 small-scale, **TRL8 large-scale**
DBT	Hydrogenation: **TRL8 small-scale**	TRL9, oil tankers	TRL9, very large-scale (hydrocarbons)	TRL9, all	Dehydrogenation: **TRL8 small-scale**
MCH	Hydrogenation: **TRL8 small-scale**	TRL9, oil tankers	TRL9, very large-scale (hydrocarbons)	TRL9, all	Dehydrogenation: **TRL8 small-scale**
MeOH	TRL9, large-scale production, usually with H_2 from natural gas but also through electrolysis	TRL9, dedicated tankers	TRL9, very large-scale (hydrocarbons)	TRL9, all	**TRL7, steam reforming to H_2** TRL9, synthesis from H_2
LSM	TRL9, small-scale production	TRL9, LNG tankers	TRL9, very large-scale	TRL9, all Pipeline not applicable.	TRL9, **steam** reforming to H_2 TRL9, evaporation:

	TRL of hydrogen carrier production in the exporting country	TRL of maritime transport	TRL of storage	TRL of inland transport (road, rail, water, pipeline)	TRL conversion plants
	TRL8, large-scale production				
NaBH$_4$	TRL9, NaBH$_4$ synthesis **TRL5, recycling steps**	TRL9, container vessels	TRL9, powders in 'big bags' and silos	TRL9, all	TRL9, NaBH$_4$ synthesis **TRL5, recycling steps**
CH$_4$ gas	see LSM	see LSM	TRL9, salt caverns and depleted gas fields	TRL9, pipeline	TRL9, **steam** reforming to H$_2$

1. Import of hydrogen carriers:

We examine four factors:

- The TRL of the hydrogen carrier production: for most hydrogen carriers large-scale production in exporting countries is technically possible, even though this is not yet proven for all carriers at this scale (order of magnitude >100 kt hydrogen). The most uncertain is the sodium borohydride chain, for which several supply chain steps have not yet been demonstrated. The liquid hydrogen and LOHC supply chains are proven at the medium scale, and scaling up would seem to be an economic rather than a technical issue (security of matching supply and demand).
- TRL of ocean-going vessels: TRL9 modes of transport are available for most hydrogen carriers, with the exception of liquid hydrogen. At present only a single vessel is operational, although there are designs and construction plans for more vessels.
- TRL of storage: TRL9 storage facilities are available for most hydrogen carriers, with the exception of large tanks for liquid hydrogen and large-scale storage facilities for sodium borohydride.
- The stability/storage life of the carrier: although differences exist between different hydrogen carriers, experts do not regard these as affecting the answer to the question of whether the supply chain requires extra storage. There is sufficient experience to be able to transport and store the hydrogen carriers such that supply security is assured.

The expert session also raised the issue of the hydrogen carrier production scalability factor: a required large growth in the scale of installations or in the transport fleet might pose reliability risks. However, this has principally to do with implementation in the preparation phase, and not with the reliability of the supply chain once formed. The expert session on adaptability concluded that the existing assets that could be employed for hydrogen carriers are already in use (for commercial purposes, with no overcapacity) and that in all cases an expansion of these assets will be needed for their application as hydrogen carrier. We do not regard technical scalability factors as differential, but the employability of assets for more than one substance does offer commercial advantages; see the annex on adaptability.

Table 19: The reliability of hydrogen carrier supply chains: importing to the Netherlands

	TRL of hydrogen carrier production in the exporting country	TRL of maritime transport	TRL of storage	Stability/storage life of the carrier	**Extra storage**
H_2 gas			TRL9, salt caverns (US)	Stable and can be stored indefinitely under pressure	0 (2030)+ 0 (2050)
NH_3	TRL9, large-scale production, usually with H_2 from natural gas but also through electrolysis	TRL9, dedicated NH_3 tankers	TRL9, large-scale	Stable and can be stored indefinitely under pressure/cooled	1 (2030)+ 0 (2050)
LH_2	TRL 9 for small to medium-scale, **TRL 7-8 for large-scale,** with the supply chain demonstrated between Australia and Japan	**TRL7-8, only 1 such ship**	TRL9 small-scale, **TRL5-6 for large-scale**	Stable, but boil-off containment needed	10 (2030) +3 (2050)
DBT	Hydrogenation: **small-scale TRL8,** all supply chain steps demonstrated (Europe)	TRL9, oil tankers	TRL9, very large-scale (hydrocarbons)	Stable and can be stored indefinitely	7 (2030)+ 3 (2050)
MCH	Hydrogenation: **small-scale TRL 8,** with all supply chain steps demonstrated (Japan) and a significant market for toluene in the chemical industry	TRL9, oil tankers	TRL9, very large-scale (hydrocarbons)	Stable and can be stored indefinitely	4 (2030)+ 0 (2050)
Me**OH**	TRL9, large-scale production, usually with H_2 from natural gas but also through electrolysis	TRL9, dedicated tankers	TRL9, very large-scale (hydrocarbons)	Stable and can be stored indefinitely	0 (2030)+ 0 (2050)
LSM	TRL9, small-scale production; **large scale production TRL8**	TRL9, LNG tankers	TRL9, very large-scale	Stable, but boil-off containment needed	0 (2030)+ 0 (2050)
$NaBH_4$	$NaBH_4$ synthesis TRL9, **recycling steps TRL5,** not all chain steps have been demonstrated	TRL9, bulk carriers (possibly containers)	TRL 9 for large-scale (powders); in due course, big bags will be replaced by alternative storage solutions – not yet fully mature	Stable if dry (additional risk for large volumes)	14 (2030)+ 6 (2050)
CH_4 gas			TRL9 salt caverns and empty gas fields	Stable and can be stored indefinitely under pressure	0 (2030)+ 0 (2050)

2. Distribution of hydrogen carriers

We examine three factors:

- The TRL of transport modalities: TRL9 modes of transport are available for most hydrogen carriers, except inland waterway tanker vessels for liquid hydrogen, and long-distance, large-diameter ammonia pipelines passing through the built environment.

- The availability of transport modality: we base this on the same sources as the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers[93]. These give the following figures: 98.5% availability for road transport, 98.6% for ordinary rail transport, 98.0% for inland waterway transport, and 99.99% for pipelines.
- The robustness of routes per modality: the chain is more reliable if fallback options exist in the event of stoppages/obstacles. If a road is blocked, there are other routes. A rail network disruption offers fewer alternative routes than those available in the case of road transport. The same applies to inland shipping, and even more so to inland shipping routes to Germany. Pipelines, too, offer no fallback options.

The expert opinion building extra storage capacity into the supply chain is only justifiable in the case of inland shipping. Period of low water usually last for some time, as do periods of high water. We have chosen to provide for 7 units of additional storage. We do not regard the lower TRL for inland shipping and tanker vessels carrying liquid hydrogen[94] and LSM, and the lower TRL of long-distance ammonia pipelines passing through the built environment[95], as a reason to organise extra storage capacity. Moreover, by 2030 these TRLs may well have improved, and will certainly have done so by 2050.

The inland shipping regulations pertaining to the use of locks may have an effect on the transportation by water of certain dangerous substances. There can be limitations, such as those for transportation of ammonia through locks. This has not been explicitly incorporated into our assessment.

---

[93] We have reversed the figures for road and rail transport as presented in the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers, as this appears to have been an omission. The original RWS source cites a 98.5% reliability figure for road transport.

[94] There are also as yet no regulations covering LH_2 transport by inland vessel.

[95] There is experience in the Netherlands with pipelines for dangerous substances such as ammonia, but this concerns relatively short distances in thinly-populated areas (TRL 9). An ammonia pipeline traversing the Netherlands, over long distances and in part through the built environment, has not yet been fully developed. The Netherlands also has no experience with large numbers of valves in long pipelines with safety devices. It might be necessary to add pumping stations to maintain a constant flow and pressure. TRL 7-8 is estimated for long-distance, small-diameter ammonia pipelines; a lower TRL is estimated for larger-diameter pipelines.

Table 20: The reliability of hydrogen carrier supply chains: distribution in/through the Netherlands

Chains step	Tank trucks (by road)	Extra storage	Tank wagon (by rail)	Extra storage	Tanker vessel (inland waterways)	Extra storage	Pipeline incl. pumps/compressors	Extra storage
H_2 gas							TRL9 – no fallback options – 99.99%	0
NH_3	TRL9 – many fallback options – 98.5%	0	TRL9 – few fallback options – 98.6%	0	TRL9 – few/no fallback options – 98.0%	7	**TRL7-8 – no fallback options** – 99.99%	0
LH_2	TRL9 – many fallback options – 98.5%	0	TRL9 – few fallback options – 98.6%	0	TRL5 – **few/no fallback options** – 98.0%	7		
DBT	TRL9 – many fallback options – 98.5%	0	TRL9 – few fallback options – 98.6%	0	TRL9 – few/no fallback options – 98.0%	7	TRL9 – no fallback options – 99.99%	0
MCH	TRL9 – many fallback options – 98.5%	0	TRL9 – few fallback options – 98.6%	0	TRL9 – few/no fallback options – 98.0%	7	TRL9 – no fallback options – 99.99%	0
MeOH	TRL9 – many fallback options – 98.5%	0	TRL9 – few fallback options – 98.6%	0	TRL9 – few/no fallback options – 98.0%	7	TRL9 – no fallback options – 99.99%	0
LSM	TRL9 – many fallback options – 98.5%	0	TRL9 – few fallback options – 98.6%	0	TRL9 – few/no fallback options – 98.0%	7		
$NaBH_4$	TRL9 – many fallback options – 98.5%	0	TRL9 – few fallback options – 98.6%	0	TRL9 – few/no fallback options – 98.0%	7		
CH_4 gas							TRL9 – no fallback options – 99.99%	0

3. Conversion installations

We examined the TRL of the conversion installations, distinguishing between the centralised and decentralised conversion of hydrogen carrier to hydrogen, and of the synthesis of some hydrogen carriers using hydrogen from the national hydrogen network.

- Our assumption is that centralised conversion installations in ports of entry only become active after the import facilities themselves are in order. In the absence of adequate certainty on the availability of raw material, the installations will not be taken into use. No extra storage is needed for the installations.
- A problem in a conversion installation results in a cutoff of hydrogen input into the pipeline network. However, redundancy through other installations, adequate storage in the network and in salt caverns allow end users' hydrogen demand to be met.
- The synthesis of hydrogen carriers using hydrogen taken from the national network needs no additional storage, as the network and underground storage offers adequate storage for this process.
- The decentralised conversion of hydrogen carriers into hydrogen does require extra storage capacity as the pipeline network offers no backup. Disruptions in the supply to decentralised conversion also disrupt the process. We therefore assume the need here for 2 units of additional storage.
- In the transition to an emission-free energy system, industrial end users will keep their connections to the natural gas network; this will then offer reserve capacity in the event of disruptions in the supply of hydrogen carriers.

Table 21: The reliability of hydrogen carrier supply chains: conversion plants

	TRL of conversion installations	Additional storage requirement
H_2 gas		
NH_3	Cracking: small/medium-scale TRL9, **large-scale TRL7, demonstrations** planned Synthesis from H_2: TRL9	Centralised 0; decentralised +2 Synthesis: 0
LH_2	Evaporation: TRL9 small-scale, **TRL8 large-scale** Liquefaction: TRL9 small-scale, **TRL8 large-scale** LH_2 import chain demonstrated between Australia and Japan	Centralised 0; decentralised +2 Synthesis: 0
DBT	Dehydrogenation: **small-scale TRL8**, all supply chain steps demonstrated (Europe)	Centralised 0; decentralised +2 Synthesis: 0
MCH	Dehydrogenation: **small-scale TRL8**, all supply chain steps demonstrated (Japan)	Centralised 0; decentralised +2 Synthesis: 0
Methanol	**Steam reforming to H_2: TRL7** Synthesis from H_2: TRL9	Centralised 0; decentralised +2 Synthesis: 0
LSM	Steam reforming to H_2: TRL9 Evaporation: TRL9	Centralised 0; decentralised +2 Synthesis: 0
Sodium borohydride	$NaBH_4$ synthesis TRL9, **recycling steps TRL5,** not all chain steps have been demonstrated	Centralised 0; decentralised +2 Synthesis: 0
CH_4 gas	Steam reforming to H_2: TRL9	Centralised 0; decentralised +2 Synthesis: 0

In conclusion

The TRL analysis above formed input for an expert session. This session also took account of other elements, such as the robustness of modalities, in order to come to an assessment of the various supply chains with regard to the public interest Reliable.

Chains with return logistics for spent fuel (LOHCs, sodium borohydride) are more complex, and therefore have more potential points of failure. This leads to lower reliability. This is automatically reflected in the scores, because storage and conversion occur more than once in these chains.

4. SAFE & SECURE

Three sub-indicators are used for the public interest Safe & Secure: external safety, cybersecurity and terrorism, and transport safety.

External safety

Hydrogen carrier supply chains present a risk to society as a consequence of unintended incidents during the transport and processing of (dangerous) hydrogen carriers. This risk is defined as the likelihood of a given incident multiplied by the negative effect (consequence) of this incident. The regional risk profile method and the country-wide national security risk analysis can be used to assess the risk of incidents.[96] As this method is very elaborate, it was employed in a simplified form in this MCA study, for a limited number of incident scenarios in the Dutch supply chain steps except for end use, and for abstract rather than specific geographical locations.

The likelihood of an incident occurring depends on the number of installations, or the number of logistical movements and the distance travelled, and the specific probability of an incident. The effects (consequences) of an incident depend on the danger presented by the substance, in terms of the number of fatalities resulting from an incident. The focus of this assessment lies on the most serious possible incident, but other effects have also been considered.

Probability class	**% per 5 years**
Very improbable	<0.05%
Improbable	0.05 - 0.5%
Somewhat probable	0.5 - 5%
Probable	5 - 50%
Very probable	50 - 100%
Impact class	**E.g. number of fatalities**
Limited	1
Substantial	1 - 4
Serious (low) (high)	4 - 16 16 - 40
Very serious (low) (high)	40 - 160 160 - 400
Catastrophic	> 400

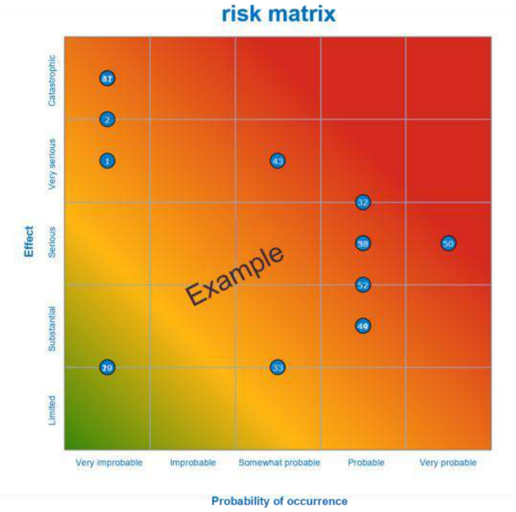


Figure 93: Scale distribution given by the regional risk profiles and example risk matrix

The external risk of a supply chain was assessed in two expert sessions that examined six types of incident to create risk matrices. Participants in these sessions included experts from national Security regions, environmental services, port authorities, the RIVM, knowledge institutes, and representatives of the provinces and of national government. Figure 93 shows an example of such a matrix; the table explains how the scales are to be interpreted. The axes are logarithmic: moving to the next box represents a factor 10 change. The experts estimated the position of each incident on the risk matrix; for each supply chain the risks of various types of incidents were summed. In discussion with the experts it was decided not to publish these matrices because when taken out of context these could be misunderstood, and mistaken interpretations could lead to confusion in the public debate. In this annex we therefore confine ourselves to a summary

---

[96] *Analistennetwerk Nationale Veiligheid, Rijksbrede Risicoanalyse Nationale Veiligheid*, 2022, Arcadis, Gemini Consultants, Houdijk Advies, Stichting Werkgemeenschap tussen Techniek en Zorg, *Handreiking regionaal risicoprofiel*, 2009.

of the qualitative arguments in the assessment. This is the result of expert judgement on the basis of the best estimates that experts in a structured discussion session could provide. Little experience with many hydrogen carriers has been accumulated to date; that is to say, there is experience with the substance, but not with its function as a hydrogen carrier. A more comprehensive scientific study is therefore advised.

Information on the probability and effect of the various incidents is multiplied to yield a ‘risk per incident’, and for each supply chain the various incidents are combined. The total risk is used to determine a relative ranking of the different supply chains.

Incident scenarios

The table shows the most serious consequences of the six incident scenarios discussed below. An ‘impact category’ can be a toxic cloud, an explosion, or a pool fire. An ‘incident scenario’ is the specification of a possible incident.

