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Comparing refrigerated and pressurised ammonia

Multi-criteria analysis of supply chains in the Netherlands

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FINAL

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MANAGEMENT SUMMARY

The Dutch government presented its vision on hydrogen carriers to Parliament in November 2024, comparing supply chains on public interests using a multi-criteria analysis. In current practice, ammonia is imported refrigerated but transported domestically under pressure.

Commissioned by the ministry of Economic Affairs and Climate Policy, together with the ministry of Infrastructure and Water Management, this study compares refrigerated and pressurised domestic ammonia supply chains by road, rail, barge and pipeline to assess whether the findings give reason to revise existing policy preferences.

KEY FINDINGS

Refrigerated vs. pressurised ammonia supply chains

1. For *all ammonia supply chains,* whether for hydrogen end use or direct ammonia end use, refrigerated ammonia supply chains achieve higher (= better) scores on the combined public interests, primarily due to higher scores on the public interests Safe & Secure and Spatial Footprint.[1] These advantages outweigh the (very) small to modest disadvantages for other public interests like Affordable, Adaptable, and Accessible. Sensitivity analyses show that the higher scores for refrigerated supply chains are a robust result.
2. For *hydrogen end use*, if this requires decentralised cracking in the hinterland, supply chains using refrigerated ammonia have significantly higher scores than chains using pressurised ammonia. This is primarily due to the decentralised storage; refrigerated ammonia storage offers substantial safety and spatial advantages over pressurised storage.
3. For *direct ammonia end use*, the differences between refrigerated and pressurised supply chains are smaller than for hydrogen end use, as decentralised storage at the end user's site falls outside the scope of this comparison. Including decentralised storage at the end user's site would have an impact on costs, spatial footprint and safety and would increase the differences between refrigerated and pressurised ammonia supply chains.

Comparing transport modalities

4. Refrigerated ammonia transport achieves higher scores than pressurised ammonia transport across all modalities, partly because the effects of an incident like a spill are smaller for refrigerated ammonia.
5. The ranking from highest to lowest score is: pipeline (pressurised ammonia), rail, inland waterway transport, road. The rankings of transport modalities are based on a sensitivity analysis

[1] This is in case decentralised storage is included in the supply chain. In other cases there are no differences between refrigerated and pressurised ammonia supply chains for Spatial Footprint.

in which the impact of decentralised storage is excluded, as differences in storage type dominate the overall scores and would otherwise obscure the contribution of transport modalities.

i. Differences between road and the other transport modalities are significant.

ii. Pipeline transport for refrigerated ammonia over 200 km is not considered a viable alternative.

iii. Inland waterway transport achieves slightly lower scores than rail due to reliability risks from prolonged low water periods.

6. From the perspective of Safe & Secure, the ranking from highest to lowest score, based on the same sensitivity analysis, is: pipeline (pressurised ammonia), inland waterway transport, rail, road. For inland waterway transport, which is currently the only modality permitted for refrigerated ammonia, the difference in scores between refrigerated and pressurised ammonia is relatively large and significant, as in case of an incident half the refrigerated ammonia dissolves in water.

Confirmation of 2024 MCA results

7. This study confirms that for hydrogen end use, cracking in the port of entry and distribution through the national hydrogen grid achieves the highest overall score. Direct ammonia end use receives higher scores than hydrogen end use after ammonia cracking, as the absence of (de)centralised cracking and decentralised storage reduces the Safe & Secure risk classification by the experts, spatial footprint and required import volumes.

8. The findings above assume that end use takes place at 200 km from the port of entry (baseline). Two variants were also investigated:

    i. *End use in the port of entry* slightly improves scores compared to the baseline, as transport and decentralised storage costs and external effects are removed from the comparison. It also eliminates score differences between transport modes and physical states of ammonia.

    ii. *Transit and export* to neighbouring countries improves scores for supply chains with decentralised conversion and storage, as their impacts are shifted outside the Netherlands.

It should be noted that refrigerated ammonia transport by road and rail is not permitted under current regulations, and that rail tank cars and, in Europe, barges for refrigerated ammonia are not yet commercially available.

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TERMS AND ABBREVIATIONS

AHP	Analytical Hierarchy Process
CAPEX	Capital Expenditures
CO_2	Carbon dioxide
DRC	Delta Rhine Corridor
EZK	Ministry of Economic Affairs and Climate Policy
H_2	Hydrogen (dihydrogen is commonly referred to as hydrogen)
I&W	Ministry of Infrastructure and Water Management
KEV	Climate and Energy Outlook
kt	kiloton
LNG	Liquid natural gas
LOHC	Liquid Organic Hydrogen Carrier
MCA	Multi-Criteria Analysis
MKBV	Social Cost-Benefit Comparison of Hydrogen Carriers *(Maatschappelijke Kosten en Baten Vergelijking (MKBV) Waterstofdragers),* a study comparing the hydrogen carriers ammonia and LOHC, commissioned by the Ministry of Infrastructure and Water Management
N_2O	Nitrous oxide ('laughing gas')
NH_3	Ammonia
NO_x	Nitrogen oxides
NPE	National Energy System Plan
OPEX	Operational Expenses
TRL	Technology Readiness Level
VIKOR	Ranking method for multi-criteria analysis, in Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje

CHAPTER 1 INTRODUCTION

1.1 COMPARISON OF REFRIGERATED AND PRESSURISED AMMONIA

The government of The Netherlands submitted its vision on hydrogen carriers to the House of Representatives in a letter to Parliament in November 2024. This vision outlines the government's preferences and key points regarding the supply chains of various hydrogen carriers - such as ammonia, methanol, liquid organic hydrogen carriers (LOHCs), and liquid hydrogen - from a broad societal perspective.

The various hydrogen carriers and supply chains were compared in a multi-criteria analysis (MCA), which applied the public interests outlined in the National Energy System Plan (NPE), supplemented by the public interest Adaptable.

The government vision is based on existing ammonia supply chains: the ammonia is imported in a refrigerated liquid state via seagoing vessels and stored in a refrigerated liquid state at the terminal in the port. Transshipment, transit, and use then primarily take place in pressurised liquid form. Due to expected benefits in areas such as external safety and energy efficiency, the ministry of Economic Affairs and Climate Policy (EZK), in collaboration with the ministry of Infrastructure and Water Management (IenW), commissioned an investigation into the advantages and disadvantages of transshipment and transit of ammonia in refrigerated liquid form.

The aim of this multi-criteria comparison between supply chains of refrigerated liquid ammonia and pressurised liquid ammonia is to provide a factual basis that can be used to determine whether the findings give reason to revise existing policy preferences.

The refrigerated liquid state of ammonia during transport to the Netherlands is the starting point. Therefore, the supply chains do not differ between refrigerated liquid ammonia and pressurised liquid ammonia prior to import into the Netherlands, except possibly in terms of volume.

The transport of refrigerated liquid ammonia by road and by rail is currently not permitted under international regulations. The results of this study may lead to further investigation into whether and under what conditions international regulations can be amended. This second step (legal options) falls outside the scope of this assignment.

1.2 ABOUT THIS STUDY

This study was based on the analysis of the 2024 MCA of hydrogen carriers, supplemented with additional literature research and input from stakeholders. The 2024 data have been updated for pressurised ammonia and extended for refrigerated ammonia. The data and data collection related to refrigerated and pressurised ammonia required more in-depth information compared to the 2024 MCA of hydrogen carriers and also more detailed than most studies conducted by third parties. However, general assumptions, definition of indicators and the weighting factors were reused. The same data were used for the ammonia import chain, as this part of the supply chain essentially does not differ between the alternatives.

The additional detail for the domestic part of the chains requires knowledge from the sector and experts to properly explain the difference between the two forms of ammonia. Several interviews with stakeholders were conducted and others were contacted for specific information. In several cases, data were drawn from confidential sources. This information has been anonymised in this report and cannot be attributed to its source. In this context, a comparison with publicly available data was made every time, to assess whether the values provided were plausible. To be able to assess differences between the forms of ammonia for the public interest Safe & Secure, a number of experts contributed to an expert session assessing the differences in risk classification per supply chain element for refrigerated and pressurised ammonia.

Throughout the study, the research team met with the client group (Ministry of Economic Affairs and Climate Policy and Ministry of Infrastructure and Water Management) on a bi-weekly basis. Details of the study's approach and outcomes were presented during two stakeholder events hosted by both ministries (4 December 2025, Utrecht and 3 March 2026, online). Feedback from the discussions and meetings has been included in this report.

1.3 DOCUMENT STRUCTURE

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

Part A, methodology, addresses the methods used.

- Chapter 2 outlines the alternatives explored.
- Chapter 3 presents the methodology followed for the multi-criteria analysis.

Part B, results, outlines the various outcomes, including the scores for the various public interests, the total scores, the sensitivity analyses and this study's conclusions and recommendations.

- Chapter 4 presents the normalised indicator scores for ammonia supply chains, arranged by public interest.
- Chapter 5 shows the results of combining the indicator scores with the weighting factors to total scores.
- Chapter 6 outlines the conclusions and recommendations of this study.

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

CHAPTER 2 AMMONIA SUPPLY CHAINS

This study is an in-depth study of ammonia supply chains with the same methodology as the MCA study of hydrogen carriers (2024). In that study seven hydrogen carriers were compared (see Figure 1), amongst others ammonia. It assumed the ammonia supply chains currently in use in the Netherlands:

- Import via sea vessels and storage at the landing site in the port as refrigerated liquid.
- Transshipment, transport, and use as pressurised liquid.

In this study we investigate the differences between supply chains for refrigerated liquid ammonia and for pressurised liquid ammonia (also referred to as 'cold' and 'warm' ammonia).

- Refrigerated liquid ammonia: liquid through cooling to -33°C at atmospheric pressure (1 bar).
- Pressurised liquid ammonia: liquid through pressure >10 bar @ 25°C

Both forms of ammonia can be used as a hydrogen carrier and as chemical or fuel. More information about the differences between pressurised and refrigerated ammonia is presented in Annex B.

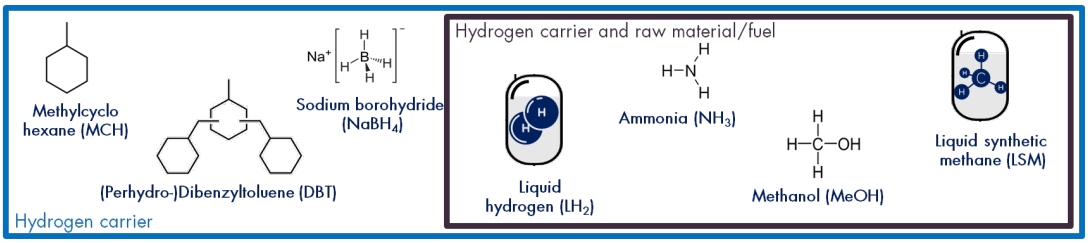


Figure 1: Two groups of hydrogen carriers used in MCA of hydrogen carriers (2024)

2.1 SUPPLY CHAINS FOR AMMONIA

This study focuses primarily on the supply chain from the moment of import into the Netherlands up to the point at which hydrogen or ammonia is first delivered to the end user's site. The chains to be studied are made up of the following steps (see Figure 2):

- Importing the ammonia into the Netherlands. This only falls within the scope in terms of chain effects relevant to assessing the chains within the Netherlands, including total costs, energy efficiency, emissions, and import supply security, without a breakdown into the contributions of raw materials, production (of hydrogen and ammonia synthesis in the exporting country), and transport to the Netherlands. Chain effects such as those related to external safety and spatial requirements are only taken into account for the section of the chain within the Netherlands.

- Storage and transshipment of the ammonia at the port of entry in refrigerated form. We assume that a heat exchanger is used to warm up refrigerated ammonia to above-zero temperature before pressurised transport, but no pressurised buffer tank is involved.
- The potential cracking of ammonia to gaseous hydrogen at the port of entry.
- Transporting the ammonia directly or the hydrogen gas after cracking. Such transport can be carried out by road, rail, inland shipping, or pipeline. Gaseous hydrogen is transported exclusively through the hydrogen network, not by road, water, or rail (in this study, although some small-scale transport by these methods does occur in reality). We base the comparison on a typical 200 km route through the Netherlands, as used in the 2024 MCA of hydrogen carriers. This typical route includes both urban and non-urban settings. The use of typical transport routes eliminates any discrepancies between the ports of entry and between the distances to various end user sites.
- Decentralised storage of the ammonia before cracking or synthesis near the end user's site.
- A potential decentralised process for cracking the ammonia to hydrogen gas, or the decentralised synthesis of ammonia using hydrogen gas sourced from the national hydrogen network.
- End use in the industrial, energy, or transport sectors is outside the scope of this study: the chains extend only to the point of delivery to the end user, or to the fuelling station or bunkering station.[2] A more comprehensive understanding would require an exploration of various applications beyond the point of delivery (whether as a raw material for various processes, or as a fuel for various types of equipment). This is beyond the scope of this study, as the ammonia policy relates to the supply chain and does not address end user requirements or impacts.

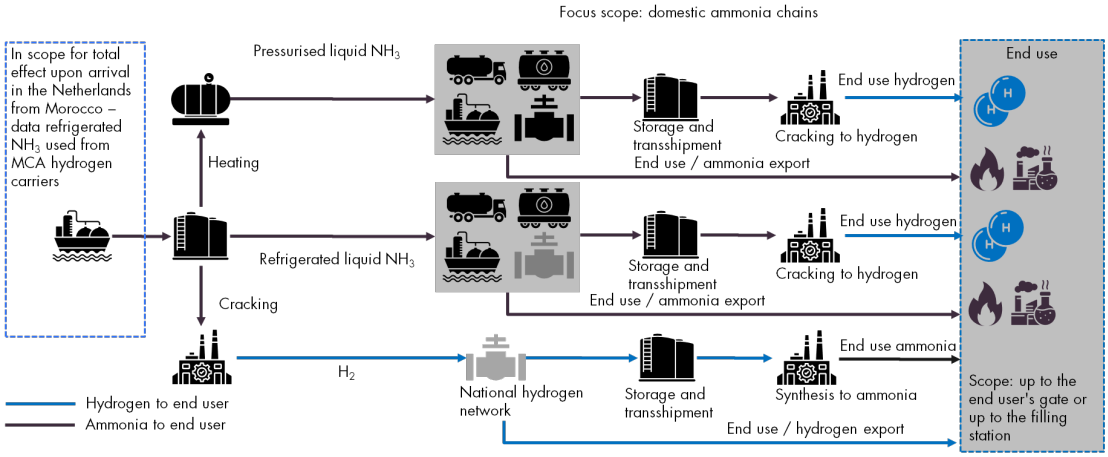


Figure 2: Scope of the multi-criteria analysis study comparing refrigerated and pressurised ammonia

It is important to note that, for the public interests Affordable and Sustainable, the costs, greenhouse gas emissions, and energy losses in the import chain and in the Netherlands are factored in from the production in the exporting country up to the point of delivery to the end user or to a

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

fuelling station. This is necessary because these costs are paid by the end users in the Netherlands, and the emissions are caused by the end users' demand. The energy losses need to be compensated by extra production and import to make sure that the same amount of hydrogen equivalent is delivered to the end users across the supply chains. Differences in ammonia import volume impact multiple public interests.

When it comes to other public interests (e.g. Safe & Secure, Spatial Footprint, Environment), only the impact within the Netherlands is taken into account (also up to and including the point of delivery). The public interest Fair does take account of the environmental impact in the exporting country.

We have divided all the potential chains into 10 types or groups, for the purpose of analysing and presenting the results. This division is similar to the ten types used in the 2024 MCA of hydrogen carriers.

The first differentiation is between: 1) chains that culminate in the delivery of hydrogen gas to the end user's site, and 2) chains that deliver hydrogen carriers to the end user's site as a raw material or fuel.

A second distinction is made between two types of chains: 1) those where the imported hydrogen carrier is converted to gaseous hydrogen at the port of entry and transported through the national hydrogen transport network, and 2) those where the imported ammonia is transported across the Netherlands as a hydrogen carrier.

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

These components are combined into 16 different supply chains, presented in Table 1. Not all combinations are possible for refrigerated and for pressurised ammonia.

- Because the imported ammonia is refrigerated ammonia and the refrigerated ammonia is immediately converted into hydrogen at the port of entry, there is only one chain with refrigerated ammonia for types 5 and 10. There is no chain with pressurised ammonia used for centralised cracking to hydrogen.
- Transport of refrigerated ammonia by long-distance pipeline is only included in the comparison as a fictitious alternative. With today's technology it is not a feasible alternative as only few kilometres of such infrastructure currently exist, and there is no useful data available (see Annex I). To gain insight in the potential impact, we present the results for a fictitious 200 km refrigerated ammonia pipeline that has the same safety level as pressurised and twice the cost of a pressurised ammonia pipeline.

Table 1: Supply chains for ammonia as hydrogen carrier included in this comparative study

	Imported ammonia	Conversion in port of entry	Means of transport-tation	Ammonia or hydro-gen during transport	Decentralised con-version, synthesis	End use as
Type 1: ammonia transport by road and conversion to hydrogen at end user						
1a	refrigerated NH_3	-	tank trucks	pressurised NH_3	cracking	H_2
1b	refrigerated NH_3	-	tank trucks	refrigerated NH_3	cracking	H_2
Type 2: waterborne ammonia transport and conversion to hydrogen at end user						
2a	refrigerated NH_3	-	tanker vessel	pressurised NH_3	Cracking	H_2
2b	refrigerated NH_3	-	tanker vessel	refrigerated NH_3	Cracking	H_2
Type 3: ammonia transport by railroad and conversion to hydrogen at end user						
3a	refrigerated NH_3	-	rail tank car	pressurised NH_3	cracking	H_2
3b	refrigerated NH_3	-	rail tank car	refrigerated NH_3	cracking	H_2
Type 4: ammonia transport by pipeline and conversion to hydrogen at end user						
4a	refrigerated NH_3	-	Pipeline	pressurised NH_3	cracking	H_2
(4b)	refrigerated NH_3	-	fictitious pipeline	refrigerated NH_3	cracking	H_2
Type 5: ammonia conversion to hydrogen in port of entry and transport by hydrogen network to end user						
5	refrigerated NH_3	Cracking	H_2 network	H_2	-	H_2
Type 6: ammonia transport by road to end user (no conversion)						
6a	refrigerated NH_3	-	tank trucks	pressurised NH_3	-	NH_3
6b	refrigerated NH_3	-	tank trucks	refrigerated NH_3	-	NH_3
Type 7: waterborne ammonia transport to end user (no conversion)						
7a	refrigerated NH_3	-	tanker vessel	pressurised NH_3	-	NH_3
7b	refrigerated NH_3	-	tanker vessel	refrigerated NH_3	-	NH_3
Type 8: ammonia transport by railroad to end user (no conversion)						
8a	refrigerated NH_3	-	rail tank car	pressurised NH_3	-	NH_3
8b	refrigerated NH_3	-	rail tank car	refrigerated NH_3	-	NH_3
Type 9: ammonia transport by pipeline to end user (no conversion)						
9a	refrigerated NH_3	-	Pipeline	pressurised NH_3	-	NH_3
(9b)	refrigerated NH_3	-	fictitious pipeline	refrigerated NH_3	-	NH_3
Type 10: ammonia conversion to hydrogen in port of entry, transport by hydrogen network and decentralised synthesis of ammonia at end user						
10	refrigerated NH_3	Cracking	H_2 network	H_2	synthesis	NH_3

Current regulatory restrictions (e.g. domestic transport of refrigerated ammonia by rail or road is not allowed) have not been used as grounds for excluding a supply chain from evaluation, as regulations may be revised if sufficiently compelling reasons arise. The scores for Safe & Secure assumed that the future regulations will be equally strict for refrigerated and for pressurised transport modalities.

2.2 DIFFERENCES IN VOLUME BETWEEN CHAINS

For each supply chain, we work on the basis that a uniform volume of hydrogen equivalents is delivered to the end users. Chain losses can occur, depending on the type of chain involved. Consequently, the required import volumes will vary, while the quantity of hydrogen equivalents supplied to end users remains constant. By factoring in the differences in specific gravity, we have translated the differences in volume into the quantities needed for storage and logistical movements. The differences in volume affect nearly every public interest, since higher volumes result in more external effects (impacting Safe & Secure, Sustainable, Environment, and Fair), higher costs (impacting Affordable, Economically Robust, Fair, and Accessible), or require more and larger facilities (impacting Adaptable and Spatial Footprint).

Most of these losses occur during the cracking of ammonia to hydrogen gas, where ammonia is also used as a fuel source for generating process heat. Slight losses occur when transporting hydrogen gas through the hydrogen network. There are also slight losses when ammonia is stored in centralised or decentralised facilities. The volume[3] assumptions are clarified in Annex B.

2.3 VARIANTS

In this study, we explore a range of situations, or 'variants', for each supply chain.

- The *baseline* situation concerns the reference year 2030, regarding the use of hydrogen or ammonia inland at 200 km from the port of entry. We refer to 2030 as a reference year, but it in fact concerns a reference period from 2030 to 2035.

Then there are the following two variants that involve alternative end use sites:

- *Port of entry:* The situation for end users who utilise the hydrogen or ammonia directly at the port of entry. In this case, inland transport and decentralised storage are eliminated from the supply chain. Decentralised conversion coincides with the centralised conversion.
- *Transit to Germany/Belgium:* The situation in which the hydrogen or ammonia passes through the Netherlands for use as hydrogen or as ammonia in Germany or Belgium. In this situation, the impact of decentralised storage, decentralised conversion, and synthesis on the Netherlands is eliminated from the chain.

In addition to comparing variants, we will also perform sensitivity analysis of the relative impacts on the scores of the supply chain elements decentralised storage and transport modalities.

[3] Even though we express the quantities of hydrogen carriers in kilotonnes (a unit of mass), we still refer to 'volume' to maintain consistency with the previously mentioned 'volume study' and 2024 MCA of hydrogen carriers.

CHAPTER 3 MULTI-CRITERIA ANALYSIS METHODOLOGY

This chapter details the methodology used for the multi-criteria analysis and how the results are presented. The same multi-criteria analysis approach was applied as in the 2024 MCA of hydrogen carriers:

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

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

3.1 ELABORATION OF PUBLIC INTERESTS

The same public interests as in the 2024 MCA of hydrogen carriers were used: i.e. the public interests as defined in the National Energy System Plan (NPE)[4] supplemented with Adaptable:

- Affordable and Economically Robust
- Reliable and Safe & Secure
- Sustainable and Adaptable
- Fair and Accessible (Participatory)[5]
- Spatial Footprint and Environment

For the purposes of this study, each public interest has been translated into one or more indicators. These are listed in Figure 3 and Table 2.

