Ministry of Climate Policy and Green Growth

Assessing hydrogen carriers - background document

Contents

1. Introduction

This background document is an annex to the Letter to Parliament on the *Government vision on hydrogen carriers* and forms an integral part of that vision. A summary of the main points of the Letter to Parliament is given below. To fully understand the content of the government vision, we recommend that you read the Letter to Parliament in its entirety prior to reading this background document.

The essence of the vision for the short term is that the government will offer plenty of scope for the deployment of hydrogen carriers for the energy and raw materials transition, including through the provision of government support. In the medium and long term, the government will steer more explicitly with regard to the choice of hydrogen carriers, end-uses and modes of transport.

From a broad societal perspective, the government sees an important role for liquid hydrogen and liquid organic hydrogen carriers (LOHCs[1]), particularly for the conversion to hydrogen gas at the import port. There is also plenty of potential for methanol and liquid synthetic methane (LSM[2]), provided sustainable carbon is used[3].

The 2004 government position on ammonia transport was reassessed in the light of the energy and raw materials transition. Broadening and nuancing this position provides a fuller picture of what the government considers as desirable and undesirable developments. The government sees a clear role for ammonia in the development of a global hydrogen market, but also acknowledges that this hydrogen carrier has disadvantages, especially in relation to the increased storage and transport volumes that are expected throughout the Netherlands. The government therefore prefers the option of ammonia end-use or conversion in seaports, and as far as possible from populated areas. Ammonia may only be transported if this can be done safely, and preferably in concentrated form by pipeline or barge. The widespread distribution of ammonia throughout the Netherlands and the expansion of ammonia transport by rail or road is undesirable, but cannot be entirely avoided. The vision provides scope for these options, for as long as suitable alternatives are lacking. The government is more optimistic about alternative hydrogen carriers to ammonia, particularly in the medium and longer term when more hydrogen carriers and modes of transport will become available. Although the market share of these hydrogen carriers may eventually surpass that of ammonia, the market for ammonia that is developed in the initial years of the transition is expected to stabilise in absolute terms.

The choices in the Letter to Parliament were made on the basis of the current knowledge regarding the market for hydrogen carriers and other relevant developments. This knowledge was derived from various studies recently conducted, including those commissioned by the relevant ministries. Because an explanation of these underpinning studies (specifically the Social Cost Benefit Comparison (MKBV) on hydrogen carriers submitted in the Letter to Parliament of 26 April 2024[4], and the hydrogen carriers comparison in the form of a multi-criteria analysis (MCA) published at the same time as this document) would be too extensive for inclusion in the Letter to Parliament itself, but at the same time forms a very essential part of the vision-forming process to date, it was decided to elaborate further on this in a background document. This document outlines how the national government has formed a vision on imported hydrogen carriers in the Netherlands.

[1] Hydrogen can be bound to LSM and extracted again at the destination.

[2] Sometimes referred to as e-LNG or e-methane.

[3] Carbon from sustainable bio-based raw materials, CO_2 captured from air or point sources, and recyclates. The EU Renewable Energy Directive sets conditions on carbon use. Sustainable carbon will potentially become a scarce resource. The NPE sets out starting points for ensuring the deployment of the highest possible grade of sustainable carbon. Large scale CO_2 reductions are achievable in supply chains, particularly in combination with sustainable carbon (from biogenic sources or captured from the air).

[4] Parliamentary Paper 32 813, No. 1385

About the starting points of this background document

The process of forming a national government vision and opinion elaborated in this background document is based on the following starting points:

- Maximum transparency about the process of developing an opinion by ensuring a broad dialogue with stakeholders.
- Consideration of public interests as described in the National Energy System Plan (NPE), being 'Affordable', 'Economically Robust', 'Reliable', 'Safe & Secure', 'Sustainable', 'Adaptable', 'Fair', 'Accessible, 'Spatial Planning' and 'Environment'. The extent to which hydrogen carrier supply chains are adaptive, and thus influence the likelihood of disinvestment or lock-in effects, was also examined in conjunction with this.
- Harmonisation with the results of various relevant studies. The most important of these for the vision are the MKBV and the MCA.
- The commitment to hydrogen gas has already been described in the NPE. The assumption is that a nationwide hydrogen pipeline network will be developed, and that if the hydrogen carrier is converted to hydrogen gas, the hydrogen gas can be fed into this nationwide network.
- This vision assumes 'green' hydrogen carriers, meaning that the hydrogen was produced from renewable energy. Other colours ('grey', 'blue' and 'purple') may affect public interests.[5] This could potentially also affect the assessment of the appreciation of hydrogen carriers.
- For simplicity's sake, all the substances considered are referred to as hydrogen carriers, although they are not strictly always hydrogen 'carriers', but could also involve liquid hydrogen or directly deployable hydrogen derivatives, for example.

The objective and scope of the various studies are described in the respective reports, as well as a detailed description of the results. The objective and scope of the vision are described in the aforementioned Letter to Parliament entitled the *Government vision on hydrogen carriers*.

Guide for readers

This document outlines how the ministries of Infrastructure and Water Management (IenW) and Climate Policy and Green Growth (KGG):

1. have structured the multitude and variety of information on hydrogen carriers for the purposes of forming a government vision
2. have assessed the advantages and disadvantages of the various hydrogen carriers, including the reasoning behind these assessments

Chapter 2 discusses the MCA (methodology, key findings, relationship with other studies). The MCA and the Social Cost Benefit Comparison (MKBV) form important building blocks for the assessment of hydrogen carriers.

Chapter 3 explains how the assessment of hydrogen carriers in combination with end-uses and end-use sites was structured.

Chapter 4 provides the results of the assessment in the form of a matrix.

Chapter 5 provides an explanation of the assessment in the matrix and the preferences revealed in it.

Chapter 6 provides the reasoning behind the assessments, both generally and specifically for each hydrogen carrier.

Finally, **Chapter 7** outlines the significance of the vision for each end-use and location.

[5] Grey: fossil-based; Blue: fossil-based with Carbon Capture and Storage; Purple: produced using nuclear power.

2. Substantiating research and analyses: MCA and MKBV

Last year, a hydrogen carrier comparison in the form of a multi-criteria analysis (MCA) was commissioned by the Ministry of Climate Policy and Green Growth, in which supply chains for various hydrogen carriers were assessed in relation to the public interests described in the NPE and mentioned in the introductory chapter. Together with the MKBV and other analyses, the MCA forms an important building block for the government vision. The methodology and key findings of the MCA are discussed below. For the sake of completeness, the key points of the MKBV as previously shared with Parliament are also reiterated. The relationship with a number of other relevant studies is also discussed.

MCA methodology

The MCA examined those hydrogen carriers about which the most data is currently available, being: liquid hydrogen (LH_2), ammonia, liquid organic hydrogen carriers (LOHCs), methanol and liquid synthetic methane (LSM[6]). Sodium borohydride ($NaBH_4$) was also included in the MCA, but the technology for this hydrogen carrier is still under development.

The study assumed a representative route from a port in the Netherlands to an end user 200 km inland with a relatively high hydrogen demand. It is assumed that the hydrogen carriers are produced in Morocco and brought to the Netherlands by ship. For domestic transport, the modes of road, rail, barge and pipeline were considered. There were also variants with end-use in the port itself and transport to Germany. Various end-uses were considered, as well as end-users with lower hydrogen demands. The time horizons were 2030/2035 and 2050.

The supply chains were assessed against the public interests described in the NPE, supplemented by the public interest ‘Adaptable’. This is discussed in more detail in Chapter 3. These interests were operationalised as indicators. The scores for the indicators used data from existing surveys as much as possible. Where no or insufficient data were available, the scores were determined during expert sessions. The scores per public interest were aggregated into a final score per supply chain by combining them with weighting factors.

The weighting factors in the MCA were determined based on input provided by a representative group of stakeholders. This group weighted the public interests ‘Safe & Secure’ (29.3%), ‘Sustainable’ (23.6%), ‘Environment’ (11.3%) and ‘Affordable’ (9.5%) most heavily. This weighting was applied in the MCA. In addition, sensitivity analyses were used to ascertain what the overall scores would look like if alternative weightings of the public interests were used.

6 Sometimes referred to as e-LNG or e-methane (if in gas form).

Results of the MCA

For hydrogen end-use, the highest-scoring supply chains are those of LH_2 and LOHCs, with conversion to hydrogen gas in the port area and transport through the hydrogen network. The methanol and LSM supply chains (transported as methane gas through the natural gas network) scored highest for end-use of the hydrogen carrier (direct use, without conversion to hydrogen gas). It should be noted that the extent to which direct use of a particular substance is a feasible option varies from one end user to another. Ammonia scores lower overall than other hydrogen carriers due to the heavily weighted public interests 'Safe & Secure' and 'Environment'. Ammonia supply chains score highest for direct use (in the port area or transported by pipeline) and for centralised conversion to hydrogen gas in the port area combined with transport through the national hydrogen network.

For supply chains involving hydrogen end-use, centralised conversion in port offers more benefits than decentralised conversion inland. Among the modes of transport, the national hydrogen network has a slightly higher score. Apart from the public interests 'Safe & Secure & Secure', 'Reliable' and 'Accessible', the mode of transport does not reveal any distinctive differences between the various hydrogen carriers. The favourable score for end-use site (in the port area) and mode of transport (pipeline) is largely a result of lower transport emissions and lower external safety risks. The latter aspect has a particularly strong influence on the score for ammonia pipelines, due to the high weighting for the public interest 'Safe & Secure' and the relatively low score in that area for ammonia transport by road and rail.

There are only small differences between the highest scores. The properties of the hydrogen carrier itself and the import costs are determining factors[7], as is the requirement of conversion in the supply chain. Direct end-use of the hydrogen carrier (if possible) is the more favourable option overall, because this avoids the costs and energy consumption of a conversion step.

Results of the sensitivity analyses

Several sensitivity analyses were carried out as part of the study. The applied weighting of public interests proved to have a strong effect on the outcomes. Alternative weightings were therefore considered. If the weighting is adjusted in a way that the public interest 'Affordable' is doubled and the public interests 'Safe & Secure' and 'Sustainable' are roughly halved, ammonia comes out among the highest-scoring alternatives. Ammonia with conversion to hydrogen gas in the port area, or with transport by pipeline to a decentralised conversion site, is given the highest score for hydrogen end-use. If all public interests are assigned the same weighting, methanol transported by road scores highest for hydrogen end-use, and LSM transported through the natural gas network scores highest for carrier end-use.

The assumptions about the source of carbon used also prove to play an important role. The standard variant for 2030/2035 assumes the use of carbon captured from industrial processes as a raw material for producing methanol and LSM. An alternative source of carbon for the production of methanol and LSM production was also considered (sensitivity analysis time horizon 2050: CO_2 based on DAC[8] instead of CCU[9]), and for carbon capture during the conversion of both hydrogen carriers to hydrogen gas (sensitivity analysis including CCS[10]). In both sensitivity analyses, the CO_2 emissions in the supply chain are reduced and the score of these hydrogen carriers improves for the heavily weighted public interest 'Sustainable'. This leads to substantially higher overall scores for methanol and LSM. The methanol supply chain with conversion in the port area and transport through the hydrogen network gets an equally high score in these analyses as the same supply chain based on LH_2. For decentralised conversion – i.e. transport of a hydrogen carrier within the Netherlands – the methanol-based chains score the highest (higher than those based on LH_2). LSM-based supply chains with a sustainable carbon source or

7 In the case of ammonia, methanol and LSM, the study assumes that the hydrogen carrier itself is used as an energy source for conversion to hydrogen gas. In that case, additional imports will be needed to provide the end user with the same amount of hydrogen equivalents. This will increase the costs and external effects of those supply chains.

8 Extracting CO_2 from the air: direct air capture, or DAC.

9 Capturing CO_2 from fossil point sources ('smokestacks') for reuse: carbon capture and utilisation, or CCU.

10 Capturing CO_2 from point sources for underground storage: Carbon Capture and Storage, or CCS.

CCS also get relatively high scores (slightly lower than methanol and LH_2).

Social Cost Benefit Comparison (MKBV)

Below is the summary of the main points of the MKBV as it appears in the Letter to Parliament.