Table 22: The most serious effect category per incident (incident scenario)

	Most serious effect category per incident					
Carrier	Road transport	Rail transport	Inland shipping	pipeline	Storage	Conversion
NH_3*	toxic cloud	toxic cloud	toxic cloud, damage above waterline	toxic cloud	toxic cloud	toxic cloud
LH_2	explosion, BLEVE (warm/cold)	explosion, BLEVE (warm/cold)	explosion	H_2 pipeline: explosion	explosion	explosion
LOHC**	pool fire	pool fire	pool fire	pool fire	pool fire	pool fire
MeOH	pool fire	pool fire	pool fire	pool fire	pool fire	pool fire
LSM	flash fire, pool fire, jet fire, BLEVE[97] (warm/cold)	flash fire, pool fire, jet fire, BLEVE (warm/cold)	flash fire, (pool fire)	CH_4 pipeline: explosion with jet fire	flash fire, pool fire, jet fire, BLEVE (hot/cold)	flash fire, pool fire, jet fire, BLEVE (hot/cold)
$NaBH_4$	explosion (on contact with water)	explosion (on contact with water)	explosion (on contact with water), damage below waterline	not applicable	explosion (on contact with water)[98]	explosion (on contact with water)

*) In practice a distinction is drawn between NH_3 that is liquid under pressure (hot) and that is liquid due to cooling (cold). The impact of the cooled liquid is smaller, as the toxic cloud spreads more slowly. On the other hand, the evaporation of a pool of ammonia creates a long-lasting emission of gases.

**) The expert session assessments drew no distinction between DBT and MCH; Both substances are combustible, but have a very limited effect area. The amount of hydrogen present principally determines the area of attention and the group risk. A new insight is that there is a difference between these two LOHCs: the greater viscosity of DBT is a favourable aspect, as DBT spreads more slowly and possibly less far than MCH. Also, MCH is toxic but DBT is not.

---

[97] Boiling Liquid Expanding Vapour Explosion. A BLEVE is the explosion of a container filled with a pressurised liquid. In a cold BLEVE the container is torn open by a collision, construction fault, or wear and tear. In a hot BLEVE the container bursts open as a result of external heating.

[98] This substance has not yet been included in environmental services’ calculations of storage risks. River flooding could pose a risk for sodium borohydride stores.

Details per incident scenario

Since we are considering incident scenarios, an incident has by definition occurred.

1. Road transport incident

A road transport accident will cause a pool fire (e.g. LOHC) or a toxic cloud (e.g. ammonia) because the tank truck's tank is torn open or leaks after a collision, for instance. Besides any human victims, there will be material damage and environmental emissions. The risk is assessed for the most serious consequences per hydrogen carrier.

The probability of an incident is related to the number of logistical movements of 200 km.

It is determined by the probability that a given incident will occur (e.g. the chance that a truck has an accident) and is also related to the number of trips made (the more logistical movements, the greater the likelihood). As the inland route length is taken as 200 km for each chain, differences in distance play no role in the comparison. The number of high-risk logistical movements is greater for liquid hydrogen (small amounts per tank truck), LOHC (return transport trips with spent fuel), and sodium borohydride (again, return transport trips with spent fuel). The likelihood of an incident is also related to the characteristics of the substance concerned[99] and the type of incident: a tear or leak in an ammonia tanker will cause an immediate toxic cloud (if being transported under pressure) or following its evaporation (if transported as a liquid; cooled liquid ammonia transport by road and rail is in fact prohibited). Other materials may not give immediate rise to a pool fire because although a pool may form, it needs to be ignited for it to start burning.

The severity of the effect is estimated to be greatest for a toxic cloud of ammonia. In any given area, those present are more likely to be exposed to a toxic cloud than to a pool fire or explosion. Liquid hydrogen is more easily ignited than LSM, but the amount of liquid hydrogen transported is smaller, and LSM burns more strongly than liquid hydrogen and the other carriers. LOHC is difficult to ignite. The effect of a methanol pool fire is estimated as similar to that of LOHC. Sodium borohydride is stable unless it comes into contact with water. This is an issue for firefighters.

2. Rail transport incident

In this incident, which is largely similar to one on the road, a pool fire (e.g. LOHC) or a toxic cloud (e.g. ammonia) may arise if a tank wagon tank is torn open or leaks as the result of a collision, for instance. Besides human victims, there will be material damage and environmental emissions. The risk is assessed for the most serious consequences per hydrogen carrier.

The likelihood of an incident is determined by the probability that a given incident will occur (e.g. the probability of an accident with a tank wagon) and is also related to the number of journeys (the more logistical movements there are, the higher the chances of an incident). The number of high-risk logistical movements is greater for liquid hydrogen (small amounts per tank wagon), LOHC (return transport trips with spent fuel), and sodium borohydride (again, return transport trips with spent fuel). The likelihood of an incident is also related to the characteristics of the substance concerned and the type of incident: a tear or leak in an ammonia tanker will generally cause an immediate toxic cloud. Other materials may not give immediate rise to a pool fire because although a pool may form, it needs to be ignited for it to start burning. A rail transport

---

[99] During storage and transport, the liquid or solid state is safer as liquids and solids are the easiest to manage in different environmental circumstances. The high pressures or low temperatures required to liquefy gas-based hydrogen carriers necessitate additional precautions for their safe handling. $NaBH_4$ powder needs to be kept dry during storage and transport. A high boiling point and a low vapour pressure are favourable to the prevention of leakages, including through boil-off. In the event of a leakage, high flashpoints (low flammability) and autoignition temperatures raise the danger of fire and explosion, and increase thermal radiation within conversion installations. Toxic materials (having a high score on the Toxicity Potential Index) that exist or become a gas during a leak can lead to a toxic cloud.

accident is less likely than a road transport accident, because there are fewer logistical movements (larger volume per wagon) and because the average incident probability per kilometre is lower for rail than it is for road transport.

The severity of the effect is estimated to be greatest for a toxic cloud of ammonia. In any given area, those present are more likely to be exposed to a toxic cloud than to a pool fire or explosion. Liquid hydrogen is more easily ignited than LSM, but the amount of liquid hydrogen transported is smaller, and LSM burns more strongly than liquid hydrogen and the other carriers. LOHC is difficult to ignite. Sodium borohydride is stable unless it comes into contact with water. This is an issue for firefighters. Compared to road transport, the effect of a rail incident is smaller because leaking liquids are absorbed by the track.

3. Inland waterway transport incident

An inland water transport incident will cause a pool fire (e.g. LOHC) or a toxic cloud (e.g. ammonia) because the vessel's tank is torn open or leaks above the waterline after a collision, for instance with a bridge. Besides human victims, there will be material damage and environmental emissions. The risk is assessed for the most serious consequences per hydrogen carrier (which are largely identical to the consequences for road and rail transport).

A worst-case scenario is assumed. That is, a leak above the vessel's waterline, allowing a toxic cloud to be released or a pool fire to form around the vessel. The exception is sodium borohydride, for which the worst-case scenario involves a leak below the vessel's waterline.

The likelihood of an incident is determined by the probability that a given incident will occur (e.g. the probability of an accident with an inland vessel) and is also related to the number of journeys (the more logistical movements there are, the higher the chances of an incident). The number of logistical movements is greater for liquid hydrogen (small amounts per tanker vessel), LOHC (return transport trips with spent fuel), and sodium borohydride (again, return transport trips with spent fuel). The likelihood of an incident is also related to the characteristics of the substance concerned and the type of incident: a tear or leak in a tanker vessel carrying ammonia will generally cause an immediate toxic cloud. Other materials may not give immediate rise to a pool fire because although a pool may form, it needs to be ignited for it to start burning. Compared to road and rail transport the likelihood of an incident is lower, because the number of journeys is smaller and because rivers are much less crowded than roads, for instance.

Compared to road and rail transport the effect of an incident on the water is larger, however, because the loads being transported are larger (even if the tanks are compartmentalised). The severity of the effect is estimated to be greatest for a toxic cloud of ammonia.[100] In any given area, those present are more likely to be exposed to a toxic cloud than to a pool fire or explosion. If ammonia is released and comes into contact with the water, it is partly dissolved and spreads partly through the water, after which warming gives rise to a thinner and less dangerous cloud than in the event of a pipeline fracture. Liquid hydrogen is more easily ignited than LSM, but the amount of liquid hydrogen transported is smaller, and the impact of an LNG flash fire is estimated to be greater than that of other carriers. Methanol is also partly dissolved in water and partly spreads across the surface, reducing the effect of a pool fire. Leaking LOHC forms a flammable layer on the water surface, but this is difficult to ignite. Sodium borohydride is stable unless it comes into contact with water, which would be the case in the event of a leak below the ship's waterline. The hydrogen released by the sodium borohydride could then be explosive. Dissolved ammonia and methanol are toxic to marine life.

---

[100] The majority opinion of the expert session was that an ammonia leak from an inland vessel would have a larger effect than an LNG leak. It was also argued, however, that ammonia can be smelled from a great distance, allowing an escape, whereas an explosion following an unnoticed (invisible and odourless) leak of LNG/LSM would kill everyone in the area.

4. Pipeline transport incident

In pipelines, two kinds of incidents are possible. The first is the failure of a compressor or pump in a compressor station. The number of compressor stations determines the risk per chain. For example, the failure of a compressor can result in a jet fire (e.g. of hydrogen) with few emissions, or in a toxic cloud (e.g. of ammonia). The material damage comprises the replacement of the installation (following a fire) or is limited in case of a toxic cloud. The second type of incident is a fracture in the main pipeline. Every kilometre of pipeline is subject to a risk of leakage as the result of a fracture or excavation damage. This failure can also result in a jet fire (e.g. of hydrogen) having few emissions, or in a toxic cloud (e.g. of ammonia). The material damage comprises the repair or replacement of the section of pipeline concerned.

It was decided to consider these two emergencies in combination. The risk is assessed for the most serious consequences per hydrogen carrier.

Transport by pipeline is the transport method with the lowest probability of an incident. The likelihood of an incident is very low for all hydrogen carriers under consideration; for LOHC it is slightly higher because of the need for both supply and return pipelines. A compressor or pump failures is more likely than a main pipeline fracture, but a fracture has more effect.

The *severity of the effect* of a pipeline fracture or pipeline compressor failure is estimated to be greatest for a toxic cloud of ammonia. In any given area, those present are more likely to be exposed to a toxic cloud than to a pool fire or explosion. The effect is much greater than that of a leaking tanker vessel because of the larger volumes released, and because on land the cloud is not 'diluted'. The larger the pipeline diameter, the larger the effect. The effect can be limited by installing safety shutoff valves in the pipeline so that the release can be stopped ('compartmentalisation'). The difference in effect between the two ammonia pipeline variants (large/small diameter, with/without compartments) is indicated in the matrix. A fracture in a natural gas or hydrogen pipeline would lead to a jet fire, rather than an explosion, because of the high inflammability of these gases. Time is a factor: once a jet fire has started its effect does not increase, while the escape of ammonia from a pipeline leads to a toxic cloud of ever-increasing size. A fracture in a methanol or LOHC pipeline does not immediately result in a pool fire, because both substances are less likely to ignite.

5. Storage tank incident

In the event of the instantaneous failure of a storage tank, the tank is lost and its entire contents are released into the environment. For instance, stored ammonia then becomes a toxic cloud, while LOHC can form a pool fire (see Table 22). It is assumed that material damage is limited to the replacement of the tank. The risk is assessed for the most serious consequences per hydrogen carrier.

The probability of occurrence of the instantaneous failure of a hydrogen carrier storage tank is very low. Storage is a static situation in which transport and handling are unnecessary, so risk levels are reduced. The risk increases when additional tanks are needed to handle the required volume of hydrogen carrier. This is particularly true for LOHC and sodium borohydride, as storage is also required for spent fuel, and for liquid hydrogen because this is stored in smaller (and therefore more numerous) tanks. Methanol, LOHC and sodium borohydride are stored in ordinary single-walled tanks, while cooled or pressurised liquids are stored in special double-walled tanks. The likelihood of an incident is therefore larger among the first three carriers than among the gaseous carriers.

In an instantaneous tank failure, its entire contents can be released, an amount in the same order of magnitude as a pipeline failure. The severity of the effect is estimated to be greatest for a toxic cloud of ammonia. This effect spreads across a large area, and therefore involves a greater exposure than is the case for a fire or explosion of a tank containing LSM or liquid hydrogen, the effects of which are generally limited to a usually thinly-populated industrial location. The effect of failure of an LSM tank is larger, because larger volumes are stored. The storage of cooled ammonia is safer than that of pressurised ammonia, as pressurised ammonia spreads more quickly through the air. This means there is less time for people to escape than when there is a pool of cooled ammonia, which must first evaporate.

6. Conversion installation incident

Conversion processes may involve high working temperatures, and the need for or generation of heat may cause safety problems through overheating. Our assumption is that installations and equipment are designed and employed in accordance with the strictest safety standards and procedures, and that all necessary precautions are taken. Standards, procedures, and safety measures are more highly developed for hydrogen carriers that have long been employed in the industry than they are for new carriers. Incidents can nevertheless occur; an incident may cause an external fire with a limited impact on the environment (limited emissions of hydrogen carriers as well as soot, CO, CO_2, and possibly toxic vapours, etc.). The material damage is considerable (requiring replacement of the installation). In this study the number of conversion installations determines the risk per supply chain, given that the volume is of limited distinctiveness. The risk is assessed for the most serious consequences per hydrogen carrier.

The probability of an incident in a conversion installation is higher than for storage tanks, because many of the processes take place under pressure or at high temperature, involve moving parts, and include linking sections between different parts of the installation, which can become weak points. Liquid hydrogen involves only heat exchange, so the likelihood of an incident is lower. This likelihood is estimated as being slightly higher for LOHC; the greater volumes involved (assuming the same tank size) require more installations.

For all hydrogen carriers, the severity of the effect is estimated as being lower than that for storage facilities because the amount of hydrogen carrier present in an installation will be smaller than that held in a storage facility. Once again, the most serious effect is the formation of a toxic cloud of ammonia following the failure of an ammonia cracker. This is an effect that extends across a wide area and therefore involves more exposure than a fire or an explosion in an evaporator or steam reformer, whose effect is generally limited to a usually thinly-populated industrial location.

Cybersecurity and terrorism

The second indicator of the public interest Safe & Secure is cybersecurity and terrorism.

A hydrogen carrier supply chain could become the target of a cyber attack or a terrorist attack. In the framework of this study, an expert session was held in order to estimate this risk. Participants included safety region experts, infrastructure managers, and representatives of industry and national government. Because of the sensitivity of the subject, it was decided not to publish the results of this discussion. In this annex we will cover only the main principles.

The risk is assessed by multiplying probability by effect. By ‘probability’ we mean the vulnerability or susceptibility of the supply chain to a cyber attack or terrorist attack. This an estimate of vulnerability in the absence of other mitigating measures beyond that which have already been implemented or is required by law. Vulnerability to a cyber attack or terrorist attack was estimated by the experts for a number of separate supply chain steps.

The likelihood of an attack is also determined by the periodic or variable threat assessment: which organisations set out to claim victims, to disrupt society, or to employ economic blackmail. There is a potential threat with regard to the energy supply, particularly pipelines and industrial installations, from state actors, activist circles, and criminal organisations committing blackmail. This is the domain of the security services, and we do not include it in our consideration. For the scores this means that the likelihood will generally be lower when the threat level is falling and higher when it is rising. This will probably not affect relative ranking levels.

The severity of the effect of an incident in a hydrogen supply chain was determined in the aforementioned expert sessions with external safety professionals. ‘External safety' concerns the probability of an incident during normal operation; ‘cybersecurity’ concerns the vulnerability of supply chain steps to intentional disruption. How easy would it be for a third party to cause an incident? The first principle is that in both cases the effect is the same. The effect can vary, however, in terms of the physical consequences (fatalities, material damage) and the economic consequences (e.g. paralysing the energy system).

A cyber attack could lead to an incident with more serious effects than an ordinary incident (as assessed for external safety). It is conceivable that an ICT hack could lead to the delayed detection of a dangerous incident such as a leak or deliberate release, or to a delayed emergency response such as the manual closure of a valve because the ICT is no longer working. In that case, a cyber attack would have more serious consequences. In principle this ‘additional’ risk could occur with any hydrogen carrier, and is therefore not taken into consideration. Moreover, this risk can be obviated if emergency shutdown systems operate autonomously and are not connected to the internet.

Transport safety

The third indicator for the public interest Safe & Secure is transport safety.