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

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

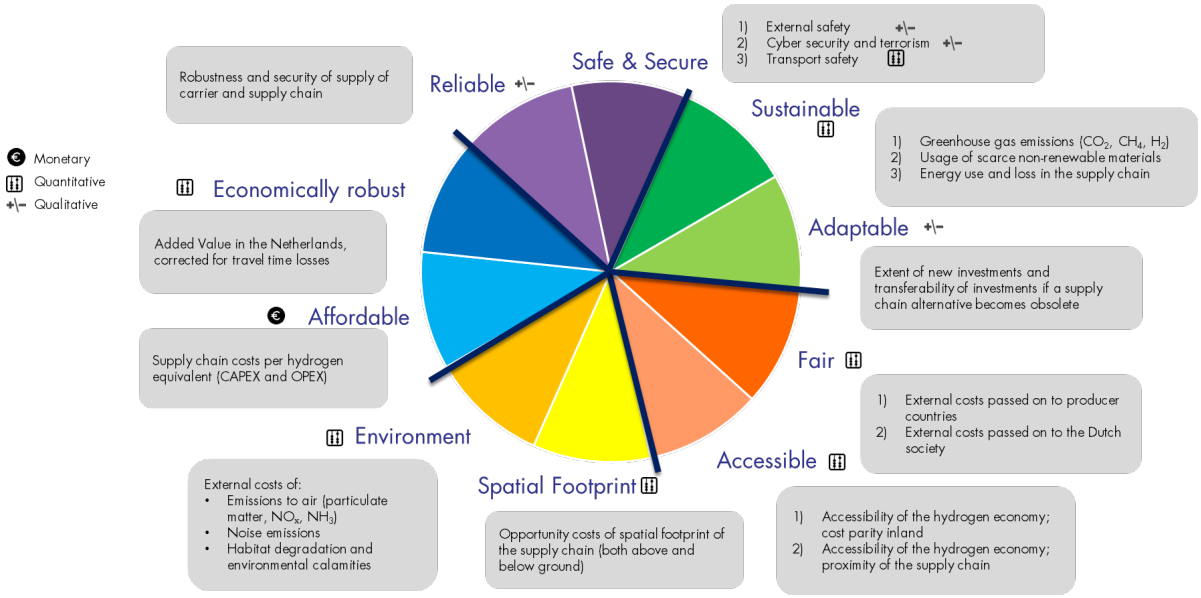


Figure 3: Summary of 10 public interests with their corresponding 16 indicators

Table 2: Indicators per public interest (same sequence as the NPE)

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

3.2 DETERMINING THE SCORE FOR EACH PUBLIC INTEREST

The scoring for public interests is primarily guided by information from existing literature and the 2024 MCA of hydrogen carriers. Where possible, interviews and expert insights were used to fill any gaps in this information with respect to the two forms of ammonia. The scoring differences between pressurised and refrigerated ammonia for External safety and Cyber security and terrorism were assessed through expert consultation (see Table 3).

Table 3: Consulted stakeholders and experts

Consulted through interview or correspondence	Participants expert session Safe & Secure
Air Products	Ministry of Economic Affairs and Climate Policy
Deutsche Bahn	DCMR Environmental Protection Agency
Essent Hydrogen	Ministry of Infrastructure and Water Management
Institute for Sustainable Process Technology	National Institute for Public Safety
Koninklijke Binnenvaart Nederland	OCI Global
OCI Global	ODNZKG Environment Service Noordzeekanaalgebied
Port of Rotterdam	Port of Rotterdam
Prorail	Province Zuid-Holland
Schenk Tanktransport	RIVM National Institute for Public Health and Environment
Smart Delta Resources	RVO Netherlands Enterprise Agency
Velin Association of Pipeline owners in the Netherlands	Veiligheidsregio Rotterdam-Rijnmond
VTG Vereinigte Tanlager und Transpoortmittel	Yara Nederland
Yara Nederland	

3.3 NORMALISING THE SCORE FOR EACH PUBLIC INTEREST

Once the scores for each public interest have been determined, they are normalised. This enables the scores to be consolidated into a total score for each chain, regardless of the different units (kilograms, ++, euros). Each supply chain is mapped onto a separate 0-to-1 scale for every public interest. We used the same normalisation method as in the 2024 MCA of hydrogen carriers but adapted the normalisation scale for some public interests.

- The public interests Affordable and Sustainable were dominated by the outlying scores for sodium borohydride. Ignoring sodium borohydride data leads to a narrower normalisation scale.
- On the other hand, the data for decentralised ammonia storage required to extend the normalisation scale for the public interest External safety.[6]

Details of the method used to determine the minimum and maximum normalisation values for each public interest are set out in Annex F.

3.4 ASSIGNING WEIGHTS TO THE PUBLIC INTERESTS

As the top score in Affordable, for example, does not automatically have the same public value as the top score in Sustainable, a comparative weighting of public interests is needed to consolidate the scores into a single total score.

[6] The normalisation scale for Spatial Footprint was slightly expanded (less than 5%).

In this study, we used the same weighting as derived for the 2024 MCA of hydrogen carriers. This set of weighting factors was developed in a Delphi process with a group of 21 stakeholders, see Figure 4. To assess the impact of the weights, two other sets of weighting factors were applied in a sensitivity analysis. Further details on the methods used can be found in Annex G.

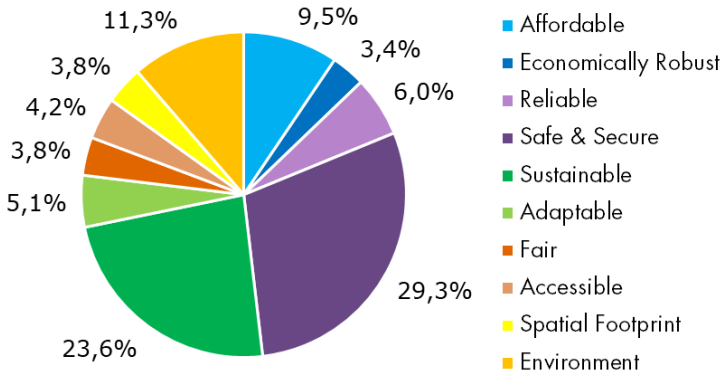


Figure 4: Weighting factors used for the baseline and variants, based on 2024 MCA of hydrogen carriers

3.5 RANKING THE ALTERNATIVES

We have ranked the alternatives (the chains) in the same manner as in the 2024 MCA of hydrogen carriers. Instead of listing the supply chains in descending order of their Utility[7] scores, we used the VIKOR Multicriteria Optimization and Compromise Solution[8] ranking. This approach considers the fact that a chain might have a very low score for one particular public interest, that can be pivotal for one or more stakeholders, and this very low score then reduces the total score more than would be the case if only the Delphi weighting would be used. More information on the method can be found in Annex H.

3.6 SENSITIVITY ANALYSIS

Finally, we analysed the sensitivity of the total score to various weighting factors (impact on ranking). We determined the total score's sensitivity to:

- a set of weighting factors where Affordable is assigned twice the weight derived from the Delphi scores, while the weights of Sustainability and Safe & Secure are each halved relative to the weighting factors obtained from those scores;
- public interests weighted *equally* (each was allocated 10%).

These are the same sensitivity analyses as in the 2024 MCA of hydrogen carriers.

Sensitivity of the results of domestic refrigerated ammonia transport by fictitious pipeline was also investigated. These results are shown between brackets; the baseline results are shown without brackets.

[7] A simple multi-criteria analysis combines the scores for public interests with the weighting factors to yield a total score. This score, referred to as the 'Utility' score, is an indicator of societal utility.
[8] In Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje

Also, a sensitivity analysis is performed to assess the relative impact of decentralised storage type and transport modality on the scores for Safe & Secure and the total scores. Specifically, it examines how scores change across transport modalities when decentralised pressurised storage is replaced by refrigerated storage, for supply chains that transport ammonia under pressure.

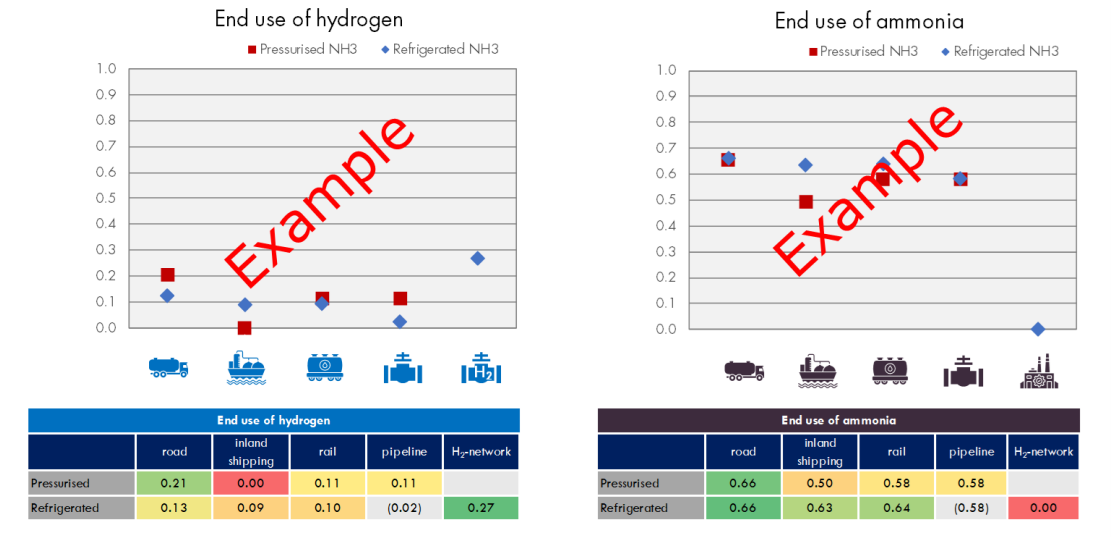
3.7 METHOD OF PRESENTING RESULTS

The results for the supply chains analyses are shown in two separate charts. The left-hand charts (see Figure 5, in blue) show all results for end uses that consume *gaseous hydrogen*. The first five supply chain types are shown on the x-axis:

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

The right-hand charts (see Figure 5, in black) show all supply chains in which the end use consumes *ammonia*. The second group of five supply chain types are shown on the x-axis:

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



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.21	0.00	0.11	0.11	
Refrigerated	0.13	0.09	0.10	(0.02)	0.27

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.66	0.50	0.58	0.58	
Refrigerated	0.66	0.63	0.64	(0.58)	0.00

Figure 5: Example of visualisation of results for public interest scores and total scores

The highest possible score is represented by 1, the lowest possible score by 0. As some scores for the alternatives are equal, the results (red squares, blue diamonds) sometimes overlap. A table below the chart ensures that the results are clear and easy to understand.

Various background colours in the table show which supply chains have the highest and lowest scores (from green to red based on ranking). Colours reflect the ranking within each chart and are therefore not comparable across charts: a green-coded chain in the left-hand chart may have a lower absolute score than a green-coded chain in the right-hand chart. Very small differences in scores may still lead to different colours. The graphs and the tables should always be seen in conjunction.

CHAPTER 4 SCORES FOR PUBLIC INTERESTS

This chapter presents the results for the public interests and indicators. It shows the normalised scores for only the public interests or indicators that have different scores for refrigerated and pressurised ammonia supply chains for the baseline situation in 2030 (first two columns in Table 4). This baseline situation concerns the supply of hydrogen from ammonia or ammonia itself to an inland end user 200 km from the port of entry in 2030. Also, the results of the sensitivity analysis for Safe & Secure are presented, in which all decentralised storage is assumed to be refrigerated. Further details about the calculations are given in Annex D. A complete overview of all results, including the scores for all public interests and the variants, is included in Annex E.

Table 4: Overview of public interests with large, small or no differences in scores between pressurised and refrigerated liquid ammonia supply chains

Large differences in scores	Small differences in scores	No differences in scores or minor differences as result of indicators
Safe & Secure – combined indicators Safe & Secure – External safety Safe & Secure – Cyber security and terrorism	Affordable Sustainable – Energy loss Adaptable Fair – for Dutch society Accessible – Cost parity Spatial Footprint	Economically Robust Reliable Safe & Secure – Transport safety Sustainable – Greenhouse gas emissions Sustainable – Material usage Fair – International Accessible – Proximity Environment Sustainable – combined indicators Fair – combined indicators Accessible – combined indicators

For each public interest, the results are presented in a graph. Per public interest, a box summarises the explanation in bullits: one for the comparison of refrigerated vs. pressurised ammonia, and one for the comparison of transport modalities. Additional bullits may highlight other noteworthy results.

4.1 SCORES FOR PUBLIC INTEREST SAFE & SECURE

We have analysed the public interest Safe & Secure using three indicators: 1) External safety (non-deliberate accidents), 2) Cyber security and terrorism, i.e. protection against cyber attacks and terrorism (deliberate disruptions and incidents), and 3) Transport safety. The scores for External safety and Cyber security and terrorism dominate, due to the high weighting factors. This chapter begins with a description of the combined and weighted results for the public interest Safe & Secure. The results for each indicator with differences for refrigerated and pressurised ammonia are then explained.

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

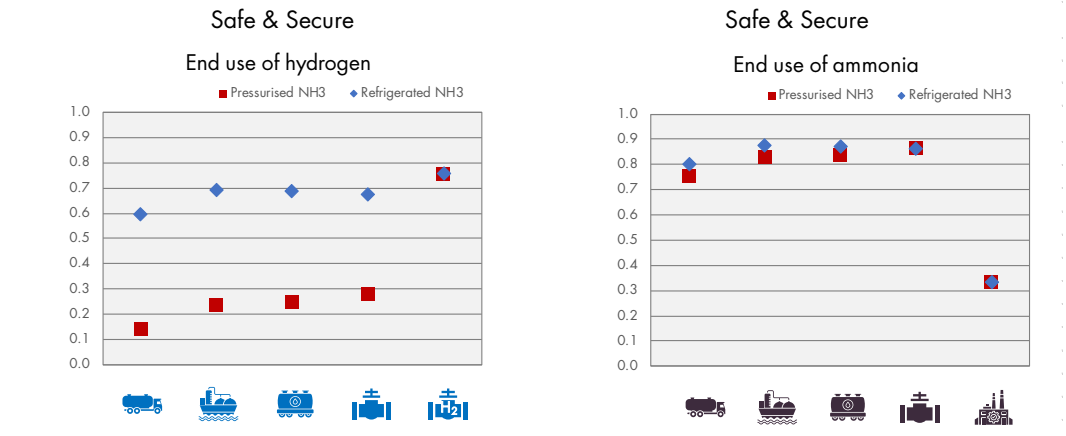
Note that a lower score does not indicate an unsafe situation: all situations that meet safety requirements are considered safe and are permitted to occur.

Results for baseline situation (2030, inland end use)

The combined and weighted results for the public interest Safe & Secure[9] are shown in Figure 6. This consistently shows lower scores for supply chains for pressurised ammonia than for refrigerated ammonia, due to the potential larger impact of a toxic gas leak. In accidents involving pressurised ammonia, a toxic gas cloud almost always forms immediately, while for refrigerated ammonia a pool of ammonia forms first before a toxic gas cloud arises. It takes the cold liquid time to evaporate into a toxic gas cloud.

The lowest scores are for supply chains that include decentralised pressurised ammonia storage (the first four supply chains in the left-hand chart). That is because the risk assessment of decentralised pressurised storage dominates the supply chain risk assessment.

Transport by road has the lowest score, as it has the highest probability of traffic accidents (indicator Transport safety, part of the composite indicator Safe & Secure) and the highest External safety risk classification according to the experts, in spite of a lower risk classification for Cyber security and terrorism (being a less attractive target than trains, barges and pipelines which transport larger volumes).



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.14	0.24	0.25	0.28	0.76
Refrigerated	0.60	0.69	0.69	(0.68)	0.76

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.76	0.83	0.84	0.86	0.34
Refrigerated	0.80	0.88	0.87	(0.86)	0.34

Figure 6: Scores for Safe & Secure for inland supply chains in 2030; hydrogen end use and ammonia end use

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

- Refrigerated ammonia supply chains have higher scores than pressurised ammonia, because in the event of an incident (breach or leak), refrigerated ammonia must first evaporate before a toxic cloud forms, giving more time to respond.
- Road transport has the lowest scores due to the highest probability of accidents (indicator Transport safety) and the highest External safety risk classification according to the experts, in spite of lower risk classification for Cyber security and terrorism.

The scores for transport by rail are higher than for transport by road, because the probability of traffic accidents is lower (Transport safety) and because experts assessed the external safety risk classification as lower.

Rail transport also has higher scores than inland waterways in most situations in Figure 6. Although inland waterway transport has a lower external safety risk classification, this advantage is insufficient to compensate for its higher Transport safety and Cybersecurity and terrorism risks classification.[10] The exception is end use of ammonia in refrigerated supply chains, where the External safety advantage of inland waterways is decisive and results in a higher combined Safe & Secure score than rail.

The score for ammonia pipeline transport is only slightly higher than for rail and inland waterway transport, despite no probability of traffic accidents (by definition) and the low risk classification for External safety. This is because ammonia pipeline transport has a higher risk classification for cyber attacks or terrorist attacks, according to the experts. Plants and pipelines containing ammonia are – more than is the case for other hydrogen carriers – seen as attractive and probable targets for cyber attacks and terrorist attacks in the eyes of the experts.

Sensitivity analysis: if all decentralised storage is refrigerated and normalisation scale is adjusted

Decentralised storage has a dominant impact on the scores. We are also interested in the impact due to the other elements of the supply chain such as transport modalities. That is why a sensitivity analysis is done to discover how large the differences are due to variations in transport modalities if the decentralised pressurised storage component were replaced by refrigerated storage, for supply chains with transport of pressurised ammonia.[11]

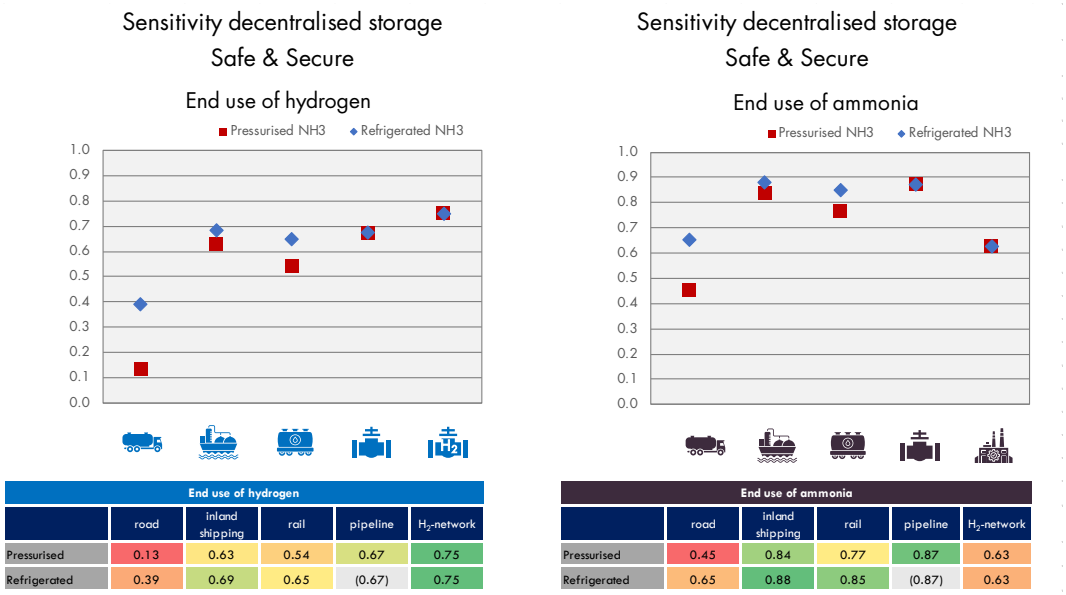
Figure 7 shows that refrigerated ammonia supply chains still have higher scores than pressurised ammonia chains, but the difference with pressurised supply chains is now smaller than in Figure 6 (baseline), due to elimination of differences in decentralised storage.

The differences in scores between the transport modalities for one type of ammonia are larger in Figure 7 than in Figure 6. The differences between transport modalities now have more impact

[10] In the expert session of 2024, a worst-case scenario was considered, namely the outflow of the entire cargo. Ammonia tankers consist of multiple compartments (typically 4). This impact is also used to determine the Cyber security and terrorism risk. Another scenario is that one compartment leaks, with higher probability but smaller impact. We cannot determine retrospectively whether this leads to a higher total risk. The experts at the time did not consider this alternative scenario to be the worst case.

[11] In the 2024 MCA of hydrogen carriers, the risk of decentralised storage was assumed to be 3/14 of the risk of centralised storage (refrigerated). When distinguishing between refrigerated and pressurised ammonia, this turns out to be incorrect. Storage under pressure has a higher risk classification than refrigerated storage. As a result, in the present analysis, the difference between the ideal score (zero risk) and the chain with the worst score has increased, expanding the normalisation scale. This means that the same difference in risk classification as in the 2024 MCA of hydrogen carriers now results in a smaller difference in score.

on the Safe & Secure score because the differences are not overshadowed by the major impact of decentralised storage on the normalisation scale. Road transport has the lowest scores.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.13	0.63	0.54	0.67	0.75
Refrigerated	0.39	0.69	0.65	(0.67)	0.75

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.45	0.84	0.77	0.87	0.63
Refrigerated	0.65	0.88	0.85	(0.87)	0.63

Figure 7: Scores for Safe & Secure for inland supply chains in 2030; hydrogen end use and ammonia end use (all decentralised storage refrigerated)

- Refrigerated ammonia supply chains still have higher scores than pressurised ammonia chains, but the difference with pressurised supply chains is smaller than in the baseline, as differences in decentralised storage are eliminated.
- Road transport still has the lowest scores. The differences between the modalities are larger in the sensitivity analysis with all decentralised storage refrigerated than in the baseline. The reason is that the expansion of the normalisation scale which was needed to accommodate the decentralised storage scores is now reversed.

4.1.1 *External safety (indicator for Safe & Secure)*

For all incidents, there is a very small probability of occurrence. However, refrigerated ammonia supply chains have much higher scores than pressurised ammonia chains due to the lower impact in case of a toxic gas leak, in particular if decentralised storage is part of the supply chain (first four columns in the left-hand chart).