Research findings

The MKBV study compared the social costs and benefits of the various supply chains. These supply chains differ by hydrogen carrier (ammonia or LOHCs) and by mode of transport (rail/ship or pipeline). LOHCs and ammonia emerged in previous studies (the so-called 'supply chain study' and 'volume study') as the most technically mature and feasible hydrogen carriers, and therefore suitable for making a thorough comparison. The alternative supply chains were compared with a 'reference variant'. To this end, the researchers applied the market situation that currently appears to be emerging (i.e. without additional government policy). This situation involves ammonia transports by water and rail.
The alternative supply chains considered were characterised by the researchers as:

- transporting ammonia directly to end-users by pipeline (pressurised, not refrigerated)
- ammonia-cracking in the port area and transporting the hydrogen gas by (natural gas) pipelines
- transporting LOHCs directly to end-users by barge and rail
- LOHC-cracking in the port area and transporting the hydrogen gas by (natural gas) pipelines

The study monetised the social costs and benefits of all alternatives as much as possible and compared them with the reference variant. The outcome of this comparison is that all alternative supply chains score higher than the reference variant, with 'LOHC cracking in the port area and transporting hydrogen gas through pipelines' having the best score. However, the differences between the alternatives are small; in terms of cost per kilo of hydrogen, the maximum difference is about 11 eurocents (which is at most a few percent of the current cost price).

So, the study did not reveal a clear preference for any of the supply chains for the monetised aspects. However, the analysis does reveal that the alternatives differ in two aspects in particular. The most significant aspect is the economic costs, with the import cost of the carrier and the conversion efficiency (when converting the carriers into hydrogen gas) as the main components. This difference arises because both the energy loss during conversion and the additional imports needed to compensate for this are included. The second difference is in the transport emissions, which are avoided when pipelines are used. This applies more to LOHCs, where the carrier also has to be returned to source. On balance, however, these two aspects do not lead to major differences in the overall social costs and benefits.

The MKBV also describes a number of qualitative factors that cannot be monetised properly or fully, and are therefore not reflected in the financial scores. Examples include the consequences of a serious incident, perceptions of safety, safety measures and broad prosperity. These factors have thus been given a more qualitative interpretation. It is important to give these factors due consideration for a comprehensive comparison.

With regard to the modes of transport, the study reveals that the use of pipelines helps to reduce transport emissions and transport costs (costs of mitigating noise pollution, vibrations and emissions). Installing pipelines will also potentially have a positive effect on the Netherlands' international competitive position, with a risk of stranded assets if the market develops differently than currently foreseen. A key concern with ammonia pipelines is the safety of the design. The study warns that an incident could have a huge impact, while the options for containing and controlling such incidents are limited.

Sensitivity analyses

The outcome of the MKBV inevitably had to be based on many assumptions. Sensitivity analyses were carried out to test the impact of these assumptions. These analyses revealed two parameters where variations in the assumptions had the most impact on the results. These parameters are primarily the cost price of the carriers ammonia and LOHCs (at what price can they be obtained?) and, additionally, the monitoring and safety costs (costs of emergency response services regarding ammonia transports).

Relationship with other studies

Prior to the MCA and MKBV[11], the government commissioned a study into the external safety of hydrogen carriers[12] and their expected import and transport volumes[13]. These studies revealed that a significant proportion of the imported hydrogen carriers will be transported through the Netherlands without first being converted to hydrogen gas, and mentioned points for concern in relation to external safety. The studies predict that ammonia will be the dominant hydrogen carrier, in any case during the early years of the transition.

In addition, the European Commission's Joint Research Centre (JRC) recently released two research reports on the costs[14] and environmental impact[15] of various import supply chains of hydrogen and hydrogen carriers. We mention these reports explicitly because the MCA used data from them[16]. The JRC reports cover a smaller group of hydrogen carriers than the MCA and the structure of the supply chains also differs. Importing liquid hydrogen by ship and hydrogen gas by pipeline get the highest scores from the JRC, both for costs and environmental impact. This is because the costs, energy consumption and materials use involved in the conversion steps at the production and end-use site are avoided.

The reports, including the MKBV and MCA, provide insight into how public interests are affected by the various hydrogen carrier supply chains. At this stage of market development, the government is cautious about attaching policy conclusions to these insights. There are only small differences between the highest scoring supply chains, and the scores are moreover partially based on assumptions. It would therefore be prudent to repeat the comparison of hydrogen carriers in a few years' time, based on the most recent findings.

11 Study report: *Maatschappelijke Kosten en Baten Vergelijking Waterstofdragers* (2024), Parliamentary paper 32813, no. 1385.
12 *Rapportage ketenstudie omgevingsveiligheid van duurzame waterstofrijke energiedragers* (2021), Parliamentary paper 32813, no. 938.
13 Study report: *Omgevingsveiligheid toekomstige stromen waterstofrijke energiedragers* (2023), Parliamentary paper 32813, no. 1192.
14 *Assessment of hydrogen delivery options* (2022): https://publications.jrc.ec.europa.eu/repository/handle/JRC130442
15 *Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe* (2024): https://publications.jrc.ec.europa.eu/repository/handle/JRC137953
16 The MCA included a sensitivity study with various cost assumptions. This was based on the JRC's high cost scenario (2022). A selection of the JRC's results (2024) were used for comparing the environmental impact and climate emissions of the hydrogen carriers. Not all emissions and environmental impacts described by the JRC were considered in the MCA. Moreover, the JRC only took into account hydrogen end-use and did not directly compare carrier end-use (without conversion to hydrogen), as was the case in the MCA.

3. Assessment structure

Differentiation and criteria

To form this vision on hydrogen carriers, a distinction was made between 1) the variables used to differentiate between the different hydrogen carrier applications and 2) the criteria used to assess the hydrogen carriers. The matrix was created based on the variables used to distinguish between the various hydrogen carrier applications (this is elaborated in Chapter 4). The assessment criteria were used to arrive at the matrix and the scores for the various hydrogen carriers by end-use.

The following variables were used for the differentiation:
- End use applications of the carrier
- Various types of end use (sectors)
- Volume demand for hydrogen and hydrogen carriers
- Geographical locations of activities
- Time horizons

The following variables were used for the criteria:
- Public interests (as described in the NPE)
- Modes of transport
- Availability of alternatives
- Existing policy principles

The hydrogen carriers considered

Several forms of hydrogen and hydrogen carriers are currently being developed or studied for application in the energy and raw materials transition. Not all of these forms are at the same stage of technological development (the Technological Readiness Level, or TRL). The higher the TRL, the closer the project or product is to commercial marketability. For the purposes of this vision, mainly hydrogen carriers with a high TRL were selected. Hydrogen carriers with a lower TRL may not be ready for commercial deployment before 2030/2035. Seven hydrogen carriers were selected based on this criterion, whereby an additional distinction was made between carriers that require end-use conversion to hydrogen gas versus carriers that can be directly deployed (see Figure 1). More hydrogen carriers are expected on the market eventually. The NPE (which is reviewed at least every five years) will incorporate new developments in hydrogen carriers.

End use is *hydrogen gas*:	End use is *hydrogen carrier* (direct use of the carrier)
1. Liquid hydrogen	1. Liquid hydrogen
2. Ammonia	2. Ammonia
3. Methanol	3. Methanol
4. Liquid synthetic methane (LSM)	4. Liquid synthetic methane (LSM)
5. Methylcyclohexane (MCH), a liquid organic hydrogen carrier (LOHC)	
6. Dibenzyltoluene (DBT), a liquid organic hydrogen carrier (LOHC)	
7. Sodium borohydride	

Figure 1: Selected hydrogen carriers and end-uses

Differentiation of hydrogen carriers

As mentioned above, the following variables were used for the differentiation: 1) the end use (hydrogen carrier or hydrogen gas), 2) the sector of end use, 3) the estimated volume of hydrogen or hydrogen carrier demand, 4) the end use site, and 5) the time horizons. These are briefly elaborated and explained below.

1. End uses

The vision distinguishes between the use of hydrogen gas (after conversion of the hydrogen carrier) and direct use of the hydrogen carrier. The vision also made an explicit distinction between use as a fuel and use as a raw material, as this largely determines the degree of flexibility the end-user has to choose an alternative hydrogen carrier and/or mode of transport. The end-use application itself has been excluded from the scope of this vision, as this is already covered by existing policy.

Example

A company producing fertiliser requires ammonia as a raw material and is thus best served by a direct supply of ammonia. A party wishing to use ammonia as a fuel could also choose to use one of the other hydrogen carriers, or hydrogen gas. In principle, all hydrogen carriers can be converted to hydrogen gas for end-use as a fuel. The aforementioned differences in flexibility have been factored into the assessment of hydrogen carriers in relation to their end use.

2. End-use applications (sectors)

The vision focuses in particular on three end-uses: industrial, power generation and mobility. These sectors are expected to be responsible for most of the demand for hydrogen carriers, as also outlined in the NPE. As mentioned above, the end-use applications themselves fall outside the scope of the vision. However, the choices that are made on the end-use side do contribute to practical realisation of the vision. Another important category of 'end-use' is transit (especially to Germany). The nature of the actual end-use application at the destination is mostly unknown, so there is less influence over these end use types (despite the fact that this could be desirable for one or more public interests).

3. Volume demand for hydrogen and hydrogen carriers

The various national and international studies into the demand and supply of hydrogen carriers show widely varying estimates. This can be explained by the fact that all studies are based on uncertain assumptions that may also change over time. Furthermore, the capacities of the modes of transport vary, and not every mode is suitable for every hydrogen carrier.

The matrix includes an indication of whether the applications of hydrogen or hydrogen carriers involve small, medium or large flows. These flows are labelled S (small, <50 kilotonne H_2 equivalents), M (medium, 50-150 kilotonne H_2 equivalents) and L (large, >150 kilotonne H_2 equivalents).[17],[18] This gives an impression of the relationships between the various flows, based on the scenarios for 2030. The volumes and limits of these flows are estimates based on the middle scenario of a 2023 external safety study by Arcadis, Berenschot and TNO (*"Omgevingsveiligheid van toekomstige stromen waterstofrijke energiedragers"*).

4. Geographical locations of activities

The location where an activity will take place, and whether it will require inland transport, storage and transhipment, is important for the assessment of the social benefits and costs, among others. The analysis therefore distinguished between three main types of sites for end-use (and if applicable, conversion), namely:

1. the port of entry
2. elsewhere in the Netherlands
3. abroad (transport to northwestern Europe, particularly Germany)

5. Time horizons

The MCA examined the period up to 2030/2035 and up to +/- 2050. These two periods were also applied in the vision. However, this background document focuses more on whether certain conditions can be achieved within the time horizon, rather than the deadlines themselves, as the basis on which the hydrogen carriers can be assessed. This can be seen in the matrix in the cells with a gradient colour.

[17] The hydrogen content of the carriers varies, so the volume of hydrogen carrier required to transport a fixed amount of hydrogen also varies. Hydrogen equivalents were therefore calculated to be able to compare the various flows.

[18] In the matrix, some end-uses are labelled 'S', while the currently estimated expected flow is actually zero (i.e. 0 kilotonne). This is because, while the relevant end-use is conceivable, there are no known concrete plans for it. This particularly concerns the direct use of hydrogen carriers for electricity generation in the port area or elsewhere in the Netherlands.

Criteria for the assessment

The shading of the cells in the matrix (the 'score', or 'colour') depends on various criteria. As indicated earlier, the following criteria were used in the analysis: 1) the public interest scores (public interests as described in the NPE, 2) the modes of transport, 3) the availability of alternative hydrogen carriers, and 4) existing policy principles. These are briefly elaborated and explained below.

1. Public interests

The MKBV and MCA studies analysed the social costs and benefits of various supply chains involving the use, conversion, storage, transshipment and transport of hydrogen carriers in the Netherlands in the period up to +/- 2050. The starting points for the MCA analyses were the nine public interests described in the NPE, supplemented by the interest 'Adaptable'. These ten public interests were operationalised by the researchers to be able to compare various hydrogen carriers in relation to them. Figure 2 contains a schematic representation of how the ten public interests were operationalised. More information on this can be found in the MCA report. For the purposes of the vision, each combination of hydrogen carrier and end-use was assessed against these ten public interests based on the outcomes of the MCA and MKBV.