The transport of hydrogen carriers by road, rail, and inland waterway may lead to an increase in the number of traffic accidents.[101] The social costs of traffic accidents are expressed by the Netherlands Institute for Transport Policy Analysis (KiM) and CE Delft in average amounts per transported volume in tonne-km.[102]

The evaluation of transport safety includes the following social costs:

- Medical costs
- Assistance costs
- Material costs
- Production loss costs
- Immaterial costs
- Traffic congestion costs

The costs for the transport safety sub-indicator are calculated by multiplying these valuation figures by the transport volumes (in tonne-km) for each supply chain (see Annex A). A correction is applied to these figures for liquid hydrogen because of its low energy density: costs are raised by a factor of 5.

Pipelines are not subject to traffic accident costs.

---

[101] The transportation of hydrogen carriers will eventually also replace that of other fuels. This will reduce the transportation of fossil fuels. This effect has not been included in our model.

[102] O. Jonkeren and J. Franke, Netherlands Institute for Transport Policy Analysis | KiM, Kennisbasis Goederenvervoer (Freight transport knowledge base), Memorandum, February 2023. CE Delft, *Toekomstverkenning, De prijs van een reis, Verkennende analyse richting 2050*, May 2022.

Table 23: Valuation figures for the marginal costs of traffic accidents (source KiM 2023 and CE Delft 2022)

Mode of transport	Average costs per 1000 tonne-km*	Explanatory notes
Road	€3.30	average truck, KiM
By rail	€0.18	average train, KiM
By water	€0.41	average inland vessel, KiM
Pipeline, H_2 net, natural gas network	€ -	

*) LH_2 correction: costs are raised by a factor of 5.

5. SUSTAINABLE

Three sub-indicators are employed for the public interest Sustainable: greenhouse gases, energy loss, and material consumption. NO_X emissions are considered in relation to the public interest Environment.

Greenhouse gases

The first sub-indicator for the public interest Sustainable is the emission of greenhouse gases. In hydrogen carrier supply chains greenhouse gases may be emitted at a number of stages:

- Carbon dioxide, as the result of motorised transport to and within the Netherlands.
- Methane through the boil-off of LSM during transport and storage and through leakages in the natural gas network.
- Hydrogen through the boil-off of liquid hydrogen during transport and storage and through leakages in the hydrogen network.
- Nitrous oxide during ammonia cracking.

The steam reforming and synthesis of LSM and methanol also release CO_2. It is assumed that CO_2 of fossil origin from an industrial point source will be used to synthesise LSM and methanol in 2030. If this CO_2 is stored in the exporting country as methane or methanol, and is released again in the Netherlands through steam reforming, this represents a net emission of CO_2 that is assigned to the supply chain. Some CO_2 also escapes during synthesis. We assume that CO_2 from direct air capture will be used in 2050. In this case, the CO_2 released during steam reforming (and also the CO_2 that escapes during synthesis) is not assigned to the supply chain.

Greenhouse gas emission during transport through fuel use

For CO_2 emissions during transport in the Netherlands we use KiM benchmark figures (based on CE), expressed in kilogrammes of CO_2 per tonne-km, for trucks, trains and inland vessels.

- We take as representative figures the average values for goods transport by road, rail and water in four ‘freight corridors’ in the Netherlands: North (through the northern Netherlands towards northern Germany), East (towards central and southern Germany), South-East (towards southern France through Luxembourg) and South (towards Antwerp and western France).
- We assume that in 2030 the emission factors for trucks, trains, and inland vessels will be down to 85% of their values in 2018-2023 because of stricter standards imposed by EU regulations and climate-related ambitions.[103] For 2050 we assume that all road and inland waterway transport will be emission-free.
- We assume that the proportion of electric train kilometres will be 75% and that of diesel train kilometres 25%. These figures are taken from the European Handbook (CE Delft 2019) for the Netherlands.
- Because liquid hydrogen has a lower energy density than the other hydrogen carriers under consideration, a factor of 5x as many logistical movements is applied.
- For pipelines we assume that compressors and pumps are electric.

For greenhouse gas emissions from seagoing transport to the Netherlands we use benchmark figures from the STREAM study by CE Delft.[104]

---

[103] The European Commission intends that in 2030 new trucks will emit 45% less CO_2 than in 2019, rising to 90% less in 2040. We assume that comparable improvements will apply to trains and inland vessels.

[104] CE Delft (2021), *STREAM Goederenvervoer 2020. Emissies van modaliteiten in het goederenvervoer* – Version 2, February

- For seagoing transport we take the values given for a deep sea bulk carrier of 35,000-60,000 dwt (deadweight tonnes), with no correction for 2030. For 2050 we assume that marine transport greenhouse gas emissions are net-zero, in line with IMO targets.

Table 24: Greenhouse gas emissions during transport (KiM, STREAM). CO_2, CH_4, N_2O expressed in CO_2 equivalents

Greenhouse gas emissions during transport (KiM and STREAM)			
Sum of tank-to-wheel+well-to-tank	g CO_2eq / tonne-km	Corrected value, 2030	Corrected value, 2050
Road	12.6	11	0
By rail	1.2	1	0
Inland shipping	4.4	4	0
Maritime shipping (import)	6.6	6.6	0
Pipeline	Depending on electricity use		0

Greenhouse gas emissions during transport through boil-off and leakage

Losses during transport and storage have already been described in Annex A:

- During transport of liquid hydrogen, hydrogen is emitted through boil-off. During maritime transport this hydrogen is used for the vessel's engine (0.2% per day, e.g. 1% for the route from Morocco to the Netherlands). Boil-off during transport by tank truck or tank wagon is lost as emissions, but in an inland vessel this boil-off can be used to fuel the engine (1% per day). These per-day losses are multiplied by the duration of the journey (see the annex on volume, page 145). The assumption is that boil-off during centralised storage becomes liquid again, but in decentralised storage it escapes (0.2% per day for 3 days).
- During the transportation of LSM boil-off causes methane emissions. As is the case for liquid hydrogen, during maritime transport this can be fed to the vessel's engine (0.2% per day for 5 days). During centralised storage boil-off turns back into liquid, but in decentralised storage it is ventilated (0.1%). Boil-off during tank truck or tank wagon transport is released (0.55%). Boil-off during inland waterway transport is fed to the vessel's engine.
- According to Gasunie, leakage from the natural gas network and the national hydrogen network amounts to 0.01% along a 200 km route.

Greenhouse gas emissions during conversion in the Netherlands and abroad

According to JRC2, conversion to or from hydrogen carriers involves the release of greenhouse gases in various ways.

- In the case of conversion from a carbon-based hydrogen carrier to hydrogen, CO_2 is emitted during the steam reforming of methane (8.89 kg CO_2 per kg of hydrogen) and methanol (9.7 kg CO_2 per kg of hydrogen). We assume that in 2030 the synthesis of methane or methanol will use CO_2 from an industrial point source. The assumption is that CO_2 capture will be 90% effective, and that 10% will therefore be released to the air. In synthesis a small fraction of the CO_2 used is lost (85 g CO_2 per kg methanol). In 2050 the CO_2 used for synthesis will be captured directly from air; then the net CO_2 balance in methanol and LSM supply chains is zero.
- According to JRC2, cracking ammonia releases a small amount of N_2O (4.89 mg per kg hydrogen), besides NO_X and ammonia.

- With the evaporation of LSM, 0.01% leaks away as gaseous methane, and in the steam reforming of LSM a small amount of methane is released (0.002%).
- Hydrogen is released during the synthesis of ammonia (0.77 g hydrogen per kg ammonia), the evaporation of liquid hydrogen (1.6%), and the dehydrogenation of DBT (3.1 g hydrogen per kg hydrogen) and MCH (values taken from DBT).
- The synthesis of methanol from hydrogen and CO_2 releases 0.2 g hydrogen per kilogramme of methanol. In 2050, the direct air capture of CO_2 during synthesis will also involve the release of hydrogen during its combustion for process heating purposes (0.25 g hydrogen per kg of hydrogen).

Table 25: Greenhouse gas emissions during the storage and conversion of hydrogen carriers (JRC2)

Emissions during storage and conversion in g/kg H_2eq in the Dutch part of the supply chain			
carrier	chain step	emission type	g/kg H_2eq
DBT/MCH	dehydrogenation	H_2	3.1
LH_2	evaporation	H_2	16
LH_2	liquefaction	H_2	20
LSM / CH_4	steam reforming	CO_2	8,890 (2050: 898)**
LSM / CH_4	steam reforming	CH_4	0.02
LSM	evaporation	CH_4	0.1
MeOH	steam reforming	H_2	2.5
MeOH	steam reforming	CO_2	9,700 (2050: 970)**
MeOH	synthesis	H_2	1.6 (without DAC) 4.49 (with DAC)
MeOH	synthesis	CO_2	676
NH_3	synthesis	H_2	4.3
NH_3	cracking	N_2O	0.00489
Emissions storage and conversion in g/kg H_2eq in producer countries			
DBT/MCH	hydrogenation	H2	1
LSM	synthesis	CO_2	0
LSM	synthesis	H_2	1.99 (without DAC) 4.51 (with DAC)
MeOH	synthesis	CO_2	676 (2050: 0)**
MeOH	synthesis	H_2	1.6 (without DAC) 4.49 (with DAC)
$NaBH_4$	not applicable	--	unknown*

*) $NaBH_4$ conversions are not considered in JRC2, and in the available literature we were unable to find information on emissions in the various stages of production, carrier conversion, and spent fuel recycling.

**) The synthesis of methanol and LSM uses CO_2 (from industrial sources or direct air capture); in conversion to hydrogen this CO_2 is released. In 2030 we include this 'embedded' CO_2 and in 2050 we exclude it in determining the supply chain greenhouse gas emissions.

Carbon Capture and Storage (CCS) sensitivity analysis of Dutch conversion installations

In the baseline situation, steam reforming installations for methanol and methane emit CO_2 to the air. We employed a sensitivity analysis to determine the effect of CO_2 capture and storage in Dutch installations; we assume that no CCS is employed during synthesis. This leads to changed assumptions with regard to CO_2 emissions in the supply chains concerned: we assume a 90% capture rate, even though this rate has not yet been achieved in practice.[105] 10% is lost to the air.

Global Warming Potentials

We employ the GWP values for the emitted greenhouse gases, as given in Table 26. Global Warming Potential is a relative measure, which expresses the climate-warming potential of a Greenhouse gas in comparison with that of CO_2 over a given period of time. The period of time matters, because some greenhouse gases remain active in the atmosphere for longer than others.

---

[105] Institute for Energy Economics and Financial Analysis, Carbon Capture and Storage, https://ieefa.org/ccs

In policy-making, a period of 100 years is usually assumed, but other periods have also been chosen, such as 20 years and 50 years. The GWP is thus the warming potential over a period of 100 years of 1 kilogramme of the gas compared to 1 kilogramme of CO_2.

Table 26: Global Warming Potentials of greenhouse gases (IPCC[106])

Greenhouse gas	Global Warming Potential (100 years)
CO_2	1
CH_4	27.9
H_2	11.6*
N_2O	273

*) The GWP of H_2 is absent in the IPCC source; this value is taken from Sand, M., et al. (2023).[107]

Environmental price of CO_2

We multiply the GWP figure by the environmental price of CO_2 emissions according to the environmental prices handbook published by CE Delft (€130/tonne CO_2).[108] For each hydrogen carrier supply chain we can then sum up the greenhouse gas emissions per kilogramme of hydrogen equivalent, monetarise it, and on this basis give each supply chain a score on a scale of 0 to 1.

Energy loss

The second sub-indicator for the public interest Sustainable is energy loss.

In hydrogen carrier supply chains an energy input is required for a number of stages:
- For the production of hydrogen in the country of export;
- For the production of the hydrogen carrier ('packing');
- For storage and transport to the Netherlands;
- For transshipment/storage in Dutch ports of entry;
- Where required, the conversion of the hydrogen carrier to hydrogen;
- For the transport of hydrogen carrier or hydrogen within or through the Netherlands by means of pipeline, inland vessel, train or truck;
- For storage at the end user's location;
- Where required, for decentralised conversion, whether of hydrogen carrier to hydrogen or of hydrogen from the hydrogen network to hydrogen carrier;
- Finally, energy is lost during end use; this occurs 'behind the end user's gate' and is not taken into consideration here.

This energy input can be regarded as energy loss. The supply chain that needs the least energy input to deliver a kilogramme of hydrogen equivalent to the end user is given the highest score in this regard. The energy input can be delivered from an external source (e.g. electricity for pumps or fuel for vessels) or taken from the hydrogen carrier itself (as in the use of LSM or methanol for process heat in steam reforming). We also include leakage in energy loss.

---

[106] Global Warming Potential Values: IPCC GWP100 values are taken from, AR6 Climate Change 2021: The Physical Science Basis, 2021. These values were adopted by JRC.

[107] Sand, M., R.B. Skeie, M. Sandstad, S. Krishnan, G. Myhre, H. Bryant, R. Derwent, et al. (2023), 'A Multi-Model Assessment of the Global Warming Potential of Hydrogen', *Communications Earth and Environment*, Vol. 4, No. 1, 2023.

[108] CE Delft (2023), *Handboek Milieuprijzen* (Environmental Prices Handbook 2023), *Methodische onderbouwing van kengetallen gebruikt voor waardering van emissies en milieu-impacts* (Methodological substantiation of benchmark figures used for valuation of emissions and environmental impacts).

Energy loss during import

The following table gives the energy losses per supply chain step up to its arrival in the Netherlands. The energy efficiency of the supply chains is determined by summing the energy losses of all the chain steps and comparing this with the energy content of the End product: a kilogramme of hydrogen (equivalent).

Table 27: Energy losses or energy supply per supply chain step until its arrival in the Netherlands

Carrier	H_2 production MJ/kgH_2	Conversion MJ/kgH_2	Carrier production MJ/kgH_2	Storage for export MJ/kgH_2	Transport to NL* MJ/kgH_2
NH_3	180				2.5
Electricity		16.3		1.38	
H_2 / carrier consumed		0			
Losses				0.14	0.0
LH_2	180				4.2
Electricity		21.6		2.4	
Losses		1.9		2.5	8.4
DBT (MCH)	180				4.1
Electricity		1.33		0	
Losses					
MeOH	180				1.98
Electricity		18.29	14.62	0	
H_2 / carrier consumed		69.8	0	0	
Losses					
LSM	180				2.6
Electricity		0	12.7		
H_2 / carrier consumed		99.7	0		
Losses		0.06		0	
$NaBH_4$	180	482.2	198.0		1.65
Recycling			423		

*) 3000 km transport to the Netherlands

**) Energy demand in an entirely electric process

It is assumed that CO_2 of fossil origin from an industrial point source will be used to synthesise LSM and methanol in 2030. For CO_2 capture, energy is needed for heat or steam and electricity for compression. The amount of energy needed depends largely on the volume of the gas stream from which the CO_2 is captured, the concentration of CO_2 in the gas stream, the process from which the CO_2 is derived, the technology employed, and whether the factory is new or adapted. Following Bargiacchi *et al.* (2020), in the case of a natural-gas powered, combined-cycle unit, we take a value of 18.6 MJ per kilogramme of hydrogen in methanol synthesis and 16.1 MJ per kilogramme of hydrogen in LSM synthesis.[109]

Energy losses within the Netherlands

The following tables give the energy input for the various supply chain steps within the Netherlands.

---

[109] Bargiacchi, Eleonora, Nils Thonemann, Jutta Geldermann, Marco Antonelli and Umberto Desideri (2020), Life Cycle Assessment of Synthetic Natural Gas Production from Different CO_2 Sources: A Cradle-to-Gate Study, *Energies*, September 2020, 13, 4579.

Table 28: **Energy losses (electricity and materials such as fuels) for centralised conversion in MJ/kg of hydrogen equivalent**

Energy loss (electricity) in MJ/kg of H_2 equivalent	output				
input	H_2	NH_3	LH_2	MeOH	CH_4
H_2		16.34	21.60	39.18	
NH_3	17.50				
LH_2	0.049/2.2*				
MCH	Market figure				
DBT	45.00				
MeOH	1.80				
LSM	0.22				0.22
CH_4	0.00				
$NaBH_4$	0.00				

Energy loss (materials such as fuels) in MJ/kg of H_2 equivalent	output				
input	H_2	NH_3	LH_2	MeOH	CH_4
H_2		0.00	0.00	139.49	
NH_3	34.74				
LH_2	0.00				
MCH	0.00				
DBT	0.00				
MeOH	25.66				
LSM	38.89				0.00
CH_4	38.89				
$NaBH_4$	0.00				

*) The higher value is for decentralised, the low value for centralised

Storage also requires energy: this is particularly true for stirring, transshipment, and the liquidation of vapour (boil-off). In the decentralised storage of liquid hydrogen, the vapour is not liquidified because this is not economically viable on the small scale of these storage tanks. For carriers not mentioned in Table 29 there is no energy loss during storage.