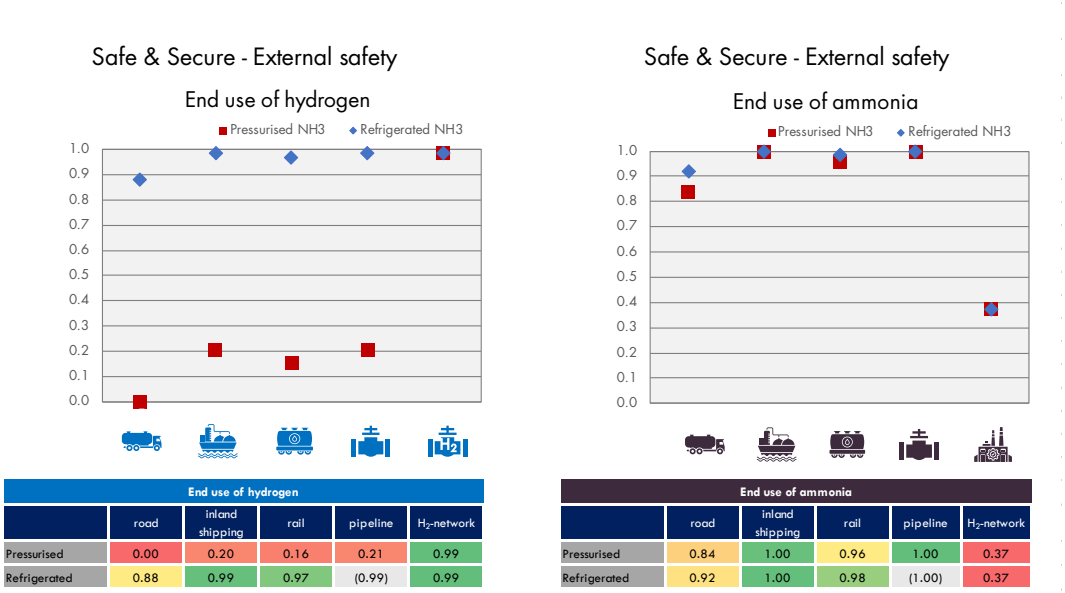
The supply chain with the lowest score for External safety is the supply chain with pressurised ammonia transported by road. The supply chain with the highest score for External safety is the supply chain without cracking/conversion and without decentralised storage and transport by pipeline.[12]

The difference between these two extremes is explained by the following:

[12] There are no detailed results for pipeline transport of refrigerated ammonia. Therefore, the supply chain with the highest score is pipeline transport of pressurised ammonia. For all modalities where both pressurised as refrigerated ammonia are assessed, the supply chains with refrigerated ammonia have a higher score.

- The storage of *pressurised* ammonia determines the difference in external safety risk score. This risk score dominates the score for Safe & Secure. Supply chains which include decentralised storage of pressurised ammonia have a low score while chains without this kind of storage have a much higher score, sometimes even rounded to 1.00. This does not mean that there is no risk, but the risk score is less than 1/200th of the risk score of the chain with decentralised storage and cracking and road transport of pressurised ammonia.
- Of all supply chains with decentralised storage and cracking, road transport has the lowest score. The modalities in descending order of risk classification are road, rail, inland shipping, and pipeline.

The risk classification for transport of *refrigerated* ammonia by road, rail or inland shipping is significantly lower because the refrigerated ammonia needs to evaporate first in the event of an incident (breach, leak). The scores in Figure 8 show that the differences in risk classification between the modalities are smaller for refrigerated ammonia (maximum spread 11 percent point) than for pressurised ammonia (maximum spread 21 percent point).



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.00	0.20	0.16	0.21	0.99
Refrigerated	0.88	0.99	0.97	(0.99)	0.99

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.84	1.00	0.96	1.00	0.37
Refrigerated	0.92	1.00	0.98	(1.00)	0.37

Figure 8: Scores for External safety for inland supply chains in 2030; hydrogen end use and ammonia end use

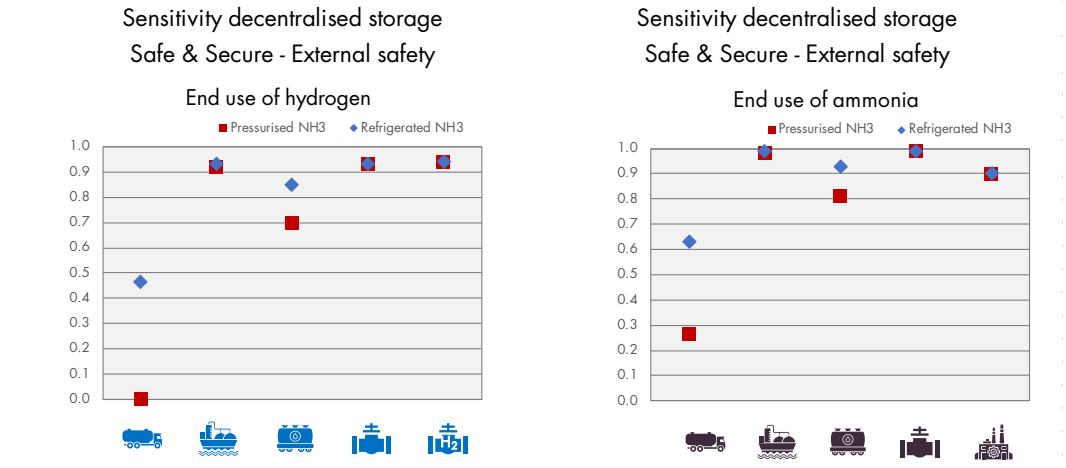
- Refrigerated ammonia supply chains have much higher scores than pressurised ammonia chains due to the lower impact in case of a toxic gas leak, in particular if decentralised storage is part of the supply chain.
- Road transport has the lowest scores due to the highest external safety risk, despite the smaller volume compared to other transport modes.

Sensitivity analysis: if all decentralised storage is refrigerated and normalisation scale is adjusted

Because of the dominant impact of the decentralised storage, a sensitivity analysis is done to discover how large the differences are due to variations in chains and transport modalities if there are no differences in the decentralised storage chain component.

In the baseline situation it is assumed that domestically transported refrigerated ammonia is stored refrigerated before cracking to hydrogen and domestically transported pressurised ammonia is stored pressurised before cracking to hydrogen. If decentralised storage is assumed not to differ between the chains but done refrigerated across the board, Figure 9 shows that there are indeed significant differences between the transport modalities (maximum spread 47 percent point for refrigerated ammonia and 93 percent point for pressurised ammonia), compared to Figure 8. The external safety risk classifications are lowest for pipeline transport and inland shipping. In these cases, the risk score of domestic transport does not determine the risk score of the whole supply chain. The risk score of decentralised refrigerated storage determines the total risk. In case of transport by road or rail, the contribution of domestic transport to the total risk classification is larger than of the decentralised storage of refrigerated ammonia.

For inland waterway transport, the difference in external safety scores between pressurised and refrigerated ammonia is negligible for both hydrogen and ammonia end use. This is because the external safety risk classification per barge is inherently low compared to road and rail transport. Although refrigerated ammonia is safer than pressurised ammonia, partly because approximately half of any spill dissolves in water, the absolute difference in risk classification between the two forms is small relative to the differences observed for road transport.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.00	0.93	0.70	0.93	0.94
Refrigerated	0.47	0.93	0.85	(0.93)	0.94

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.27	0.98	0.81	0.99	0.90
Refrigerated	0.63	0.99	0.93	(0.99)	0.90

Figure 9: Scores for External safety for inland supply chains in 2030; hydrogen end use and ammonia end use (all decentralised storage refrigerated)

- Refrigerated ammonia supply chains have higher scores than pressurised ammonia chains, but the difference with pressurised supply chains is smaller compared to the baseline, as differences in decentralised storage are eliminated.
- Road transport still has the lowest scores. The differences between the modalities are larger than in the baseline because these differences are not overshadowed by the major impact of decentralised storage on the normalisation scale.
- The differences between refrigerated and pressurised ammonia via inland waterway transport seem negligible as the external safety risks are small compared to rail and road transport.

4.1.2 *Cyber security and terrorism (indicator for Safe & Secure)*

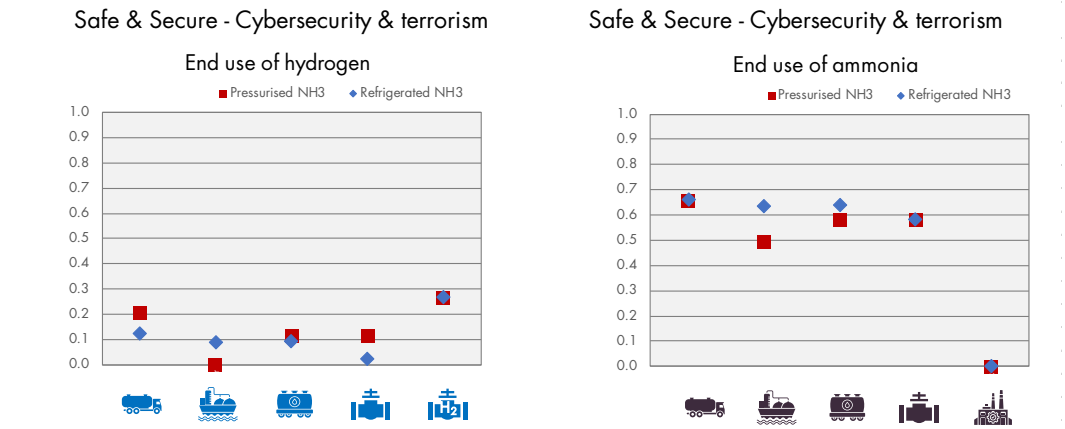
The experts expect that any cyber or terrorist attacks will probably be targeted at supply chain assets and substances with the largest negative impact, rather than on supply chain assets and substances with less catastrophic effects. Therefore, the likelihood of an incident or attack on a storage tank is larger than on a truck. However, the experts estimate there is no difference in the likelihood of an attack on pressurised or refrigerated ammonia assets.

Consequently, the scores of refrigerated ammonia chains are higher (see Figure 10) if there is no decentralised storage because the risks are lower.The likelihood for pressurised and refrigerated supply chain elements is the same, and the impact is lower for refrigerated ammonia as per tank trailer, rail tank car or barge the volume of refrigerated and pressurised ammonia is about the same.

However, if decentralised storage is part of the supply chain, pressurised ammonia chains have higher Cyber security and terrorism scores because the impact of an incident is smaller due to smaller decentralised storage volume of an individual pressurised ammonia tank (and the likelihood is the same for refrigerated and pressurised).

The exception is inland shipping, where in spite of the decentralised storage, refrigerated ammonia has a higher score than pressurised. Although refrigerated ammonia requires larger decentralised storage volumes, its lower transport risk classification outweighs this disadvantage for cyber and terrorism risks. The advantage for refrigerated ammonia is relatively large as in case of spill half the refrigerated ammonia dissolves in water.

Road transport has higher scores than other transport modalities due to the assumed lower probability of a cyber attack as it is less sensitive to IT issues. An incident also causes less societal disruption because of dispersed transport of relatively small volumes. The centralised storage in the port of entry determines these scores for all supply chains in equal measure.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.21	0.00	0.11	0.11	0.27
Refrigerated	0.13	0.09	0.10	(0.02)	0.27

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.66	0.50	0.58	0.58	0.00
Refrigerated	0.66	0.63	0.64	(0.58)	0.00

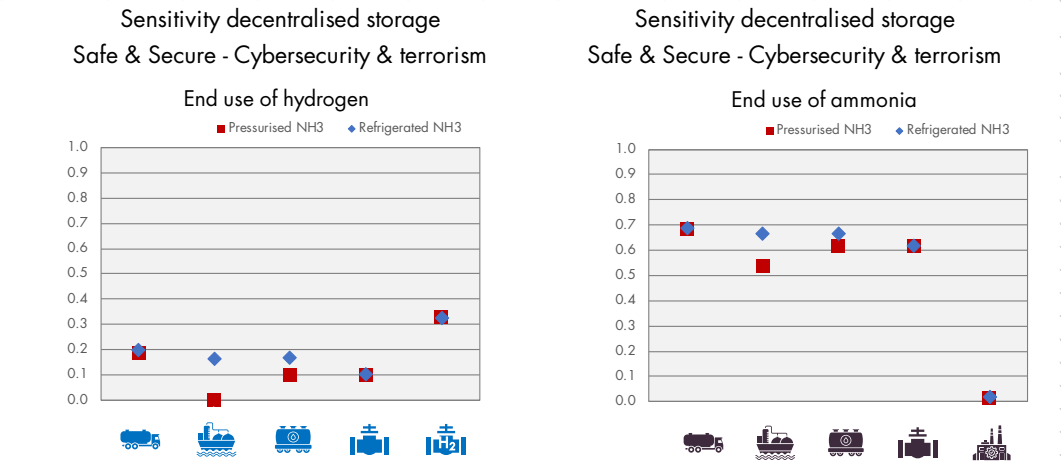
Figure 10: Scores for Cyber security and terrorism for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have overall higher scores than pressurised ammonia chains, if there is no decentralised storage. The probability of an incident is the same but the impact is lower for refrigerated ammonia.
- Pressurised ammonia supply chains have higher scores than refrigerated ammonia chains, if the impact of decentralised storage is included. The impact is smaller because of the smaller volume of a pressurised storage tank than a refrigerated tank.
- Road transport has higher scores than other transport modalities due to the assumed lower probability of a cyber attack and the small volume per truck.
- An exception is inland shipping: despite the higher cyber security and terrorism risk classification of larger decentralised refrigerated storage volumes, refrigerated ammonia still has higher scores than pressurised ammonia. This is because in the event of a spill during transport, approximately half of the refrigerated ammonia dissolves in water, substantially reducing its impact, an advantage that outweighs the storage disadvantage.

Supply chains with end use of hydrogen (left-hand chart, Figure 10) have lower scores than those with end use of ammonia (right-hand chart, Figure 10). With the end use of ammonia, less ammonia is needed because the ammonia is not required as fuel and cracking does not pose an additional risk.

Sensitivity analysis: if all decentralised storage is refrigerated and normalisation scale is adjusted

Figure 11 shows the results assuming that all decentralised ammonia storage is done refrigerated. The scores for supply chains with domestic pressurised ammonia (first four supply chains in the left-hand chart) transport become lower compared to Figure 10 (baseline). This is because the advantage of the smaller pressurised storage tanks compared to refrigerated storage disappears. Refrigerated ammonia has higher scores than pressurised ammonia because of the lower transport risks. Road transport still has higher scores than other transport modalities.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.19	0.00	0.10	0.10	0.33
Refrigerated	0.20	0.16	0.17	(0.10)	0.33

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.68	0.54	0.62	0.62	0.02
Refrigerated	0.69	0.66	0.67	(0.62)	0.02

Figure 11: Scores for Cyber security and terrorism for inland supply chains in 2030; hydrogen end use and ammonia end use (all decentralised storage refrigerated)

- In this sensitivity analysis, pressurised ammonia supply chains also have overall lower scores than refrigerated ammonia chains, as domestic transport determines the differences in scores and refrigerated ammonia has lower risks than pressurised ammonia transport.
- Road transport has higher scores than other transport modalities, just like in the baseline, due to the assumed lower probability of a cyber attack and the small volume per truck.

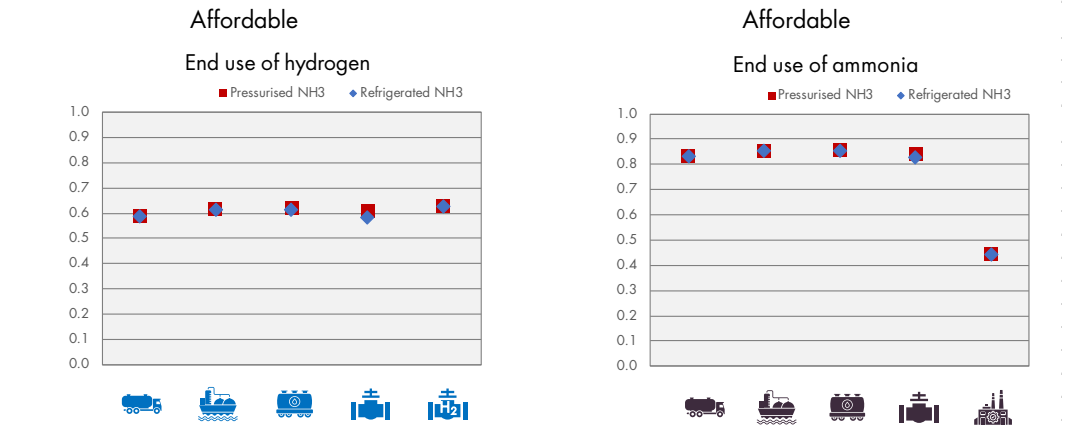
4.2 SCORES FOR PUBLIC INTEREST AFFORDABLE

Figure 12 shows the normalised scores for the affordability of hydrogen and ammonia for the various supply chains for inland use. The higher the score, the lower the cost price per kilogramme of hydrogen equivalent. The bandwidth used is 2.50 euros (score 1) to 8 euros (score 0).

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

Results for baseline situation (2030, inland end use)

Ammonia has the highest scores if this substance is used directly (right-hand chart, Figure 12), without cracking. The scores are lower when conversion to hydrogen is necessary (left-hand chart). A combination of centralised cracking and synthesis to ammonia at the end user results in the lowest scores. This is due to the costs for cracking and conversion back (synthesis) to ammonia and the use of ammonia as fuel for the cracking process.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.59	0.62	0.62	0.61	0.63
Refrigerated	0.59	0.62	0.62	(0.58)	0.63

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.83	0.85	0.86	0.84	0.44
Refrigerated	0.83	0.85	0.85	(0.83)	0.44

Figure 12: Scores for Affordable for inland supply chains in 2030; hydrogen end use and ammonia end use

- Pressurised ammonia supply chains have overall slightly higher scores than refrigerated ammonia chains, as domestic transport and decentralised storage of refrigerated ammonia have higher costs than of pressurised ammonia.
- Rail transport and inland shipping have the highest scores for ammonia transport due to the lowest transport costs per hydrogen equivalent. Transport of hydrogen through the hydrogen network requires less costs and has the highest scores in case of hydrogen end use, but the differences between the alternatives are small, because import costs are much higher than domestic transport costs.

The choice of inland transport mode has little effect on the overall costs due to low transport and storage costs compared to the import costs. As differences between refrigerated and pressurised ammonia only affect the domestic transport costs and subsequent storage, the differences are small and do not result in different values. Only the colour coding indicates that pressurised ammonia chains have a (slightly) higher score than refrigerated ammonia chains (less than one percent point) due to the more costly equipment needed for storing and transporting refrigerated ammonia. This outweighs the costs of heating the stored refrigerated ammonia before transporting it in pressurised form (ambient heat is generally used). The exception is the value between brackets for the chain with fictitious refrigerated ammonia pipeline transport. The maximum difference for Affordable is 3 percent points even though the domestic transport costs of refrigerated ammonia by pipeline are assumed to be twice as high. That is because the import costs make up the largest part of the costs for the end user.

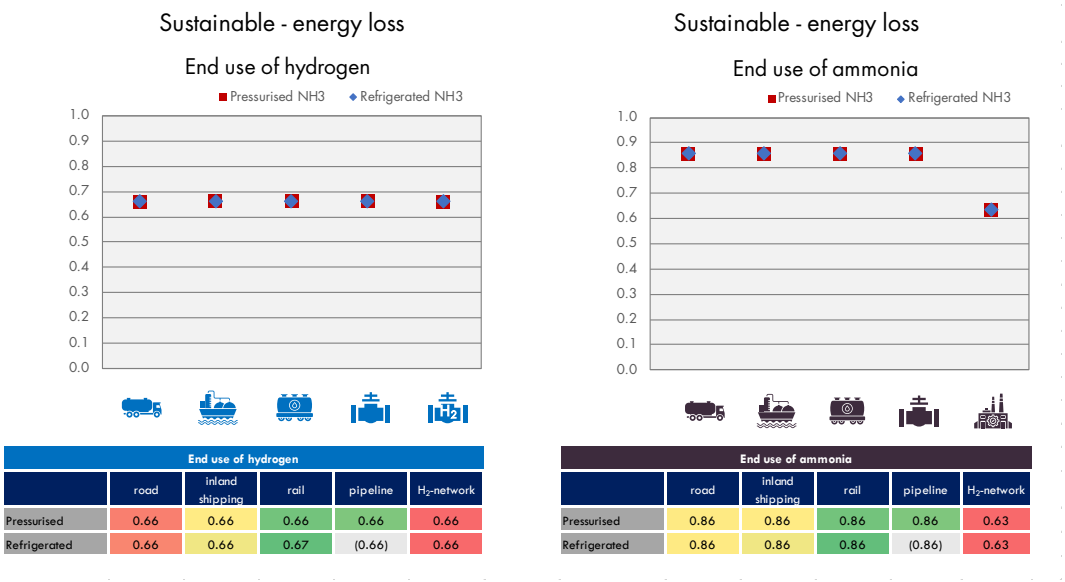
4.3 SCORES FOR PUBLIC INTEREST SUSTAINABLE

The public interest Sustainable has been quantified using three indicators: 1) Greenhouse gas emissions, 2) Energy loss and 3) (critical raw) Material usage. Only the results for Energy loss are described in this section, as the scores for the other indicators are the same for pressurised and refrigerated ammonia chains. More information on the other indicators and the combined results is described in Annex E.

Results for baseline situation (2030, inland end use) – indicator Energy loss

The energy losses per kilogramme of hydrogen equivalent include energy for electrolysis and ammonia synthesis (in the producing country), cracking, transport and losses due to leakage and boil-off. The theoretically most efficient supply chain, in which the total energy use is exactly equal to the energy content of a kilogramme of hydrogen (no losses), is assigned a score of 1. The supply chain with the highest energy losses per kilogramme of hydrogen is assigned a score of 0.

Use of the hydrogen carrier to fuel the conversion process results in lower scores, see Figure 13. Some of the ammonia is consumed during cracking. This contributes to the energy losses for these supply chains, as larger volumes of ammonia must be produced in the exporting countries to supply comparable quantities of hydrogen equivalent for end use. This is the same for pressurised and refrigerated ammonia.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.66	0.66	0.66	0.66	0.66
Refrigerated	0.66	0.66	0.67	(0.66)	0.66

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.86	0.86	0.86	0.86	0.63
Refrigerated	0.86	0.86	0.86	(0.86)	0.63

Figure 13: Scores for Energy loss for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia chains have slightly higher scores than pressurised supply chains because the imported refrigerated ammonia must first be heated before it can be transported as pressurised ammonia. This difference is barely visible in the ranking colours. as the differences in energy loss, if any, are negligible.
- Rail transport and pipeline transport have the highest scores, but the differences with other modalities are small and visible only in the ranking colours.

The only difference is that pressurised ammonia chains have slightly higher energy loss than refrigerated ammonia chains because the imported refrigerated ammonia must first be heated before it can be transported as pressurised ammonia. This is generally done using heat exchangers with ambient heat, but can also involve external energy input. Either way, the effect is small compared to other energy losses and within rounding (except for the chain with rail transport in left-hand chart). Consequently, the differences between refrigerated and pressurised ammonia chains are only visible due to the slightly different colours that indicate the ranking. The yellow colour of transport of refrigerated ammonia by barge has a green touch, while the colour of transport of pressurised ammonia by barge is plain yellow. Ambient heating is generally used for evaporating the ammonia before cracking.