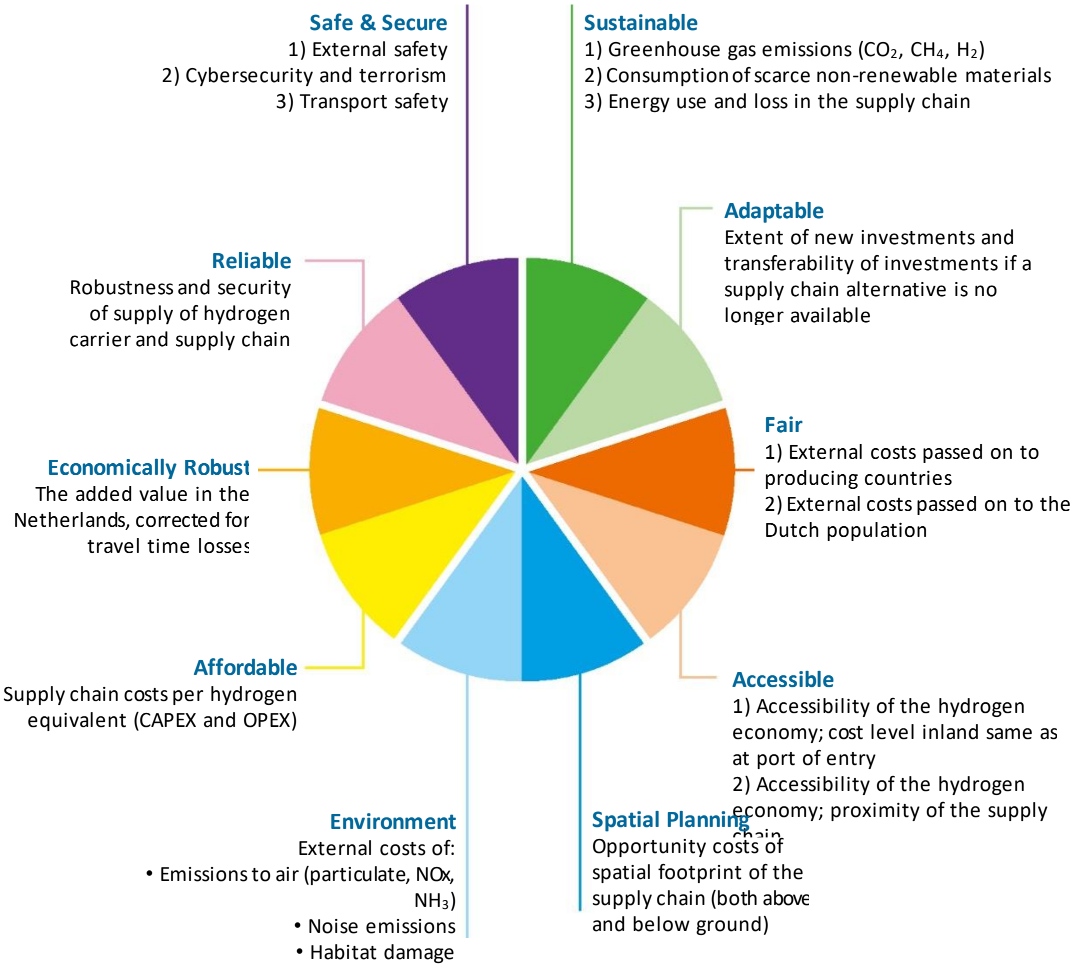

Figure 2: Operationalisation of the ten public interests in the MCA

2. Modes of transport

The modes of transport identified in the analysis are pipeline, barge, rail and road. Not all modes are suitable for all substances. For example, there are technical limitations to transporting cooled liquid ammonia over long distances by pipeline. There are also more formal restrictions to transporting dangerous goods based on international regulations, such as the prohibition on transporting certain dangerous goods by specific modes of transport. In practice, the mode of transport (pipeline, barge, rail or road) strongly depends on the destination and the volume to be transported.

The availability of the various modes of transport is expected to change over time. Examples are pipelines like the national hydrogen transport network or the Delta Rhine Corridor, and seagoing vessels which may in time be able to transport LH_2 (expected to become available on a sufficient scale only in the longer term). The preferred order of the modes of transport may differ by hydrogen carrier. For the assessment, this means that the score is higher for hydrogen carriers that are transported by a preferred modality. Symbols have been included in the matrix to indicate a permanent or temporary specific preference of modality.

3. Availability of alternatives

Another variable is the availability of alternative hydrogen carriers. More alternative hydrogen carriers will become available in the longer term. So, a score may change over time as more alternative hydrogen carriers become available. A score that changes over time can be identified in the matrix by a colour transition.

4. Existing policy principles

Finally, the analysis also took into account the existing policy principles of the relevant departments. These particularly concern the intention for the Netherlands to remain an international energy hub as defined in the NPE, the principles for a safe and healthy energy and raw materials transition[19], the commitment to diversification of hydrogen carriers[20], the central principles of the National Strategy on Spatial Planning and the Environment (NOVI) with regard to the spatial planning, and the preliminary draft National Spatial Strategy. The modes of transport are also subject to an order of preference in this vision.

[19] Parliamentary paper 32 813, no. 1113, *Verantwoord omgaan met veiligheid en gezondheid in de energietransitie*
[20] Parliamentary Paper 29 023, no. 431

4. Combining variables in the matrix

A colour matrix was used to provide a clear and coherent overview of the assessment of the above mentioned variables. This matrix reveals how each combination of hydrogen carrier (column) and end-use (row) is considered under the government vision. The end-use application is a combination of the end-use type and the end-use site. The various end-uses are given in Figure 3.

End-use applications of hydrogen gas	End-use applications of hydrogen carrier (direct use)
Raw material for the industry	**Raw material for the industry**
Conversion in the port area	End-use in the port area
Conversion elsewhere in Netherlands	End-use elsewhere in Netherlands
Conversion in Germany	End-use in Germany
Fuel for the industry	**Fuel for the industry**
Conversion in the port area	End-use in the port area
Conversion elsewhere in Netherlands	End-use elsewhere in Netherlands
Conversion in Germany	End-use in Germany
Fuel for electricity generation	**Fuel for electricity generation**
Conversion in the port area	End-use in the port area
Conversion elsewhere in Netherlands	End-use elsewhere in Netherlands
Conversion in Germany	End-use in Germany
Fuel for mobility	**Fuel for mobility (bunker fuels)**
Conversion in the port area	End-use in the port area (maritime shipping)
Conversion elsewhere in Netherlands	End-use in the port area (inland shipping)
	End-use elsewhere in Netherlands (inland and maritime shipping)
	Fuel for mobility (road transport)
	End-use elsewhere in Netherlands

Figure 3: End-use applications (end-use and end-use site) of hydrogen carriers distinguished by end-use as hydrogen gas or as hydrogen carriers

Various public interests, modes of transport, volumes and time horizons were considered in the assessment. The results of the studies (MKBV and MCA) and the discussions with, and input received from, the stakeholders were also included. The matrix is not broken down by public interest, but these interests largely determine the colours of the cells in the matrix.

Matrix legend

The colours used

The matrix uses colours (see the legend in Table 1) to indicate how the Government scores the various hydrogen carriers in relation to the various 'end-uses' from a broad societal perspective. The colours range from green (highest score) to red (lowest score). The matrix describes the 'desirability' of combinations of hydrogen carriers and end-uses, and in particular, the extent to which the vision provides scope for government (or other) support, or whether the end-use is to be discouraged (where possible). The instruments to steer the vision will be developed in the follow-up process.

The colour green ('incentivise') means the government (or another party) may encourage this end-use by supporting it financially or otherwise. The colour yellow ('facilitate') means that a public authority may choose to actively encourage this end-use by changing laws, regulations, spatial planning procedures, etc. The colour orange ('accept') means that the government will not take any additional or alternative steps to support applications than is currently the case for fossil energy or raw materials, or as required by law. The colour dark orange ('discourage') means that the government considers the relevant end-use to be undesirable, without specifically anticipating in what manner it can and will be discouraged.

Shaded cells	Colour	Explanation
	Green	**Incentivise** (scope for financial and other support)
	Green/yellow	Temporarily incentivise, then facilitate
	Yellow	**Facilitate** (scope for non-financial support)
	Yellow/orange	Temporarily facilitate, then accept
	Orange	**Accept** (no action other than what is required by law)
	Orange/Dark orange	Temporarily accept, then discourage
	Dark orange	**Discourage** (where possible, because undesirable)
	Grey	Not applicable

Table 1: Legend colours in matrix

It is assumed that the energy and raw materials transition will be mostly achieved by 2050, in line with the Dutch goal to be climate neutral and circular by 2050. In principle, no other form of government support will be needed after 2050 than is currently the case for fossil energy and raw materials. Temporary support refers to (policy scope for) support that is currently considered useful, but that at a later date (somewhere between now and 2050) no longer will be, for example because better alternatives are expected to be available by then (e.g. alternative hydrogen carriers and/or better access to the national hydrogen infrastructure). For this interim period, the vision uses a standard period around (indicative) 2035.Where no such date is mentioned in the legend, it is assumed that there will also be scope for support after 2035.

We further assume that future stimulation will focus on supply chain innovations and optimisations that contribute to the energy and raw materials transition, and their upscaling. Expansions of existing fossil infrastructure will not qualify for these incentives in principle, except in the case of modifications for the purpose of reusing this infrastructure. To illustrate: technology development and scaling up of direct air capture (DAC) could greatly contribute to the sustainability and scalability of methanol and LSM carriers. The same applies to the further development of synthetic methane production (methanisation). For LH_2, the vision primarily describes scope for incentives for the further development and scaling up of large-scale storage and transport by ship. All spending on fossil infrastructure (such as existing natural gas networks or underground gas storage) falls outside the scope of the hydrogen carrier vision.

Current policies aimed at making end-users and their facilities more sustainable do not fall under the vision. As such, the colours in the matrix are not indicative of the extent to which the government provides scope for supporting sustainability measures of end-users (industry, mobility and power generation sectors).

As mentioned above, the vision on hydrogen carriers itself will not be used to provide support. However, it does provide a framework under which the government can act in relation to hydrogen carriers. Public authorities and other stakeholders can also use the vision as a policy framework. The vision does not anticipate budgetary choices regarding support for hydrogen carriers. The same applies to forms of non-financial support provided by the national government, such as for spatial planning and licensing procedures. It should be noted that hydrogen carrier initiatives can already be supported under the current subsidy instruments. Hydrogen imports are also a theme of the exploratory phase of the Multi-Year Energy and Climate Infrastructure Programme (MIEK).

Symbols

In addition to colours, the matrix also uses a number of symbols (see legend in Table 2). These symbols indicate that a particular assessment (colour) is subject to a provision in terms of the mode of transport or application.

The symbols thus add additional information to the colours mentioned above. A provision could be that an end-use will only be incentivised or facilitated if it meets additional requirements. If these requirements cannot be met, the government will classify this application as less desirable (or even undesirable). Where the symbols provide scope for more than one mode of transport, the government may still have a preference for a specific mode. See also the justification of the matrix in Chapter 4.

Symbol	Description	Explanation
	Provided the mode of transport is by pipeline[1]	[1] Currently not available for all hydrogen carriers. Interim phase: transport by barge as temporary solution. LSM involves transporting methane gas through the natural gas network.
	Provided the mode of transport is by barge	
BET	Rail is acceptable provided the Betuweroute corridor is used[2]	[2] Given its connection to the Betuweroute corridor, this implies that Rotterdam must be the point of origin. Other industrial clusters require detours or other transportation steps, and so are less desirable.
K	Provided the incentive is focused exclusively on developing or scaling up ammonia-cracking technology.	

Table 2: Symbols

Assessment of hydrogen carriers (matrix)

The matrix is depicted in Table 3 on the next page. The matrix provides a graphical representation of the government's preferences[21] in the form of a table with colours.

[21] There is no 100% match with the supply chain combinations described in the MCA. For example, methanol for direct use in road transport is not included in the MCA.