Table 29: **Energy losses (electricity) in centralised and decentralised storage, in MJ/kg of hydrogen equivalent (JRC)**

	centralised		decentralised	
NH_3 storage	1.38	MJ per H_2eq	1.38	MJ per H_2eq
LSM storage	2.38	MJ per H_2eq	2.38	MJ per H_2eq
storage LH_2	2.38	MJ per H_2eq	0.00	MJ per H_2eq

Carbon Capture and Storage (CCS) sensitivity analysis of Dutch conversion installations

In the baseline situation, steam reforming installations for methanol and methane emit CO_2 to the air. We deployed sensitivity analysis to determine the effect of CO_2 capture and storage in Dutch installations; we assume that no CCS is used in the country of export. This leads to changed assumptions with regard to energy loss. Following PBL (2020) we assume the following values:[110]

- Electricity required to compress CO_2 for injection into a transport pipeline: 5.4 MJ per kilogramme of hydrogen in methanol reforming and 5.1 MJ per kilogramme of hydrogen in LSM reforming.
- Heat or steam for the CO_2 capture facility: 10.5 MJ per kilogramme of hydrogen in methanol reforming and 9.7 MJ per kilogramme of hydrogen in LSM reforming.
- JRC2 calculates a negligible amount of energy for the transport of CO_2 (less than 0.0002 MJ/kgH_2/km electricity), and does not include the energy demand for underground storage. We therefore also discount the energy demand for CO_2 transport and storage.

Energy losses during inland transportation

Table 30 gives the energy requirements of inland transport in 2030 and 2050.

Table 30: Energy losses of the inland transportation of hydrogen carriers in 2050 in MJ/tonne-km

Energy consumption MJ/tonne-km	Road	By rail	Inland shipping
2030	0.90	0.12	0.40
2050	0.45	0.08	0.20

Material consumption

The third sub-indicator for the public interest Sustainable is material consumption. This concerns the use of materials for installations and processes, and as raw material for hydrogen carriers. If large amounts of scarce materials are required for the hydrogen carrier supply chain we regard this as being less sustainable. While the use of scarce materials also has economic and geopolitical ramifications, these have not been taken into consideration here. Although materials may not necessarily be used up if a closed cycle that includes reuse/recycling is established, the use of these materials nevertheless contributes towards their scarcity. In order to estimate this effect we used the following methodology:

- For each supply chain step we determined which, and how much scarce material is needed for each unit of hydrogen equivalent. We regard a material as ‘scarce’ if it appears on the list of critical and strategic materials maintained by the European Commission.[111] This concerns nickel, platinum and copper in particular (used in catalysers for the conversion of hydrogen carriers), and boron (a constituent of the hydrogen carrier sodium borohydride).
- The most important source for the material intensity of conversion processes is the LCA study JRC2 covering the supply chains for the ammonia, liquid hydrogen, DBT, methanol, and LSM hydrogen carriers. For sodium borohydride, we made our own estimates on the basis of publicly available sources and market information. No data is available for MCH. We have therefore regarded DBT and MCH as being equivalent for the purposes of this public interest.
- We multiply the materials requirement per unit of hydrogen equivalent by the volumes per supply chain as given by the calculations described in Annex A.

---

[110] Values for the SDE++ subcategories of new CO_2 capture in existing installations, such as for methane reforming, and new CO_2 capture in new installations, such as in methanol reforming, according to PBL (2020), *Conceptadvies SDE++ 2021. CO_2-afvang en -opslag (CCS), Planbureau voor de Leefomgeving*, 5 May.

[111] List of critical and strategic materials given by the European Commission.

- We multiply the materials need per supply chain by the market price, because we assume that this price expresses the degree of scarcity of the materials. Market prices are, of course, snapshots.
- We plot the resulting amounts per supply chain on a scale of 0 to 1, whereby 0 stands for the greatest impact of use of materials and 1 for the lowest.

The material use values are summarised in Table 31

Table 31: Material use values according to JRC2, supplemented by team analysis for sodium borohydride. Critical materials (according to the EU Critical Raw Materials list) in bold.

Conversion	Amount*	Market price**	Costs per kgH_2
NH_3 cracking			
Magnesium oxide (94%) and **nickel oxide (6%)**	1.46 g/kgH_2, of which 6wt% nickel oxide with 78.6wt% nickel (Ni)	€16.79/kgNi	€0.0012/kgH_2
DBT dehydrogenation			
Platinum (Pt)	0.16 mg/kgH_2	€27,852/kgPt	€0.0045/kgH_2
MeOH synthesis			
64% **copper oxide**, 24% zinc oxide, and 12% aluminium oxide	133 mg/kg MeOH, of which 64wt% copper oxide with 79.9wt% copper (Cu)	€7.78/kgCu	€0.0005/kg MeOH or €0.004/kgH_2
MeOH steam reforming			
Nickel	0.20 g/kgH_2	€16.79/kgNi	€0.0034/kgH_2
Iron oxide (29%), chrome oxide (3%), copper oxide (33%), and zinc oxide (35%)	1.1 g/kgH_2, of which 33wt% copper oxide with 79.9wt% Cu	€7.78/kgCu	€0.0022/kgH_2
LSM synthesis			
Nickel applied to carrier material **(15wt% Ni)**	15wt% * 0.41g/kgLSM	€16.79/kgNi (plus carrier material)	€0.001/kg LSM or €0.004/kgH_2
LSM steam reforming			
Nickel	0.20 g/kgH_2	€16.79/kgNi	€0.0034/kgH_2
Iron/chrome/copper/zinc composite catalysts, same as in MeOH steam reforming	1.1 g/kgH_2, of which 33wt% copper oxide with 79.9wt% Cu	€7.78/kgCu	€0.0022/kgH_2
$NaBH_4$			
Boron 28.56wt% in $NaBH_4$	B/H_2 ratio is 28.56%/10.66wt%, but the H_2 yield doubles (due to reaction with H_2O), resulting in 1.33 kgB/kgH_2	€34/kg$NaBH_4$, or €119/kgB	€158/kgH_2 single use, but for 6 cycles per year and 20 years: €1.32/kgH_2 [112]

*) Sources for amounts column: JRC2, sodium borohydride team estimate on the basis of market information
**) Sources for market price column:

- Nickel: www.lme.com (London Metal Exchange), https://www.lme.com/Metals/Non-ferrous/LME-Nickel#Summary Nickel#Summary

---

[112] We chose not to include this amount in the import costs for the public interest Affordable in order to keep the two public interests separate and avoid counting the effects twice.

- Platinum: https://stonexbullion.com/en/charts/platinum-price/kilogram/1year/
- Copper: https://www.cablesrct.com/en/copper-prices
- Al_2O_3: https://www.fishersci.nl/shop/products/aluminum-oxide-puriss-honeywell-2/15651010,
- Zeolite: https://www.transparencymarketresearch.com/specialty-zeolites-market.html#:~:text=The%20prices%20of%20specialty%20zeolites%20range%20between%20US%24%2010%20per,zeolite%20product%20to%20be%20manufactured
- $NaBH_4$: https://www.globalsources.com/product/sodium-intermediate-chemical-chemical_1196806149f.htm

Table 32 gives the results of this exercise. If a supply chain has several conversion and synthesis steps, the relevant values are summed.

Table 32: Conversion costs of material use from carrier to hydrogen and vice versa

price of material use per kt				of H_2eq output			
input	H_2	NH_3	LH_2	MeOH	LSM	DBT / MCH	$NaBH_4$
H_2		€ -	€ -	€4207	€4108	€ -	€1,318,812
NH_3	€1156						
LH_2	€ -						
MCH / DBT	€4456						
MeOH	€5613						
LSM / CH_4	€5613						
$NaBH_4$	€ -						

6. ADAPTABLE

By ‘adaptability’ we mean the degree to which hydrogen chains are future-proof. Technological and market developments will create a greater or lesser demand for hydrogen carriers and delivery modalities. To quantify this indicator we examine the additional, inflexible investments involved with each of the supply chains. The lower these investments, the more adaptive the supply chain.

The assessment of adaptability is subject to many uncertainties, but by using a standardised method for all supply chains we assume that the scores will at least be representative with regard to each other. In general, and therefore also with regard to this analysis, there are many uncertainties surrounding the energy transition and the associated products, timeframes, etc. The analysis itself also makes a number of assumptions. It is therefore important that its outcomes are not treated as fixed and certain data, but as an indicative expectation. Moreover, there are considerable uncertainties surrounding the pipeline transport of ammonia, with regard to the choice of pipeline diameters (multiple smaller 8” or 10” diameter pipelines, or a single larger 24” or 32” diameter pipeline).

Methodology

Our methodology is as follows:

- For each supply chain we sum all investments in chain steps to arrive at an overall investment figure. We do this on the basis of the literature and our own calculations of the necessary volumes delivered by the chain in question.
- Together with the experts, for each chain step we estimate (1) the part for which no investment is needed in 2030 because adequate capacity, installations, or modes of transport already exist, available for use in the import streams; and (2) the part of the investment value that can be reused after 2030 or otherwise employed if the market chooses a different hydrogen carrier or modality.

Principles of the calculations

In all supply chains the end use is 1578 kilotonnes of hydrogen equivalent. This figure is taken from the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers and follows the middle variant from the earlier ‘volume study’. For the purposes of this assessment of adaptability, this volume is taken as being equal for all chain steps. This is to simplify matters: each supply chain displays differences in actual volumes per chain step, because more or less hydrogen equivalent will be lost during conversions or due to leaks, depending on the route. For the purposes of chain comparability, our assumption is that the same total volume flows through every chain. In reality, different supply chains will probably be developed at the same time. As it is unclear what the maximum share of each of these chains will be, we assume that the entire volume will pass through a single chain. This choice has an effect if part of the required investment is already present and could be used. This appears to be the case for only a part of the storage of ammonia and transport through the natural gas network and hydrogen network.

By applying hydrogen weight percentages of the carriers and conversion yields in each chain, we can determine how much carrier has to be stored, converted, and transported for each chain. We calculate the required number of installations and means of transport using assumptions about capacities and associated investment costs (from the literature), and about transport times (see Annex B).

We take no account of differences in lifespan. Investments with a short lifespan are favourable to adaptability, but unfavourable to average annual costs (annuity). For LOHCs and sodium borohydride, we assumed double the required storage volumes because the return flow must also be stored temporarily. With pipeline transport of LOHCs, a delivery pipeline and a return pipeline are both required.

A. Inland transport

1. Total investments

The total investment required to transport the volume of hydrogen equivalent are determined by dividing the end use of 1578 kt hydrogen equivalent by the annual transported volume per means of transport (Table 33), and by multiplying the number of necessary means of transport by the estimated investment per means of transport (Table 34).

Table 33: Maximum transport capacity per means of transport in kilotonne (kt) of hydrogen carrier per year

	Pipe/H_2 network	Road	Train/tank wagon	Ship
H_2	1,971			
NH_3	8,200	7.06	6.70	168.81
LH_2		1.05	1.10	31.94
DBT	1,000	7.06	7.96	168.81
MCH	1,000	7.06	7.96	168.81
MeOH	6,893	7.06	7.69	168.81
LSM		4.87	5.48	91.25
$NaBH_4$		7.06	6.69	168.81

The annual transported volumes are determined by the number of days that a truck, tank wagon, or tanker vessel is under way (1.5 days, 3 and 4 days respectively, see the annex on volume) and its maximum capacity (see Table 10, annex on volume).

Table 34: Investment for transport per means of transport in million euros

Input	Pipe / H_2 network	Road	Train/tank wagon	Ship
H_2	260	Outside the scope of this study	Outside the scope of this study	Outside the scope of this study
NH_3	143.60	0.23	0.22	15.00
LH_2	Not possible	0.81	0.42	41.00
DBT	454.40*	0.20	0.19	12.00
MCH	454.40*	0.20	0.19	12.00
MeOH	143.60	0.20	0.19	12.00
LSM	Not possible	0.23	0.22	15.00
$NaBH_4$	Not possible	0.20	0.19	12.00

*) The investment is for the combined delivery and return pipelines.

Table 35 shows the investments needed to transport 100% of the end use in 2030 in a single supply chain.

Table 35: The investments needed to transport 100% of the end use in 2030 in a single supply chain

Supply chain step	Tank trucks (by road)	Tank wagon (by rail)	Tanker vessel (inland waterways)	Pipelines, incl. pumps/compressors
H_2	Outside the scope of this study	Outside the scope of this study	Outside the scope of this study	€260 mln.
NH_3	1259 trucks, €287 mln. in all.	1325 wagons, €296 mln. in all.	53 vessels, €789 mln. in all	€156 mln.
LH_2	1508 trucks, €1214 mln. in all.	1441 wagons, €605 mln. in all.	49 vessels, €2026 mln. in all*	Not possible
DBT	3630 trucks, €708 mln. in all.	3219 wagons, €614 mln. in all.	152 vessels, €1821 mln. in all	€11,640 mln. **
MCH	3652 trucks, €712 mln. in all.	3238 wagons, €618 mln. in all.	153 vessels, €1832 mln. in all	€11,709 mln. **
MeOH	1778 trucks, €347 mln. in all.	1631 wagons, €311 mln. in all.	74 vessels, €892 mln. in all	€261 mln.
LSM	1291 trucks, €295 mln. in all.	1147 wagons, €256 mln. in all.	69 vessels, €1032 mln. in all	Not possible
$NaBH_4$	1058 trucks, €206 mln. in all.	1115 wagons, €213 mln. in all.	44 vessels, €531 mln. in all	Not possible
CH_4	Outside the scope of this study	Outside the scope of this study	Outside the scope of this study	Already present

*) An LH_2 tanker vessel will be relatively expensive in 2030. This is a projection for a type of ship that does not yet exist.

**) Several pipelines are required, because of volume and throughput speeds, and also because of doubling for the return flow (spent fuel).

2. Part of investment already made by 2030

Table 36 shows whether the required transport means are already present and available for use for the import of hydrogen carriers. Many of the transport means are given as ‘in use’. By this we mean that although suitable transport means exist, they cannot be taken into use for the volumes of hydrogen carriers because their capacity is already being used for other purposes.

Table 36: Part of investments already present in 2030 (source: experts)

Supply chain step	Tank trucks (by road)	Tank wagon (by rail)	Tanker vessel (inland shipping)	Pipelines, incl. pumps/compressors
H_2 gaseous	Outside the scope of this study	Outside the scope of this study	Outside the scope of this study	Existing investment in H_2 network, to clusters
NH_3	Several hundred, but already in use	Tank wagons available, but already in use	A few dedicated tanker vessels, but already in use	Not yet committed in plans
LH_2	Additional specific trucks needed	Suitable tank wagons not yet available	No suitable tanker vessels	Not possible
DBT	Tank trucks available but already in use	Tank wagons available, but already in use	1500 suitable tanker vessels, but already in use	A suitable pipeline is available for the outbound route, but the return is unlikely, as it may already be in use
MCH	Tank trucks available but already in use	Tank wagons available, but already in use	1500 suitable tanker vessels, but already in use	
MeOH	Tank trucks available but already in use	Tank wagons available, but already in use	1500 suitable tanker vessels, but already in use	Methanol-compatible pipelines exist, though they could already be in use
LSM	Very specific trucks, but already in use	A few tank wagons available, but already in use	A few suitable tanker vessels, but already in use	Not possible
$NaBH_4$	Available for dry loads, but already in use	Tank wagons available, but already in use	3000-4000 suitable dry bulk vessels, mostly in use	
CH_4				In use

Table 36 shows the current or imminent availability of assets that could be used to transport hydrogen carriers.

- For some carriers (ammonia, LSM, methanol, liquid hydrogen) few transport means by road, rail, or waterway are available on the market. For other carriers (LOHCs) the transport means for hydrocarbons can be used. In all cases, the assets are in principle already in use: according to the experts, no spare capacity is available. The market itself can make certain choices: be ahead of the curve, replace infrastructure, organise logistics differently, etc. Transporters will only invest in transport modalities on the basis of signed transport contracts that provide security of return on investment.[113] At this time, few dry bulk transporters hold the ADR certificate needed for the transportation of hydrogen carriers (UN code).

---

[113] There is a difference between public and private investment in pipelines: the Dutch State has decided to build and manage the hydrogen network as part of the Netherlands' national infrastructure, along with its roads, railways, waterways, and natural gas network, water supply system, and electricity grid. Pipelines for hydrogen carriers, like the current existing pipelines for all kinds of hydrocarbons, are regarded as private initiatives to support commercial activities.