4.4 SCORES FOR PUBLIC INTEREST ADAPTABLE

Figure 14 shows the normalised scores for the public interest Adaptable for the various supply chains for inland use. The scores that resulted from expert sessions for the 2024 MCA of hydrogen carriers were reviewed for the present study, with differentiation between pressurised and refrigerated liquid ammonia assets. Supply chains that require fewer high-risk investments are assigned a higher score. The bandwidth used is 26 euros (score 0) to 0 euros (score 1) of high-risk investments per kilogramme of hydrogen equivalent. High-risk means that additional investments must

be made and that these have no other applications if the supply chain for the hydrogen or ammonia is not successful.[13]

Results for baseline situation (2030, inland end use)

The investments in conversion have the largest effect on the scores. Supply chains with one or more conversion steps (cracking, synthesis back to ammonia) have the lowest score, as conversion plants cannot generally be reused for other processes (other than recycling for parts/scrap). Neither are there existing facilities available for use (they do not exist or they are already in use).

Although investments in means of transport are higher[14] for refrigerated than for pressurised ammonia, the difference in scores between supply chains is small (maximum spread all chains of 11 percentage points), and is often visible only in the ranking colours. This is due to two factors:

- The investments in means of transport are part of the total investments at risk. The required investments at risk in conversion facilities (maximum 2.01 million euro per kton hydrogen equivalent decentralised cracking) are larger than the investments required in means of transport (up to 0.60 million euro per kton hydrogen equivalent) or storage facilities (maximum 0.05 million euro per kton hydrogen equivalent for decentralised storage). Differences between means of transport for refrigerated and pressurised ammonia are even smaller up to 0.16 million euro per kton hydrogen equivalent.
- The normalisation scale, equal to the one used in the 2024 MCA of hydrogen carriers, is much larger than the maximum difference in the ammonia supply chains. Therefore, differences in investment at risk only correspond to 11 percentage points of the normalisation scale and differences between refrigerated and pressurised ammonia for the same means of transport are less than 1 percentage point.

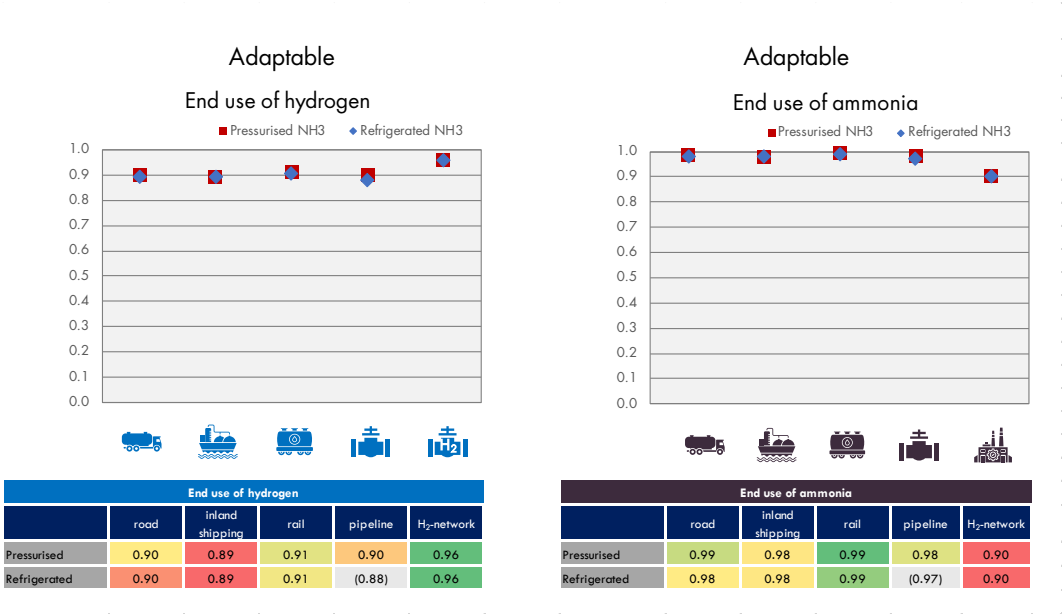
A substantial part of the required investments in centralised ammonia storage has already received a building permit or concerns retrofit of existing facilities. This means that less additional risky investments are needed in the target year 2030 but the centralised storage does not differ between refrigerated and pressurised ammonia supply chains. Centralised storage is always refrigerated in the supply chains that we compare.

The means of transport with the highest scores is the hydrogen network. The investment decision was already taken and there are few additional high-risk investments needed. Inland shipping has the lowest scores (besides the fictitious refrigerated pipeline) due to the highest high-risk investments per hydrogen equivalent.

In relation to the scores for Adaptable, note that the extent to which the investments are reusable is based on an expert judgement and that the values for the required investments in the literature are uncertain.

[13] The possibility for stepwise expansion has not been considered in the operationalisation of Adaptable.

[14] 6% higher investment costs per kton hydrogen equivalent for transport by inland waterways, 46% for transport by road and 208% for transport by rail.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.90	0.89	0.91	0.90	0.96
Refrigerated	0.90	0.89	0.91	(0.88)	0.96

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.99	0.98	0.99	0.98	0.90
Refrigerated	0.98	0.98	0.99	(0.97)	0.90

Figure 14: Scores for Adaptable for inland supply chains in 2030; hydrogen end use and ammonia end use

- Pressurised ammonia supply chains have overall slightly higher scores (visible in the ranking colours) than refrigerated ammonia chains, as the means of transport for refrigerated ammonia require more high-risk investments than for pressurised ammonia.
- Inland shipping has the lowest scores for ammonia transport (besides the fictitious refrigerated pipeline) due to the highest high-risk investments per hydrogen equivalent. The hydrogen network has the lowest additional high-risk investments as the investment decision was already taken.

4.5 SCORES FOR PUBLIC INTEREST FAIR

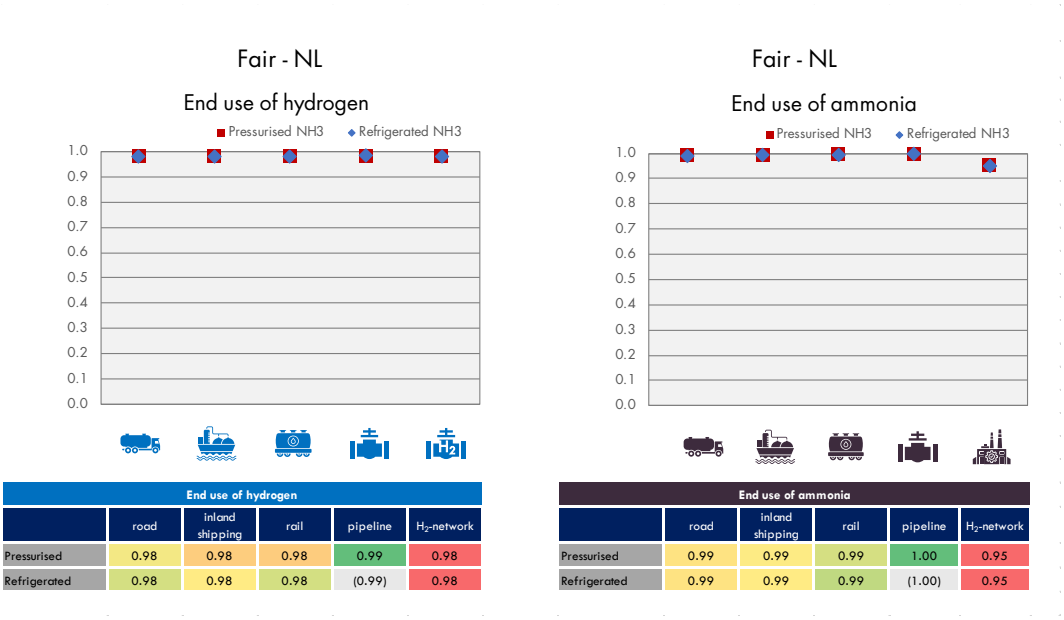
The normalised scores for the public interest Fair are a combination of two indicators: 1) Fair for exporting countries and 2) Fair for Dutch society. The stakeholders assessed these indicators as approximately equally important. Only the results for Fair for Dutch society are described in this section, as the results for Fair for exporting countries are the same for chains with pressurised or refrigerated ammonia. More information on the other indicator and the combined results is to be found in Annex E.

Results for baseline situation (2030, inland end use) – Indicator Fair for Dutch Society

The higher the score, the smaller the difference between the 'true costs' and the private costs[15], the less the external effects are shifted onto Dutch society. A supply chain is assigned a score of 1 if there is no difference between the true costs and the private costs; in this case, the true costs divided by the private costs is 100%. The supply chain with the largest percentage difference is assigned a score of 0.

[15] Private costs are the direct expenses incurred by an individual or firm in producing or consuming goods and services, excluding any external costs imposed on society. 'True costs' is a concept that encompasses the private costs along with all external costs (social and environmental costs). True costs is a tool for exposing the hidden costs associated with the production of goods and services.

The score for Fair for Dutch society is determined by the supply chain steps from import and storage up to and including conversion at the end user's site. The difference between true costs and private costs for the domestic ammonia supply chains in the Netherlands is small compared to the normalisation scale. The maximum difference of the true and private costs in the ammonia supply chains is 48 percent. This corresponds to 5 percentage points of the normalisation scale, resulting in a high score for Fair for Dutch society, see Figure 15. The scores for refrigerated ammonia chains are slightly higher than for pressurised ammonia chains because the private costs are somewhat higher while the external costs are the same. The differences between refrigerated and pressurised ammonia are equal to a maximum difference of the ratio between true and private costs of two percent.[16] This difference is so small that the difference in the normalised scores is visible only in the ranking colours. Due to the favourable ratio between the true costs and private costs of domestic transport, pipeline transport has the highest scores, but the differences with other modalities are small.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.98	0.98	0.98	0.99	0.98
Refrigerated	0.98	0.98	0.98	(0.99)	0.98

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.99	0.99	0.99	1.00	0.95
Refrigerated	0.99	0.99	0.99	(1.00)	0.95

Figure 15: Scores for Fair for Dutch society for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have overall slightly higher scores (visible in the ranking colours) than pressurised ammonia chains, as the private costs are slightly higher than for pressurised ammonia, while the external costs are the same (by definition excluding External safety and Cyber security and terrorism).
- Pipeline transport has the highest scores, due to the favourable ratio between the true costs and private costs of domestic transport, but the differences with other modalities are small.

4.6 SCORES FOR PUBLIC INTEREST ACCESSIBLE

The public interest Accessible consists of two indicators: 1) Cost parity (level playing field) for end users both inland and in the port of entry, and 2) Proximity of the supply chain to inland consumers. Of these two indicators, an Accessible cost level for end users has the highest

[16] Excluding differences in External safety and Cyber Security and terrorism.

weighting. Only the results for Accessible by cost parity are described in this section because the results for Accessible by proximity are the same for supply chains with pressurised or refrigerated ammonia. More information on the other indicator and the combined results is described in Annex E.

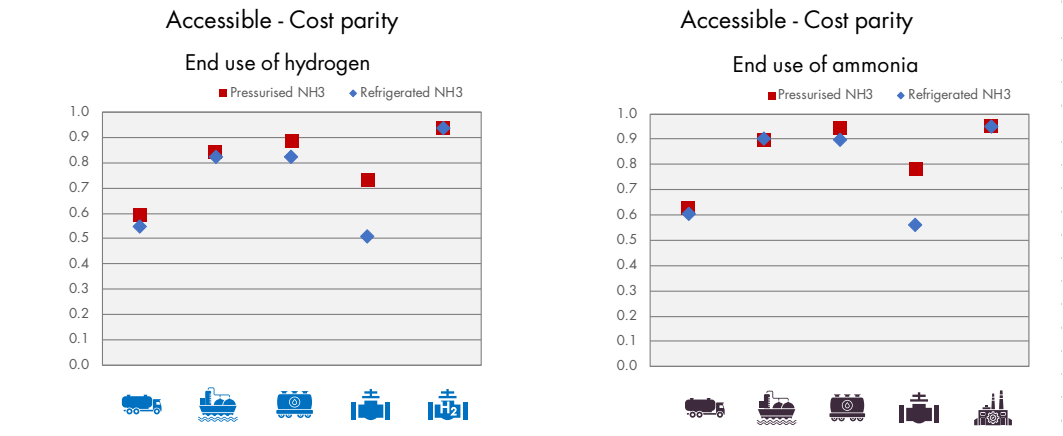
Results for baseline situation (2030, inland end use) - indicator Accessible by Cost parity (level playing field)

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

Refrigerated ammonia supply chains scores are lower than for pressurised ammonia due to somewhat higher transport costs (more expensive transport equipment).

The supply chains that use the hydrogen network for transport in the Netherlands have the highest scores for this indicator due to a small price difference between the port of entry and the end user inland, based on the assumed hydrogen network transport fees, see Figure 16. The supply chains with high additional transport costs have the lowest score (road transport). Pipeline transport with the ISPT safe & compliant design adds more costs for an inland end user than transport by inland shipping or rail.

The scores for the fictitious pipeline with refrigerated ammonia are the lowest. These are based on the rough assumption of twice the costs of the pipeline with pressurised ammonia.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.59	0.84	0.89	0.74	0.94
Refrigerated	0.55	0.83	0.82	(0.51)	0.94

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.63	0.89	0.94	0.78	0.95
Refrigerated	0.61	0.90	0.90	(0.56)	0.95

Figure 16: Scores for Accessible by Cost parity for inland supply chains in 2030; hydrogen end use and ammonia end use

- Pressurised ammonia supply chains have overall higher scores than refrigerated ammonia chains, as the costs of domestic transport are lower for pressurised than for refrigerated ammonia.
- Transport by hydrogen network has the highest scores, due to the assumed low domestic transport costs and the absence of decentralised storage.

4.7 SCORES FOR PUBLIC INTEREST SPATIAL FOOTPRINT

To assign a score for the public interest Spatial Footprint, we assessed the physical space that each supply chain occupies. A supply chain with no additional spatial requirements is assigned a score of 1. A supply chain with a score of 0 has spatial requirements valued at 0.4 euros per kilogramme of hydrogen equivalent.

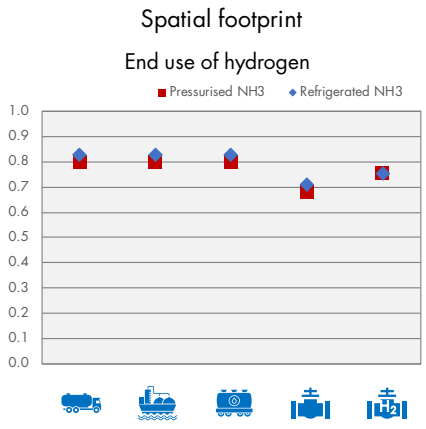
Results for baseline situation (2030, inland end use)

Differences between the supply chains are due to the different spatial requirements for pressurised or refrigerated decentralised storage, due to the spatial need for additional pipelines and due to the differences in volume (expressed in hydrogen equivalent). The cause for the latter, in case of end use of hydrogen, is that ammonia is used as fuel for cracking.

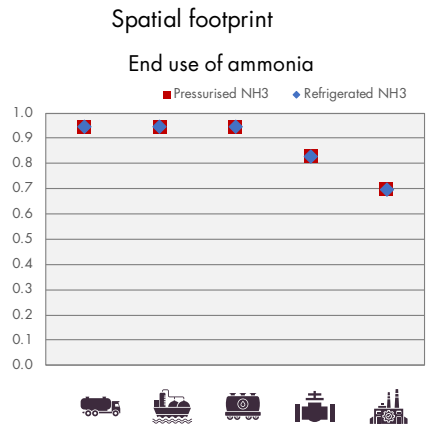
Refrigerated ammonia has a higher score than pressurised ammonia in supply chains for hydrogen end use that include decentralised storage, because pressurised ammonia requires more storage space (multiple tanks with lower capacity each) than refrigerated ammonia. The overall differences are small.

The spatial needs are by definition higher for end use of hydrogen because the chains then include decentralised storage and cracking within the system boundaries. No decentralised storage is assumed in the modelling of supply chains for end use as ammonia, even though end users may have storage on their site.

The supply chains with the highest scores are those that do not require new pipelines, have modest spatial requirements for storage facilities and do not involve cracking, see Figure 17. No supply chain has a score of 1, because every supply chain requires at least space for centralised storage.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.80	0.80	0.80	0.68	0.76
Refrigerated	0.83	0.83	0.83	(0.71)	0.76



End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.95	0.95	0.95	0.83	0.70
Refrigerated	0.95	0.95	0.95	(0.83)	0.70

Figure 17: Scores for Spatial Footprint for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have higher scores than pressurised ammonia chains if decentralised storage is included, because the spatial footprint of decentralised pressurised storage is higher than for decentralised refrigerated ammonia storage.
- Transport by pipeline has the lowest scores, due to the substantial spatial need for additional pipelines.

CHAPTER 5 TOTAL SCORES

This chapter presents the total scores for three situations: first the baseline situation in 2030 with the sensitivity analyses of decentralised pressurised storage, followed by two variants with different locations of the end user.

- *Baseline situation:* This concerns the situation for end users located inland, at a distance of 200 km from the port of entry (the length of the assumed typical route).
- *Port of entry:* The first variant of the baseline situation location applies to end users who utilise the hydrogen or ammonia directly at the port of entry. In this case, inland transport and decentralised storage are eliminated from the supply chain.
- *Transit and export:* The second variant involves a situation in which the hydrogen or ammonia is routed through the Netherlands for use in Germany or Belgium. In this situation, decentralised storage, conversion, and synthesis are eliminated from the chain.

This chapter also provides the results of sensitivity analysis of the weighting factors.

The total score is the outcome of the combination of:

- The individual scores for the individual public interests;
- the normalisation scales for the individual public interests;
- the weighting factors for the public interests;
- and the VIKOR ranking methodology, which combines the weighting factors with penalties for lowest scores on each public interest.

To explain differences in scores between supply chains, one component can be more more important for a certain difference than another. In this MCA, we needed to expand the normalisation scale for Safe & Secure (indicator External safety) considerably to accommodate the scores for decentralised storage, while maintaining the weighting factors. At the same time, the scale for Reliable, among others, was narrowed by omitting the outlying sodium borohydride scores. As a result, the total scores of supply chains without decentralised pressurised storage sometimes turn out differently than one might expect at first glance, as will be explained in the following paragraphs.

5.1 TOTAL SCORES FOR BASELINE SITUATION

The results for the public interests (Chapter 4 and Annex E) are combined into total scores with the weighting factors agreed during the Delphi session in 2024 MCA of hydrogen carriers. The results are shown in Figure 18, for the supply chains in which the end user consumes hydrogen in the left-hand chart, and for the supply chains in which the end user consumes ammonia in the right-hand chart.

Hydrogen end use (left-hand chart)

The five highest-scoring alternatives[17] for hydrogen end use are:

1. Centralised cracking and domestic transport through the hydrogen network
2. Domestic transport of refrigerated ammonia by rail
3. Domestic transport of refrigerated ammonia by road
4. Domestic transport of refrigerated ammonia by inland shipping
   (Domestic transport of refrigerated ammonia by pipeline)
5. Domestic transport of pressurised ammonia by pipeline

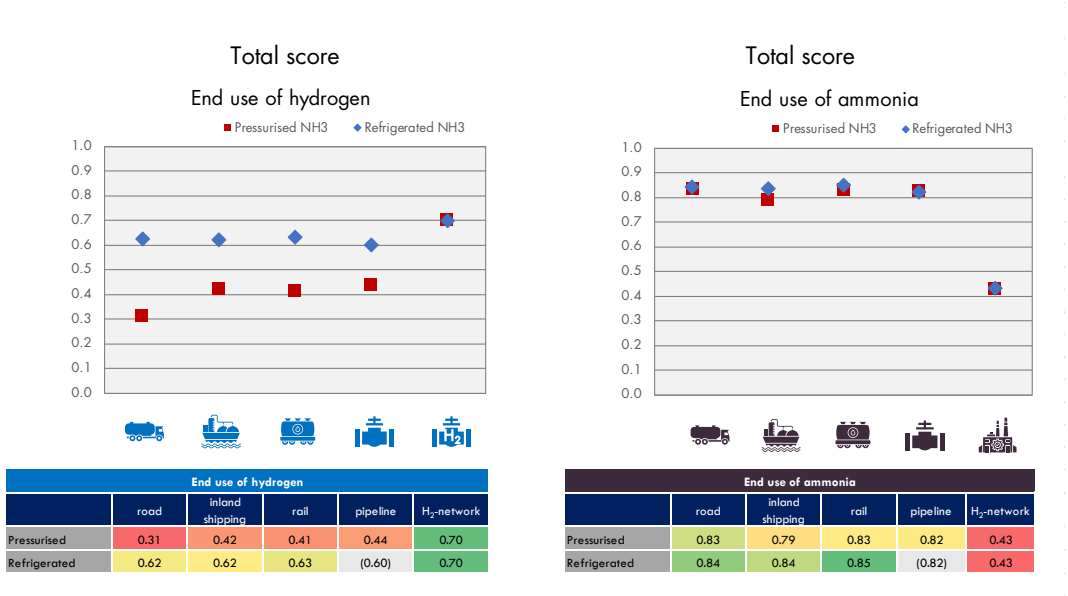
Centralised cracking following import has the highest score, and in general, the supply chains with refrigerated ammonia have higher scores than with pressurised ammonia. The difference between supply chains with refrigerated and pressurised ammonia is largely explained by the impact of decentralised storage of pressurised ammonia. This impact determines the scores for the public interest Safe & Secure, which in turn dominates the total score due to its high weighting and due to the fact that differences between both forms of ammonia are all smaller or even non-existing for other public interests.

The safety risks (and also Spatial Footprint, with a lesser weighting in the total score) of decentralised storage of pressurised ammonia are much larger than for refrigerated ammonia. This is an improved insight compared to the 2024 MCA of hydrogen carriers, when this distinction between the two types of ammonia was not clearly made.

The large impact of decentralised storage also explains the difference in scores between the pipeline with pressurised ammonia and the fictitious pipeline with refrigerated ammonia. Although we assumed the costs for the fictitious pipeline to be twice as high as for the pipeline with pressurised ammonia and the safety risk classification of both pipelines to be equal, the total score for the fictitious pipeline is higher (0.60 instead of 0.44). The reason is that after domestic transport through pipeline the pressurised ammonia is stored pressurised before cracking and the refrigerated ammonia is stored refrigerated. The impact of this decentralised storage for Safe & Secure and Spatial Footprint is so large that the total score of the supply chain with refrigerated ammonia transport via pipeline is significantly higher than for the supply chain with pressurised ammonia via pipeline.

The differences between the other transport modes seem small, in particular for the refrigerated supply chains (left-hand chart) and the end use of ammonia (right-hand chart). This is the result of the dominant impact of decentralised pressurised storage, and the expansion of the normalisation scale for External safety that was required to include its scores. This reduces the differences between modalities for External safety, Safe & Secure and the total scores.