Table 3 Matrix showing relationships between end-uses and hydrogen carriers

	Estimated volume	End-use applications of hydrogen gas	LH_2	Ammonia	LOHC (DBT & MCH)	Methanol	LSM (e-LNG)	$NaBH_4$*
1	L	**Raw material for the industry**						
1a	M	Conversion in the port area	Green	Green/yellow, K	Green	Green	Green	Green/yellow
1b	S	Conversion elsewhere in Netherlands	Green/yellow	Orange/Dark orange, barge	Yellow	Green/yellow	Green, pipeline	Yellow/orange
1c	M	Conversion in Germany	Yellow	Yellow, pipeline	Yellow, barge	Yellow, pipeline, barge	Yellow, pipeline	Yellow/orange
2	L	**Fuel for the industry**						
2a	L	Conversion in the port area	Green	Green/yellow, K	Green	Green	Green	Green/yellow
2b	S	Conversion elsewhere in Netherlands	Green/yellow	Orange/Dark orange, barge	Yellow	Green/yellow	Green, pipeline	Yellow/orange
2c	M	Conversion in Germany	Yellow/orange	Yellow, pipeline	Yellow/orange, barge	Yellow/orange, pipeline, barge	Yellow, pipeline	Yellow/orange
3	L	**Fuel for electricity generation**						
3a	S	Conversion in the port area	Green	Green/yellow, K	Green	Green	Green	Green/yellow
3b	M	Conversion elsewhere in Netherlands	Yellow/orange	Orange/Dark orange, barge	Yellow/orange	Yellow/orange	Green, pipeline	Yellow/orange
3c	M	Conversion in Germany	Yellow/orange	Yellow/orange, pipeline	Orange/Dark orange	Orange/Dark orange	Yellow, pipeline	Yellow/orange
4	L	**Fuel for mobility**						
4a	L	Conversion in the port area	Green	Green/yellow, K	Green	Green	Green	Green/yellow
4b	M	Conversion elsewhere in Netherlands	Green	Dark orange	Yellow	Yellow	Green, pipeline	Yellow/orange

	Estimated volume	End-use applications of hydrogen carrier (direct use)	LH_2	Ammonia	LOHC (DBT & MCH)	Methanol	LSM (e-LNG)	$NaBH_4$*
5	L	**Raw material for the industry**						
5a	M	End-use in the port area	Green	Green	Grey	Green	Green	Grey
5b	M	End-use elsewhere in Netherlands	Green	Yellow, barge	Grey	Green	Green, pipeline	
5c	M	End-use in Germany	Yellow	Yellow, pipeline, barge, BET	Grey	Yellow	Yellow, pipeline	
6	L	**Fuel for the industry**						
6a	S	End-use in the port area	Grey	Yellow/orange	Grey	Green	Green	Grey
6b	S	End-use elsewhere in Netherlands	Grey	Orange/Dark orange, barge	Grey	Green/yellow	Green, pipeline	Grey
6c	M	End-use in Germany	Grey	Yellow/orange	Grey	Yellow	Yellow, pipeline	Grey
7	L	**Fuel for electricity generation**						
7a	S	End-use in the port area	Grey	Yellow/orange	Grey	Green	Green	Grey
7b	S	End-use elsewhere in Netherlands	Grey	Orange/Dark orange, barge	Grey	Green/yellow	Green, pipeline	Grey
7c	L	End-use in Germany	Grey	Yellow/orange, pipeline	Grey	Yellow	Yellow, pipeline	Grey
8	L	**Fuel for mobility (bunker fuels)**						
8a	S	End-use in the port area (maritime shipping)	Green	Green/yellow	Grey	Green	Green	Grey
8b	S	End-use in the port area (inland shipping)	Green	Yellow	Grey	Green	Green	Grey
8c	M	End-use elsewhere in Netherlands (inland and maritime shipping)	Green	Yellow/orange	Grey	Green	Green, pipeline	Grey
9	S	**Fuel for mobility (road transport)**						
9a	S	End-use elsewhere in Netherlands	Green	Orange/Dark orange	Grey	Green	Green, pipeline	Grey

Shaded cells	Colour	Explanation
	Green	**Incentivise** (scope for financial and other support)
	Green/yellow	Temporarily incentivise, then facilitate
	Yellow	**Facilitate** (scope for non-financial support)
	Yellow/orange	Temporarily facilitate, then accept
	Orange	**Accept** (no action other than what is required by law)
	Orange/Dark orange	Temporarily accept, then discourage
	Dark orange	**Discourage** (where possible, because undesirable)
	Grey	Not applicable

Symbol	Description	Explanation
(pipeline)	Provided the mode of transport is by pipeline[1]	[1] Currently not available for all hydrogen carriers. Interim phase: transport by barge as temporary solution. LSM involves transporting methane gas through the natural gas network.
(barge)	Provided the mode of transport is by barge	
BET	Rail is acceptable provided the Betuweroute corridor is used[2]	[2] Given its connection to the Betuweroute corridor, this implies that Rotterdam must be the point of origin. Other industrial clusters require detours or other transportation steps, and so are less desirable.
K	Provided the incentive is focused exclusively on developing or scaling up ammonia-cracking technology.	

Letter	Hydrogen equivalents
S	<50 kilotonnes $H_{2\text{-eq}}$ per year
M	50-150 kilotonnes $H_{2\text{-eq}}$ per year
L	<150 kilotonnes $H_{2\text{-eq}}$ per year

** Pure $NaBH_4$ (as assessed) may not be transported in bulk and is therefore not a feasible option.*

5. Explanation of the assessment in the matrix

This chapter outlines the general insights that serve as reasoning behind the assessment in the matrix. Explanations per individual hydrogen carrier follow in Chapter 6.

Preference for conversion and/or end-use in the import port

Conversion and/or end-use of hydrogen carriers in the import port is preferred to conversion and end-use elsewhere in the Netherlands or in Germany. The studies reveal that this preference will avoid or reduce the external effects, infrastructure and other costs, and energy consumption involved in the transport of hydrogen carriers (particularly if this transport would have to take place via water, rail and road). Moreover, conversion and/or end-use in the import port reduces pressure on, and congestion of, the modes of transport. Account will have to be taken of the available physical space and environmental limitations in the import port, and the cumulative impact on safety, also in relation to the area surrounding the port.

Preference for modes of transport

Based on the current knowledge and understanding, the following general order of preference applies to the transport of dangerous goods:

1. by pipeline
2. by barge
3. by rail
4. by road

a) The following five points should be taken into account in this consideration: the order of preference applies generically; there may be reasons to deviate from this order of preference depending on the hydrogen carrier. Nuances are further explained in the explanation per individual hydrogen carrier.
b) In relation to pipelines, extra attention must be paid to safety measures to ensure the pipeline meets the prescribed conditions. This particularly applies to ammonia pipelines. Currently only a direct link up to the German border is envisaged for ammonia. The development of a widespread network of ammonia pipelines is considered unlikely. The desirability of any initiatives to develop one or more branch pipelines will be examined on a case-by-case basis.
c) The Betuweroute corridor was developed specifically to accommodate rail freight transport from Rotterdam to Germany and avoid densely populated areas. Hydrogen carriers should therefore be transported by rail over the Betuweroute corridor where this is feasible.
d) Flexibility with regard to the choice of end-use site is smallest with a pipeline and greatest with road transport. All end-users and end-use sites are accessible by road, but not all have a waterfront, even fewer have a rail connection, and fewer still are located nearby a pipeline. Pipelines will involve transporting very large volumes, while road transports always involve only relatively small volumes.
e) European and global agreements impose restrictions on the transport of dangerous goods. If certain of these restrictions are found to frustrate the goals of the energy transition, the Dutch government will seek to change these agreements. A number of specific examples are discussed later in this document. Such changes can only be made if there is agreement at the relevant European or global level they are safe and technically justified. It is important to keep in mind that, realistically, such

changes will often involve drawn-out procedures.

Preference for pipelines for large hydrogen carrier volumes

Both the MKBV and the MCA reveal that transport by pipeline scores more favourably than other modes of transport. In the MKBV, this is mainly due to avoided transport emissions and a lower impact on transport safety (traffic accidents) compared to transport by road, rail or water. In the MCA, transport by pipeline does not only score higher for safety, but also for reliability (security of supply). Unlike other modes of transport, transport by pipeline will not lead to traffic congestion or accidents.

Besides transportation of hydrogen gas through the national hydrogen transport network, pipelines are also a option for the transport and distribution of ammonia, some LOHCs[22], methanol and synthetic methane. Unlike the regulation of rail, barge and road transport (which are subject to international agreements), the Netherlands can regulate pipeline transport itself, and thus make additional technical provisions to ensure increased safety compared to the other modes of transport. It is not yet clear which pipelines will be available for the various hydrogen carriers, nor when these might be realised and where. So, many end-users/end-use sites do not yet know if, and if so when, they will have access to a pipeline for a specific hydrogen carrier.

Preferences in other modes of transport

The other modes of transport for liquid hydrogen and hydrogen carriers are by barge, rail and road. It is not realistic for all hydrogen carriers that transportation within the Netherlands (for end-use and decentralised conversion) will take place by pipeline.

Pipelines will not be a feasible mode of transport in many cases. This is partly due to demanded small volumes and/or the relatively large geographical distribution of the end-users. In such cases, there is a preference for transport by barge[23]. Barges can transport relatively large volumes per trip, leading to fewer emissions and a lower risk of incidents. Moreover, the distance between the transport infrastructure and built-up areas is usually greater than for transport by rail and road, which means better external safety and a smaller spatial footprint. A point of concern in transport by barge is reliability (security of supply), especially during periods of high or low water levels.

Where barge transport is not an option, transport by rail is the next preference. As stated earlier, the preference is to use the Betuweroute corridor for rail transport where this is feasible. Rail transport is further subject to the principles of the *Basisnet* (policy on the fundamental transport network for dangerous substances) to connect the Dutch large industrial parks with chemical industry (Industry clusters). Transport by road is most suitable for smaller volumes. Some end-use sites do not have an alternative mode of transport. For example most filling stations and businesses located outside the major industrial clusters (so-called 'Cluster 6' industry) can often only be supplied by road.

[22] Some LOHCs are less suitable or unsuitable for transport by pipeline due to the viscosity of the substance.

[23] In the MCA, transport by barge scores slightly lower overall compared to rail, but this difference is mainly caused by the factor 'Reliable'. This conclusion supports the preference for barge transport, with rail as a fallback option during periods when inland shipping routes are temporarily unavailable. Furthermore, rail transport is electric, which is preferable in terms of emissions (public interest 'Sustainable'), but barge transport can be expected to develop in this respect.

Implications for the content in the matrix

The mentioned notions in this chapter so far are made visible in the matrix in the following way: in a number of cases, the use of pipelines is a precondition of the assessment (in the long term). If a pipeline is ultimately considered unfeasible, this would result in the outcome of the assessment being less positive .
Temporary non-financial government support for the construction of pipelines may be legitimised, for example with regard to spatial planning procedures. An alternative mode of transport can be temporarily used while waiting for a planned pipeline to be built. In some cases, decentralised conversion can be temporarily facilitated or accepted pending the construction of the national hydrogen network. Once the hydrogen network has been built, this end-use will become less desirable or even undesirable.

Preferred hydrogen carrier end-use (where possible and appropriate)

End-use of hydrogen carriers (without conversion to hydrogen gas) avoids energy losses and, depending on the technology, emissions that would be released in the conversion process.
Moreover, conversion facilities place additional demands on the available space. So, direct use of hydrogen carriers is generally the preferred option. However, for a comprehensive assessment, the end-use site, the mode of transport (and the related risks and spatial footprint), and the emissions at the end-use site should also be taken into consideration.

In the case of end-use inland, conversion in the import port may still be preferable, for example if it leads to a lower risk and spatial footprint inland, and using existing pipelines (with the hydrogen transport network as the preferred mode). A specific example of this is ammonia used as fuel. If direct use in a port is not possible, and a safe ammonia pipeline is not available, the preferred option will be conversion to hydrogen gas in the port and transport through the hydrogen pipeline network. This is due to the substantially lower scores on public interests for ammonia transport by modes other than pipelines. The MCA did not include the spatial impact of environmental or safety zones, as these zones were not easily measurable or quantifiable in all cases.

Additional information about the preferences

The preferences listed will not always be mutually compatible. Not every end-user is sited in the import port or can directly use a hydrogen carrier without first converting it to hydrogen gas. Not all end-users have access to all modes of transport, either geographically and/or based on their required volumes. The listed preferences should be seen as the initial principles. In the matrix and the explanation per hydrogen carrier, these principles have been applied to each end-use and compared with each other (where relevant).

In addition to the generic preferences mentioned above, the direct use of hydrogen carriers in the port area requires less support in the form of an extensive supply chain, because conversion to hydrogen gas and transport are both avoided. Also, supporting conversion and end-use in Germany is not the remit of the Dutch government. The German government could play a role here if desirable.

6. Explanation per hydrogen carrier

This chapter describes how each of the hydrogen carriers was assessed based on the studies and additional analyses. It explains how the colours of the corresponding cells in the matrix were chosen. After a brief introduction, the following aspects are discussed for each carrier: (a) the score for the public interests and initial principles, and (b) the differences in the scores in relation to the different end-uses and end-use sites (social applications).

Furthermore, it should be noted that some hydrogen carriers are also carbon-based energy carriers, and therefore 'carbon carriers' according to the definitions applied in the NPE (e.g. methanol, LSM, MCH and DBT). For the purposes of this document, these carriers are classified as hydrogen carriers.

Relationship with the public interests described in the NPE

The people of the Netherlands must be able to count on their government to always take their public interests into account in their stance with regard to the developments related to hydrogen carriers, and not just the interests of one or more sectors.