- There are pipelines for hydrocarbons that could be re-purposed to transport LOHCs or methanol, but these, too, are not readily available for use. Uniquely, for the hydrogen network natural gas pipelines were available that had been intended for the northern European ‘gas roundabout’. LOHCs need two pipelines: one for the hydrogen-rich and one for the hydrogen-lean carrier. The current pipelines are ‘single point’ pipelines: they only go one way. The direction of travel can technically be reversed if a pipeline becomes available, but it is hard enough to find a single unused pipeline, let alone a to-and-fro route. In theory LOHCs and methanol can be transported using existing (non-dedicated) pipelines if these are converted to ‘multi-product pipeline’ use. If this is not anticipated in the design, however, it is no easy matter. The products being sequentially transported also have to be compatible: no contamination may occur. The degree to which this forms a risk depends on the client's specifications.
- We do not expect the demand for fossil fuels to have fallen strongly by 2030. If this is the case, there are also other products that could take their place, such as bio-LNG in LNG tank trucks, liquid CO_2 in tanker vessels, or sustainable aviation fuel (SAF) in pipelines. That is why we conclude that an entirely new fleet of transport modalities and pipelines should be built for hydrogen carriers: no investments at all have yet been made. Existing transport options chould be used only for pilot projects and first steps. Towards 2050 it may be that certain assets will become available because of a shrinking demand for fossil-fuel products. We assume that in 2050 part of the assets that are present, but in use for other purposes, and which have a longer lifespan than 25 years, can be put to use for hydrogen carriers. We estimate the part of existing assets that can be repurposed by taking the length of the period remaining until 2050 (about 25 years) and dividing this by the lifespan of the assets. This means that tank trucks cannot be reused (having a lifespan of 8-10 years) while vessels and pipelines can (having a lifespan of 50 years, or an indeterminate life expectancy, depending on the design criteria).

3. Part of investment that is reusable for other carriers

Table 37: Part of investment that is reusable for other carriers (source: experts)

Supply chain step	Tank trucks (by road)	Tank wagon (by rail)	Tanker vessel (inland shipping)	Pipelines, incl. pumps/compressors
H_2 gas	Outside the scope of this study	Outside the scope of this study	Outside the scope of this study	100% reusable (biomethane)*
NH_3	0% reusable	No 75%[114]	30% reusable	50% reusable
LH_2	0% reusable	0% reusable	30% reusable	Not possible
DBT	100% reusable*	100% reusable*	100% reusable*	100% reusable*
MCH	100% reusable*	100% reusable*	100% reusable*	100% reusable*
MeOH	100% reusable*	100% reusable*	100% reusable*	100% reusable*
LSM	0% reusable	10% reusable (ethylene)	30% reusable after conversion	Not possible
$NaBH_4$	100% reusable*	100% reusable*	100% reusable*	Not possible
CH_4 gas	Outside the scope of this study	Outside the scope of this study	Outside the scope of this study	100% reusable (biomethane)*

*) In practice the reusability value will be a little less than 100% because there will always be cleaning work and minor adaptations such as a new coating, new measuring instruments, etc.

Table 37 shows the part of the assets for hydrogen carriers that according to expert judgement can be reused (for another hydrogen carrier or material) if the carrier turns out to be a less successful choice. In principle everything is fully in use, but individual parties can deploy transport means in other ways.

- Transport means for liquid hydrogen, ammonia, and LNG/LSM are specially designed and classified for these substances. This means that they may only be used to transport substances falling into the same class. This applies to ethylene in LNG transport means. However, ethylene is transported almost exclusively by pipeline; part of this transport could take place by rail or inland waterway. The declassification and reapproval of transport means is theoretically possible, but does not occur in practice. In practice much transport is dedicated, i.e., a tanker container is always used for the same substance and not for a variety of different ones, to save on cleaning time and costs. Moreover, transport of a different, heavier substance in the tank truck can lead to an excess axle load, which means that the tank cannot be completely filled. This is not the case for transport by rail or vessel.
- Vessels can be adapted to transport other substances than the ones for which they were designed. The hull, engines, wheelhouse and so on can be reused; only the storage tanks and pipework need to be replaced. Of the investment in vessels built to transport liquid hydrogen carriers, 30% is reusable for dry bulk transportation. For tank trucks and wagons we assume that the owners have no incentive for this adaptation.

---

[114] The 75% reusability of these specialised tank wagons only applies if there are not too many of them, otherwise the market is flooded. We assumed 0% to calculate the score.

- Transport means for LOHC and methanol can also be employed for other liquids (100% of the investment is reusable). It may be the case that the safety standards are overly strict, so that the investment in these vessels and tank trucks is higher than necessary.[115]
- We assume that sodium borohydride is transported in waterproofed big bags in standard transport containers. These containers and the associated transport means are entirely reusable for other applications.
- Pipelines for hydrogen or synthetic methane can be reused for biomethane. An ammoniapipeline can be reused for liquids; since it then possesses overly strict safety standards, such pipeline transport is more expensive than necessary. We therefore consider 50% of the investments to be reusable (50% capital destruction).[116]

B. Storage and conversion installations

1. Provisional total investments

The total investments for storage facilities and conversion installations for 1578 kt of hydrogen equivalent end use are estimated by multiplying the required storage and conversion capacity per hydrogen carrier by the investment per kilotonne of carrier (Table 38).

Table 38: Investment for storage and conversion in million euros per kilotonne (kt) of hydrogen carrier

	Conversion		Storage	
	centralised	decentralised	centralised	decentralised
Conversion (dehydrogenation/cracking/evaporation)				
NH_3	€0.69	€1.56	€0.650	€0.75
LH_2	€0.43	€0.60	€16.6	€16.76
LOHC DBT	€14.66	€25.42	€0.264	€0.32
LOHC MCH	€14.58	€25.27	€0.264	€0.32
MeOH	€1.12	€2.12	€0.252	€0.46
LSM	€13.14	€13.14	€4.40	€4.40
$NaBH_4$	€14.66	€25.42	€0.04	€0.04
CH_4 gas	€13.14	€13.14		
Synthesis (including liquefaction)				
NH_3	€1.49	€1.49		
LH_2	€5.75	€5.75		
MeOH	€2.64	€2.64		

---

[115] We assume that 70% of the investment in such tanker vessel is reusable as a dry bulk vessel after conversion.

[116] Ammonia and LH_2 storage tanks can also, in principle, be reused for other liquids such as methanol and certain LOHCs; here too the safety standards in place are overly strict, leading to higher storage costs than when using tanks specifically designed for these liquids.

Table 39 shows the investments needed to transport 100% of the end use in 2030 in a single supply chain.

Table 39: The investments needed to transport 100% of the end use in 2030 in a single supply chain

Supply chain step	Centralised storage at port of entry	Centralised conversion to H_2	Decentralised storage	Decentralised conversion to H_2	Decentralised conversion of H_2 to carrier
NH_3	341 kt, €221 mln. in all	8,884 kt, €1,087 mln. in all	73 kt, in all €55 mln.	8,884 kilotonne, in all €2,461 mln.	8,884 kt NH_3, in all €2,345 mln.
LH_2	61 kt, in all €1,006 mln.*	1,578 kt, €679 mln. in all	13 kt, in all €217 mln.*	1,578 kilotonne, in all €95 mln.	1,578 kt LH_3, in all €9,079 mln.
DBT	1966 kilotonne, in all €518 mln.	25617 kilotonne, in all €23,140 mln.	422 kilotonne, in all €136 mln.	25,617 kt, in all €40,119 mln.	
MCH	1976 kilotonne, in all €522 mln.	25,769 kilotonne, in all €23,004 mln.	424 kilotonne, in all €136 mln.	25,769 kt, €39,883 mln. in all	
MeOH	481 kt, €121 mln. in all	12,545 kt, €1766 mln. in all	103 kilotonne, in all €47 mln.	12,545 kt, €3345 mln. in all	12,545 kt MeOH, in all €4,163 mln.
LSM	241 kt, €1060 mln. in all	6,280 kilotonne, in all €20,729 mln.	52 kt, in all €227 mln.	6,280 kilotonne, in all €20,729 mln.	
$NaBH_4$	572 kilotonne, in all €24 mln.	7,464 kilotonne, in all €23,140 mln. **	122 kilotonne, in all €6 mln.	7,464 kilotonne, in all €40,119 mln. **	
CH_4 gas				6,280 kilotonne, in all €20,729 mln.***	

*) LH_2 storage is relatively expensive; it involves a large number of relatively small tanks because of the TRL.
**) Conversion costs to H_2 per kg of H_2 equivalent assumed equal to LOHC, for lack of more accurate information.
***) This concerns supply chains with centralised evaporation of LSM.

2. Part of investment already made by 2030

Table 40: Part of investments for storage and conversion already available in 2030

Supply chain step	Centralised storage at port of entry	Centralised conversion to H_2	Decentralised storage	Decentralised conversion to H_2	Decentralised conversion of H_2 to carrier
NH_3	6 x 15 kt (OCI, YARA, Dow); 60 kt OCI final investment decision taken	Not available	OCI	Not available	Not available
LH_2	Air Products Botlek (production terminal)	Not available	Not available	Not available	Not available
DBT	Can be stored in diesel tanks; capacity is present (30-40 kt), but not necessarily available.	Not available	Not available	Not available	
MCH		Not available		Not available	
MeOH	Specialised tanks, Rotterdam, Zeeland, Dordrecht, not necessarily available	Not available	Not available	Not available	Not available
LSM	GATE and Eemshaven (floating), Zeeland in planning, already in use, possible ‘peak shaving’ tank at Gasunie	Steam methane reforming, capacity currently in use by refineries	Not available	Decentralised steam methane reforming; low capacity	
$NaBH_4$	Existing powder silos	Not available	Not yet in use	Not available	
CH_4 gas				Decentralised steam methane reforming; low capacity	

Table 40 shows the current or imminent availability of assets that could be used for the storage and conversion of hydrogen carriers.

- For ammonia, methanol and LSM, storage capacity already exists in several ports. Ammonia storage and transfer facilities are still nowhere available at scale, except at existing production and use locations. Its large-scale use, as a hydrogen carrier as well as for feedstock, will require considerable expansion as well as a more finely meshed distribution network (with hubs alongside main transport axes). Similar situations will apply to LSM if this is taken into use as a large-scale energy carrier (other than regasification).

- With regard to liquid hydrogen, the storage capacity available at the Air Products production location could also, in principle, be used for its importation. LOHCs can be stored in existing tanks for hydrocarbons, and sodium borohydride in existing powder silos. There are many plans for expansion of import terminal storage facilities.
- There are as yet few decentralised storage facilities available for hydrogen carriers other than hydrocarbons and ammonia storage at Chemelot.
- Conversion installations to release hydrogen from hydrogen carriers do not yet exist, except for steam methane reformers at oil refineries and fertiliser plants. This steam methane reforming could be used for the conversion of LSM. Equally, conversion installations to synthesise hydrogen carriers from hydrogen do not yet exist in the Netherlands; there are, however, plans for methanol production using hydrogen produced in the Netherlands.
- We do not expect the demand for fossil fuels to have fallen strongly by 2030. If this is the case there are also other products that could take their place in oil tanks and LNG tanks, such as sustainable aviation fuel (SAF) in diesel tanks[117] or bio-LNG in LNG storage facilities.
- We therefore conclude, just as for the transport means, that an entirely new tank farm and installed base of conversion installations needs to be built for hydrogen carriers. The first investments are to be made in the near future. For instance, the company OCI has received a licence to construct a 60 kilotonne storage tank for cooled ammonia in Rotterdam. This is planned for completion in 2030, and we have therefore included it in Table 40 as an investment already made. For other hydrogen carriers we assume that no investments have yet been made.
- Towards 2050 it may be that certain assets will become available because of a shrinking demand for fossil-fuel products. With this in mind we assume that on the basis of its remaining lifespan, part of these existing assets will be available for reuse.

---

[117] Only for JetFuel (JET A-1); as far as we know no alternatives are yet available for AVGAS (aviation gasoline), but this concerns a small amount.

3. Part of investment that is reusable for other carriers

Table 41: Part of investments for storage and conversion that is reusable for other carriers (source: experts)

Supply chain step	Centralised storage at port of entry	Centralised conversion to H_2	Decentralised storage	Decentralised conversion to H_2	Decentralised conversion of H_2 to carrier
NH_3	0% reusable	0% reusable	0% reusable	0% reusable	0% reusable
LH_2	0% reusable	0% reusable	0% reusable	0% reusable	0% reusable
DBT	100% reusable*	0% reusable	100% reusable*	0% reusable	
MCH	100% reusable*	0% reusable	100% reusable*	0% reusable	
Methanol	0% reusable	0% reusable	0% reusable	0% reusable	0% reusable
LSM	0% reusable	0% reusable	0% reusable	0% reusable	
$NaBH_4$	100% reusable*	0% reusable	100% reusable*	0% reusable	
CH_4 gas				After transport by pipeline	

*) In practice the reusability value will be a little less than 100% because there will always be cleaning work and minor adaptations such as a new coating, new measuring instruments, etc.

Table 41 shows the part of the assets for hydrogen carriers that can be reused (for another hydrogen carrier or substance) if the carrier turns out to be a less successful choice.

- Storage tanks for liquid hydrogen, ammonia, and LSM are specially designed and classified for these substances (0% of the investment is reusable). The choice of construction materials and safety measures are specific to the characteristics of the substance for which the storage is intended.
- Storage tanks for LOHC and methanol can also be employed for other liquids (100% of the investment is reusable). It may be the case that the safety standards are overly strict, so that the storage is more expensive than necessary.
- A storage silo used for sodium borohydride can also be used for other dry materials. If sodium borohydride is delivered in packaged form, the storage facility will have to meet the requirements of the PGS 15 legislation on the storage of packaged hazardous goods. This makes storing it more expensive than ordinary dry loads.
- Installations for the conversion of hydrogen carriers to hydrogen are specially designed and classified for these substances (0% of the investment is reusable). The choice of construction materials, process steps, and safety measures are specific to the characteristics of the substance for which the installation is intended (pressures, temperatures, corrosion, etc.). It might be possible to take the (de)hydrogenation installations built for one LOHC and with minor adaptations employ it for another LOHC, but there is as yet no experience of this in practice.

7. FAIR

The public interest Fair is elaborated in terms of two sub-indicators: fairness for production countries and fairness for the Netherlands.

Production countries

As a sub-indicator of fairness for the production countries, we calculate the total value of external effects per supply chain in those countries (before export to the Netherlands) and divide this by the costs of import into the Netherlands for that supply chain. The higher the ratio, the more the external costs are passed on to producer countries, which is less fair. The external effects we consider here are the environmental costs and the greenhouse gas emissions abroad.

The import costs are taken from the estimations for the public interest Affordable. The external costs abroad are taken partly from the JRC2-LCA study[118] in combination with environmental price factors taken from CE Delft.[119] The JRC2 study gives the necessary inputs and outputs of materials and energy for the chain steps of hydrogen carrier synthesis in the exporting country up to and including the delivery of hydrogen after conversion in the import country. However, sodium borohydride is not considered in this study. For this carrier we collected information from scientific articles and market parties.

Supply chain effects in the Netherlands

The second sub-indicator for the public interest Fair has to do with supply chain effects in the Netherlands. Residents of the Netherlands experience the external effects of the transportation and conversion of hydrogen carriers, such as traffic emissions, noise nuisance, and the risks of accidents and incidents involving hydrogen carriers. The more these external effects are included in the costs of hydrogen carriers to the end user, the fairer from the standpoint of ‘the polluter pays’ principle.

As an indicator of fairness with regard to the supply chain effects in the Netherlands, we calculate the total value of external effects per supply chain within the Netherlands and divide this by the costs of the chain steps in the Netherlands.

- The numerator is an estimate of the difference between the true price of the activities in the Netherlands and the costs actually paid. This difference represents the external costs of the supply chain steps in the Netherlands. The external costs we calculate comprise the monetarised emission of greenhouse gases, the monetarised environmental impacts, and the costs of transport safety in the Netherlands. These have been estimated for other public interests.
- The denominator in the comparison is the sum of all the costs estimated for the public interest Affordable, from the moment of import, namely the costs of transshipment and storage at the port of entry, conversion costs, the costs of inland transport, and the costs of second storage at the end user’s site after transportation by road, rail, and water.

The external costs of cybersecurity and external safety are not monetised, and therefore cannot be included in this indicator. This leads to a more favourable score for alternatives which have a high risk in terms of external safety, cybersecurity and terrorism.

---

[118] JRC2: European Commission, Joint Research Centre, Arrigoni, A. et al (2024), Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe, Publications Office of the European Union, Luxembourg.

[119] CE Delft (2023), *Handboek Milieuprijzen* (Environmental Prices Handbook 2023), *Methodische onderbouwing van kengetallen gebruikt voor waardering van emissies en milieu-impacts* (Methodological substantiation of benchmark figures used for valuation of emissions and environmental impacts).

8. ACCESSIBLE

In this study we present the public interest Accessible using two sub-indicators: accessible cost level and physical proximity of the supply chain.