[17] Pipeline transport of refrigerated ammonia over 200 km is fictitious and therefore not a realistic alternative. It is therefore between brackets.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.31	0.42	0.41	0.44	0.70
Refrigerated	0.62	0.62	0.63	(0.60)	0.70

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.83	0.79	0.83	0.82	0.43
Refrigerated	0.84	0.84	0.85	(0.82)	0.43

Figure 18: Total scores for inland supply chains in 2030; hydrogen end use and ammonia end use

Ammonia end use (right-hand chart)

The five highest-scoring alternatives[18] for ammonia end use are:

1. Domestic transport of refrigerated ammonia by rail,
2. Domestic transport of refrigerated ammonia by road,
3. Domestic transport of refrigerated ammonia by inland shipping,
4. Domestic transport of pressurised ammonia by road,
5. Domestic transport of pressurised ammonia by rail.

In case of ammonia end use, the decentralised storage is out of scope as it is assumed to be located after the end user's gate. It should be noted, however, that decentralised storage at the end user's site does impact public interests such as Affordable, Spatial Footprint and Safe & Secure even though it falls outside the scope of this comparison.

Because decentralised storage is not taken into account, the scores of refrigerated and pressurised ammonia chains appear close to each other and higher in case of ammonia end use than for the chains with end use of hydrogen gas. The exception is the chain with decentralised synthesis with hydrogen from the hydrogen network to ammonia. This results in a lower score than for direct use of ammonia for all public interests except for Reliable and Accessible because two conversion steps cause more costs, high-risk investments, emissions, material usage and energy loss, and spatial needs.

The External safety normalisation scale is dominated by the risks of decentralised pressurised storage. Therefore, the differences between supply chains without decentralised pressurised storage and between transport modes seem small, but in fact they are obscured by the adjustments made to the method in order to accommodate decentralised pressurised storage in the normalisation scale.

[18] Pipeline transport of refrigerated ammonia over 200 km is fictitious and therefore not a realistic alternative.

Box 1: Explanation of changes in ranking of pressurised ammonia compared to 2024 MCA of hydrogen carriers

Changes in the order of scores for pressurised ammonia chains in this study compated with the 2024 MCA are the result of (a combination of) the following differences/changes:

- The decentralised storage of pressurised ammonia (which is within scope for the four chains with decentralised cracking to hydrogen) proves to be decisive for:
    i. the External safety scores and, due to the great weight assigned to External safety, also for the total scores.
    ii. the normalisation scale for External safety. This required expansion to be able to include the scores for chains with decentralised pressurised ammonia storage.

  Consequently, differences between chains with different transport modalities regarding the public interest External safety become smaller than in 2024 MCA of hydrogen carriers, which did not explicitly distinguish between the two forms of ammonia in decentralised storage. This is also reflected in the total score.
- The chosen normalisation scales (without sodium borohydride, unlike the 2024 MCA of hydrogen carriers, see paragraph 3.3) results in narrower normalisation bandwidths for the public interests Affordable, Energy loss, Material use, and Reliable. Consequently, differences between the depicted ammonia chains become larger regarding these public interests than in the 2024 MCA of hydrogen carriers.
- The low scores of chains with decentralised pressurised storage for External safety receive extra emphasis in the total scores as a result of the VIKOR ranking (a chain with a low score is penalised in the total score, see Annex H).
- For hydrogen end use, road transport now shows a smaller disadvantage on the total score than in the 2024 MCA of hydrogen carriers compared to inland waterway transport. This is because:
    i. The disadvantage compared to inland waterway transport decreases due to the larger normalisation bandwidth for External safety; and
    ii. The impact on External safety is now dominated by decentralised pressurised ammonia storage, which affects both modalities equally.
- Also, for hydrogen end use, rail transport now has a 1 percentage point lower score than inland waterway transport. This was previously a 1 percentage point higher score. This is because:
    i. The scores for External safety of rail and inland waterway transport chains are now much closer to the lowest score due to decentralised storage. As a result, they are penalised in the VIKOR ranking. Because rail is closer to the lowest score than inland waterway transport, this penalty causes rail to end up just below inland waterway transport.
- For ammonia end use, road transport now has a higher total score than inland waterway transport. This was not the case in the 2024 MCA of hydrogen carriers. This is because:
    i. The disadvantage of road transport for External safety decreases due to the larger impact of decentralised pressurised storage, for which the normalisation scale was expanded. In the case of direct use of ammonia, decentralised storage is not in scope, and both alternatives have a relatively high score.
    ii. For the public interest Safe & Secure, road transport does have a small disadvantage (due to Transport safety and External safety), but the benefits on Reliable and Accessible outweigh the disadvantage in the total score, while transport by barge is penalised in the VIKOR ranking for its low score for Reliable and Accessible (Proximity).
- Also, for ammonia end use, rail transport has a higher total score than inland waterway transport (4 percentage points). This was a 1 percentage point difference in the 2024 MCA of hydrogen carriers. The reasons are:
    i. The difference in scores between pressurised inland waterway transport and pressurised rail transport for External safety has become smaller (from 18 percentage points higher for waterway transport to 4 percentage points higher) because the normalisation scale for External safety was expanded.
    ii. The difference in scores between pressurised inland waterway transport and pressurised rail transport has become larger for Reliable (from 31 percentage points higher for rail to 37 percentage points higher for rail) because for Reliable the normalisation scale was narrowed.

Some of the resulting differences require detailed explanation, in particular the high score for road transport and changes in ranking of pressurised ammonia chains compared to the previous 2024 MCA of hydrogen carriers, see Box 1. This high score is the result of necessary method adjustments but should not be considered representative without re-evaluation of the weighting factors and normalisation scales.

Impact of refrigerated and pressurised ammonia on public interests

The largest differences in supply chain scores occur for chains with domestic transport and decentralised cracking. The difference between refrigerated and pressurised ammonia for other supply chains is small, in particular for end use of ammonia. The reason is that the advantages and disadvantages per form of ammonia for the public interests differ. As a result, high scores on one public interest are more or less compensated by lower scores on others.

Refrigerated ammonia chains have significantly higher scores for:

- Safe & Secure (External safety for all supply chains, and Cyber security and terrorism except for supply chains with decentralised storage),
- Spatial Footprint (in case decentralised storage is included in the supply chain).

Refrigerated ammonia supply chains also have slightly higher scores for Sustainable (Energy loss) and Fair (for Dutch society), but these advantages are negligible compared to Safe & Secure and Spatial Footprint.

The advantages of refrigerated ammonia outweigh the small to modest disadvantages compared to pressurised ammonia for:

- Safe & Secure (Cyber security and terrorism for supply chains with decentralised storage),
- Accessible (Cost parity).

Pressurised ammonia supply chains also have slightly higher scores for Affordable and Adaptable, but these advantages are very small. Scores do not differ between these two forms of ammonia for other public interests.

5.2 SENSITIVITY ANALYSIS OF DECENTRALISED PRESSURISED STORAGE

The baseline results show that decentralised storage of pressurised ammonia has a dominant impact on the scores, especially for the public interest Safe & Secure which 1) has the highest weighting and 2) shows the largest difference in scores between refrigerated and pressurised ammonia supply chains. To remove the obscuring effect of this dominance, a sensitivity analysis was carried out with the assumption that for Safe & Secure all decentralised storage in each supply chain for hydrogen end use is as refrigerated ammonia. The impact on the total scores is shown in Figure 19.

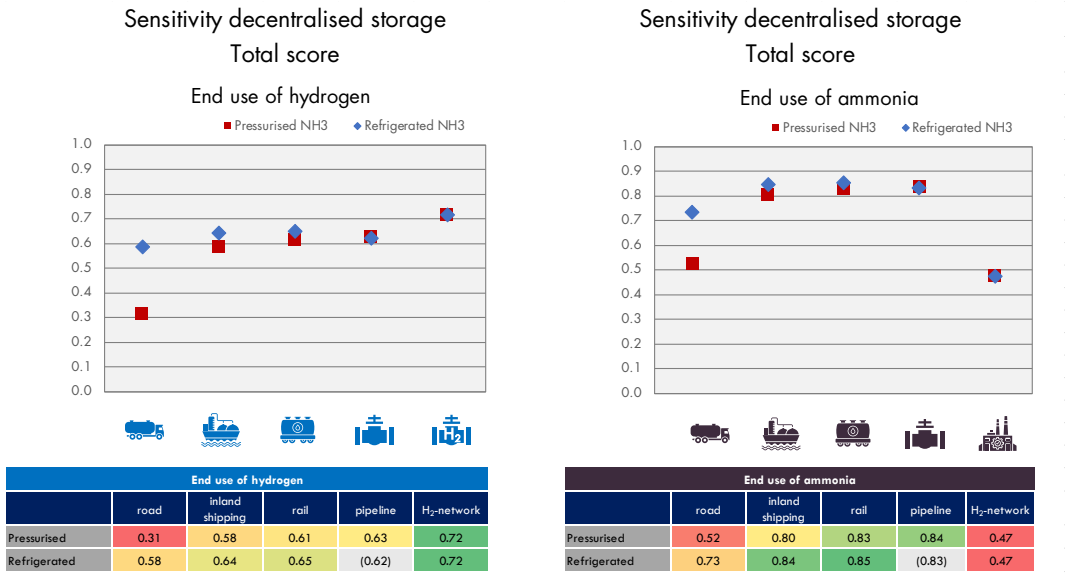
In this situation the five highest-scoring alternatives[19] for hydrogen end use are:

1. Centralised cracking and domestic transport through the hydrogen network (same as baseline)
2. Domestic transport of refrigerated ammonia by rail (same as baseline)
3. Domestic transport of refrigerated ammonia by inland shipping (fourth in baseline)

[19] Pipeline transport of refrigerated ammonia over 200 km is fictitious and not a realistic alternative. It is therefore between brackets.

4. Domestic transport of pressurised ammonia by pipeline (fifth in baseline)
   (Domestic transport of refrigerated ammonia by pipeline) (same in baseline)
5. Domestic transport of pressurised ammonia by rail (not in top-5 in baseline)

Supply chains with pressurised ammonia transport by road and inland shipping and refrigerated transport by road have lower scores than the five highest scoring alternatives.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.31	0.58	0.61	0.63	0.72
Refrigerated	0.58	0.64	0.65	(0.62)	0.72

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.52	0.80	0.83	0.84	0.47
Refrigerated	0.73	0.84	0.85	(0.83)	0.47

Figure 19: Sensitivity analysis of replacing decentralised storage of pressurised ammonia by refrigerated ammonia and adjusted normalisation scale for External safety (no other changes)

The five highest-scoring alternatives[19] for ammonia end use are now supply chains with:

1. Domestic transport of refrigerated ammonia by rail (same as baseline)
2. Domestic transport of refrigerated ammonia by inland shipping (third in baseline)
3. Domestic transport of pressurised ammonia by pipeline (not in top-5 in baseline)
4. Domestic transport of pressurised ammonia by rail (fifth in baseline)
   (Domestic transport of refrigerated ammonia per pipeline) (not in top-5 in baseline)
5. Domestic transport of pressurised ammonia by inland shipping (not in top-5 in baseline)

Chains with pressurised and refrigerated ammonia transport by road and double conversion (centralised cracking and decentralised synthesis) have significantly lower scores than the five highest scoring alternatives.

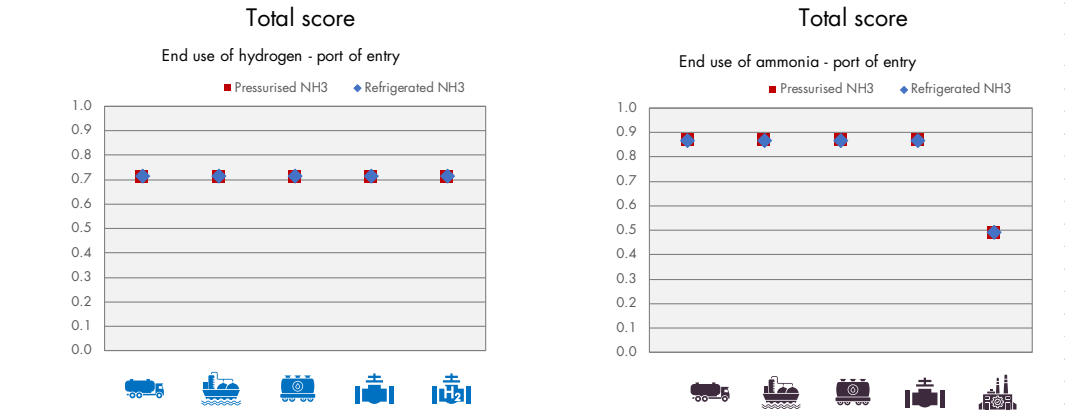
The results show that if the differences in impact between decentralised pressurised and refrigerated storage are excluded from the comparison, there is a significant difference in the total scores due to the transport mode selected. Choosing pipeline, rail and inland shipping leads to higher scores than road transport. Choosing refrigerated ammonia transport leads to higher scores than pressurised ammonia. Though supply chains with transport by barge have higher scores on Safe & Secure than chains with rail and even pressurised ammonia pipeline transport, the total scores are lower because of the lower scores on Reliable, due to the risk of prolonged low water periods when barges cannot sail or can only do so with a reduced cargo load. The total scores of chains with pipeline transport are slightly lower than in the 2024 MCA as we assumed a safer design for the ammonia pipeline and higher costs for the hydrogen network.

These results also illustrate the large impact of the decentralised storage.[20] Without the impact of decentralised pressurised storage, differences in risk classification for Safe & Secure have a similar impact as in the 2024 MCA and are not obscured by the impact on the scores of decentralised pressurised storage.

5.3 END USE IN PORTS OF ENTRY IN 2030

The variant 'end use in the port of entry' is derived from the baseline results. This variant means that in the 2030 baseline situation, the effects of the supply chain steps involving inland transport and decentralised storage do not apply (see results in Figure 20).

The total scores are slightly higher due to the eliminated costs, energy losses and investments in means of transport and decentralised storage, as well as transport-related externalities. In this variant, pressurised ammonia has a markedly higher score than in the baseline situation, because the impact of elements which differ from refrigerated ammonia disappears. Consequently, there is no meaningful difference between supply chains of refrigerated and pressurised ammonia anymore. The largest effect on the total scores compared with the baseline occurs for the supply chain with road transport and pressurised ammonia. In this variant the costs and externalities of domestic transport and decentralised storage are absent, while relatively high in the baseline situation.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.71	0.71	0.71	0.71	0.71
Refrigerated	0.71	0.71	0.71	(0.71)	0.71

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.87	0.87	0.87	0.87	0.49
Refrigerated	0.87	0.87	0.87	(0.87)	0.49

Figure 20: Change in total scores for variant with end use in the port of entry in 2030; hydrogen end use and carrier end use

Every supply chain consists of centralised import and storage of refrigerated ammonia. In addition, there are three options:

1) no extra step – just end use of ammonia (first four chains in the right-hand chart),
2) centralised cracking and end use of hydrogen (all five chains in left-hand chart), or

[20] Without the impact of decentralised pressurised storage, the scores of pressurised ammonia transport are similar to the results of the 2024 MCA of hydrogen carriers, though there are small differences due to small changes and corrections in the data used.

3) cracking followed by synthesis to ammonia (fifth chain in the right-hand chart). This supply chain is included to be complete, but it is not a realistic option in a port of entry where ammonia can be supplied directly.

5.4 TRANSIT AND EXPORT IN 2030

Another variant derived from the baseline is the situation in which hydrogen and ammonia are forwarded to other countries, see Figure 21. In this case, the impact for Environment, Safe & Secure, Spatial Footprint, Economically Robust and Adaptable of the supply chain steps decentralised conversion and storage are shifted outside of the Netherlands and therefore out of scope of the comparison.[21]

This results in fewer environmental impacts, reduced spatial requirements, and fewer safety and security risks in the Netherlands. In addition, fewer high-risk investments are required in the Netherlands (public interest Adaptable). The added value for the Netherlands decreases (public interest Economically Robust). These changes also have impact on the public interest Fair. Proximity is considered irrelevant in this situation and thus scores are all assumed equal. As a result, end use of ammonia transported by pressurised pipeline has a 1 per cent point higher score, because no disadvantage on Proximity is considered.

The scores for centralised cracking in the Netherlands are lower than for end use inland (baseline) because in this variant the effects of decentralised cracking happen outside of the Netherlands and are therefore not part of the scores. This impacts the scores for Environment, Safe & Secure, Spatial Footprint and Adaptable. The scores for supply chains in which the safety and security risk and environmental emissions partly shift to other countries improve compared to the baseline (all columns except column five in the left-hand chart and column five in the right-hand chart improve).

Compared to the baseline, this variant has the largest effect on the scores of pressurised ammonia chains with end use of hydrogen, as the impact of decentralised storage of pressurised ammonia is dominant. For end use of ammonia abroad this variant only impacts the chain with ammonia synthesis at the end user (column five, right-hand chart), because decentralised synthesis and storage are no longer taken into account. Direct transport of ammonia by pipeline or another mode of transport still has higher total scores than transport as hydrogen through the hydrogen network. The main reason is that no extra ammonia is needed as fuel for cracking.

[21] This is a different situation from the sensitivity analysis of decentralised storage (see paragraph 4.1). In the sensitivity analysis pressurised storage is replaced by refrigerated storage, which allows also the normalisation scale for External safety to be adjusted. In the variant Transit and Export, only the impact of some public interests is out of scope for decentralised storage and cracking/synthesis but the normalisation scale is not adjusted.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.76	0.71	0.75	0.75	0.70
Refrigerated	0.77	0.77	0.78	(0.75)	0.70

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.83	0.79	0.83	0.83	0.68
Refrigerated	0.84	0.84	0.85	(0.82)	0.68

Figure 21: Change in total scores for variant with end use abroad in 2030; hydrogen end use and carrier end use

5.5 SENSITIVITY ANALYSES OF WEIGHTING FACTORS

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

- *Neutral weighting*: all public interests equally important (each 10%).
- *Affordable weighted higher*: the result of the Delphi session was adjusted by doubling the weighting for Affordable, halving the weightings for Safe & Secure and Environment and distributing the remaining percentages proportionally.

The pie charts in Figure 22 show the distribution of the used weighting factors.

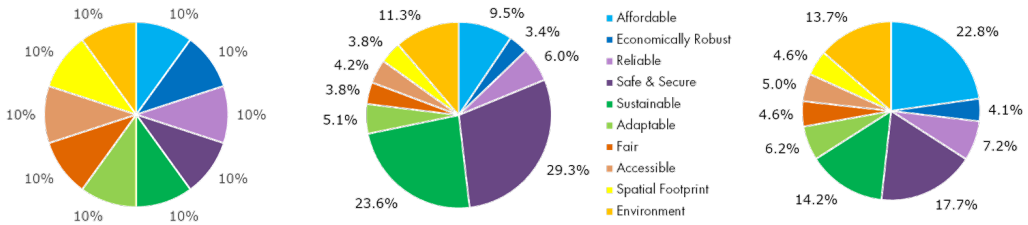


Figure 22: Visual representation of the weighting factors; the Delphi weighting of the baseline situation is shown in the middle, the neutral weighting on the left, the higher weighting of Affordable on the right

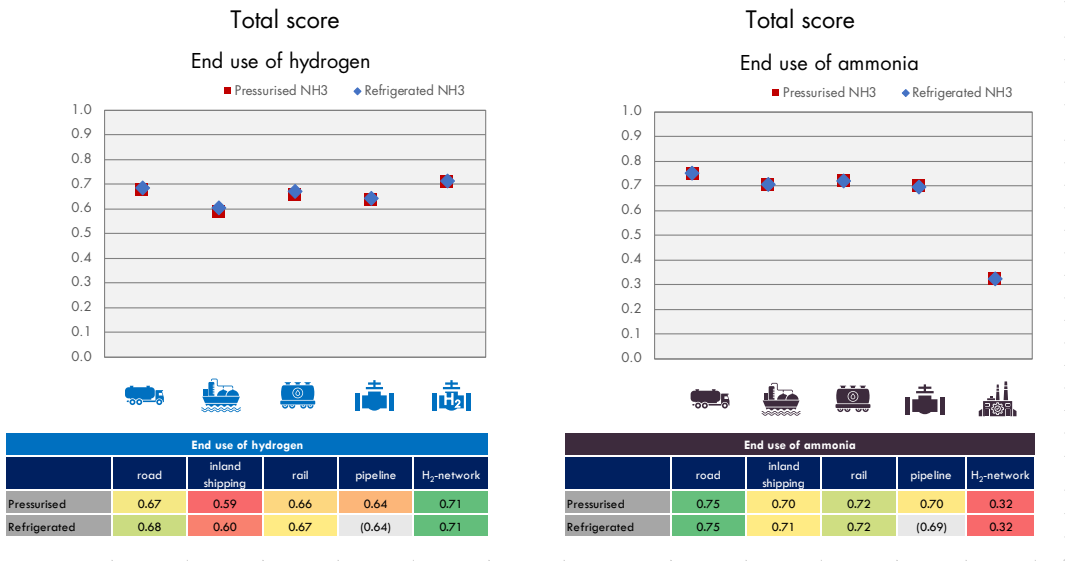
Neutral weighting

The neutral weighting differs from the Delphi weighting as follows (see Figure 22): Economically Robust, Reliable, Adaptable, Fair, Accessible and Spatial Footprint are weighted higher, Environment, Safe & Secure and Sustainable are weighted lower and Affordable is weighted almost the same.

Figure 23 shows that weighting has a major impact on the total score. The differences between refrigerated and pressurised ammonia chains diminish if neutral weighting is applied, in particular because

of the lower weight (10% instead of 29.3%) of Safe & Secure. Still refrigerated ammonia consistently has higher or equal scores compared with pressurised, except for the fictitious pipeline in combination with ammonia end use (0.69 instead of 0.70). This is because the larger disadvantage on Affordable and Adaptable of the pipeline for refrigerated transport compared to pressurised transport is not compensated by the smaller advantages of a fully refrigerated supply chain on Energy loss (indicator Sustainable).

Pressurised ammonia has higher scores as well, because the lower scores for Safe & Secure, Sustainable (Energy loss), Fair (for Dutch society) and Spatial Footprint are compensated more than in the Delphi weighting by higher scores and higher weighted Affordable, Adaptable and Accessible (Cost parity).



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.67	0.59	0.66	0.64	0.71
Refrigerated	0.68	0.60	0.67	(0.64)	0.71

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.75	0.70	0.72	0.70	0.32
Refrigerated	0.75	0.71	0.72	(0.69)	0.32

Figure 23: Sensitivity analysis of neutral weighting factors; hydrogen end use and ammonia end use

Adjusted weighting factors: Affordable weighted higher

In this sensitivity analyses the public interest Affordable is assigned a much higher weighting (see Figure 22). The weighting assigned to Affordable is doubled, the weightings assigned to Safe & Secure and Sustainable are halved, with the remaining percentage points distributed proportional across the other public interests.