At the same time, most of these sectors directly or indirectly serve various public interests, for instance the energy supply, food security and economic prosperity. This often involves finding a balance between the costs for a local community versus the benefits for the wider public. This means a focus on developments that best serve the public interest, as long as they do not overly harm the interests of individuals. This perspective forms the basis for the approach to public interests in the National Energy System Plan (NPE) which underpins this vision. These public interests do not automatically go hand in hand. In fact, in the realm of energy system choices, they are regularly at odds with each other. This is why it is important that public authorities at all levels provide full transparency about the way in which they assess and compare the various public interests, and that they remain in close dialogue with each other and with the stakeholders.

General remarks

Given the high uncertainty about the exact course of the energy and raw materials transition, the exact nature, scale and timeframe of the demand for hydrogen and hydrogen carriers in the aforementioned sectors is not yet known. This poses a challenge to parties involved in existing (and future) supply chains. Moreover, a wide range of technological innovations and optimisations are currently still being implemented in the various supply chains. As a result, the advantages and disadvantages of the various hydrogen carriers are in flux. This calls for adaptive government policies.

In its vision on hydrogen carriers, the government provides as much clarity as possible to the market – based on the currently available information – as to its preferences for specific combinations of hydrogen carriers, end-uses and transport modes, and the considerations on which they are based. The method of assessing the public interests as described in the NPE will continue to be consistently applied in the future. With this vision, in line with the NPE, the government aims to steer the direction and increase the pace of the desired developments, and fulfil the government's role as authority responsible for managing both the energy and the raw materials transition, and the just distribution of scarcity (of space, the environment, infrastructure capacity, etc.). Like the NPE, the vision on hydrogen carriers will be updated periodically.

This chapter discusses a variety of combinations of hydrogen carriers, end-uses and locations that are at least theoretically conceivable. While remarks on the feasibility of a few options are mentioned, generally, all options are discussed without commenting on their feasibility.

Specific additional considerations are mentioned in some cases, but this is not the case for all carriers.

Liquid hydrogen (LH_2)

General

This document uses the term LH_2, which refers to liquid hydrogen.

Public interests

LH_2 scores highly for the public interest 'Sustainable' in the MCA, mainly because of the relatively low energy loss in the supply chain (compared to other hydrogen carriers, less hydrogen has to be produced and imported to produce the same amount of hydrogen equivalents for the end-user). The low energy loss is partly due to the fact that conversion to hydrogen gas involves fewer steps, lower energy use, and less use of infrastructure. For this reason, liquid hydrogen also scores highly for the public interests 'Spatial Planning' and 'Adaptable'.

For the public interest 'Environment', LH_2 scores about as high as most other hydrogen carriers. If more emissions, material properties, production impacts and the use of transport resources were included in the MCA comparison, LH_2 would probably score higher than other hydrogen carriers for 'Environment' (and 'Sustainable'), as is evident from the JRC's analysis[24]. In terms of the public interest 'Affordable' too, LH_2 scores roughly in the middle (comparatively fairly high, in general). The score of LH_2 for the public interest 'Safe & Secure' is reasonably high, and close to that of most other hydrogen carriers. The MCA gives LH_2 a lower score for 'Reliable' (security of supply). Liquid hydrogen currently lags behind in terms of technical and commercial maturity compared to ammonia, methanol and LOHCs, for example. New and innovative ships will be needed for its transportation, while some other hydrogen carriers can be transported using existing ship designs and technology. In the future, when it becomes more technologically mature, LH_2 will score higher for the public interest 'Reliable'.

Guiding principles

When considering all public interests together, LH_2 scores high in the MCA for all modes of transport and both end-use applications. This translates into a mostly positive assessment in the matrix, with scope for a supporting role by the government (both financial and non-financial). Points of concern are the challenges for large-scale transport. Due to its extremely low temperature, LH_2 is not suited for transportation by pipeline. International regulations currently prohibit transport by barge. Until this becomes possible, LH_2 is mainly suitable for conversion to hydrogen gas in the import port and small-scale distribution of hydrogen by road, such as for the mobility sector. Small-scale transport of LH_2 already takes place in a number of cases using specially designed containers.

Support for LH_2 ('incentivise' in the matrix) could focus on increasing 'Reliable' (security of supply) by promoting the technological development and scaling up of the supply chain. This also contributes to the government's commitment to diversify hydrogen carriers to decrease dependency on a single source of origin and technology. LH_2 is suitable for conversion in the import port (efficiency of the process, limited use of energy and space) and transport by the hydrogen pipeline network (after conversion). In the slightly longer term, it is expected that LH_2 could also be a very efficient way to distribute hydrogen to companies not connected to the hydrogen pipeline network, such as filling stations and Cluster 6 industry. In this form, LH_2 can contribute to the robustness of the Netherlands' position as an international energy and hydrogen hub.

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[24] JRC (2024), *Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe*, https://publications.jrc.ec.europa.eu/repository/handle/JRCi37953

End-uses

End-use as hydrogen carrier (direct use)

The most promising end-use for LH_2 is considered to be direct use as a fuel in maritime and inland shipping, aviation and possibly heavy road transport. Direct use of LH_2 scored positively for mobility in the matrix because there are only limited alternatives for this type of end-use, it is a relatively clean fuel, and the government is broadly committed to the application of hydrogen in the mobility sector. There are also applications of liquid hydrogen in the semiconductor and electronics industries, and the general interest in and volumes of these applications are expected to increase.

End-use as hydrogen gas

End-use of LH_2 as hydrogen gas requires a (relatively simple) regasification step. Incentives for decentralised conversion (if any) will preferably be temporary, in anticipation of a pipeline network for hydrogen gas (primarily focused on end-use in the Netherlands). LH_2 has promising applications in the area of decentralised conversion for supplying filling stations and fuel storage tanks for heavy road transport, barges and airports, as well as Cluster 6 companies that cannot be connected to the hydrogen network. As a rule, there are no plans to connect filling stations and fuel storage tanks to the hydrogen pipeline network, including in the longer term. Many business parks are also unlikely to be connected to the hydrogen network. Supplying these businesses with hydrogen in the form of LH_2 will substantially reduce the number of transport movements required compared to using pressurised hydrogen gas, as LH_2 has a higher energy density. An important additional advantage is that, as LH_2 evaporates and expands, it quickly reaches the required pressures of 350 or 700 bar (for fuelling compressed hydrogen gas), without the need for compressors or additional purification (compared to using hydrogen supplied by the national hydrogen transport network). This provides benefits at the relevant end-use sites in terms of noise pollution, spatial footprint, costs, energy use and safety. In the short term, the vision provides a scope for financial incentives for the technological developments described above, and in the longer term for non-financial support.

The score for decentralised conversion of LH_2 for use as hydrogen gas in power plants is lower. This is because of the potentially (much) larger volumes and the disadvantages of LH_2 for long-term decentralised storage (being energy loss and boil-off). The vision provides scope to temporarily make non-financial support available for the application of LH_2 in power plants. After this period, there will be no scope for additional support for this particular application of LH_2 as part of the energy transition.

The German government will mainly be responsible for incentivising and facilitating any onwards transport to Germany. The transport of LH_2 for decentralised conversion in Germany was given a lower score than centralised conversion in the Netherlands. Again, this is due to the potentially large volumes, energy losses and emissions caused by the longer supply chain. Transport of hydrogen gas by pipeline is preferable here. The vision provides temporary scope to facilitate transport to Germany, but from the medium term onwards, the support for this end-use should focus mainly on centralised conversion, and on exceptional cases involving (small-scale) decentralised conversion in the Netherlands.

Additional specific considerations

As mentioned above, international regulations currently prohibit transport by barge. The government plans to join forces with sector parties to explore how transport by barge could be permitted, including by seeking changes to international regulations.

Ammonia

General

Public interests

Ammonia scores lower in the MCA for end-use as hydrogen gas than the other hydrogen carriers for all modes of transport, with the exception of pipelines. Ammonia transport by road in particular scores much lower than the other modes of transport. Ammonia transports overland also score relatively poorly in the MKBV. Ammonia achieves an average score for all public interests combined for supply chains that depend on pipelines.

However, ammonia gets high scores for the public interests 'Affordable', 'Economically Robust' and 'Reliable' if these are considered separately. This is because of the low import costs and the maturity of the technology and the supply chains (ammonia has a long history of use in the chemicals industry).

Like most other hydrogen carriers, ammonia produces few greenhouse gas emissions and involves only limited consumption of critical materials, contributing to a high score for the public interest 'Sustainable'. Ammonia scores lower for energy use than LH_2 and LOHCs, because the conversion to hydrogen gas requires heat that is produced using part of the hydrogen carrier (just as with methanol and LSM). This affects the score for the supply chain more than the power consumption required for conversion of other hydrogen carriers, because this energy is also imported via the carrier and thereby increases the import volume.

Ammonia scores low on the public interest Safe & Secure, due to the potentially major effects on the surroundings in the event of an incident or accident involving a large ammonia outflow, and the associated toxic cloud that can extend over a large area and where effects can manifest themselves for a long time. Given the large volumes that can be transported in pipelines, this mode of transport also entails the risk of large releases of ammonia in the event of a rupture or leakage. It is therefore important that ammonia pipeline designs incorporate specific additional features to reduce the probability of a rupture or leakage, and limit the volume released in the event of a rupture or leakage. Studies are currently being conducted into ammonia pipeline safety, the conclusions of which have not yet been incorporated in the vision and this background document.

With the exception of the Betuweroute corridor, most rail transport takes place nearby or through residential areas. Although the Netherlands has a very safe rail and road infrastructure, and the modes of transport meet the strictest requirements, the options for managing and containing an accident involving the release of large volumes of ammonia are limited, and so the potential impact is such that ammonia scores poorly for the public interest 'Safe & Secure'. Ammonia also scores poorly for the public interest 'Fair'. This is due to environmental impacts and costs in the export country compared to the relatively low import costs. Ammonia scores similar to other carriers for the public interest 'Spatial Planning'.

Guiding principles

Ammonia is given lower scores in the matrix, particularly for decentralised conversion and direct use of the carrier inland. Ammonia supply chains that depend on modes of transport other than pipelines also score relatively poorly. The preferred end-use is in clusters of activities in the port area, so that the emissions and safety risks are also clustered. Where ammonia transport is facilitated or accepted, this is often subject to additional conditions and preferred modes of transport.

Unlike LH_2 and LOHC, ammonia as a hydrogen carrier scores quite highly for 'Reliable'. This is because it has a long history of use and makes use of technologically and commercially mature production plants and modes of transport. An exception are the ammonia crackers, as ammonia is a relatively new hydrogen carrier application, and the crackers cannot yet produce at the scale that will likely be required. With a view to diversifying import supply chains and avoiding transport of ammonia inland, the vision allows for the temporary support of cracking technology development or scaling-up in port areas. If ammonia has to be transported inland or further into northwestern Europe, this can best be done through a pipeline, provided it meets specific conditions. The vision therefore also provides a scope for facilitating the development of ammonia pipelines.

Due to the nature of ammonia, a guiding principle for pipelines will be that more additional measures will be required than normally applied by the industry to date. Ammonia has not previously been transported in such volumes and over such distances in the Netherlands. The government therefore requires additional safety measures which will be costly, but not disproportionate given the unique situation. With these additional safety measures, the current 'site-specific risk standard' (10-6/year) should be met at a distance of 5 metres. This leads to a more-or-less inherently safe pipeline (very low failure probability) with a small spatial footprint, while the use of valves (compartmentalisation) ensures that any damage to the surrounding area will be relatively limited in the unlikely case of an incident.

End-uses

End-use as hydrogen carrier (direct use)

The main end-use of ammonia, being direct use or conversion to hydrogen gas, will take place in the import port. But even within the port areas, careful consideration will need to be given to the safety impact and the consequences thereof for developments in and outside the area. The vision provides a scope for the direct use of ammonia as a raw material where no good alternative is available, also because this will involve comparatively small volumes compared to the use as fuel in the industry or for power/electricity generation. For this reason, decentralised end-use of ammonia (as raw material) scores higher than decentralised conversion of ammonia to hydrogen gas.

Pipelines are the preferred mode of transport for ammonia that is used as a raw material in the industry (in the Netherlands or in Germany), followed by barge, and where neither is possible by rail, with the Betuweroute corridor having preference as a transport route. Transport by road is expected to play a very limited role given the relatively small volumes that can be transported (making the transport of larger volumes very costly), and the risk of accidents (highest for road transport).

The end-use of ammonia as a fuel for power generation or as a fuel for the industry elsewhere in the Netherlands is undesirable. It is not always known whether ammonia that is transported to Germany is used as a raw material or as a fuel.