Cost level for inland and port of entry

The first sub-indicator is concerned with cost differences. An ‘accessible cost level’ exists when companies throughout the country can participate in the hydrogen economy. The degree to which this is the case depends on factors including the cost level of the hydrogen carriers to which they have access. We compare the costs of the hydrogen carriers for a variety of end users in one of the ports of entry with the costs further inland in the Netherlands (at the end of a typical 200 km route).

In ports of entry the costs per hydrogen equivalent are lowest because inland transportation costs and extra storage at the end user’s site are absent. The higher the costs inland compared to the costs at the port of entry, the less accessible the cost level. When costs inland are significantly higher, the resultant disparity makes it more difficult for companies based in these areas to compete with those at one of the ports of entry.

The indicator for this public interest is the ratio of costs further inland in the Netherlands (or Germany) to those at the ports of entry. The variables for this comparison were derived from the figures for the public interest Affordable.

- The nominator in the comparison is the sum of all the costs estimated for the public interest Affordable, namely the costs of import, transshipment and storage at the port of entry, any conversion costs, the costs of inland transport, and the costs of second storage at the end user’s site after transportation by road, rail, and water.
- The denominator comprises only the costs of import, transshipment and storage in the port of entry and any on-site conversion costs.

During the Delphi session it was argued that a cost advantage for companies in the Dutch ports of entry actually favours their competitive position with regard to companies abroad. On the other hand, development of foreign markets is important to justifying Dutch investments in facilities for import, storage, conversion and throughput. If foreign companies experience serious cost disadvantages, they will be less inclined to make the Netherlands part of their import route.

Proximity (sub-indicator)

The ability to participate in the hydrogen economy depends not just on an accessible cost level but also on the physical accessibility of important hydrogen carriers. Companies need to be able to access these hydrogen carriers at their own locations.

To determine the accessibility of various hydrogen carriers inland, we employed a methodology inspired by the proximity factor used in other domains (see Proximity statistics by Statistics Netherlands). We represent this sub-indicator as the number of industrial estates in the Netherlands accessible by road, a railway station, an inland port, or a pipeline connection.

- All industrial estates in the Netherlands are connected to the road network and the natural gas network.
- We determined the proportion of industrial estates with access to the railway network and to waterborne deliveries with the help of the IBIS database. This database lists, for every industrial estate in the Netherlands (3791 areas in total), whether it is also connected by rail or water.
- It is unknown whether these industrial estates will be close enough to the Delta-Rhine Corridor or the national hydrogen network in 2030 to be connected to them, not least

because their exact routes have not yet been determined. An indicative route has, however, been defined. As an approximation we assume that industrial estates will be able to obtain a connection if they lie in a municipality through which the Delta-Rhine Corridor is planned to run. Industrial estates in other municipalities then have no connection. A list of municipalities in the Delta-Rhine Corridor was made available by the project directors of the Delta-Rhine Corridor. There are 382 industrial estates in these municipal areas.

- For the intended national hydrogen network, there is no list of possibly connected municipalities. Based on maps of today's natural gas infrastructure and simplified visualisations of the hydrogen pipeline network, we drew up a list of municipalities through which the hydrogen network will probably pass. The total number of industrial estates in these municipalities is 1391.

Table 42: Proximity to potential end users

	Number of industrial estates with a potential connection	Percentage of 3791 industrial estates with access	Explanatory notes
Road	3791	100%	
By rail	519 of 3,709 for which data are available	14%	all industrial estates adjacent to a railway (cat. B, C, D, E)
By water	685 of 3,713 for which data are available	18%	all industrial estates adjacent to a waterway (cat. A, B, C, D)
Specific pipeline (Delta Rhine Corridor)	382	10%	based on reports from municipalities bypassed
H_2 network	1,391	37%	estimate of municipalities bypassed
Natural gas network	3,791	100%	

9. SPATIAL PLANNING

The public interest Spatial Planning is elaborated by determining the spatial footprint of the steps of each supply chain, multiplying this by the volumes of hydrogen equivalent delivered by these chains to the end users, and multiplying this by the land price. This applies to the following:

- Space for the storage and transshipment of hydrogen carriers at ports of entry and at end users' sites
- Space for conversion installations, both centralised and decentralised
- Space for pipelines
- Other transport modalities make use of public infrastructure, which also takes up space The monetarised social costs of this form of space use are included in the elaboration of the public interest Economically Robust.

In this instance, the public interest is physical space. The Delphi process raised the point that the available environmental and external safety space may be scarcer than the available physical space, and where physical space exists development may nevertheless be prevented due to a lack of adequate environmental space and safety zones. We have not elaborated on this aspect.

Storage installations

For ammonia and LOHC the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers gives the spatial footprint of storage terminals in m^2 per kilotonne of hydrogen carrier. This is determined by measuring the surface area of terminals seen in aerial photographs. Supplementary information was obtained from storage company experts. One storage company estimates the space needs of a new-built ammonia terminal as being half of what the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers gives, the reason being that new tanks can, and are permitted to, be built higher than before. Since mostly new tanks will have to be built for hydrogen carriers (see the public interest Adaptable) we base our assumptions on the benchmark figures for new tanks. We have therefore halved the spatial requirements of LOHC storage compared to the figure in the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers.

We have filled in gaps by scaling the storage terminals of ammonia or LOHC on the basis of the difference in specific gravity. For liquid hydrogen and sodium borohydride we have taken the space requirements of existing ammonia tanks as the starting point, because these hydrogen carriers will need a large number of smaller storage tanks and silos respectively; this makes the spatial requirement larger than it is for hydrogen carriers in larger tanks.

For each supply chain we then determine the necessary spatial requirements for storage (in m^2) for volumes corresponding to 14 days of supply/throughput at the port of entry and 3 days at the end user's site. We determine the spatial investment required by multiplying the number of square metres by the industrial land price (€304 per m^2). This industrial land price, corrected for price level and site preparation costs, is based on the price used in the Social Cost-Benefit Comparison (MKBV).

LOHCs and sodium borohydride also involve a return flow. This return flow has its own storage requirements. This means that the storage space requirements for these hydrogen carriers are twice as large.

For carriers transported to the end user by pipeline, no storage at the end user's site is assumed. For gaseous hydrogen and natural gas, no additional storage is assumed beyond the underground storage planned for hydrogen and that already exists for natural gas in salt caverns and gas fields.

Table 43: **Hydrogen carrier storage spatial footprint in m^2 per kilotonne of carrier**

Carrier	Density (tonne/m^3)	Storage space (m^2 per kt of carrier)	Source	Storage space (m^2 per kt of H_2eq)
NH_3	0.735	134	Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers: existing tanks Market information: new tanks	752
LH_2	0.071	2,764	Scaled from existing NH_3 tanks	2,764
MCH	0.769	197	Scaled from new DBT tanks	3,224
DBT	1.040	146	Social Cost-Benefit Comparison (MKBV): existing tanks 292. Correction for new tanks according to market information	2,370
MeOH	0.792	124	New tanks: scaled from NH_3	985
LSM	0.420	234	Scaled from new NH_3 tanks	930
$NaBH_4$	1.074	183	Scaled from existing NH_3 tanks	864*

*) With dehydrogenation of sodium borohydride, half of the H_2 comes from H_2O, halving the storage volume.

Conversion installations

For ammonia and LOHC the Social Cost-Benefit Comparison (MKBV) gives the spatial footprint of conversion installations in m^2 per kilotonne of hydrogen. This is based on the feasibility study of an ammonia cracker in Rotterdam. This study has not been made public.[120] For LOHC dehydrogenation, the Social Cost-Benefit Comparison (MKBV) states that the same footprint per unit of hydrogen produced is assumed as for an ammonia cracker, because no reliable information could be found on the required land surface area. No other data on the surface area requirements of conversion installations were found. A request made to experts also yielded no additional information. For this reason we assume the same spatial requirement for all conversion installations, namely 79 m^2 per kilotonne hydrogen equivalent. This applies to conversion from hydrogen carrier to hydrogen and vice versa (synthesis from the hydrogen network). For the evaporation of liquid hydrogen and synthetic methane we assume that half of this surface area will suffice.

For each supply chain, the space required for the relevant conversions (in m^2) was then estimated by multiplying it by the annual volume of hydrogen equivalent. We determine the spatial investment required by multiplying the number of square metres by the industrial land price.

To check the orders of magnitude involved we compared the storage and cracking of ammonia. Its storage in the port of entry represents 14/365 of the annual volume of carrier delivered by a supply chain; its conversion represents the entire annual volume. The spatial footprint for storage is then 14/365 * 752 = 28.8 units, and the spatial footprint for cracking is then 1 x 79 units (i.e., less than three times as much). This seems reasonable.

Pipelines

In this study our calculations are based on a representative route of 200 km. The spatial footprint of a pipeline is 5 metres on either side, i.e., 10,000 m^2 per km of pipeline.[121] The route travels for

---

[120] The *Executive summary pre-feasibility study large-scale industrial ammonia cracking plant*, which has been made public, reports a larger spatial footprint of 200-450 m^2 per kilotonne of hydrogen capacity, but this figure includes surface area for storage.

[121] Ministry of Economic Affairs and Climate Policy, *Ontwerp-Programma Energiehoofdstructuur, Ruimte voor een klimaatneutraal energiesysteem van nationaal belang*, 2023

180 km through rural (agricultural or natural) areas and for 20 km through or alongside the built environment.

A pipeline for ammonia or methanol would have to be constructed. The natural gas network is already in place. For the most part the national hydrogen network makes use of existing natural gas pipelines; 40 km will have to be constructed in order to connect industrial areas. 20 km of this passes through rural areas and 20 km through industrial areas. LOHCs can be transported through existing oil pipelines, but it is not self-evident that these would be available for that purpose, so here too we assume the need for new pipelines.

We assume that the spatial investment for new-built pipelines will cost 8 euros per m^2 in rural areas and 304 euros per m^2 in industrial areas.

As is described in Annex A, the capacity of modelled LOHC and methanol pipelines is not adequate to transport the full volume. The spatial costs were therefore corrected to reflect the number of pipelines (26 for LOHC, and also doubled because spent fuel has to be piped back, and 2 for methanol). Since the buffer zones on either side of a pipeline can overlap, 2 methanol pipelines need a 15 m wide strip in total. If several pipelines carry the same substances, such as a LOHC, even higher pipeline concentration is expected to become possible. In the ZWN (LSNed) pipeline strip and other such strips in Rotterdam a safety strip of 1 m is often used.[122] On this basis, a 52-pipeline strip would need to be 61 m wide. A reduced spatial footprint could also result from the use of pipelines having a larger diameter, and therefore requiring fewer lines, than the standard JRC2 size. We were, however, unable to find relevant information about the properties of pipes with larger diameters.

Table 44: Summary of values for determining the spatial investment for hydrogen carrier pipelines

	Existing pipeline	new-built on agricultural land	new-built on industrial land	unit
Pipeline for NH_3, MeOH*, LOHC	0	180	20	km
natural gas network	200	0	0	km
H_2 network	160	20	20	km
land price		8	304	€ / m^2
surface area	10,000			m^2 per km length
surface area MeOH (2 pipelines)	15,000			m^2 per km length
surface area LOHC (52 pipelines)	61,000			m^2 per km length

*) MeOH : two pipelines provide adequate capacity.
**) LOHC: 26 pipelines for adequate capacity, plus as many return pipelines

10. ENVIRONMENT

For the public interest Environment we chose a combined indicator comprising air pollution due to transport and emissions arising from storage and conversion, transport noise nuisance, and transport-related habitat degradation. These are aspects for which valuation figures are available, allowing us to quantitatively compare supply chains on the basis of monetised figures.

---

[122] Reference: NTA 8036 (2021), *Eisen voor de gezamenlijke ligging van buisleidingsystemen in een leidingenstrook*.

Transport-generated air pollution (sum of NO_X and PM)

The transportation of hydrogen carriers generates air pollutant emissions due to the combustion of the fuel required for transport. We use KiM's benchmark figures (based on CE)[123], expressed in kilogrammes of NO_X and PM per tonne-km, for trucks, trains and inland vessels.

- We take as representative figures the average values for goods transport by road, rail and water in the four 'freight transport corridors' in the Netherlands.
- We assume that in 2030 the emission figures for trucks, trains, and inland vessels will be down to 85% of their values in 2018-2023 because of stricter energy efficiency standards imposed by EU regulations and climate-related ambitions.[124] For 2050 we assume that all road, rail, and inland waterway transport will be emission-free (electric).
- We assume that the proportion of electric train kilometres will be 75% and that of diesel train kilometres 25%. These figures are taken from the European Handbook (CE Delft 2019) for the Netherlands. Because the transport of liquid hydrogen is relatively inefficient (a much lower energy density than the other hydrogen carriers under consideration), a factor of 5x as many logistical movements is applied.
- For pipelines we assume that compressors and pumps are electric. In 2030, electricity production in the Netherlands will not yet be free of greenhouse gases and pollutant emissions (NO_X).

The emissions per tonne-km are then multiplied by the environmental costs for a variety of different emission types, following the Environmental Prices Handbook (CE Delft).[125] This results in the valuation figures in Table 45.

---

[123] O. Jonkeren and J. Franke, Netherlands Institute for Transport Policy Analysis | KiM, Kennisbasis Goederenvervoer (Freight transport knowledge base), Memorandum, February 2023. CE Delft, *Toekomstverkenning, De prijs van een reis, Verkennende analyse richting 2050*, May 2022.

[124] The European Commission and Parliament want new trucks to emit 45% less CO_2 in 2030 than in 2019, rising to 90% less by 2040. We assume that comparable improvements will apply to trains and inland vessels.

[125] CE Delft (2023), *Handboek Milieuprijzen* (Environmental Prices Handbook 2023), *Methodische onderbouwing van kengetallen gebruikt voor waardering van emissies en milieu-impacts* (Methodological substantiation of benchmark figures used for valuation of emissions and environmental impacts).

Table 45: Valuation figures for the marginal costs of air pollution (sum of NO_X and PM (source: KiM 2023 = CE Delft 2022)

Valuation figures for air pollution costs	Average costs per 1000 tonne-km in 2022*	Average costs per 1000 tonne-km in 2030*	Average costs per 1000 tonne-km in 2050*	Explanatory notes
Road	€0.11	€0.09	€ -	average truck, KiM
By rail	€0.15	€0.13	€ -	average freight train, KiM
By water	€0.14	€0.12	€ -	average inland vessel, KiM
Pipeline, H_2 net, natural gas network	€ -	€ -	€ -	

*) LH_2 correction: costs are raised by a factor of 5.

For the NO_X and PM emissions caused by marine transport to the Netherlands in 2030 we use benchmark figures given by the STREAM study (CE Delft) for a deep sea bulk carrier of 35,000 - 60,000 dwt.[126] For 2050 we assume the IMO targets for net-zero maritime transport. This implies a transition to CO_2-neutral fuels.

Table 46: NO_X and particulate matter emission figures for a deep sea bulk carrier (source: STREAM study)

Air pollution emissions	PM (g/tkm) (*tank-to-wheel*)*	NO_X (g/tkm) (*tank-to-wheel*)*
Deep sea bulk carrier 2030	0.003	0.13
Deep sea bulk carrier 2050	0.000	0.06

Emissions from storage and conversion installations

JRC2 gives the emissions per kilogramme of hydrogen equivalent for a variety of supply chain steps, including conversion. The following emissions occur. Greenhouse gases (carbon dioxide, methane, hydrogen, nitrous oxide) are not considered here (as they are covered in public interest Sustainable, sub-indicator 'greenhouse gases').

The JRC study assumes that these emissions dissipate in the air. For the NO_X emissions from ammonia crackers we use a value based on the feasibility study of an ammonia cracker in Rotterdam. DeNO_X post-treatment will need to be employed for this type of installation to be licenced in the Netherlands. We assume that DeNO_X post-treatment is also applied to ammonia synthesis in the Netherlands, but not in the country of export.

The shadow costs of methane emissions include its effect as a greenhouse gas and its environmental impact. Its environmental impact is included here. The costs of methane we include here comprise the shadow cost of methane (€4.70 per kg of methane) minus the effect already included in the sub-indicator greenhouse gas for the public interest Sustainable.

---

[126] CE Delft (2021), *STREAM Goederenvervoer 2020. Emissies van modaliteiten in het goederenvervoer* – Version 2, February

Table 47: Emissions during the storage and conversion of hydrogen carriers (JRC2)

Emissions during storage and conversion in g/kg H_2eq in the Dutch part of the supply chain			
carrier	**chain step**	**emission type**	**g/kg H_2eq**
DBT/MCH	dehydrogenation	NO_X	0*
NH_3	storage	NH_3	0.0002 x 5.63
NH_3	cracking	NH_3	0.007
NH_3	cracking	NO_X	0.14**
NH_3	synthesis	NH_3	1.63 x 5.63
NH_3	synthesis	NO_X	1.0 x 5.63 x 7%
LSM	steam reforming	CH_4	4.70 / 3.63 = 1.07
Emissions storage and conversion in g/kg H_2eq in producer countries			
NH_3	storage	NH_3	0.0002 x 5.63
NH_3	synthesis	NH_3	1.63 x 5.63
NH_3	synthesis	NO_X	1.0 x 5.63
$NaBH_4$	not applicable	--	unknown***

*) When using electrical heating, apart from emissions from electricity generation.