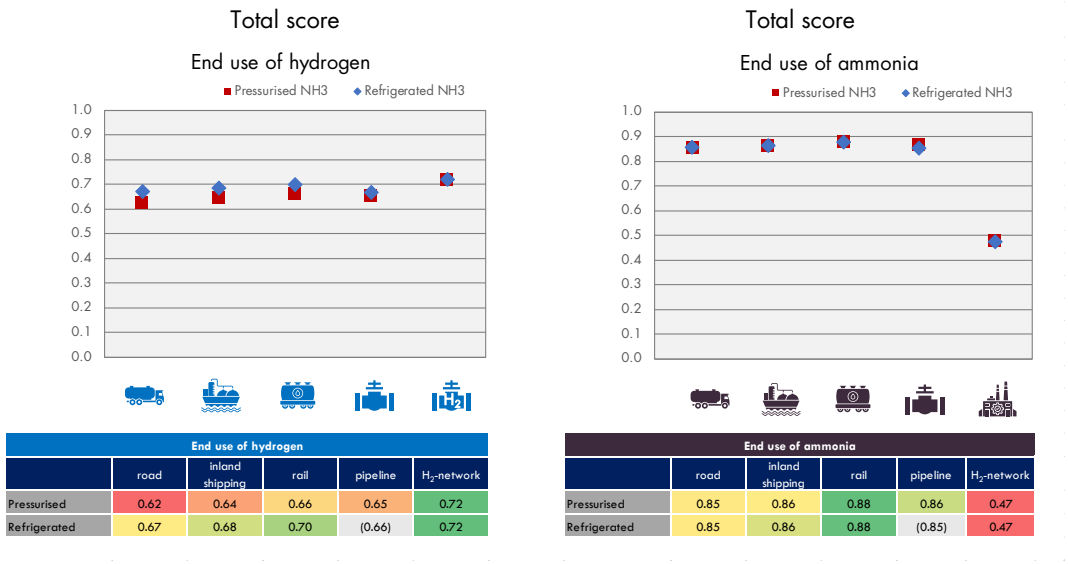
Figure 24 shows that the results are comparable to the neutral weighting, though the remaining differences between pressurised and refrigerated ammonia supply chains are slightly larger in the case of hydrogen end use. The reason is again the lower weighting (17.7% instead of 29.3%) of Safe & Secure.

Refrigerated ammonia chains consistently have higher or equal scores compared with pressurised ammonia chains, except for the fictitious pipeline combined with ammonia end use (0.85 instead of 0.86). This is because the larger disadvantage on Affordable and Adaptable of the pipeline for refrigerated transport compared to pressurised transport is not compensated by the smaller advantages on Energy loss (indicator Sustainable).

Pressurised ammonia chains have higher scores than in the baseline Delphi weighting for the same reasons as described under the neutral weighting scenario above. The lower scores for moderately weighted Safe & Secure, Sustainable (Energy loss), Fair (for Dutch Society) and Spatial Footprint are

partly compensated by higher scores for higher weighted Affordable, Adaptable, and Accessible (Cost parity).

Pressurised ammonia keeps a lower total score compared to refrigerated ammonia when decentralised storage is part of the supply chain (maximum 4 percentage points), which is larger than the maximum 1 percentage point difference under neutral weighting because the weighting factor for Safe & Secure is in-between the Delphi and neutral weighting.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.62	0.64	0.66	0.65	0.72
Refrigerated	0.67	0.68	0.70	(0.66)	0.72

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.85	0.86	0.88	0.86	0.47
Refrigerated	0.85	0.86	0.88	(0.85)	0.47

Figure 24: Sensitivity analysis of other weighting factors; hydrogen end use and carrier end use

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 REFRIGERATED VS. PRESSURISED AMMONIA SUPPLY CHAINS

For domestic ammonia supply chains, refrigerated ammonia achieves higher (meaning better) total scores, primarily due to higher scores on the following public interests:

- Safe & Secure (External safety for all supply chains, and Cyber security and terrorism except for supply chains with decentralised storage),
- Spatial Footprint (in case decentralised storage is included in the supply chain).

Refrigerated ammonia supply chains also have slightly higher scores for Sustainable (Energy loss) and Fair (for Dutch society), but these advantages are negligible compared to Safe & Secure and Spatial Footprint.

The advantages of refrigerated ammonia outweigh the very small to modest disadvantages compared to pressurised ammonia for Affordable, Adaptable, Safe & Secure (Cyber security and terrorism for supply chains with decentralised storage), and Accessible (Cost parity). Other public interests show no differences between the two forms.

Score differences arise primarily for Safe & Secure (External safety and Cyber security and terrorism). Final outcomes therefore depend heavily on that score, that is based on the ready knowledge and experience of a broad safety expert group (see Chapter 3) supplemented with the most current available literature on both forms of ammonia. This sensitivity should be kept in mind when interpreting the results.

Differences in total scores between supply chains are driven primarily by the risks of decentralised ammonia storage, which is the dominant factor in determining the Safe & Secure score. When decentralised storage is present in the supply chain, the chains for refrigerated ammonia achieve notably higher scores than for pressurised ammonia. Without decentralised storage, the normalised differences between refrigerated and pressurised supply chains are smaller. Centralised storage is refrigerated in all chains and therefore does not produce differentiated scores.

Hydrogen end use

The supply chains with refrigerated ammonia have significantly higher scores than with pressurised ammonia, if decentralised cracking in the hinterland is part of the supply chain. This difference is largely explained by the impact of decentralised storage of pressurised ammonia before cracking. The external safety risk classification and spatial footprint of decentralised storage of pressurised ammonia are much larger than for refrigerated ammonia. In the case of transport of refrigerated ammonia, the differences between the modalities become substantially smaller than in the case of pressurised ammonia transport. Refrigerated ammonia is consistently placed in a lower risk classification than transport or storage under pressure. Therefore, differences between transport modalities for refrigerated transport are smaller than for transport of ammonia under pressure.

Ammonia end use

For ammonia end use, the differences between refrigerated and pressurised supply chains are smaller than for hydrogen end use, except for the chains with double conversions (cracking in the port of entry followed by decentralised synthesis). The reason is that decentralised storage at the end user's site falls outside the scope of this comparison in case of direct ammonia end use. Including decentralised storage at the end user's site would have an impact on costs, spatial footprint and safety and would increase the differences between refrigerated and pressurised ammonia supply chains.

Effect of weighting factors

The weighting of public interests has a significant influence on total scores. Two sensitivity analyses using alternative weighting factors derived from the Delphi process both assigned a lower weight to Safe & Secure, which reduces the advantage of refrigerated over pressurised ammonia. Nevertheless, refrigerated ammonia supply chains continue to achieve equal or higher scores than pressurised ammonia across all weighting scenarios. The higher scores for refrigerated ammonia supply chains are a robust result.

6.2 COMPARING TRANSPORT MODALITIES

Refrigerated ammonia transport achieves higher scores than pressurised ammonia transport across all modalities, partly because the effects of an incident like a spill are smaller for refrigerated ammonia.

The ranking from highest to lowest score is: pipeline (pressurised ammonia), rail, inland waterway transport, road. The rankings of transport modalities are based on a sensitivity analysis in which the dominant impact of decentralised storage is excluded, rather than on the baseline total scores. This was necessary as differences in storage type dominate the overall scores and would otherwise obscure the contribution of transport modalities.

- Differences between road and the other transport modalities are significant.
- Pipeline transport for refrigerated ammonia over 200 km is not considered a viable alternative.
- Inland waterway transport achieves slightly lower scores than rail due to reliability risks from prolonged low water periods.

From the perspective of Safe & Secure, the ranking from highest to lowest score, based on the same sensitivity analysis, is: pipeline (pressurised ammonia), inland waterway transport, rail, road. For inland waterway transport, which is currently the only modality permitted for refrigerated ammonia, the difference in scores between refrigerated and pressurised ammonia is relatively large and significant, as in case of an incident half the refrigerated ammonia dissolves in water.

It should also be noted that transport of refrigerated ammonia by rail and road is not permitted under current regulations; only transport by barge is allowed. Furthermore, rail tank cars and, in Europe, barges for refrigerated ammonia are not yet commercially available.

6.3 CONFIRMATION OF 2024 MCA OF HYDROGEN CARRIER RESULTS

Cracking ammonia in the port of entry achieves the highest overall score for hydrogen end use, consistent with findings from the 2024 MCA of hydrogen carriers. This is due to the absence of decentralised storage in the supply chain and the hydrogen network transport's high scores for Affordable and Safe & Secure.

Supply chains with direct ammonia end use achieve higher scores than those requiring cracking to hydrogen, as they involve neither (de)centralised cracking nor decentralised storage. This reduces the Safe & Secure risks and spatial footprint and lowers the required import volume, since no ammonia is consumed as fuel for the cracking process. Direct use involving decentralised synthesis at the end user's site using hydrogen from the national hydrogen network results in a lower score compared to other direct end use supply chains.

The findings above assume that end use takes place at 200 km from the port of entry. Like in the 2024 MCA of hydrogen carriers, this baseline situation is compared with two variants: end use in the port of entry, and transit and export to neighbouring countries. Scores change as follows because the negative effects of transport and decentralised storage or conversion are partially avoided.

Port of entry

Total scores are slightly higher due to eliminated inland transport and storage costs, energy losses, investments, and transport-related externalities. Consequently, the difference between refrigerated and pressurised ammonia and the differences between transport modes disappear.

Transit and export to Germany

End use in a neighbouring country eliminates the domestic impact of decentralised storage and cracking at the end user's site.[22] As a result, scores for decentralised cracking and synthesis improve. The safety and security risks, environmental emissions, and spatial footprint are lower because impacts are shifted outside the Netherlands and fewer domestic high-risk investments (Adaptable) are required. Only the added value (Economically Robust) for the Netherlands decreases. This variant has the largest effect on supply chains with pressurised ammonia and hydrogen end use, given the dominant impact of decentralised pressurised storage.

6.4 POLICY RECOMMENDATIONS

The aim of this study is to provide a factual basis, not to make policy recommendations. Nevertheless, the following suggestions emerge from the research and discussions with stakeholders.

Differences in regulations

Chains with transport of refrigerated ammonia have higher total scores than with pressurised ammonia, primarily due to higher scores on External safety. However, refrigerated ammonia transport is currently permitted for inland shipping only, while pressurised ammonia transport by inland shipping, road, and rail is permitted within current regulations. It is therefore recommended to:

- Investigate whether regulations can be adjusted to permit refrigerated ammonia transport by other modalities.
- Investigate how public and private sector alike can be encouraged to adopt refrigerated ammonia for new applications and new ammonia supply chains, such as for cracking or for ammonia as maritime bunker fuel.

[22] In this situation, the impact on the Netherlands of decentralised storage is eliminated. In the sensitivity analysis of decentralised storage, pressurised decentralised storage has been replaced by refrigerated decentralised storage. Therefore, scores of the Transit and export variant and the sensitivity analysis of decentralised storage are not the same.

Incentive for refrigerated storage for small quantities

Decentralised pressurised ammonia storage carries a significantly higher external safety risk, yet it remains the default option for smaller quantities. All stakeholders may consider whether and how refrigerated storage can be stimulated for small-scale ammonia storage as well. This is also relevant for decentralised storage behind the end user's gate.

Consideration of transition costs

Given the higher overall scores for refrigerated ammonia, society may benefit from a shift to refrigerated ammonia supply chains. For existing pressurised ammonia chains, however, a transition is not straightforward, as it requires simultaneous action by all chain parties and involves write-off of existing infrastructure. It is recommended to investigate whether existing pressurised ammonia chains can receive policy support if a switch is desired.

6.5 RECOMMENDATIONS FOR FOLLOW-UP STUDIES

The following questions arose during the study and could not be fully resolved within the scope of the assignment.

Combination of normalisation and weighting

In an MCA the normalisation scale and the weighting of criteria strongly influence final outcomes. This study reused the weighting factors from the hydrogen carrier MCA while adjusting the normalisation scale. This was necessary because the normalisation scales for the public interests Affordable and Sustainable were dominated by the outlying scores for sodium borohydride and the data for decentralised ammonia storage required to extend the normalisation scale for the public interest Safe & Secure. Ideally, adjustments to the normalisation scale should be accompanied by a review of weighting factors. For a new MCA, it is recommended to invest more time in a tailored combination of normalisation and weighting, and to consider developing weighting factor sets for distinct stakeholder groups (industry/end users, logistics parties, environmental representatives, government) as a multi-actor multi-criteria analysis.

Assessing combined decentralised storage

This study assumed that domestically transported refrigerated ammonia is stored refrigerated prior to cracking, and pressurised ammonia is stored pressurised. This led to results strongly influenced by the safety risk classification of decentralised pressurised storage. In practice, combined storage (partly pressurised, partly refrigerated) and cooling of pressurised ammonia prior to storage also occurs. Given the significant impact of decentralised storage types on the results, it is recommended to investigate whether (a proportion of) decentralised refrigerated ammonia storage, after pressurised delivery, would improve overall scores. The additional costs, risks, spatial requirements, and energy losses of this 'pressurised-to-refrigerated' step were not included in the current sensitivity analysis.

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Websites

Ammonia Energy Association website.

CBS website.

CIMC Enric website.

Delta Rhine Corridor website.

ISGINTT website.

ITP Interpipe website.

Kustvaartforum website.

MAGPIE project website.

PGS12 website.

Schenk UK website.

VOTOB website.

WITS website.

Market information: various companies supplied information during this study. This information was treated and processed confidentially.

ANNEX A: SOURCES AND ASSUMPTIONS FOR THE MODELLING

This multi-criteria analysis draws on substantial amounts of baseline data and numerous assumptions. This annex provides an overview of the sources and key assumptions underpinning the modelling.

SOURCES

This study builds on the data used in the 2024 MCA of hydrogen carriers supplemented with literature and stakeholder data to detail the two forms of ammonia and address any data gaps.

Affordable, Economically Robust:

- We derived the import costs for liquid hydrogen, ammonia, methylcyclohexane (MCH), and methanol from the Dutch HyDelta study (2022). This study examined the costs of importing these carriers from eight different countries, covering the costs of the hydrogen production chain in the exporting country through to centralised conversion in the Netherlands.
- We determined the costs of inland chain steps using data from JRC1 (2022). This study explored the costs and energy losses involved in the import chains for liquid hydrogen, ammonia, (perhydro-)dibenzyltoluene (DBT), and methanol. This includes the costs from the hydrogen carrier's production chain in the exporting country through to centralised or decentralised conversion in the importing country.
- the costs incurred by maritime transport are part of HyDelta. We relied on data from Panteia, CE Delft, the Netherlands Institute for Transport Policy Analysis (KiM), and various market information sources for details of the costs associated with inland transport. We derived the costs of pipelines from JRC1 and verified them against market information sources.
- The figures for electricity costs in the Netherlands and CO_2 prices were sourced from the Climate and Energy Outlook (KEV25 for 2030).
- With regard to the public interest Economically Robust, we used KiM benchmark figures to determine the costs associated with congestion and infrastructure usage.

Sustainable, Environment:

- Most of the data on energy loss, emissions, and material usage was sourced from a life-cycle analysis by JRC, which builds on the JRC cost analysis (JRC1, 2022) described above.
- For 2030, we adopted the KEV emissions factor for electricity production in the Netherlands (0.07 g/kWh). PBL's projections show that, by 2030, the emissions factors for NO_X and particulate matter will be 0.09 g/kWh and almost 0 g/kWh respectively.

- Benchmark figures on transport-related energy losses and emissions, as well as environmental cost factors for monetising emissions, were sourced from studies by CE Delft and KiM.

Safe & Secure, Reliable, Adaptable, Spatial Footprint:

- For some public interests, little or no published information was available. For this reason, as part of the 2024 MCA of hydrogen carriers, five expert sessions were conducted to address the public interests Safe & Secure (covering External safety, Cyber security and terrorism, using risk matrices to illustrate the likelihood and impact of various incidents), Reliable (relative security of supply), and Adaptable (additionality and reusability of investments in the supply chains). The sessions drew on expertise from government agencies, public sector organisations, and industry and market parties. The resulting assessments were totalled for each step within the individual chains. We used the outcome of these sessions together with an additional expert session on External safety and Cyber security and terrorism risks for the two forms of ammonia. Indicators for external safety and vulnerability to cyber attacks and terrorism were determined by multiplying the qualitative scores for probability and impact, as estimated by experts, to produce a risk classification for each supply chain step.
- Benchmark figures from KiM and CE Delft were used to derive the transport safety indicator (traffic accidents).
- In addressing the public interest Spatial Footprint, we used spatial footprint estimates for each chain step (provided by companies), wherever such data was available. In cases where information was neither found nor supplied, estimates for steps were made by scaling existing data on chain steps, based on the specific gravity differences between hydrogen carriers.

Fair, Accessible:

- Scores for the public interest Fair were based on the results in other public interests, specifically Affordable, Safe & Secure, Sustainable (Greenhouse gas emissions indicator), and Environment. There was no need for separate data in this instance.
- The Cost parity indicator for the public interest Accessible for inland users and in the port of entry was derived from the information required for the Affordable public interest. There was no need for separate data in this instance.
- The Proximity indicator for the public interest Accessible was determined by using the IBIS database to discover how many industrial estates are connected to rail or waterways. Planned routes for the national hydrogen network and Delta Rhine Corridor pipelines were also reviewed to determine how many industrial estates lie in municipalities along these routes.

ASSUMPTIONS USED IN THE MODELLING

Scope:

- For the public interests Affordable and Sustainable, the costs, greenhouse gas emissions, and energy losses in the import chain, and domestic transport are factored in up to the point of delivery to the end user or to a fuelling station. When it comes to other public interests (e.g. Safe & Secure, Spatial Footprint, Environment), only the impact within the Netherlands is taken into account (also up to and including the point of delivery).

The public interest Fair does take account of the environmental impact in the exporting country.

- The results are expressed per kilogramme of hydrogen equivalent supplied to the end user, wherever applicable. Allowances are made here for conversion and other supply chain losses, which may cause the import volume to exceed the volume that the end user ultimately receives.
- We base our approach on the 2030 mid-range variant from the volume study by Arcadis/Berenschot/TNO, using it as the only situation for 2030.
- Direct end use only involves gaseous hydrogen and ammonia. Gaseous hydrogen is transported exclusively through the hydrogen network, not by road, water, or rail.
- With regard to ammonia, the current government position was adopted as the guiding principle for planned safety measures in the chains, except for pipeline transport. For ammonia pipeline transport we substituted data from the 2024 MCA of hydrogen carriers with data from the ISPT safe & compliant design.[23] As no further measures were assumed to be put in place to enhance safety standards, no additional costs were assumed.

Geography:

- In the baseline situation and other variants, the country of origin of the imported hydrogen is Morocco (a distance of 3000 km). The figures for this route were supplied by HyDelta.
- Allowance was made for a typical 200 km transport route within the Netherlands, in line with the 2024 MCA of hydrogen carriers. The use of typical routes eliminates any discrepancies between the ports of entry and between the distances to various end user sites.
- End use could also occur outside the country. In this case, the impact of chain steps of decentralised storage and conversion on the public interests for Safe & Secure, Economically Robust, Adaptable, Spatial Footprint, Environment and Fair, will no longer apply. Accessible - Proximity scores are all assumed equal because of lack of relevance.
- End use could also occur in the port of entry. In this case, inland transport and decentralised storage do not apply. Decentralised conversion will then coincide with centralised conversion.

Emissions and energy loss:

- Various steps in the chain may be associated with emissions of greenhouse gases and other substances. These are then monetised using environmental cost factors, and totalled for each chain. It is assumed that the electricity used in the exporting country's supply chain for water electrolysis and hydrogen carrier synthesis is emissions-free. In the Netherlands, the KEV electricity mix is assumed to apply to chain steps such as dehydrogenation and transport (including electric transport).

[23] ISPT (2025). Design and Safety Aspects for large-scale Clean Ammonia Pipelines. Clean Ammonia Innovation Platform. Public report.

- Emissions are totalled up to the point of delivery to the end user or to a fuelling station. We decided not to include the emissions and energy losses associated with the direct use of carriers by end users, since this encompasses a broad spectrum of technologies (fuel cells, burners, turbines, internal combustion engines, process reactors, etc.).
- By 2030, maritime and domestic transport (road, inland waterways, rail) will still be emitting CO_2, although this is expected to be less than today's levels.
- The assumption is that $DeNO_X$ post-treatment will be used at ammonia conversion plants in the Netherlands, but not in the exporting country. This results in a 93% reduction in NO_X-emissions compared to the value listed in the JRC1 dataset.

ANNEX B: PRESSURISED VS. REFRIGERATED AMMONIA

Ammonia is a gas under normal ambient conditions. It becomes a liquid under pressure or by cooling, or a combination of the two. In practice, two situations are common for storage and transport:

- **Refrigerated (cryogenic):** -33°C at atmospheric pressure (1 bar); density 683 kg/Nm^3. During transport both temperature and pressure will rise due to heat influx and evaporation.
- **Pressurised**: >10 barg at 15-25°C; density 602 kg/Nm^3 (10 bar, 20°C). Pipeline transport is at higher pressure (15-22 barg) to move the mass.

After sea transport, refrigerated ammonia arrives at the import port and is stored there. Ammonia produced in the Netherlands is also stored refrigerated at the factory. It can then be distributed refrigerated or pressurised. Ammonia is usually transported under pressure by rail, road, or inland waterway, but refrigerated transport is also possible, although not always permitted. Ammonia storage at the customer's premises is pressurised for smaller quantities (up to 2-3 ktons), and refrigerated for large quantities (tens of ktons).

Transitioning from refrigerated to pressurised ammonia requires ambient heat (from surface or wastewater) through a heat exchanger. The transition from pressurised to refrigerated ammonia occurs through expansion (from a pressure storage tank to an atmospheric refrigerated tank). This process converts some of the liquid ammonia into a gas, which can be captured and utilised.

Volume / mass

This comparative study, like the 2024 MCA of hydrogen carriers (2024), assumes the same volume of hydrogen equivalents (ammonia or hydrogen derived from it) delivered to the end user at the factory gate or filling station for all the chains under investigation. Weight percentages (see Table 5) are used to calculate the hydrogen carrier volumes for each chain from the hydrogen equivalent volume. (In fact, we calculate the mass of a hydrogen carrier for each chain, but we adhere to the terminology in the 2024 MCA of hydrogen carriers.)

Table 5: Hydrogen content of ammonia

Hydrogen carrier	Mass percentage H_2	H_2 equivalent
NH_3	17.8	5.63

Source: Berenschot, Arcadis (2024)

Selected physicochemical properties of ammonia

- Ammonia is a toxic, colourless gas with a sharp, penetrating odour. Exposure to concentrations as low as 5 to 15 parts per million (ppm) can cause irritation to the eyes, nose, and throat, which serves as a warning signal. At levels above 300 ppm, ammonia becomes flammable and potentially fatal in confined spaces. It can cause coughing, chest tightness, and

shortness of breath and breathing difficulty, lung damage, skin burns, and potential asphyxiation (fatal).