End-use as hydrogen gas

Cracking ammonia to form hydrogen gas in port areas will play a role in both the short and long term to ensure a sufficient supply of hydrogen gas. Because of the lack of alternative hydrogen carriers in the short term, incentives will be provided for cracking at import ports to ensure that the demand for hydrogen gas for mobility and the industry can be quickly met. For this reason, the vision specifically provides scope to temporarily incentivise cracking in the import port to minimise external effects and cluster the relevant activities in a single area. This will help reduce transport movements of ammonia through the Netherlands. This concerns volumes of hydrogen that will potentially not be able to be imported using alternative hydrogen carriers, or only to a lesser extent, in the initial phase of the energy transition.

Once alternative hydrogen carriers become available in larger volumes, these alternatives will be preferred. The market share of these alternatives may eventually exceed that of ammonia, but in absolute terms the market for ammonia that is developed in the coming years is expected to stabilise even after alternative hydrogen carriers become viable.

A supply chain for end-use of hydrogen gas as a fuel (with ammonia as the carrier and conversion taking place elsewhere in the Netherlands) is less desirable. However, it may be a temporary option for end-use sites that are not yet connected to the hydrogen pipeline network. Assuming alternative hydrogen carriers become available and the hydrogen pipeline network is further rolled out, this option will become undesirable in the longer term. Cracking ammonia elsewhere in the country to supply the mobility sector is undesirable, given the additional handling and storage this will require at or near filling stations, many of which are in or near the built environment. Here, the end-use is not the carrier itself, so distributing liquid hydrogen from the import port to the filling station is seen as a more desirable and logical alternative.

Transport within the Netherlands and to Germany

This vision discourages transportation of ammonia in general. The starting point for ammonia supply chains that are temporarily or permanently facilitated or accepted is that the transport will take place by pipeline or by barge, and only by rail (via the Betuweroute corridor) if there is no other option available. Due to the sometimes limited volumes, it is not realistic to transport all ammonia to end-use sites (with decentralised conversion) by pipeline. In these cases, the preferred mode of ammonia transport will be by barge. If transport by barge is not possible (for example due to the lack of a waterway or during periods of high or low water levels), then rail transport can be a (temporary) solution. This involves a specific preference for transport via the Betuweroute corridor (and specifically for transports from Rotterdam). Transporting ammonia by rail over routes other than the Betuweroute corridor is undesirable given the building density along these routes. Road transport may be temporarily acceptable for business parks that are not located next to a waterway or railway line and for which no other alternative is yet available. However, this is by no means the preferred option, and will only be accepted in very specific cases. Given the limitations, risks and costs of road transport, this mode is expected to play only a very limited role.

It is assumed that the demand for ammonia for direct use as a raw material in Germany will not change significantly compared to the current situation (there are already companies in Germany that use ammonia as a raw material, e.g. for fertiliser production). A major factor here is the amount of energy required in Germany: ammonia can carry more energy than hydrogen (as a gas) per same volume , but it is uncertain how this technology will develop. Any government support for transport will in any case be non-financial and focus specifically on pipelines (analogous with the planned ammonia pipeline as part of the Delta Rhine Corridor, or DRC).

Additional specific considerations

In the government position on ammonia of 2004, no distinction was made between liquid (cold) ammonia and compressed (warm) ammonia. The vision presented in this background document assumes the existing ammonia supply chains, i.e. that ammonia is imported as a liquid by maritime vessels and stored in liquid form near the landfall site in the port. The ammonia is generally transhipped, transported and used in a compressed state. International regulations currently prohibit transportation by road and rail in liquid form. However, because of the expected benefits of this type of transport (in terms of external safety and energy efficiency, among others), there is reason to further explore whether and under what conditions the international regulations could be changed. This exploratory study will also examine the transport of liquid ammonia by barge.

Liquid organic hydrogen carriers (LOHCs)

General

Several substances fall under the LOHCs, including the following compounds:

- benzene-cyclohexane
- toluene-methylcyclohexane (MCH)
- dibenzyltoluene perhydro-dibenzyltoluene (DBT)
- N-ethylcarbazole (Ho-NEC) - perhydro-N-ethylcarbazole (H12-NEC)
- 1,2-dihydro-1,2-azaborine (AB) – 1,2-BN cyclohexane (BNC)
- naphthalene-decalin

Several LOHCs are also still under development. Not all LOHCs are at the same stage of technological and/or commercial maturity. LOHCs are hydrocarbons that are already used in the Dutch chemicals industry. When the MKBV was initiated, it was decided to study the LOHC DBT[25]. For the MCA, the selection was expanded to include MCH. The main reasons for this choice are that these two LOHCs appear to be at the furthest stage of technical and commercial maturity, sufficient data were available for them in comparison with other hydrogen carriers, and there are (or were) concrete plans to develop projects in the Netherlands for both these LOHCs.

The two LOHCs score very differently for some public interests, but much the same for others. For the purposes of this vision, the two LOHCs were combined into one group. For the meantime, it is assumed that other LOHCs not included in the study will have similar properties.

Public interests

LOHCs (both DBT and MCH) converted in the port area generally score highly for public interests in both the MCA and MKBV. It is notable here that LOHCs score lower than ammonia or methanol for ‘Affordable’, but are comparable to these hydrogen carriers for ‘Economically Robust’. In the MCA, the import costs of the carrier have the most impact on the public interests ‘Affordable’ and ‘Economically Robust’.

LOHCs score higher than other hydrogen carriers for external safety, cybersecurity and terrorism (that all fall under the public interest ‘Safe & Secure’). These carriers score slightly lower for transport safety because of the many transport movements required, which is related to the lower volume of hydrogen released during conversion and the need for an additional pipeline for the return flow (if a pipeline is used). When converted, specific LOHCs may involve the use and possible release of so-called substances of very high concern (ZZSs). ZZSs have proven harmful effects on humans and the environment and are therefore isolated from the living environment wherever possible, and in any case where these substances meet one or more of the hazard assessment criteria of Article 57 of the European REACH regulation. This has been taken into account in the assessment. Several types of LOHCs are currently under development, including ones without ZZSs.

Due to the volumes that must be transported, stored, and converted, LOHCs score lower for the public interests ‘Spatial Planning, ‘Accessible’ (due to higher transport costs) and ‘Adaptable’ (due to the required investments in storage and conversion plants). It should be noted here that LOHCs can be transported using the existing fossil hydrocarbon infrastructure (such as ships and storage tanks). In the medium term, however, it is expected that this infrastructure will still largely be used for the current fossil flows. In the longer term, the reduction of the fossil hydrocarbon economy may provide an opportunity for more efficient scaling-up of LOHCs, but until then it is expected that new LOHC infrastructure will also be required.

LOHCs score lower than ammonia and methanol, but higher than LH_2, LSM and $NaBH_4$ for the public interest ‘Affordable’. In terms of the public interest ‘Reliable’ (security of supply), LOHCs score lower than carriers that are already widely transported, such as ammonia, methanol and liquid methane (LNG), but higher than other relatively new/innovative carriers such as LH_2 and $NaBH_4$.

Guiding principles

[25] The hydrogen-rich version is actually perhydro-dibenzyltoluene (PDBT), but we use the abbreviation DBT as it is more common.

The commitment to LOHCs contributes to the goal to use a diversity of hydrogen carriers and so avoid becoming dependent on a single carrier. LOHCs can also play a role in long-term energy storage. LOHCs are stable in storage, so they are also expected to be suitable for strategic stockpiling or other longer-term storage goals.

As with LH_2, any support for LOHCs could focus on increasing reliability (security of supply), for example through the technological development and further scaling-up of conversion plants. It should be noted that some LOHCs are more technologically mature than others (see for example the appendix of the MCA report for more details). LOHCs are suitable for conversion in the import port and transport by the hydrogen pipeline network.

For certain LOHCs, the use and potential release of ZZSs are a health and safety concern for the energy transition. ZZSs can also be formed during the conversion process. Companies are expected to focus on developing supply chains that are free of ZZSs, make maximum efforts to minimise the use of ZZSs and, where this is not possible, take appropriate measures to minimise releases into the living environment and human exposure.

End-uses

End-use as hydrogen carrier (direct use)

Some LOHCs are already used in the industry, such as toluene in the chemicals industry and DBT as a heat exchange fluid, but this is not true for all LOHCs. These are not growth markets. Therefore, only supply chains with hydrogen gas end-use were considered in the assessment.

End-use as hydrogen gas

The preferred option is centralised conversion in the import port and transport of hydrogen gas through the hydrogen pipeline network. Transport of LOHCs via pipelines to the end-use site (with local conversion) appears to have only limited potential for the time being, because this involves a return flow (the carrier without hydrogen) and so would require two pipelines, while a single pipeline will suffice for the other hydrogen carriers. In addition, certain LOHCs probably cannot be transported by pipeline because of their viscosity. The vision provides scope for supporting decentralised conversion of LOHCs, for example where no hydrogen pipeline network is planned in the vicinity.

Decentralised conversion may be a suitable temporary solution at end-use sites where centralised conversion is not an option, for example because there is currently no connection to the hydrogen pipeline network. For the short and medium term, the vision provides scope to provide non-financial support to such developments.

For medium-sized flows, the government's preference is for this transport to take place by barge where possible. If rail transport is required, then preferably via the Betuweroute corridor. Road transport may be an option for small volumes.

Transport of LOHCs for decentralised conversion in Germany for power generation is considered undesirable in the medium term. This is because of the large volumes required for this end-use. This is partly also because a cross-border hydrogen pipeline network is expected to be in place by then.

Additional specific considerations

There are new, innovative LOHCs under development, including by Dutch companies. These companies emphasise they are developing an LOHC without ZZSs and with lower energy requirements for the dehydrogenation phase (the separation of the hydrogen from the carrier). These LOHCs may be given a slightly higher score for this reason, and may become an option for decentralised processes in the future.

However, Spatial Planning and transport Safety remain a point of concern for these LOHCs too.

Methanol

General
Methanol has a long history of use in the chemicals industry, and can be considered a climate-neutral hydrogen carrier if the carbon used to produce it is of non-fossil origin (e.g. extracted from the atmosphere). If the CO_2 released during the conversion or combustion of methanol is captured (and possibly reused), the net result could be negative emissions (carbon removal). Methanol is included in the MCA as representative of a 'family' of potential alternative hydrocarbons that could also be considered as carriers (dimethyl ether, ethanol, etc.) and may also have a role to play in the future. Carriers like ethanol and methanol are carbon-based and so also carbon carriers according to the NPE definition.

Public interests
Methanol scores in the middle range in the MCA for hydrogen as an end-use if it is synthesised in the export country using industrial carbon (with CCS). However, methanol scores highest across the board in the analyses in the situation where sufficient sustainable carbon is available for the synthesis process.

Methanol has significant advantages on the various public interests over other hydrogen carriers, both for intercontinental transport and transport within the Netherlands. Methanol does not need to be cooled, nor does it involve a return flow (unless the CO_2 is captured and transported). This makes it a relatively easy substance to store and transport. Methanol is not substantially different from other fuels and raw materials that are already widely transported through the Netherlands, and therefore raises fewer new policy concerns than other hydrogen carriers. Methanol is a toxic substance, but if it is accidentally released into the environment it does not produce a toxic cloud, as ammonia does.

Despite the fact that methanol contains carbon, the supply chain can be made climate-neutral if a sustainable carbon source is used in the production of the methanol. Several routes are available to this end. Sustainable carbon can be sourced from sustainable bio-based raw materials, CO_2 captured from air or point sources, and recyclates. The EU Renewable Energy Directive sets conditions on carbon use. Sustainable carbon will potentially become a scarce resource. The NPE sets out starting points for ensuring the deployment of the highest possible grade of sustainable carbon. The production of sustainable methanol will require further development and monitoring of the sustainable carbon chain. A combination of sustainable carbon and Carbon Capture and Storage (CCS) in methanol end-uses can help to achieve negative emissions (carbon removal).

Guiding principles
Methanol is already widely used in the industry, and modes of transport and storage facilities are already available, although additional capacity will need to be developed. The vision provides scope for financial incentives for the development and scaling up of methanol-to-hydrogen gas conversion facilities in the port area. This technology has not yet seen large-scale application. The same applies to technologies for producing sustainable carbon, such as Direct Air Capture (DAC).

Such non-financial incentives should be used to develop a market for negative emissions as part of the transition to climate neutrality in 2050. The deployment of methanol will contribute to the policy goal of diversification of the hydrogen carriers used. Encouraging the replacement of fossil methanol with sustainable methanol will provide an incentive to the supply chain as a whole and also directly lead to reducing the greenhouse gas emissions of existing end-users.