**) Based on the feasibility study of an ammonia cracker in Rotterdam. This study assumes an emission requirement limiting NO_X emissions to 140 tonne/year (a 93% reduction) for 1 Mtonne of H_2 production. This value is also used in the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers. We assume that ammonia synthesis will also apply post-treatment that reduces NO_X emissions by 93%.

***) $NaBH_4$ conversions are not considered in JRC2, and in the available literature we were unable to find information on emissions in the various stages of production, carrier conversion, and spent fuel recycling.

Noise

The environmental costs of noise pollution are calculated by multiplying the transport volumes (tonne-km) by benchmark figures taken from KiM/CE.[127] A correction is applied to these figures for liquid hydrogen because of its low energy density: costs are raised by a factor of 5. The noise generated by installations is not included, for lack of data.

Table 48: Valuation figures for the marginal costs of noise pollution (source: KiM 2023 = CE Delft 2022)

Valuation figures for noise costs	Average costs per 1000 tonne-km*	Explanatory notes
Road	€0.60	average truck, KiM
By rail	€0.36	average freight train, KiM
By water	€ -	average inland vessel, KiM
Pipeline, H_2 net, natural gas network	€ -	

*) LH_2 correction: costs are raised by a factor of 5.

Habitat degradation due to transport

'Habitat' is the living domain of animals and plants. The transportation of hydrogen carriers can cause damage to habitats, because the infrastructure used takes up space (habitat loss) or causes

---

[127] O. Jonkeren and J. Franke, Netherlands Institute for Transport Policy Analysis | KiM (2022), Kennisbasis Goederenvervoer (Freight transport knowledge base), Memorandum, February 2023. CE Delft, *Toekomstverkenning, De prijs van een reis, Verkennende analyse richting 2050.*

fragmentation or pollution of the habitat. We do not include ecological damage through air pollution, the spoiling of views (this does not have to do with nature itself, but with the human experience of nature), the opportunities for exotic plant invasion provided by infrastructure, or light pollution.

The environmental costs of habitat degradation caused by the transportation of hydrogen carriers are calculated by multiplying the transport volumes (tonne-km) by benchmark figures taken from CE Delft.[128] A correction is applied to these figures for liquid hydrogen because of its low energy density: costs are raised by a factor of 5. We were unable to find any benchmark figures for the habitat degradation caused by pipelines. Although pipelines largely go underground, some habitat degradation will inevitably occur. We have included no costs for this damage, due to a lack of relevant information. This is therefore an underestimation.

Table 49: Valuation figures for the marginal costs of habitat degradation (source CE Delft 2019)

Valuation figures for habitat degradation costs	Average costs per 1000 tonne-km*	Explanatory notes
Road	€1.51	average truck
By rail	€1.24	electric freight train
By water	€0.94	average inland vessel
Pipeline, H_2 net, natural gas network	€ -	no benchmark figures available

*) LH_2 correction: costs are raised by a factor of 5.

Environmental impact of an incident

An incident involving the storage, transport or conversion of a hydrogen carrier will have an impact on people and also on the environment. We examined whether this was a significant effect over and above the environmental impacts we have already considered. The calculation method used was to multiply the probability of an incident (according to the national risk manual) by the released volume of material and the environmental damage costs of the substance (according to the environmental prices handbook published by CE Delft).

A limitation of this approach is that environmental costs are not known for all hydrogen carriers. They are only know for ammonia, methane, and hydrogen. Because ammonia is probably the substance with the greatest environmental impact, we first performed these calculations for the supply chain in which the inland transportation of ammonia takes place by road. This showed the effect of the environmental incident to be 0.1% of the overall environmental costs for this chain.

Because of this result, and due to the lack of environmental cost information for the other hydrogen carriers, we have not given further consideration to the environmental impacts of incidents. Note: the potential impact on the habitat in the direct surroundings of an incident is nevertheless extremely large ('dead zones').

---

[128] CE Delft (2019), Handbook on the external costs of transport.

ANNEX D: AMENDED ASSUMPTIONS FOR 2050

This annex contains the assumptions for the 2050 variant with conservative assumptions and the sensitivity analysis for the 2050 variant with progressive assumptions. Only the changes relative to the dataset for 2030 are shown here. The changes that apply to both the conservative variant and the sensitivity analysis are shown first, followed by the differences.

Volume

We assume a quadrupling of the hydrogen volume for end use compared to 2030, based on the high variant (for 2030) in the volume study carried out by Berenschot, Arcadis and TNO.

Affordable

The table below shows the costs of importing hydrogen carriers from Morocco to the Netherlands in 2040, in euros per tonne of hydrogen equivalent delivered to the end user. As HyDelta does not have a dataset for 2050, we have used the 2040 dataset for 2050. This assumes the use of direct air capture to synthesise methanol from methane.

Table 50: The costs of importing hydrogen carriers from Morocco to the Netherlands in 2040, in euros/tonne of hydrogen equivalent delivered to the end user

Morocco 2030 HyDelta	H_2 in NH_3	H_2 in LH_2	H_2 in MCH	H_2 in MeOH
Local H_2 production	€1,830	€1,790	€2,108	€2,154
Compressed H_2 storage	€32	€31	€58	€42
Additional feedstock	€ -	€ -	€ -	€940
H_2 to carrier conversion	€916	€514	€303	€309
Carrier export and storage	€210	€716	€400	€63
Transport: shipping	€33	€215	€423	€52
Transport: pipeline	€ -	€ -	€ -	€ -
Carrier import and storage	€182	€651	€287	€52
Carrier to H_2 conversion	€298**	€188	€713	€123
Total costs *	€3,500	€4,106	€4,292	€3,734

*) Import costs are the sum of costs up to the first horizontal line: excluding storage in the port of entry and conversion to hydrogen.

**) HyDelta takes no account of the application of $DeNO_X$ post-treatment when cracking ammonia. We do assume the application of this post-treatment in this study.[129]

---

[129] According to IPLO, investment in selective catalytic reduction (SCR) is €3-100/Nm^3/per hour. The waste gas stream contains at most 80 mg/m3 of NO_X; this is 140 tonnes/year. The overall waste gas stream is then 200 Nm^3/hour. 1 million tonnes/8760 hours = 114 tonnes/hour of H_2 are produced. This brings the CAPEX costs to €5-18/tonne of H_2. The operational costs of SCR are €150-00 per tonne of removed NO_X for the reagents, plus €0.33/(Nm^3 of flue gases per hour) for the catalyst. These amount to €0.021-0.28 per tonne of H_2 and €0.058 per tonne of H_2 respectively, both of which are negligible compared to the CAPEX costs.

- For LSM, we assume a reduction of 25% in the import costs in 2050 compared to 2030, which is comparable to the reduction for methanol and ammonia predicted by HyDelta, and a reduction of 3% in the storage costs, as is the case for ammonia. The costs of steam reforming will be the same as in 2030. For sodium borohydride, we assume that the energy costs in the exporting country will fall from 3 cents to 2 cents per kWh. No other changes are assumed.
- The costs of inland transport in 2050 will remain the same as in 2030 for all transport modes.
- The CO_2 price will rise to €176 per tonne and the price of electricity will rise to €98 per MWh (source: KEV).

Energy losses and emissions

- In 2050, the CO_2 used to synthesise methanol and LSM will come from direct air capture. This means that CO_2 emissions from the supply chains that include carbon-based hydrogen carriers will fall and that the energy losses will rise. See Table 25 in Annex C for the effect on CO_2.
- The CO_2 emissions from maritime transport in 2050 will be net zero, in line with the targets of the International Maritime Organization. For NO_X and particulate matter, we also assume a reduction in emissions to zero in 2050 due to the use of emission-free energy carriers, such as liquid hydrogen, and effective post-treatment technologies for the remaining fuels.
- The energy losses from inland road, rail and water transport will fall, as shown in Table 30 in Annex C. It is assumed that the energy consumption for pipelines will remain the same.

Reliability

- We assume that the technologies that still have lower TRLs in 2030 will be developed to TRL 9 by 2050. This means they will become more reliable.
- The experts assume that in 2030, the supply chains that include decentralised conversion will be less reliable (lower security of supply). The assumption is that, by 2050, sufficient experience will have been accumulated with these supply chains to eliminate these uncertainties. We therefore base our calculations for 2050 for decentralised conversion on zero additional storage units in the supply chains.

Differences between conservative variant and sensitivity analysis with progressive assumptions

The table below shows the differences that we assume in the 2050 variant and the sensitivity analysis for each step of the supply chains.

For the 2050 variant, we use conservative assumptions about how the conversion processes will improve compared to 2030, with around 5-7% higher energy efficiency, depending on the supply chain step (electrolysis, synthesis, DAC and conversion to hydrogen). Some of these assumptions are sourced from IRENA[130] or JRC1, while others are our assumptions derived from these sources.

---

[130] IRENA (2022), Global hydrogen trade to meet the 1.5°C climate goal: Part II – *Technology review of hydrogen carriers*, International Renewable Energy Agency, Abu Dhabi.

For the sensitivity analysis, we chose more progressive assumptions to examine the effects of this differentiation on the final results. To do so, we use the assumptions from IRENA and JRC1, as well as our own assumptions.

Table 51: Differences between assumptions for the baseline situation in 2050 (conservative) and the sensitivity analysis for 2050 (progressive)

	Conservative: 2050 vs. 2030	Progressive: 2050 vs. 2030
NH_3 synthesis	6% efficiency improvement (own assumption)	23% efficiency improvement (IRENA)
NH_3 cracking	5% efficiency improvement (own assumption)	50% efficiency improvement (IRENA)
LOHC hydrogenation	4% efficiency improvement (IRENA-pessimistic)	6% efficiency improvement (IRENA-optimistic)
LOHC dehydrogenation	5% efficiency improvement (own assumption)	10% efficiency improvement (own assumption)
LH_2 liquefaction	5% efficiency improvement (IRENA)	26.5% efficiency improvement (IRENA)
LH_2 evaporation	5% efficiency improvement (own assumption)	60% efficiency improvement (IRENA)
CH_4 synthesis	6% efficiency improvement (own assumption, equal to NH_3)	23% efficiency improvement (same improvement as NH_3 assumed)
CH_4 steam reforming	5% efficiency improvement (own assumption, equal to NH_3)	Efficiency same as for conservative variant, as the technology is already mature
Methanol synthesis	6% efficiency improvement (own assumption, equal to NH_3)	23% efficiency improvement (same improvement as NH_3 assumed)
Methanol steam reforming	5% efficiency improvement (own assumption, equal to NH_3)	50% efficiency improvement (same improvement as NH_3 assumed)
Direct air capture	5% efficiency improvement (own assumption)	37% efficiency improvement *
$NaBH_4$ synthesis	2050 2 cents/kWh vs. 3 cents/kWh 2030, energy efficiency the same as in 2030 (own assumption)	Costs the same as in the conservative variant, energy efficiency 10% higher (own assumption)
Water electrolysis	7% efficiency improvement	12% more efficient than 2030 (based on JRC)
Ocean-going vessels	10% efficiency improvement (own assumption)	20% efficiency improvement (own assumption)
Investment in LH_2 inland vessel	€25 million (own assumption) (2030: €41 million)	€18 million (20% more expensive than NH_3 or LNG vessel) (own assumption)

*) Based on IEA (2022), *Direct Air Capture. A key technology for net zero*, April. This gives a specific energy consumption range in GJ per tonne of CO_2 of 7.2-9.9 for solid DAC and 5.5-8.8 for liquid DAC. For 2030 we assume 7.2 GJ per tonne of CO_2 and 5.5 GJ per tonne of CO_2 for the 2050 progressive variant.

ANNEX E: EXPLANATION OF NORMALISATION METHOD

For normalisation, this study adhered as much as possible to the method of global normalisation. This means that we used a fixed normalisation scale between the highest (possible) score and the lowest (possible) score. The highest (possible) score was given a value of 1 and the lowest (possible) score a value of 0. Global normalisation is based on the theoretical minimum and maximum scores and thus guarantees that all calculated scores for all interests will be within the bandwidth used for normalisation.

The normalisation bandwidth between the lowest and highest score is important, because when the weighting factors are applied, it matters what the absolute difference is between the supply chains assessed as worst and best; for Affordable, for example, is the difference 1 cent, 1 euro or 10 euros per kilogramme? In the Delphi questionnaire, a bandwidth was given for the values for each public interest. This gave the participants a reference to compare alternatives. It should be noted that most of the participants will not consciously have taken the bandwidth into account when assigning a weighting to the public interests.

The best (theoretical) score for each public interest is generally easy to determine. For instance a situation with zero emissions, no spatial requirements, or 100% proximity. For the public interest Affordable, we assume that the best possible score equates to a cost price of 2.50 euros per kilogramme of hydrogen. This is the approximate cost of grey hydrogen (the benchmark). In the basic set, the best possible scores for many public interests were indeed reached by one of the alternatives (sometimes after rounding). With the assumptions made for 2050, several of the ammonia alternatives achieve the best score for Affordable, all the alternatives involving transport by road or the natural gas network achieve the best score for proximity, and all the alternatives involving pipeline transport achieve the best score for transport safety.

The lowest possible score cannot generally be determined theoretically, except for proximity. The lowest possible score for proximity was set at 0%, as this is the worst possible score (if no industrial estates whatsoever have access to this hydrogen supply chain).

For the other public interests, we used the lowest score for that public interest in any of the studied variants in the analysis. Where possible, these scores are shown for each public interest in Chapter 6.

Table 52: Bandwidth used for normalisation

Public interest	Worst score	Best score
Affordable	Lowest score in model	2.50 euros per kg H_2, this value is achieved by the supply chain with the highest score in 2050 (benchmark)
Economically Robust	Lowest score in model	Highest score in model
Reliable	Lowest score in model	No additional storage compared with existing flows of current energy carriers (benchmark)
Safe & Secure – External safety	Lowest score in model	No risk (theoretical score)
Safe & Secure – Cyber & Terrorism	Lowest score in model	No risk (theoretical score)
Safe & Secure – Transport safety	Lowest score in model	No risk (theoretical score)
Sustainable – Greenhouse gas emissions	Lowest score in model	No emissions (theoretical score)
Sustainable – Material consumption	Lowest score in model	No critical materials consumed (theoretical score)
Sustainable – Energy losses	Lowest score in model	100% (no additional energy needed above 120 MJ/kg H_2) (theoretical score)
Adaptable	Lowest score in model	0 (theoretical score)
Fair – for producing countries	Lowest score in model	0% (true price equal to import costs) (theoretical score)
Fair – for Dutch society	Lowest score in model	0% (true price equal to costs of supply chain in the Netherlands) (theoretical score)
Accessible – cost parity	Lowest score in model	100% no additional costs inland (theoretical score)
Accessible – proximity	0% (theoretical score)	100% of companies have access to the supply chain (theoretical score and also the best score in the model)
Spatial Planning	Lowest score in model	No spatial requirements (theoretical score)
Environment	Lowest score in model	No environmental impact (theoretical score)

ANNEX F: EXPLANATION OF DELPHI AND AHP

In order to assign weightings to the public interests, a Delphi process with various stakeholders was chosen. The Delphi approach was combined with the AHP method to guarantee a structured decision-making process. The Delphi approach and the AHP are explained below in brief.

MODIFIED DELPHI APPROACH

The Delphi method is a research method in which a large number of participants (experts or stakeholders) are asked for their opinions about a subject for which no consensus exists. The method aims to generate a consensus by holding several rounds, in which the answers of other participants are (anonymously) fed back to participants. The Delphi method resolves several of the shortcomings of traditional forecasting methods (including the theoretical approach, quantitative modelling or extrapolation) in areas that lack accurate scientific laws. The method works by recognising the value of the opinion, experience and intuition of participants and using these in the absence of comprehensive scientific knowledge. Comparisons with traditional methods have shown that the Delphi method produces more accurate forecasts than these methods.[131]

The Modified Delphi method is derived from the original Delphi method.[132] The traditional Delphi method is very time consuming, due to the many written iterations required to reach a consensus. There may also be questions that cannot easily be distilled into hypotheses, or that give the stakeholders/experts too little opportunity and freedom to add new ideas and points of view outside the realm of the ideas prepared by the research team. The Modified Delphi method addresses these problems. In this method, only the scoring is carried out anonymously and in writing, not the entire process. The differences identified from the written questionnaire are discussed during the group discussion(s). This saves time. To ensure that participants with particular personality traits do not excessively influence the discussion, amendments to previous answers must be properly justified and be logically related to the discussion, for example because new arguments are presented.