- When ammonia is released, it combines with humidity in the air to form a visible vapour cloud, which can travel long distances at ground level posing significant risk to populations near the release. The cloud is more visible in case of refrigerated ammonia than pressurised ammonia. The more humid the air, the more visible the cloud is because water vapor condenses.
- Ammonia dissolves well in water, but is toxic to aquatic organisms. When refrigerated ammonia at -33°C touches water, about half will evaporate immediately, forming a toxic vapour. The remaining half will dissolve in the water.
- Ammonia does not burn readily thanks to its narrow flammability range, high ignition temperature and low laminar burning velocity. The risk of an ammonia fire is lower compared to other fuels. A fire or explosion only occur in badly ventilated rooms. The flame produces little soot and is therefore barely visible. The heat it generates is not enough to evaporate an ammonia spill on land and to sustain the ammonia fire. A fire may be sustained if there is an external heat sources, such as warm(er) soil or water.
- With refrigerated ammonia, the temperature difference with the surrounding environment is the driving force for evaporation, while with pressurised ammonia, it is the pressure difference with the surrounding environment.
- When refrigerated ammonia leaks or is spilled, it first absorbs (ambient) energy before evaporating and spreading. As ammonia's boiling point under normal atmospheric conditions is -33°C, it evaporates at temperatures below water freezing. As ammonia draws a lot of heat from its surroundings when it evaporates, it cools the surrounding environment, so that less energy is available in the surrounding environment for evaporation of the ammonia. Vapour diffusion from a refrigerated ammonia leak is therefore slower than from a pressurised ammonia leak.
- The speed of the release determines the options available for firefighters. Vapour may be controlled by dissolving it in extinguishing water or blocking it with a water screen, but this creates a larger cryogenic liquid pool, spreading it over a larger (warm) surface area, which promotes evaporation.
- Ammonia is highly corrosive to certain metals over time, especially under high pressure or moisture exposure, and this can cause leaks.[24] Stress corrosion cracking (SCC) is the phenomenon of cracks being formed in carbon steel in contact with ammonia due to presence of oxygen. The cracks are small at the surface but may be deep, in the worst case penetrating through the entire thickness of the metal. To avoid this, ammonia equipment such as tanks, pipes and hoses needs to be inerted and rinsed with nitrogen. Allowing 0.2% water in the

[24] Equipment failure: worn-out valves, seals, compressors, or gaskets; poor installation: faulty welding, incorrect piping alignment, or outdated system components can introduce weak points; operational mistakes: poor training or failure to follow proper procedures can lead to accidental releases; lack of preventive maintenance: small undetected issues can become serious problems if left unchecked. GAENNS (2025). Ammonia Leaks: Causes, Risks, Detection, and Prevention.

ammonia and applying stainless steel are other measures.[25] Other causes of leaks may be equipment failure and human errors (poor installation, operational mistakes, lack of preventive maintenance).

The physicochemical properties define that refrigerated ammonia is inherently safer than pressurised ammonia.[26] This is further explained in the box.

Effects of pressurised and refrigerated ammonia leaks or spills[27]

Pressurised ammonia

- If a tank or pipe containing pressurised ammonia leaks, the ammonia will 'flash' at the outlet because the temperature of ammonia is above its boiling point. During the flashing, the liquid ammonia evaporates quickly, forming a gas cloud. This initial gas cloud determines the impact distances, which may be several hundred metres or even kilometres.
- Depending on the circumstances, some of the liquid ammonia will be carried out as small droplets, which will partly evaporate and partly rain out, forming a puddle from which the ammonia evaporates. This evaporated ammonia contributes to the second gas cloud. This process also occurs in the tank or pipe. After all, there is still liquid ammonia there, which also wants to evaporate now that there is an opening to the outside air. The ammonia that then evaporates also contributes to the second gas cloud. This cloud is considerably smaller than the first gas cloud.
- The complete evaporation of the still-present ammonia in these systems can last a long time because the rate at which ammonia evaporates decreases. This phase therefore determines the duration of the incident. The temperature of the initial gas cloud is low because energy is drawn from the surroundings to evaporate ammonia. The refrigerated ammonia gas cloud then behaves like a heavy gas, because cold gases are heavier than air. In this phase, the ammonia cloud is visible as a white mist, due to water vapour condensing in the cold air. This mist limits visibility in the surrounding area.
- In a cold-boiling pool or cold-boiling system, the gas cloud is not visible because little ammonia evaporates. The dispersion of an incident with pressurised ammonia is much larger than for a similar incident with refrigerated ammonia, because of the pressure. The resulting ammonia cloud is much larger than with refrigerated ammonia, resulting in larger effects. In an open area, the effects extend further than in a residential area. There are potentially fewer people in the affected area, but accessibility and available fire-fighting water facilities are less.

Refrigerated ammonia

- In the first phase of a leak, the refrigerated ammonia will flash, but this effect is less pronounced than with pressurised ammonia. The initial gas cloud formed when refrigerated ammonia is released is smaller and travels less far than with pressurised ammonia.
- If the released amount of refrigerated ammonia is large and the liquid cannot completely evaporate immediately, a pool of liquid ammonia can form on the ground. This pool continues to evaporate (cold-boiling pool) and feeds the gas cloud. This is the second phase of the leak.
- The energy for evaporation is taken from the surrounding environment, and the ground will freeze. There is no vigorous evaporation because the ammonia pool is already cold. Pool evaporation is therefore limited, meaning this phase can last from hours to days, depending on the tank's contents and whether or not the supply is stopped. The environmental impact of this phase is therefore much more limited.
- At high humidity, water condensation also occurs here, but less than with pressurised ammonia due to the lower ammonia concentration in the air.

[25] Fertilizers Europe (n.d.). Ammonia Stress Corrosion Cracking. Also: Fuminori Yanagimoto, Kazuhiko Shiotani, Yohei Sakakibara, Yutaka Wanatabe, Eiji Tada (2025). Stress corrosion cracking of steels in liquid ammonia: A comprehensive literature review. *International Journal of Hydrogen Energy* **120**, 89-100. https://doi.org/10.1016/j.ijhydene.2025.03.280

[26] This conclusion is supported by the 'Red Squirrel' ammonia field experiments that were carried out to study the dispersion characteristics for pressurised and refrigerated ammonia in form of two-phase releases and liquid spills on concrete and water, respectively. S. Dharmavaram, M. J. Carroll, E. M. Lutostansky, D. McCormack, A. Chester, D. Allason (2023). Red Squirrel Tests: Air Products' ammonia field experiments. *Process Safety Progress* **42**, 3, 481-498. https://doi.org/10.1002/prs.12454.

[27] Based on Antea Group SAVE, NIPV, GB Rotterdam & H2K (draft 2025). Incidenten waterstofdragers. Voor Ministerie van Infrastructuur en Waterstaat. Projectnummer 0502980.100, concept revisie 1.0, 18 december 2025.

Supply chains for ammonia

1. Ammonia production

Ammonia is primarily produced via the Haber-Bosch process, in which nitrogen (N_2) from the air and hydrogen (H_2), usually from natural gas, are combined under high pressure and temperature in the presence of an iron-based catalyst to form ammonia (NH_3). The production of green ammonia is essentially the same, except that green hydrogen is used from electrolysis. Ammonia has been widely used and transported for decades, resulting in extensive expertise on the safety and technical aspects of handling this substance. In recent years, many visions and plans foresee the import of green ammonia to western Europe as a hydrogen carrier. Studies indicate that cracking of green ammonia, produced in countries with abundant renewable energy, will provide cheaper green hydrogen than 'home-grown' green hydrogen.

2. Import via ocean shipping

Worldwide, 17 to 20 million tons (about 10% of total production) of refrigerated ammonia is transported via ocean going vessels, typically Midsize Gas Carriers (MGCs) with around 37,000 cbm or 25.2 ktons of ammonia capacity.[28] There are more than 200 terminals in 122 ports with the ability to import or export ammonia. Around 170 gas carriers can transport ammonia (of which 40 'dedicated'). In 2024, the imports of anhydrous ammonia to the Netherlands amounted to 123.7 ktons, mainly from Algeria, the United States and Egypt.[29]

In a study for the HyDelta programme, TNO concluded that a shortage of shipping capacity is unlikely to be a major obstacle to the adoption of ammonia as a hydrogen carrier. Existing ships can be repurposed, or new ships can be constructed quickly to accommodate any foreseeable increase in demand.[30]

3. Storage in port of entry, including transfer

The ammonia arrives in the port refrigerated and is also stored in refrigerated atmospheric tanks. At the end user ammonia is stored under pressure in cylinders and spheres, as well as in refrigerated atmospheric tanks. Due to the toxic nature of ammonia, strict regulations and operational procedures apply to its storage method.[31] The PGS12 guideline for safe storage and transfer of (refrigerated) ammonia[32] has been updated, ensuring that the storage regulations now comply with current technology. The storage facility must have a lifespan of at least fifty years, be a full-containment storage tank, have a thick concrete outer wall, internal pumps, a foundation on piles, and a completely free wall and bottom to minimise the risk of leakage.

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[28] 'Ammonia pipelines: existing networks, future deployments, and safety considerations', Ammonia Energy Association website, 26 June 2025. Also VOTOB website.
[29] WITS website.
[30] TNO (2024). HyDelta 3. D 3B.3 – Ammonia Tanker Fleet Analysis.
[31] VOTOB, the association of Dutch tanks storage companies, developed a curriculum with the aim to provide personnel working at Dutch terminals with the knowledge and insights required to ensure safe processing during the storage and transfer of ammonia. Antea, *VOTOB Curriculum voor personeel op ammoniak terminals*, 19 augustus 2025. Also: Antea, *VOTOB Veiligheidsstandaarden in de ammoniakketen*, 26 augustus 2025.
[32] PGS12 website.

OCI currently stores ammonia in two tanks of 15 ktons each in the port of Rotterdam and has received a permit to build additional 60 kton storage. Vesta in Vlissingen received a permit to repurpose two existing storage tanks for refrigerated ammonia (2 x 20 ktons), and build one additional tank (30 kton). In addition, several companies have plans to store ammonia on a large scale and/or crack it into hydrogen.

Ammonia storage also takes place at ammonia production plants operated by OCI (Chemelot) and Yara (Sluiskil).[33] Connected pressurised buffer tanks are used to load barges, rail tank cars and/or trucks. OCI uses the import terminal for balancing ammonia production at Chemelot. Yara does not import ammonia but does load refrigerated sea going gas tankers for exports. Loading of refrigerated ammonia onto barges, rail tank cars and trucks would require minor technical adaptations to the facilities.

Pressurised ammonia is stored in smaller quantities than refrigerated ammonia. Therefore, in the event of an incident, a larger outflow is expected from cold tanks. However, quantitative risk assessments show that on site where both types of storages take place, the pressurised storage dominates the risk contours despite smaller volumes. Small-scale ammonia storage is usually pressurised but can also be refrigerated. For a given volume, the choice for refrigerated storage will reduce the risk contours around the storage site.

The transfer of ammonia at the terminals poses the largest safety risks. During loading (from ship to tank and from tank to barge/train/truck), the loading arm can leak or break. The consequences are significantly smaller than those of an (unlikely) tank failure, but the risk is greater. To reduce the risk, according to the new PGS 12, only special loading arms equipped with automatic couplings and automatic emergency dry-break systems may be used.

4. Ammonia transport in and via the Netherlands

We consider four modes of transportation: by barge on inland waterways, by rail tank car on railroads, by tractor-semitrailer combination on roads, and by pipeline.[34]

For road and rail transport, the regulated axle loads and the bearing capacity of the road surface or railway embankment limit the quantities that can be transported. Cryogenic rail tank cars are heavier than pressurised ammonia rail cars due to double-walled tanks with insulation and control equipment, and this is detrimental to the payload. The difference is smaller for tank trucks. For ships, the volumetric capacity (loading space) determines the amount of ammonia that can be transported. We assume that this capacity is the same for pressurised or refrigerated ammonia. The density of refrigerated ammonia is slightly higher, but the thicker walls of double-walled and

[33] This production is integrated into chemical industry clusters that also produce nitric acid, urea, ammonium nitrate melamine, nitrates and liquid CO_2.The production capacity for ammonia is 1.9 Mton/a at Yara(2020) and 1.2 Mton/a at OCI (2017). Lamboo, S. (2024). Update report: Decarbonisation options for the Dutch fertiliser industry. PBL publication number: 5449.

[34] The international dangerous goods transport regulation classify ammonia as follows: UN1005 – Ammonia, anhydrous: Toxic and corrosive gas (2TC), Particularly dangerous for water bodies (N1); Transport via portable tanks (T50); Pressure equipment (P200); Allowed in tankers and packaged form (T) for inland shipping. And UN9000 – Refrigerated ammonia: Cryogenic liquefied toxic and corrosive gas (3TC); Only allowed to be transported in tanker vessels.

insulated cryogenic tanks also take up available space. Table 6 lists the capacities of the ammonia transport means; this will be elaborated in the next section.

Table 6: Typical capacities of transportation means in tons of ammonia

Capacity	Semi-trailer truck	Rail tank car	Barge[35]
Pressurised NH_3	25	50	1,500
Refrigerated NH_3	25	40	1,700

Sources: Panteia (2023), JRC1 (2022), OCI, VTG (rail tank car), Schenk Tanktransport (semi-trailer truck), KBN (barge)

A. Inland waterway transport

Inland waterway transport is the main transport modality for ammonia in the Netherlands, in the amount of 200-300 ktons per year according to CBS data over recent years. Pressurised ammonia is loaded at the OCI terminal in Rotterdam. Yara use their loading facilities for seagoing vessels to export their produced ammonia. The inland port of Stein has a terminal to receive ammonia for Chemelot, and other cargoes are transported to neighbouring countries.

While pressurised ammonia transport is established in western Europe, refrigerated transport is the standard in the United States of America.[36] From the 1960s to 1990s two Dutch inland vessels were operated for refrigerated ammonia.[37] Transport of refrigerated ammonia by inland waterway transport is still included in the dangerous goods transport regulations (ADN). As inland vessels can be ordered and built in less than two years, refrigerated ammonia transport could make a quick comeback if the market asks for it. Multiple Rhine ports including Duisburg and Mannheim are showing interest in hosting ammonia terminals.[38]

Pressurised vs refrigerated gas tankers

There are currently 86 Type G gas tankers operating in the Netherlands. 5 to 10 are dedicated to ammonia transport[39], the others can also carry ammonia but are typically already contracted for other transports. Dedicated transport is preferred, as it eliminates the need for time-consuming and expensive interim clearing and cleaning of tanks and pipes. The 110-meter vessels currently carry an average of 1,000 ton of ammonia per voyage (5 bar, 5°C). Larger vessels will be deployed with increased demand, carrying 2,000-3,000 ton and measuring 135 meters.

[35] Based on the difference in specific gravity, a cargo tank of certain volume can hold 15 mass-percent more refrigerated ammonia than pessurised ammonia.

[36] The U.S. ammonia barge fleet comprised 31 barges in 2012, all refrigerated. Most vessels stem from the 1970s. Ray Hattenbach (2012). Transportation & Delivery of Anhydrous Ammonia. Chemical Marketing Services, Inc.

[37] The vessels Alaska and Arctica (built in 1965-1966) carried ammonia for BASF from Ludwigshafen to Antwerp. The vessels were decommissioned in 1991, presumably because demand ended when BASF built its ammonia plant in Antwerp.

[38] E.g., LBC Tank Terminals Group and duisport signed a Memorandum of Understanding in November 2025 for a joint development of a new inland ammonia and CO_2 terminal in Duisburg, Germany.

[39] The vessel sails for 5 days per trip, carrying 50 loads of 1,000 tons per year, i.e. 50 ktons each. According to CBS data, the total has been 200-300 ktons in recent years (only in the Netherlands, with more international transport), so it can be operated with approximately six vessels with ideal planning/utilization.

A gas tanker is basically a standard cargo vessel with gas tanks positioned in the hull. The tanks are typically sized 380 cbm (cubic metres or m^3), but can be up to 1,000 cbm with certain adaptations. 1000 cbm liquid ammonia equals approximately 600 ton (pressurised) to 700 ton (refrigerated). Cryogenic tanks are more expensive than pressure tanks.[40] The estimated investment cost of a 110-m pressurised gas tanker is € 10-12 million, and the added costs for cryogenic tanks is € 2 million. For our modelling we assume investment costs for a 135-meter gas tanker for 1,500 ton pressurised ammonia transport of € 15 million and of 1,700 ton refrigerated ammonia transport of € 18 million.[41] The difference in cargo mass is due to the difference in specific gravity, also the maximum degree of filling of the cargo tank is 91% for pressurised ammonia and 95% for refrigerated ammonia.[42]

The trend in seagoing gas tanker shipping is to operate multi-gas carriers, and inland shipping is also looking at this. The German company HGK[43] has announced the development of a refrigerated ammonia and/or CO_2 carrier, and sources in the sector believe that other companies are also considering similar plans.

Regulation and procedures

The Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN)[44] prescribes that ammonia is transported in pressurised or refrigerated state in accordance with the ADN's (transport) requirements. This is the responsibility of shippers and carriers, with the Netherlands Human Environment and Transport Inspectorate (ILT) as the enforcement authority.

The two 1960s-1990s refrigerated ammonia tankers used refrigeration systems based on freon. Their tanks were not insulated. The ADN regulation prescribes the use of a refrigeration system. Sector spokesmen argue that this is unnecessarily expensive because today's cryogenic tanks provide effective insulation. Seagoing gas carriers are not obliged to use refrigeration systems.

According to KBN, there are no known cases of ammonia spills from gas tankers, even after collisions. The sector promotes responsible operations based on applicable protocols and procedures, as laid down in the ISGINTT handbook – International Safety Guide for Inland Navigation Tank-barges and Terminals.[45] The riskiest link is the transfer. This applies to road and rail transport just as it does to inland shipping. The technology for loading and unloading of ammonia is designed to be safe, but operational errors remain possible due to human factors. A distinction must be made between external safety and personnel safety: if something happens, the risk to external safety is low, whilst the risk to personnel may be greater.

ISGINTT prescribes special procedures for loading and unloading of ammonia. Ammonia is transported using nitrogen as an inert gas and nitrogen purging of hoses to reduce the risk of

[40] Besides pressurised and refrigerated gas tankers, there are also semi-refrigerated gas tankers. These use the same type of pressure tanks but from low temperature steels.
[41] Pers.comm. Ton Wingelaar and Maurits van der Linde, Koninklijke Binnenvaart Nederland, 17 December 2025.
[42] Cristian Chiriță, Viadonau (2025). Transport of ammonia by maritime and inland vessels. Ammoniak-Workshop, 3. Juni 2025.
[43] HGK did not provide more information than what was published in its press release (April 2024).
[44] Dutch version: Regeling vervoer over de binnenwateren van gevaarlijke stoffen.
[45] KBN (2025). Veilig vervoer van ammoniak via de binnenvaart. CTGG Veiligheidsdag, 28 November 2025; ISGINTT website.

static charge, formation of carbamates (chemicals) from reaction of NH_3 with CO_2, and accelerated stress corrosion cracking of the tank due to presence of oxygen in air. The purge leads into the cargo tank, avoiding emissions to the air.

B. Rail transport

Over 1,500 ktons of ammonia are transported in Western Europe by rail every year, mainly for European fertiliser and chemical producers. In the Netherlands, ammonia is loaded for pressurised rail transport at the ammonia production plant of OCI at Chemelot, at OCI's ammonia terminal in Rotterdam. The ammonia production plant of Yara in Sluiskil also has the facilities and permits in place.[46] Cryogenic rail tank cars for transport of refrigerated ammonia can be built,[47] but refrigerated transport is not included in the dangerous goods transport regulations (RID) and according to stakeholders there is no market demand or sign of initiatives for refrigerated ammonia transports by rail. Increasing the volume of pressurised ammonia rail transport will also be challenging due to the limited surplus capacity on the Dutch rail network.

Pressurised vs. cryogenic rail tank cars

The pros and cons of pressurised vs. cryogenic rail were discussed with rail operator Deutsche Bahn and with rail tank car supplier VTG.[48]

In theory rail tank cars designed for pressurised ammonia can be loaded with refrigerated ammonia, as over shorter distances the ammonia will not heat up too much. Problems will arise over longer distances. Refrigerated/cryogenic transport of ammonia involves lower pressure, until the tank heats up, activating a safety valve that vents ammonia gas, which is obviously undesirable. This is particularly significant as rail tank cars may also serve as temporary storage at the customer's premises. Pressurised ammonia can remain in storage for 30 days, whereas cryogenic tankers have shorter storage life due to venting.

To avoid venting, the tank would be designed for better insulation, using insulating material between double layers of thinner steel. The overall result is a thicker-walled tank. It is assumed that safety criteria in homologation lead to the same level of integrity of the tank in the event of an accident than with today's pressurised transport. The cryogenic tank cars would be much heavier and could carry 20% less payload, so that more rail tank cars are needed to transport the same tonnage.

As the current supply chain is not designed for cryogenic transport, changing to refrigerated rail transport requires a huge investment. This is less of a problem at seaport terminals than at recipients. A cryogenic tank for unloading product is much more expensive than a pressurised tank. Furthermore, maintaining the tank's temperature requires energy.

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[46] 'Spoorvervoer wordt weer belangrijker voor Yara Sluiskil', ZVA, 18 July 2025.

[47] Such rail tank cars exist for other cryogenic gases such as LNG. VTG note that the homologation process for rail tank cars is lengthy and expensive. Standardisation is key as small changes to a design require new homologation. The process would only be started if a clear and substantial market demand for refrigerated ammonia tank cars is demonstrated.

[48] Pers.comm. Jelle Rebbers, Deutsche Bahn, 11 November 2025; pers.comm. Chris Bogaerts and Casper van Hooije, VTG, 13 November 2025. VTG is working with energy company RWE to develop an ammonia supply chain by rail from the German port of Brunsbüttel.

In summary, the business case for cryogenic ammonia transport is not positive: it requires new and more expensive rail tank cars (double to triple the investment costs[49]), the conversion of loading terminals, the construction of receiving infrastructure, it involves additional energy costs for storage at recipients, and leads to more transport movements required for the same tonnage of cargo.

Current ammonia rail tank cars can also be used for other products such as LPG, but in that case they do not have the optimum dimensions (tare weight/payload ratio).

Regulation and procedures

The Regulation concerning the International Carriage of Dangerous Goods by Rail (RID)[50] prescribes that ammonia should be transported in pressurised state in accordance with the RID's (transport) requirements. This is the responsibility of shippers and carriers, with the Netherlands Human Environment and Transport Inspectorate (ILT) as the enforcement authority. Refrigerated rail transport of ammonia is currently not included in the RID and thus de facto not permitted.