End-uses

End-use as hydrogen carrier (direct use)

Like ammonia, methanol can be used directly as a raw material or fuel, but it has a lower safety risk. The vision provides scope for incentivising supply chains for the direct use of methanol as a replacement for fossil raw materials in the industry, or fossil fuels in the industry and mobility sector, to make these sectors more sustainable in line with the desired transition of the carbon supply chain in the NPE.

The preferred mode of transport for methanol is by pipeline or barge. Decommissioned oil pipelines could potentially be used for this purpose in the future. Supply chains involving the end-use of methanol as a carbon-based raw material in the industry or as a maritime fuel score favourably as a replacement of fossil carbon-based raw materials. If significant effort has already been invested in binding carbon to hydrogen in the country of origin, it would be inefficient to release this carbon into the atmosphere in the Netherlands after use, especially given the increasing demand for sustainable carbon and carbon removal.

Due to its carbon content, methanol has the advantage of a higher energy value when used directly as a fuel in the industry and for power generation. However, in principle, these uses contradict the starting point for carbon supply chains in the NPE, namely to restrict the use of sustainable carbon to situations where no alternatives are available (due to potential future scarcity). The NPE thus focuses on alternative technologies for electricity generation and energy use in the industry. To facilitate a rapid transition, the vision provides scope to incentivise supply chains for the direct use of methanol. Methanol can also be used directly as a fuel, particularly in shipping, and there are already ongoing initiatives to develop this. Here too, the vision provides scope to incentivise the replacement of fossil fuels in this supply chain.

Any support (incentives or facilitating) should focus primarily on deployment as a raw material or fuel for international aviation and shipping, because potential alternatives are expected to be scarcer here than in other types of end-use, with a continuing demand for carbon-based hydrogen carriers as fuel for the time being due to their energy density.

End-use as hydrogen gas

If the methanol is converted to hydrogen gas, there is a preference for this process to take place in the port area, at the landfall site. With centralised conversion, it is easier to capture the CO_2 and thus achieve zero-emissions or even negative emissions for the supply chain as a whole.

In general, there are relatively few public objections to the transport, storage and decentralised conversion of methanol, because the risk profile is similar to that of substances commonly transported today.

LSM (e-LNG)

General

Methane is the main constituent of natural gas and has a long history of use in various applications in the Netherlands. Liquefied methane is called LNG (liquid natural gas). Sustainable alternatives include bio-methane (green gas) or synthetic methane obtained from renewable hydrogen (also known as e-methane). LSM (liquid synthetic methane, also known as e-LNG) is the synthetic variant of LNG.

Like methanol, LSM (and also synthetic methane) is considered a sustainable hydrogen carrier if sustainable carbon is used to produce it.

Carbon dioxide is released when methane is burned or converted to hydrogen gas. If the CO_2 released during the conversion to hydrogen gas or combustion of LSM is captured (and possibly reused), the net result could be negative emissions (as long as the CO_2 source is sustainable). DAC is not expected to become sufficiently technologically mature in the short term (2030/2035), requiring the use of either biogenic CO_2 or fossil sources of carbon in the short term. LSM based on non-sustainable carbon will be less sustainable in this case. The production of sustainable LSM will require further development and monitoring of the sustainable carbon chain. A combination of sustainable carbon and Carbon Capture and Storage (CCS) in LSM end-uses can help to achieve negative emissions.

Public interests

Like methanol, LSM is given an average score for conversion to hydrogen in the baseline scenario, but it achieves a much higher score when used directly as a carrier (if CCS is applied) and in the 2050 variant (with carbon obtained through DAC). If LSM based on sustainable carbon is regasified to produce methane gas and transported through the existing natural gas network for direct use, it is among the highest-scoring options when considered from a broad societal perspective. This score is comparable to direct use of methanol and higher than the score for direct use of ammonia (insofar as the end user has the flexibility to choose between carriers).

LSM scores lower than liquid hydrogen and the two LOHCs when used as a hydrogen carrier (i.e. the hydrogen gas has to be separated from the carrier), mainly due to the low score for the public interest 'Sustainable'. Like methanol, LSM scores lower than the other hydrogen carriers for end-use as hydrogen gas (for the period up to 2030/2035), assuming the carbon is fossil-based and conversion to hydrogen gas therefore leads to fossil carbon emissions (delayed or otherwise). The 'Sustainable' score improves closer to 2050, as it is assumed that the carbon required for synthesis will be able to be extracted from the air via DAC. Because methane leakage of itself has a large greenhouse effect, LSM scores lower for 'Sustainable' than methanol, for example.

The production (synthesis) of methane consumes a relatively large amount of energy. Just as for methanol, in LSM, if significant effort has already been invested in binding carbon to hydrogen in the country of origin, it would be inefficient to release this carbon into the atmosphere in the Netherlands after reforming, while there is an increasing demand for sustainable carbon.

LSM scores highly for the public interest 'Reliable'. This is partly to do with the maturity of the technologies and supply chains.

LSM can make use of the existing infrastructure for LNG and natural gas. In terms of the public interest 'Safe & Secure', LSM scores slightly lower than other hydrogen carriers, with the exception of ammonia (which scores significantly lower). LSM scores relatively highly for the public interest 'Environment', because the related emissions (methane emissions or CO_2 emitted during combustion) mainly influence the public interest 'Sustainable'[26], for which LSM has a lower score. LSM as a hydrogen carrier scores relatively lower for the public interest 'Affordable' due to the energy losses during conversion to hydrogen and the additional volumes that need to be imported to compensate for this.

LSM scores slightly lower for the public interest 'Economically Robust'. This is due to the higher costs of the imported carrier, partly a consequence of the relatively low energy efficiency of this supply chain as a whole.

[26] Eco-toxicity and smog-forming are included in the public interest 'Environment'.

Guiding principles

The main difference between LSM and LNG is the origin: is it produced with renewable energy, renewable hydrogen and sustainable carbon (in the case of LSM) or with fossil sources (in the case of LNG). The existing infrastructure comprising LNG terminals, regasification plants and the natural gas infrastructure can be used for storage and transport in the Netherlands. Additional capacity for LSM storage and conversion may temporarily be required. The vision provides scope to facilitate and, where necessary, encourage innovations and optimisations in the LSM supply chain. This will help to maintain or even strengthen the Netherlands' existing position as an energy hub.

Because so much experience has already been gained with LNG and natural gas, there are no specific new safety or health issues that need to be taken into account. Evaporation to methane gas or conversion to hydrogen gas in the import port are the preferred end-use options. This will allow for transport through the natural gas network or, in the case of conversion to hydrogen gas, through the hydrogen pipeline network.

Encouraging the replacement of fossil methane with sustainable methane will provide an incentive to the supply chain as a whole and also directly lead to reducing the CO_2 emissions of existing end-users (as long as the production of sustainable methane does not compete with other carbon-rich raw materials).

End-uses

End-use as hydrogen carrier (direct use)

LSM will mainly serve as a more climate-friendly alternative to LNG and/or natural gas. It can also be classified as an RFNBO (Renewable Fuel of Non-Biological Origin) and as such meets the binding European RFNBO targets in the Renewable Energy Directive (RED).
Companies that do not have access to the hydrogen infrastructure, but do have access to the natural gas network, can improve their sustainability by regasifying LSM into methane gas and transporting the gas through the natural gas network. However, due to the potential future scarcity of sustainable carbon, the NPE proposes minimising the use of sustainable carbon carriers (including LSM) for applications for which carbon-free alternatives are also feasible. LSM can also be used in liquid form in the mobility sector, such as in heavy road transport (although this sector also prefers carbon-free alternatives where possible) or in shipping (where LNG is already used). The vision provides scope for supporting LSM supply chains to help these end-users become more sustainable.

End-use as hydrogen

Instead of converting it to hydrogen, it is more logical and efficient to directly use methane gas obtained through LSM. If LSM is converted to methane gas, analogous with the current practice with LNG, it will make little difference where in the supply chain it is converted to hydrogen gas (if at all). Methane gas can be transported through the existing natural gas network, and there are plenty of storage facilities above and below ground. LSM can be transported by other modes, but this is less desirable and logical at a larger scale for reasons of cost efficiency, energy efficiency, transport capacity and safety, among others.

Additional specific considerations

As grey (fossil) hydrogen is already produced from methane (natural gas) and from imported LNG, it will be important to closely monitor the sustainability of LSM supply chains. LSM needs to be improved if it is to play a significant role as a hydrogen carrier, mainly in the area of energy efficiency and the cost of DAC and methane synthesis. LSM currently appears only somewhat competitive in comparison with other hydrogen carriers. This will change if higher efficiencies can be achieved for DAC (or for biogenic carbon capture) and methane synthesis.

The vision provides scope for government support (financial or non-financial) primarily focused on these technological innovations.
Given the strong similarities between LSM and LNG, a focus on LSM could give the impression that fossil raw materials and the associated infrastructure are to be maintained, or that they have become locked in. Decision-making on facilitating, and where necessary incentivising, LSM should take this into account.

Sodium borohydride ($NaBH_4$)

General

Public interests

$NaBH_4$ scores highly for the public interests 'Safe & Secure', 'Fair, 'Accessible' and 'Environment' in the MCA. However, $NaBH_4$ has the lowest score of the carriers in the comparison for the public interests 'Affordable' and 'Economically Robust'. $NaBH_4$ is the most expensive carrier. This is primarily because the production of the carrier and recycling after the hydrogen has been extracted are energy intensive processes. Also, the carrier material is expensive. High import costs result in a lower score for the public interest 'Economically Robust'. $NaBH_4$ also scores relatively poorly for the public interest 'Reliable'. This is because this is a new supply chain, and not all steps in the process have been demonstrated and proven as yet.

Regarding the public interest 'Adaptable', storage tanks and modes of transport that have been used for $NaBH_4$ can be efficiently reused for other substances (in comparison with other carriers). However, this carrier does require investment in conversion plants, and this financial factor carries more weight and so results in a relatively low score for 'Adaptable'. This is because the production and recycling of the carrier are energy intensive processes, and boron is a very rare raw material. For the public interest 'Sustainable', $NaBH_4$ is given similar scores to other carriers for greenhouse gas emissions, but lower scores for energy consumption in the supply chain and materials use. These scores result in a lower overall score for the public interest 'Sustainable'.

$NaBH_4$ is a solid, which makes various 'niche' applications conceivable that would be unsustainable if applied to other carriers. This has been taken into account in the assessment in the matrix.

Guiding principles

Based on the above, for the time being, a role for $NaBH_4$ is envisaged only for specific 'niche' applications. In this respect, $NaBH_4$ will not contribute substantially – certainly in terms of volume – to the intended diversification of carriers in the short and medium term. Nor is a significant role foreseen for $NaBH_4$ in the Netherlands as an international energy hub for the time being. $NaBH_4$ could potentially contribute to a safe and healthy energy transition, but there are currently a number of substantial obstacles to using this carrier. It is still uncertain whether these obstacles can be removed in the longer term, either for $NaBH_4$ itself, or for an alternative substance very similar to $NaBH_4$ that is not dependent on the critical raw material boron, for example.

End-uses

End-use as hydrogen carrier (direct use)

$NaBH_4$ has no direct application as a carrier. However, applications are known where a vehicle is 'refuelled' with $NaBH_4$ and it is converted to H_2 in the vehicle. This leaves a residual product to be recycled.

End-use as hydrogen

$NaBH_4$ must be converted to hydrogen gas for end-use. Incentives will preferably go to centralised conversion in the import port in the interim. This is to ensure the relevant industrial activities are clustered as much as possible. Decentralised conversion could temporarily be incentivised in situations where there is no access to the national hydrogen pipeline network, particularly for niche applications in small industry and the mobility sector (also given the transport constraints mentioned below). Due to the stability of solid-state $NaBH_4$ (if stored dry), sodium borohydride is a suitable carrier for long-term $NaBH_4$ storage, although the demand for the scarce resource boron may preclude a major contribution to the energy transition.

Additional specific considerations

$NaBH_4$ has the advantages of a solid and remains stable if kept and stored in completely dry conditions. Another advantage of $NaBH_4$ is that, during the reaction to produce hydrogen gas, twice as much hydrogen is released as was used to produce the carrier. This extra hydrogen comes from the water that is used to separate the hydrogen from the salt. This reaction also releases a limited amount of heat.

However, a very large amount of energy is needed for this supply chain as a whole. This is related to the recovery of sodium and boron from the aqueous salt solution (the brine that remains after the reaction). The process of recycling and producing $NaBH_4$ from the return stream also uses up a lot of space and energy. Another disadvantage of $NaBH_4$ is that it is dependent on the critical raw material boron. As a result, $NaBH_4$ will in all likelihood continue to be available only in smaller quantities.