The various steps in the Modified Delphi approach used in this study are as follows:

1. Preparing and testing a briefing on strategy, indicators and sub-indicators, alternatives to be considered and an evaluation form. To avoid misunderstandings and ambiguities, we first tested the form and explanation (comprehensibility, size, balance, neutrality, etc.) with the advisory group.
2. Written round with a broadly composed group, in which participants give and motivate their opinion on the pairwise comparison of the public interests based on various indicators.

---

[131] Shankar Basu & Roger G. Schroeder (1977), “Incorporating Judgments in Sales Forecasts: Application of the Delphi Method at American Hoist & Derrick”, INFORMS, vol. 7(3), pp. 18-27, May.

[132] RAND developed the Delphi method between 1950 and 1960 to address the shortcomings of traditional forecasting methods. Various studies have been carried out since then. Shankar Basu & Roger G. Schroeder (1977), “Incorporating Judgments in Sales Forecasts: Application of the Delphi Method at American Hoist & Derrick”, Interfaces, INFORMS, vol. 7(3), pp. 18-27, May. Dalkey. N. and Helmer, O. (1963). An experimental application of the DELPHI Method to the use of experts. Management Science, 9, 3: 458-467. https:/ /doi.org/10.1287/mnsc.9.3.458

3. Analysis of the answers by the research team and aggregation of the respondents' individual scores to produce an overall picture.
4. Discussion of the aggregation of the individual scores and accompanying arguments during the physical Delphi meeting. The goal is to identify differences in answers that result from an incomplete picture, unfamiliarity with relevant arguments and aspects or ambiguities in the methodology, for example about how something should be interpreted.
5. Opportunity for the participants to amend the individual scores in response to new information and insights.
6. Analysis of the final answers by the research team and aggregation of the respondents' individual scores to produce a set of weighting factors for use in the multi-criteria analysis.

ANALYTICAL HIERARCHY PROCESS (AHP)

AHP is a method designed to guarantee a structured decision-making process.[133] The method is used to assign a value to the criteria that are important when making the correct decision. The potential solutions can then be determined and calculations carried out for these solutions. We use the method to produce an accurate estimate of the weightings of various public interests. The knowledge and experience of the participants in the Modified Delphi method described above are used to estimate the relative size of the weighting factors using pairwise comparisons. Each respondent compares the relative importance of each pair of public interests or indicators and gives a score on a 9-point scale.

---

[133] R.W. Saaty, The analytic hierarchy process-what it is and how it is used, Mat/d Modelling, Vol. 9, No. 3-5, pp. 161-176, 1987. R.W. Saaty, Relative Measurement and Its Generalization in Decision Making. Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors, The Analytic Hierarchy/Network Process, vol. 102 (2), 2008, pp. 251–318.

Table 53: Scale used for scores

9-point scale (Saaty's 9-point scale)	Numerical score
Absolutely more important than	9
(between very much more important than and absolutely more important than)	8
Very much more important than	7
(between more important than and very much more important than)	6
More important than	5
(between somewhat more important than and more important than)	4
Somewhat more important than	3
(between equally important and somewhat more important than)	2
Equally important	1

In the example below, the participants assessed that the greenhouse gas emissions indicator is 4.2 x more important than energy consumption.

Not all 21 participants assessed all comparisons. However, at least 19 usable scores were available for each comparison.

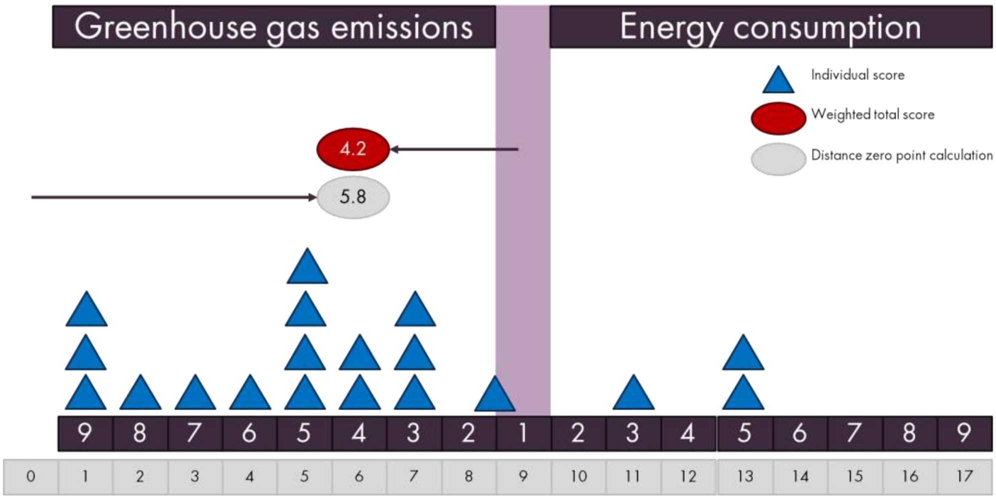


Figure 94: Illustration of individual scores and weighted final scores of 19 participants in AHP pairwise comparison

The centroid of all the scores (4.2 in this example) is determined by solving the following formula for x:

$$\sum_{i=1}^{n}(vi - x)$$

For which:
i = score for all participants,
n = number of participants with a usable score for the comparison
v_i = distance of the score from the left side of the chart for participant i; the first '9' has a distance of 1, the last '9' has a distance of 17
x = distance between the centroid and the left side of the chart.
In this case, the calculated value of x = 5.8. This means the centroid represents a score of 4.2 for greenhouse gas emissions.

ANNEX G: EXPLANATION OF VIKOR METHOD

The final scores for the various alternatives are a combination of the weighting factors that emerged from the Delphi process and the scores for the individual public interests. Annex F explains how the weighting factors were determined. The results are described in Chapter 5. The scores for the individual public interests are given in Chapter 6. The background behind these is explained in Annex C.

We ranked the final scores using the VIKOR ('Multicriteria Optimisation and Compromise Solution') method.[134] This results in a nuanced picture: we consider not just the highest score for the combination of the Delphi weighting and the scores for the hydrogen carrier supply chains for the individual public interests, but also whether a given supply chain has a very low score for one or more of the individual public interests. For those who attach great importance to that public interest, the hydrogen carrier supply chain with the lowest score of all for that public interest will probably be unacceptable.

METHOD

The VIKOR method determines the attractiveness of a supply chain based on:

1) the distance to the ideal score for each public interest
2) the distance to the least ideal/worst possible score for each public interest

The 'ideal score' is for a *notional* supply chain with the best score for all public interests (value 1), such as the combination of ammonia for Affordable and pipeline transport for transport safety.

The 'worst possible score' is for a *notional* supply chain with the worst possible score for all public interests (value 0), for example the combination of the transport safety score for road transport and the Affordable score for sodium borohydride.

The distance to these two scores can be compared in any given relative proportion, although a 50-50 weighting is generally used. We have used that weighting in this study:

1) Half of the final score is determined by the standard multi-criteria calculation ('Utility'): weighting factor x score for each public interest ('what do we want the most').
2) Half of the final score is determined by the 'regret' method: this penalises alternatives with relatively low scores for one or more public interests (comparable to the right of veto: 'what we don't want').

The supply chain that performs best for this combination achieves the best overall score. This is a chain that is reasonably close to the best score for each public interest and reasonably far from the lowest score for each of those interests. If three alternatives achieve the same score for the Utility value (e.g. 0.5), then the alternative that scores closest to the worst possible score for one of the public interests will have the highest regret deduction, and the alternative that scores furthest from the worst possible score will have the lowest regret deduction, and thus the smallest points deduction.

---

[134] In Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje

EXAMPLE

To illustrate, we will show the method with a simple example.

Imagine that we consider only the public interests Affordable and Safe & Secure and that we consider these public interests to be equally important (i.e., the weighting factors are both 50%).

There are three alternatives with various scores for these two public interests, as shown in Table 54. If we follow the standard MCA method (Utility score), then all three will obtain the same score: 0.5. For the chosen weighting factors, none of the three alternatives is favoured.

Table 54: Score for 3 alternatives using the standard MCA method

Alternative	Score Affordable (weighting 50%)	Score Safe & Secure (weighting 50%)	Utility score
A	1	0	0.5 (50% x 1 + 50% x 0)
B	0.5	0.5	0.5 (50% x 0.5 + 50% x 0.5)
C	0	1	0.5 (50% x 0 + 50% x 1)

With the VIKOR method, the normalised distance to the ideal utility score counts for half of the overall score and the maximum regret score counts for the other half. This is the maximum normalised distance between an alternative and the best score for one of the public interests.

- For alternative A, this distance is 1 x 50%, because A has a distance of 1 for Safe & Secure and a weighting factor of 50%.
- For alternative C, this distance is 1 x 50%, because C has a distance of 1 for Affordable and a weighting factor of 50%.
- For alternative B, the maximum distance is 0.5 x 50%, because B has a distance of 0.5 for Safe & Secure and Affordable and a weighting factor of 50%.

The lowest overall score is thus the best alternative identified by the VIKOR method.

The VIKOR score is calculated using the following formula:

$$VIKOR = factor * \frac{S_{\cdot i} - S_{\cdot}^{+}}{S_{\cdot}^{-} - S_{\cdot}^{+}} + (1 - factor) * \frac{R_i - R^{+}}{R^{-} - R^{+}}$$

For which:

factor = 50%, i.e., the Utility score and the Regret score count equally
S_i = Utility score for supply chain i
S^+ = Best Utility score of all supply chains (the ideal utility score)
S^- = Worst Utility score of all supply chains
R_i = Regret score for supply chain i
R^+ = Best Regret score of all supply chains
R- = Worst Regret score of all supply chains

In this example, the lowest score is the best. To avoid confusion in the presentation of the final scores in the main text, we have inverted the scores produced by the VIKOR method: 1 rather than 0 is the best score. Alternative B performs better than A and C because it has a more ‘average’ score and does not have the worst score for any public interest.

Table 55: Score for 3 alternatives using the VIKOR method (standard and inverted)

Alternative	Distance to ideal Utility score	Regret score Affordable	Regret Score Safe & Secure	Maximum Regret (Ri)	VIKOR score Standard (lowest = best)	VIKOR score reversed (highest = best)
A	0 (0.5 – 0.5)	0 x 50%	1 x 50%	0.5	50% x 0 + 50% x 0.25/0.25 = 0.5	0.5 (1 - 0.5)
B	0 (0.5 – 0.5)	0.5 x 50%	0.5 x 50%	0.25	50% x 0 + 50% x 0/0.25 = 0	1 (1 - 0)
C	0 (0.5 – 0.5)	1 x 50%	0 x 50%	0.5	50% x 0 + 50% x 0.25/0.25 = 0.5	0.5 (1 - 0.5)

The calculation is visualised in Figure 95. It is important to note that all weighted public interests contribute to the Utility score, while only the greatest weighted distance for one of the public interests counts for the Regret score.

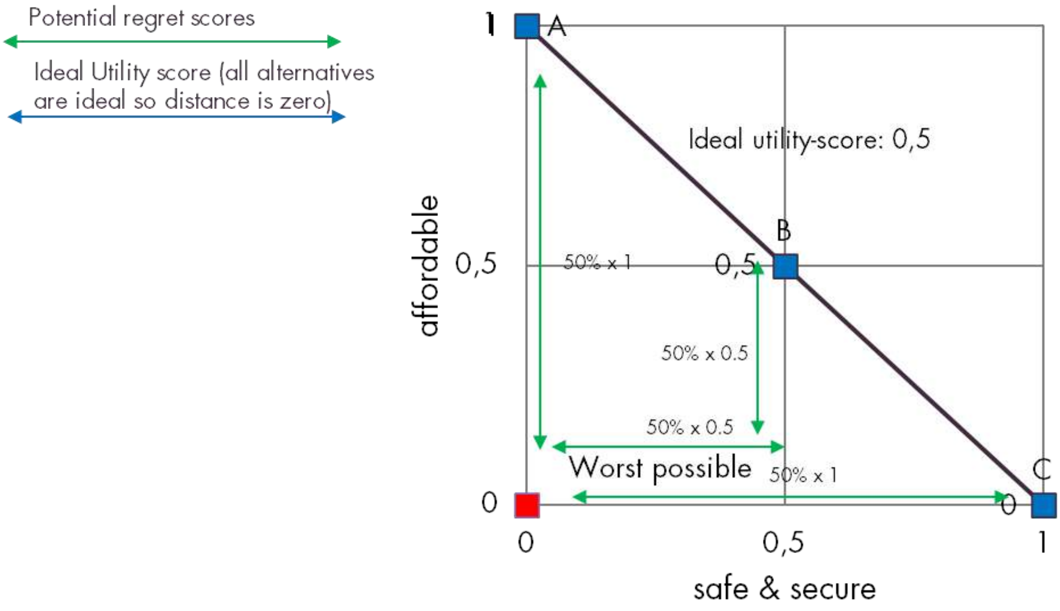


Figure 95: Visualisation of VIKOR method for example

ANNEX H: DIFFERENCES BETWEEN LOHCS

TWO LOHC TYPES: DBT AND MCH

The principle behind LOHCs is that an unsaturated aromatic compound absorbs hydrogen during an exothermic hydrogenation reaction (at high pressure and low temperature) and that the hydrogen is released during an endothermic dehydrogenation reaction (without pressure at high temperature). For this study, we chose two LOHCs: DBT and MCH. The most important reason for the choice is the availability of sufficient data for the modelling process.

- DBT is the short name for the reversible pair Dibenzyltoluene (H0-DBT) and perhydro-dibenzyltoluene (H18-DBT). The first contains no hydrogen, the second contains 6.16wt% hydrogen. Relatively small quantities of DBT have been used for decades in industrial heat exchange applications.
- MCH is the short name for the reversible pair toluene and methylcyclohexane. The first contains no hydrogen, the second contains 6.12wt% hydrogen, which is similar to H18-DBT. Both are components of the naphtha fraction refined from crude oil. Natural gas extraction also produces toluene. Its extensive availability is reflected in a lower market price than that of DBT.

Table 56 shows the values used for modelling in this study for both substances. The key differences are shown in bold. Because we could not find information about all aspects for both variants, we have taken some values from the other LOHC.

Table 56: Values used to model DBT and MCH in this study.

Property	Unit	DBT	MCH
Mass	Tonne/m^3	**H18-DBT 0.91 (outward)** **H0-DBT 1.04 (return)**	**MCH 0.77 (outward)** **TOL 0.87 (return)**
State during storage, transport and conversion		**Viscous, flammable liquids. The substance tends to become lumpy at low temperatures**	**Volatile, flammable and non-viscous liquid**
Price of material	€/kg	**5**	**0.9**
Energy input to produce the carrier material	MJ/kg	17.2	Unknown, we use the same value
H_2 content	wt%	**6.16 (H18-DBT)**	**6.12 (MCH)**
Safety characteristics		Flammable, non-toxic, potential substance of very high concern (potential substance of very high concern)	Flammable, toxic, not a substance of very high concern but a byproduct, benzene, is
CAPEX hydrogenation	€ million	280 (1000 kilotonnes H_2eq/year)	Unknown, we use the same value
OPEX hydrogenation	%/year of CAPEX	1.5	Unknown, we use the same value
Energy hydrogenation	MJ/kgH_2eq	**1.332**	**0.9**
Loss of H_2 during hydrogenation	g/kgH_2	1	Same as DBT
CAPEX dehydrogenation	€ million	Centralised 669 (1000 kilotonnes H_2eq/year) + 229 (PSA) Decentralised 20 (16.6 kilotonnes H_2eq/year) + 6 (PSA) Fuelling station 4 (373 tonnes H_2/year) + 0.5 (PSA) + 0.4 (compression)	Unknown, we use the same value; however **without PSA for centralised or decentralised dehydrogenation for industrial use**
OPEX dehydrogenation	%/year of CAPEX	1.5	Unknown, we use the same value
Energy dehydrogenation	MJ/kgH_2eq	Centralised/decentralised 45.0 Fuelling station 48.6 + 7.7 (compressor)	Central/decentralised market information (electrical process) Fuelling station as DBT
Purity after dehydrogenation		**Purification with PSA (Pressure Swing Absorption), although not necessary for all industrial end users**	**Market information – sufficient for industrial use, PSA required for fuel cell quality**
Loss of carrier material during dehydrogenation		0.013%	(market information)

Sources: JRC 1 (2022), Oner and Khalilpour (2022), market information, RIVM (2022), Clematis et al. (2023), IEA (2019)