An important point for concern is that it is currently prohibited to transport $NaBH_4$ in bulk. Various international regulations for the transport of dangerous goods stipulate that $NaBH_4$ may not be transported in tanks and large packaging, and only in hermetically sealed drums (break-bulk cargo). This means large-volume applications will be insufficiently profitable, if not unprofitable. The prohibition stems from European regulations for the transport of dangerous goods by road (ADR), rail (RID) and inland waterways (ADN), as well as global regulations for the transport of dangerous goods by sea (IMDG code). The reason for the prohibition is the high reactivity of $NaBH_4$ with moisture or water, which can lead to a violent and dangerous reaction.

7. Significance by type of end-use and end-use site

General

This background document is primarily intended to elaborate how the public interests in the NPE are taken into account in the preferences for various hydrogen carriers in combination with modes of transport and end-use applications (end-use and end-use site). The way the matrix is designed does not immediately provide an end-user, supplier or other stakeholder with a clear picture of what this means for the relevant sector. This chapter therefore provides a summary of the key elements of this background document by user group and type of end-use site.

This chapter presents the results of the previous chapter in a different way, but the general principles still apply. The elaboration by sector and type of end-use site is kept relatively brief and there are many conceivable nuances, not all of which are covered in detail. This chapter should be read primarily as a description of the currently understood state of affairs. The government vision is adaptive, but while developments in technology and the market may lead to new insights, the assessment framework itself (based on all public interests) remains a stable factor. It is worth repeating that the options for steering the vision will have to be elaborated in more detail in the follow-up process, which will also involve various public authorities, port operators and network operators. Finally, it goes without saying that the central government must always be mindful of all public interests.

Explanation per end-use

Use of hydrogen and hydrogen carriers as industrial raw material

There is a wider range of industrial sectors that are considering hydrogen carriers as a means of improving raw materials sustainability than those already currently using hydrogen as a raw material for, or component of, their production process. Of the current sectors, fertiliser production in particular stands out, because this sector already produces relatively large volumes of ammonia. Another notable sector is the petroleum refining industry, which uses a lot of hydrogen. More sectors are expected to use hydrogen and hydrogen carriers as a raw material in the future, particularly the chemicals industry (for replacing fossil hydrocarbons). Sustainable carbon-based hydrogen carriers are specifically being considered here.

Where the industry uses hydrogen carriers as raw material (ammonia, methanol or LSM), the vision provides scope to transport the carrier to the relevant industrial site (including ammonia, although the vision encourages seeking alternatives to ammonia where possible). The order of preference for the various modes of transport modes was described at the start of Chapter 5.

Where hydrogen is used as a raw material, the vision describes a clear preference for conversion and end-use of the carrier at the landfall site, or transportation of the gas through the national hydrogen pipeline network.

Use of hydrogen and hydrogen carriers as industrial fuel

The main applications of hydrogen and hydrogen carriers as industrial fuels are in high-temperature processes that are difficult or impossible to electrify. The volumes required here can vary widely, but are generally expected to be substantial. Some users will be able to choose between various sustainable options (i.e. various hydrogen carriers). Other users will have no or only very limited choices, for example because of their location and the availability of modes of transport.

In principle, direct use of hydrogen carriers is the preferred option for fuels. This will avoid energy losses and emissions, as well as preventing the need for additional space and avoiding the safety risks involved in conversion facilities. The preferred sites for this type of end-use are at or nearby the landfall sites. Direct use is also the preferred option for end-users at other sites. This applies especially to carriers whose transport has a relatively low spatial footprint and impact on external safety. The exception here is the use of ammonia as a fuel (due to its specific properties). If direct use in the port area is not possible, and a sufficiently safe ammonia pipeline is lacking, the preferred option is conversion to hydrogen gas in the port area and transport through the hydrogen pipeline network.

Carbon-based hydrogen carriers such as methanol and LSM will preferably be used only for the highest-grade applications, and used as fuel as little as possible (with the exception of aviation and shipping).

If the industry is located in the port area where the hydrogen carrier made landfall, the vision provides for direct use of the carrier as a fuel. This is regardless of the type of carrier, as this does not require any transport of dangerous goods outside the industrial cluster.

Use of hydrogen and hydrogen carriers as fuel for electricity generation

The Netherlands is investing heavily in renewable electricity production from the wind and sun. Hydrogen can play a role in this energy system during periods when the electricity demand exceeds the renewable supply. Hydrogen carriers can contribute to the security of supply of this end-use. Depending on the overall configuration of the national electricity system, above-ground hydrogen carrier storage and underground hydrogen gas storage will, to an extent, function as 'communicating vessels'.

The principle of using hydrogen and hydrogen carriers as fuel for electricity production is equally applicable to their use as fuel in the industry, namely a preference for direct use of the hydrogen carrier (especially in case of end-use in the port area) and transport through the hydrogen pipeline network (in the case of end-use of hydrogen gas). One difference is that electricity generation by definition involves large volumes, which must be available quickly at peak times. This requires a supply infrastructure with sufficient capacity (e.g. the hydrogen pipeline network) or substantial storage capacity at the power plant. These conditions will usually be met in the port where the hydrogen or hydrogen carrier makes landfall, and so the vision provides for the use of any type of carrier.

For power plants elsewhere in the country or in Germany, there is, based on the broader public interests, a clear preference for the carriers LSM and methanol, whose transport and storage have a relatively low spatial footprint and impact on external safety. The only conceivable role for ammonia here is where it can be transported by a pipeline that meets very stringent requirements. Transport of LOHCs to Germany and end-use and/or conversion of ammonia elsewhere in the Netherlands are less desirable end use types in the longer term (when better alternatives become available), and will be discouraged in the longer term (in any case based on the current knowledge). In the case of LOHCs, this is mainly due to the relatively low volume of hydrogen released from this carrier (the volumes likely required for electricity generation are such that network congestion would soon become an issue).

Use of hydrogen and hydrogen carriers as fuel for mobility

In this background document and vision, mobility is understood to mean road transport, shipping (inland and maritime) and aviation. Electrification is expected to continue to play an important role in road transport, but hydrogen will also have a role, especially for heavy transport and long-distance transport. For aviation and shipping, the NPE clearly supports the possible deployment of carbon-based hydrogen carriers such as methanol and LSM. For road transport, the aim is to phase out the use of carbon carriers over time.

Ammonia is being considered as a bunker fuel for maritime shipping. Where this carrier is used for maritime shipping, it will usually be able to be stored near the landfall site in seaports. For this end-use, the vision provides scope for direct use of any type of carrier. When deploying hydrogen or a hydrogen carrier for inland shipping, aviation or road transport, direct use of the carrier as a fuel can be considered to avoid energy losses during conversion. The vision does not provide scope for the distribution of ammonia to filling stations, bunkering stations and airports, as alternatives are available with a lower impact on external safety. Conversion of ammonia to hydrogen gas at filling stations is discouraged. This is because, in addition to undesirable distribution risks, it involves a larger spatial footprint and safety risks due to the required conversion facility (ammonia cracker).

Explanation per end-use site

End-use in the port area

Generally speaking, seaports are the preferred sites for using hydrogen and hydrogen carriers, or for conversion to hydrogen gas, rather than decentralised hydrogen carrier end-uses, as this avoids domestic transport movements. Note that this will require far-reaching clustering of industrial activities in areas where space is already a scarce resource and where space is also required to meet other interests, including for the energy transition. So, it cannot be taken for granted that the required space for end-uses of hydrogen carriers will be available. The government and other public bodies are currently working to find a solution to this problem within the Novex programme, which calls for further elaboration in the National Spatial Strategy[27], among others.

The vision provides a scope for supply chains involving end-use or conversion into the requested form in the seaport, with direct use of the carrier being the preferred option. The seaport is also where hydrogen carriers can be converted to hydrogen gas for further transportation through the hydrogen pipeline network. In many cases – and for ammonia in particular – this is also the preferred option, hence there is a strong preference for ammonia cracking facilities to be located in the port areas (rather than decentralised), to avoid ammonia transport movements. The vision therefore provides scope for supporting this type of end-use.

End-use elsewhere in Netherlands

End-use elsewhere in the Netherlands involves using hydrogen or a hydrogen carrier outside the seaports, i.e. application outside the major industrial clusters ('Cluster 6' industry) or at the Chemelot industrial park. Chemelot currently produces hydrogen (from fossil sources) and ammonia domestically, and also transports ammonia by barge. Cluster 6 industries currently make very little use of hydrogen or hydrogen carriers (other than natural gas, which is mainly methane; chemically the same as methane gas from LSM), but the sustainability transition will certainly bring about a change in this situation.

The vision also favours direct use of the hydrogen carrier when used elsewhere in the Netherlands. An exception is the ammonia-based supply chain: here, the vision favours conversion to hydrogen gas in the port area and transport through the hydrogen pipeline network. Pipelines are the preferred mode of transport for ammonia, provided the network is sufficiently safely designed. The alternative is transport by barge. If rail transport is unavoidable, the Betuweroute corridor is the preferred route, although this would seem to be mainly suitable for transports to Germany, and especially from Rotterdam. Rail transport via other routes is considered less desirable. The natural gas network can be used to transport methane gas obtained through LSM to the customer. Note, however, that in most cases the distribution network of the regional operators does not have redundancy built in. This entails a choice between

[27] Nota Ruimte

continuing to use the relevant network infrastructure for methane gas (in this case from LSM) or converting it to hydrogen gas.

For the other carriers, the reuse of the existing pipeline distribution networks does not appear feasible, and a new transport flow will be created if direct use of the carrier is opted for. However, the greater the impact (including in terms of external safety and congestion of transport routes), the less desirable the carrier will be. Conversion losses also play a role here. From a public interest perspective, decentralised end-use of ammonia is the least desirable option. This end-use will increasingly be discouraged as better alternatives (in terms of hydrogen carriers and infrastructure) become available. However, for the shorter term, and in the absence of alternatives, the vision does provide scope for this as an interim solution, with all the caveats and preferences already mentioned continuing to apply. Both the national government and other relevant public bodies want to be involved, from an early stage, in any initiatives involving high-risk carriers such as ammonia, so that they can help to minimise the impact on society.

Transport to Germany or Belgium
Transport to Germany and transport to Belgium are entirely different matters, in the sense that transport to Belgium usually involves maritime shipping via the Western Scheldt (which is formally an estuary and not an inland waterway) that connects to Antwerp. This is a very different situation to Germany, where the ports are industrial hubs, in the Ruhr region in particular. These industrial sites are mostly accessible by barge (the Rhine), but there are also large transport flows of goods by rail and also by road. This is true to a lesser extent for dangerous goods, as less than 2% of dangerous goods are currently transported by rail. Moreover, a dedicated railway line has been constructed for rail freight that does not pass through densely populated areas: the Betuweroute corridor. It goes without saying that this is the preferred route for transporting hydrogen carriers by rail (when transport by pipelines or barge is not feasible).

It is not yet known what volumes of hydrogen carriers will be transported to Germany. In any case, a connection between the Dutch hydrogen pipeline network and Germany is on the drawing board. An uncertainty here is what the future total energy and resource demand of German industry will be, and to what extent it will be served by the hydrogen network. The end-uses of the carriers that are transported to Germany or Belgium are usually not known. The preference described in the vision is for large flows of hydrogen carriers to Germany to be transported as concentrated flows, and preferably by pipeline. Where pipelines are either not yet planned or currently unavailable (because the volumes are not yet large enough, or the pipelines are under construction), the preferred mode of transport is by barge.

Freight transport via the Betuweroute corridor to Germany has grown significantly over the past few years. Transporting large volumes of ammonia or methanol by rail can run into capacity constraints. For transport to Germany, this mode should therefore be considered mainly as a potential interim or fallback option, for example when inland waterways are inaccessible due to low water levels. Transporting large volumes by rail is not preferred. The port of Rotterdam has the best connection to the Betuweroute corridor. Connecting Zeeland to the Betuweroute corridor would involve transporting ammonia through heavily urbanised areas (particularly Zeeland and Brabant, and close by the Drechtsteden conglomeration). So, for ammonia storage and transports that take into account rail transport as a fallback option, the port of Rotterdam is preferred to the ports in Zeeland.

Final remark

As mentioned in the introduction, the government has sought a high degree of transparency in the process of developing the current government vision on hydrogen carriers. The desire is to maintain the valuable network of stakeholders that has been developed, and further encourage interaction among all involved parties.

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