Prorail, the Dutch government organisation responsible for the maintenance and extension of the national railway network infrastructure, focuses on the safety of rail traffic, primarily preventing collisions and derailments for all rail traffic (regardless of the substance and whether it is transported refrigerated or pressurised). The way ammonia is transported has no influence on any rail infrastructure measures taken by Prorail, but does impact the safety region organisation and fire brigade response to any incidents.[51]

When cryogenic rail tank cars were to enter the fleet, all freight rail personnel must be trained in handling these cryogenic tank cars when they are coupled into mixed trains. If a train breaks down, protocols prescribe that rail tank cars with dangerous goods must be separated from the train. Operating dedicated refrigerated ammonia trains would avoid such handling costs.

Fertilizers Europe has drawn up a Guidance for the transport and handling of ammonia in order to ensure high safety standards in operations involving ammonia transport.[52] Ammonia is transported using nitrogen as an inert gas and nitrogen purging of hoses to reduce the risk of stress corrosion cracking of the tank due to presence of oxygen in air.[53]

C. Road transport

While precise numbers for the Netherlands are lacking, it is known that only few ammonia transports take place by road. They serve customers that use ammonia as a refrigerant in industrial plants. Pressurised ammonia can be loaded for road transport at the ammonia production plants of Yara and OCI. Cryogenic tank trucks that can be used for transport of refrigerated ammonia are available, but refrigerated transport is not included in the dangerous goods transport regulations (ADR). There is one market initiative known to the researchers to build a refrigerated ammonia supply chain that includes road transport.

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[49] The investment cost for a pressurised rail tank car is € 220,000 according to MKBV Waterstofdragers (2024).
[50] Dutch version: Reglement betreffende het internationaal spoorwegvervoer van gevaarlijke goederen (RID) versie 2023.
[51] Pers. comm. Peter Robbe, Prorail, 10 November 2025.
[52] Fertilizers Europe (2014). Guidance for transporting ammonia by rail.
[53] Fertilizers Europe (n.d.). Ammonia Stress Corrosion Cracking.

Pressurised vs. cryogenic tank trucks

Tank trucks are standardised products that need certification for specific products. Both tank trucks for pressurised gases such as ammonia and for cryogenic gases such as refrigerated ammonia are widely for sale.[54] According to Schenk Tanktransport,[55] the cryogenic semi-trailer truck is more expensive (€430,000 versus €295,000) with a slightly smaller payload (20-25 ton versus 25 ton). We choose 22.5 tons for the modelling. Investment cost is only one factor to set the price per kilometre (km), which also depends on factors such as the annual mileage, hours worked, and potential driver surcharges for shifts, nights, and weekends.

Regulation and procedures

The Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)[56] prescribes that ammonia should be transported in pressurised state in accordance with the ADR's (transport) requirements. This is the responsibility of shippers and carriers, with the Netherlands Human Environment and Transport Inspectorate (ILT) as the enforcement authority. Refrigerated road transport of ammonia is currently not included in the ADR and thus de facto not permitted.

The way ammonia is transported has no influence on any road infrastructure measures taken by Rijkswaterstaat, but does impact the safety region organisation and fire brigade response to any incidents.

Several specialist transport companies (such as Schenk Tanktransport, Jongeneel, and Den Hartogh) know how to handle various liquid gases safely in accordance with ADR and industry best practices.[57]

D. Transport by pipeline

Pipelines are the most suitable means of transport for very large volumes of gases, liquids or solids slurries. Several long-distance pipelines are in operation for transporting ammonia. One operational ammonia pipeline connects seven states in the American Midwest, transporting 1,500 ktons per year. Mexico has an ammonia pipeline connecting the Gulf of Mexico to the Pacific Ocean. Europe has several short-distance ammonia pipelines, the longest of which is a 74-km stretch in Italy that transports 300 ktons per year.[58]

OCI operates a 5-km pressurised ammonia pipeline that connects the inland terminal in Stein with Chemelot. Long-distance ammonia pipelines are also considered in the Netherlands. The inclusion of an ammonia pipeline in the Delta Rhine Corridor has been postponed until the later

[54] The article A cryogenic transport trailer buyer's guide (Keith Hall, 2019, on www.gasworld.com) discusses various aspects that define the suitability of cryogenic trailers for different purposes. Refrigerated ammonia can also be transported over short distances/short periods in an ammonia pressure vessel. Tests conducted with tanker trucks showed no problems up to 100 miles, with a few degrees of warming and no significant vapour build-up, but this would pose problems for longer distances/periods. Pers.com. Seshu Dharmavaram, Air Products, 24 November 2025.
The Chinese company CIMC Enric specifically developed a cryogenic ammonia semitrailer in 2023.
[55] Pers. comm. Rob Looijmans and Peter Teurlings, Schenk Tanktransport, 19 December 2025.
[56] Dutch version: Overeenkomst betreffende het internationale vervoer van gevaarlijke goederen over de weg (ADR).
[57] The entire process and procedures for ammonia transport by road is described on the Schenk UK website.
[58] The nearly 2500 km long Togliatti-Odesa pressurised ammonia pipeline that was built in 1975-1981 was taken out of service in 2022 because of the Russian attacks on Ukrain.

2030's, as hydrogen and CO_2 pipelines will be prioritised and available in 2031-2033.[59] North Sea Port, Smart Delta Resources and the province have studied the feasibility of an ammonia pipeline that connects the Zeeland industrial cluster to the Delta Rhine Corridor.[60]

To make a pipeline feasible (i.e., economically justifiable), consumption volumes must first increase significantly, and this will initially have to happen via other modes (rail and barge).

The Dutch Institute for Sustainable Process Technology (ISPT) published a techno-economic feasibility study[61] of a pressurised ammonia pipeline from the Port of Rotterdam in the Netherlands to Germany over a 550 km trajectory comparable to the proposed Delta Rhine Corridor. The report was drawn up with members of the institute and other industrial stakeholders. It describes the best available technology for safe pipeline operations over long distances, including infrastructure such as pumping stations. In the scenario studied, ammonia is stored as a liquid at approximately -33°C in large storage tanks under atmospheric pressure. For the pipeline, it is necessary to warm up the liquid ammonia to above 5°C (to prevent freezing) and pressurise it to 50 bar. The pipeline in the study is designed for an annual flow capacity of 7 million tons of ammonia. We take this study as the basis for our data about ammonia transport by pipeline, scaling the trajectory down to 200 km.

Pipelines for refrigerated liquid ammonia (-33°C and 2-5 barg) are generally only used over distances of less than 5 km, as the refrigeration infrastructure would be very expensive and higher pressures are required for transport over longer distances.[62] We have attempted to model a refrigerated ammonia pipeline using data for a long-distance LNG pipeline, based on a Chinese academic article. This raised a number of questions, that are discussed in Annex I. It was decided together with the client not to include transport of refrigerated ammonia by long-distance pipeline in the comparative study.

Regulation and procedures

There are currently no guidelines available for safely constructing and operating an ammonia pipeline in Europe. The ISPT approach was to apply inherently safe design practices with state-of-the-art designs. Among other things, intermediate pumping (booster) stations were included to reduce the ammonia volume in the pipeline to one-third by narrowing the diameter to 20 inches (instead of 32 inches). This reduces the potential ammonia spill in the event of a leak. Thermal expansion protection between the segments would be applied, with shut-off valves between the pipeline segments and emergency shut-off valves (ESD valves) for a rapid response time. Current European regulations do not specify the exact locations between the shut-off valves; a spacing of 5 km was evaluated as the safest in view of toxic cloud formation. Other risk reduc-

[59] Rijksoverheid (2025). Kabinet zet in op waterstof- en CO2-infrastructuur in Delta Rhine Corridor, 5 December 2025. See also Delta Rhine Corridor website.
[60] WSP en AVIV (2024). Haalbaarheidsstudie Ammoniakpijpleiding. Publieke management samenvatting, 14 November 2024
[61] ISPT (2025). Design and Safety Aspects for large-scale Clean Ammonia Pipelines. Clean Ammonia Innovation Platform. Public report. ISPT provided additional unpublished data.
[62] ISPT (2024). Clean Ammonia Roadmap.

tion measures include a minimum soil cover of 2 metres and protective plates on top of the pipelines. The safety approach results in a risk contour of a 20" pipeline below the legally required 5 metres, and of 1,800 metres for the pumping stations.[63]

The safety of (pressurised) ammonia pipelines is also discussed in recent reports by Witteveen+Bos (2024) and Antea Group (2025) and an academic article by Kuchta et al. (2025)[64], which will be taken into account for the public interest Safe & Secure. No such studies are available for refrigerated ammonia pipelines.

5. Ammonia cracking

Ammonia is split into nitrogen and hydrogen through catalytic cracking. Ammonia is vaporised before entering the reactor, using ambient heat. The reaction takes place at temperatures between 500 and 900°C without a catalyst, or at a lower temperature of 400 to 700°C with a catalyst. After the cracking process, the gas mixture contains both hydrogen and nitrogen, which must be separated.

Cracking can start from refrigerated or pressurised ammonia, depending on location and logistics. Refrigerated ammonia will be used if the cracker is adjacent to a storage terminal, and alternatively a pipeline is required with pressurised buffering tanks for operational security if the cracker is at distance. Both variations occur in the plans for cracking facilities in the port of Rotterdam.[65] For our modelling we assumed the former situation (cracker beside the terminal)

Table 7: Conversion efficiency of ammonia to hydrogen and vice versa

Efficiency	Output	
Input	H_2	NH_3
H_2 gas		100%
Refrigerated and pressurised NH_3	78%	

For conversion losses, we use figures from JRC2. For modelling the conversion of ammonia to hydrogen (cracking), we assume that part of the hydrogen carrier volume is used as fuel for process heat (see Table 7). Alternatively, electrified processes and using external waste heat are not mature yet, and electrified cracking also requires a heavy grid connection. We assume that there is no difference in conversion efficiency between refrigerated and pressurised ammonia. In both cases,

[63] However, critics argue that the inclusion of ESD valves introduces new weak links as the valves with gaskets can fail or leak.

[64] Witteveen+Bos (2024). Veiligheid transport van ammoniak door buisleidingen. Voor Ministerie van Infrastructuur en Waterstaat, 17 juni 2024. Antea Group (2025). Ammoniakleiding incidenten en beheersbaarheid. Onderzoek naar de consequenties en beheersbaarheid van een ongeval met een ammoniak buisleiding. Voor Ministerie van Infrastructuur en Waterstaat, 25 augustus 2025. Kuchta, T.; Wróblewska, A.; Holewa-Rataj, J.; Król, A. Threats and Challenges Associated with Ammonia Transport via Pipeline Systems. *Appl. Sci.* **2025**, *15*, 11465. https://doi.org/10.3390/app152111465

[65] Pers.comm. Alan Dirks and Thomas Stijntjes, Port of Rotterdam, 8 December 2025. Air Products and VTTI among others have plans for ammonia cracking in Rotterdam, as does Vesta in Vlissingen.

the ammonia must first be vaporised. This requires more energy for refrigerated ammonia, but this does not compromise the conversion efficiency.

DNV has performed Quantitative Risk Analyses for a fictive case of centralised ammonia cracking in the port of Amsterdam, but only for refrigerated storage.[66] The risk contours increase with increasing capacity of the cracker, caused mainly by the risks associated with ship-to-shore transfer (the larger the capacity, the more often and longer ship-to-shore ammonia transfers take place).

Essent/E.On are developing a supply chain for decentralised cracking based on refrigerated ammonia.[67] The aim is to supply hydrogen to decentralised industries (like bakeries, asphalt plants or food and beverage industries) that will not (or not soon) be connected to the national hydrogen network. The potential hydrogen demand is in the range of 1.8 to 3.6 ktons per year (5-10 tons per day) per regional cluster of companies, i.e. one or two orders of magnitude smaller than centralised cracking. Hydrogen from decentralised ammonia cracking is expected to be cheaper than from local electrolysis. Plug & play ammonia crackers are for sale starting from 5 tons a day, offered by companies such as Technip, Duiker and H2SITE (as well as Topsoe one size bigger). The ammonia is delivered by road or barge and stored in cryogenic buffer tanks, similar to those used for liquid CO_2 or LNG. The ammonia is vaporised before entering the cracker using atmospheric heat. Hydrogen is then transported to clients via local pipelines. The reason to prefer refrigerated ammonia is that risk assessments show substantial smaller safety distances compared to pressurised ammonia (half to one-third).

In general, the import price of ammonia determines the hydrogen price for 75%. Economies of scale (for example, centralised versus decentralised cracking) have little impact on the final price.

6. End use as ammonia or hydrogen

Today, the main use of ammonia is as raw material for fertilisers. It is also used in the production of various industrial chemicals and applications, including explosives, plastics, and synthetic fibres. It is a key ingredient in the production of nylon and other polymers. Other applications include as a coolant in industrial cooling systems, particularly in food processing and storage, and in water purification processes, both to regulate pH and in biological treatment processes. Furthermore, ammonia can serve as a reagent in DeNOx systems to reduce NOx emissions.

In general, the markets for these applications are saturated. The interest to import ammonia is mainly driven by expectations about new markets for ammonia or hydrogen end use.

- Ammonia can be used as a fuel, primarily in shipping, with specially adapted (mono or dual fuel) combustion engines. Ammonia could become a major bunker fuel. Alternatively, ammonia can also be converted into hydrogen on board a ship, which is then used in a fuel cell, or used directly in a fuel cell.

[66] DNV (2025). Onderzoek omgevingsveiligheid energietransitie. Gemeente Amsterdam, Havenbedrijf Amsterdam en Provincie Noord-Holland. Rapport nr.: 10481843-1, Rev. 4, 3 februari 2025.
[67] Pers.comm. Fred Hage, Essent Hydrogen, 17 November 2025.

- Ammonia can also be used as a fuel for electricity generation,[68] initially through co-combustion in coal- or gas-fired power plants, and there are developments for power plants that run on up to 100% ammonia. A concern during combustion is the formation of NOx.
- Hydrogen from ammonia cracking can be used in the variety of end uses for hydrogen.

For most end uses it does not matter whether the ammonia is delivered refrigerated or pressurised, as is needs to be vaporised anyway. For ammonia as shipping fuel, there is a clear preference for refrigerated ammonia.

Ammonia as maritime bunker fuel

Green ammonia as a fuel can help the shipping sector meet its carbon reduction goals. When combusted, ammonia emits no CO_2 or other carbon-based climate pollutants such as methane, although greenhouse gases are emitted in the supply chain (N_2O in particular, both emitted directly and formed by conversion of NOx and NH_3 emissions).

The Ammonia Energy Association[69] monitors the number of suitable vessels: as of December 2025, 84 ammonia-ready vessels are operational worldwide. Out of another 59 ordered ammonia-fuelled vessels, 29 vessels are ammonia carriers; 18 vessels are bulk carriers. Also 302 ammonia-ready (dual-fuel) vessels have been ordered and announced. Whether these dual-fuel vessels will actually use ammonia depends on price developments.

A study[70] for the European Maritime Safety Agency (EMSA) concluded that in 2030 and 2050, blue and green ammonia-fuelled vessels could have a relatively high TCO of up to 3 to 3.5 times higher than a similar ship using conventional marine fuels.[71] However, the market may evolve so as to increase the demand for low or zero carbon international freight, thus potentially curbing the expected TCO. In addition, international and regional policies may also contribute to bridge the TCO gap between blue or green ammonia and conventional fuels, according to the study.

Ammonia-fuelled vessel designs

An ammonia-fuelled vessel is equipped with ammonia fuel tank(s), supply system, bunker station, ammonia release mitigation system, and combustion technology. Depending on the specific ship design and type, additional considerations that determine the fuel system design are applicable, such as handling and ventilation (e.g., vent mast and inert system). In absence of harmonised international rules, class societies are allowed to use well-established, risk-based 'alternative design' approval methodologies which have been used for alternative fuels to support shipowners.

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[68] ISPT has initiated the Ammonia to power project explores ammonia's role in new and retrofitted gas turbines across Europe.

[69] Ammonia Energy Association website.

[70] European Maritime Safety Agency (2023), Potential of ammonia as fuel in shipping [updated], American Bureau for Shipping, CE Delft and Arcsilea for EMSA, Lisbon.

[71] Schreuder et al. came to a more positive conclusion: 'We found that the TCO increments by at least 25 %, assuming 50 % engine efficiency and low green ammonia prices.' Wouter Schreuder , J. Chris Slootweg & Bob van der Zwaan (2025). Techno-economic assessment of low-carbon ammonia as fuel for the maritime sector. *Applications in Energy and Combustion Science* **22**, 100330, https://doi.org/10.1016/j.jaecs.2025.100330.

The abovementioned study for the European Maritime Safety Agency (EMSA) assessed several designs for ammonia-fuelled ships from the risk and safety perspectives: one oil tanker, one bulk carrier and one Ro-Pax ship. The main safety concern in relation to ammonia is associated with its toxicity and gas-dispersion properties. While solutions are available, additional research and studies are needed to further reduce or fully mitigate the associated risks.

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) published a best practices guide for ammonia-fuelled ship design principles.[72] One key design decision is the state in which the ammonia is stored on board (refrigerated vs. pressurised). This choice has a major impact on the scope of safety features and barriers required in the design phase.

Ammonia bunkering: preference for refrigerated

Among others in the EU supported MAGPIE project,[73] the Port of Rotterdam has conducted a port readiness level study on ammonia bunkering, to assess where in the port area it can take place safely. This included a pilot in April 2025 in the port area, involving transfer of 500 tons of refrigerated ammonia between two ships.[74] The demonstration validated the port of Rotterdam safety framework for ammonia bunkering, establishing that it is possible to do this safely and without ammonia release in the port. A map of potential bunkering locations in the port area has been created based on risk contours, but further analysis from a nautical perspective is still needed before it is published. The QRA shows that the 10^{-6} risk contours are consistently smaller for refrigerated ammonia bunkering than for pressurised ammonia bunkering (roughly two-thirds to three-quarters).[75]

The Port takes the position that although handling of pressurised ammonia is as safe, bunkering of cold ammonia is recommended because of the smaller risk contours, Best Available Technology policy, and the shipping lines bunker policy. Moreover, ammonia is already available refrigerated in the port.

Two ammonia bunker barges have been announced, one by Victrol (under with OCI to supply the ammonia) and another by Deltatank, both for bunkering in Antwerp-Rotterdam region.[76] Bunker barges are more expensive than regular barges (Victrol 80 million euro, Deltatank 68 million euro) because they have more tanks for higher capacity (5,000-7,000 ktons), an automatic

[72] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2024). Emerging ship design principles for ammonia-fueled vessels. October 2024.
[73] MAGPIE project website. MAGPIE is short for 'sMArt Green Ports as Integrated Efficient multimodal hubs'.
[74] 'Port of Rotterdam takes important step in making shipping more sustainable: pilot prepares port for safe bunkering of ammonia', PoR website 14 April 2025. Similar ammonia transfer and bunkering trials have taken place in other ports worldwide.
[75] Port of Rotterdam (2025). Confidential presentation on ammonia bunkering studies.
[76] 'Press release: OCI Global and VICTROL Partner to Develop Clean Ammonia Bunkering Network in the Netherlands and Belgium', Victrol website 9 October 2025; Deltatank received a CEF AFIF grant: 24-EU-TG-ZEBRA | Zero Emission BunkeRing with Ammonia | Project cost € 68.600.000 | Grant € 10.000.000 | The project deals with the deployment of an ammonia bunkering barge in three core port systems between Belgium and the Netherlands: Rotterdam, Antwerp / Brugge and Gent, Vlissingen and Terneuzen. The capacity is planned to 8,000 and 10,000 cubic meters and will be dual fuel, hydrogen – diesel as back up and a battery pack with a fuel cell using hydrogen generated by the boil- off ammonia.

loading arm, and safety features to prevent spillage during transfer, both on the barge side and on the receiving vessel side, in case of hose/coupling rupture. Part of the explanation of the high costs may also be that the vessels are estuary designs.

The American Bureau of Shipping presented a technical and operational advisory for ammonia bunkering.[77] One important aspect is inerting before and purging after bunkering. Inerting of the bunkering systems involves displacing air with inert gas, typically dry nitrogen, in order to control the moisture but also remove any flammable gas mixture. After inerting, a gassing-up operation is to be carried out to replace the inert atmosphere with ammonia vapour, preventing nitrogen entering in the fuel tank. A leak/pressure test is to be carried out to verify the integrity of the bunkering system prior to starting the transfer operation. After bunkering, the bunker hoses are to be drained and any remaining liquid or vapour in the bunkering lines should be purged using the inert gas so that they are free of ammonia. All ammonia must be captured by the ammonia treatment and venting systems during venting, for the safety of personnel in the vicinity of the bunkering facility and the environment. The ammonia is then flared to avoid emissions.

[77] ABS (2024). Ammonia bunkering: technical and operational advisory.

ANNEX C: ELABORATION OF PUBLIC INTERESTS

1. AFFORDABLE

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

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

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

The resulting costs are significantly affected by the assumptions made. Consequently, we attempted to use the same source for different carriers whenever feasible. The key sources are HyDelta and the Joint Research Centre (JRC), which offer the most comprehensive and transparent information on the costs associated with importing hydrogen carriers. We factored in the transport costs in the Netherlands, using benchmark figures from the Social Cost-Benefit Comparison (MKBV) of Hydrogen Carriers, Panteia, and the Netherlands Institute for Transport Policy Analysis (KiM).[78] We did not include the costs of end use equipment, since this encompasses a broad spectrum of technologies (fuel cells, burners, turbines, internal combustion engines, process reactors, etc.).

2. ECONOMICALLY ROBUST

The public interest Economically Robust emphasises the Netherlands' current (and future) earning capacity. To this end, we estimated the added value for the Netherlands across the various chains. Added value (absolute) is calculated as the difference between 1) projected domestic or export revenues, including profit margins, and 2) the costs associated with imports. Consequently, chains that incur low import costs achieve high scores, even if the storage, conversion, and transport costs in the Netherlands are high. After all, the associated expenditure ultimately benefits the Dutch economy.[79]

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

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

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

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

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

3. RELIABLE

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

This is influenced by the following factors:

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

Literature sources are lacking for some of these factors, particularly concerning their relative evaluation. Thus, in consultation with a panel of experts, we determined the scores for each step of

the chain qualitatively in the 2024 MCA of hydrogen carriers, taking their relationship to other steps into account.

4. SAFE & SECURE

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

External safety

External safety concerns the risks to Dutch society posed by potential incidents during the storage and transshipment, conversion, or transport[80] of hydrogen or ammonia. Because hazardous substances are involved, there is a risk of injury, environmental degradation, and damage to property. The actual risk involved depends on the impact of an incident and the probability that it will occur.

The scoring methodology used for external safety draws upon the Dutch government's regional risk profile method and the country-wide national security risk analysis (slightly simplified). Together with a panel of experts, we evaluated the probability and impact of incidents involving ammonia and hydrogen in the 2024 MCA of hydrogen carriers, for each incident scenario (such as leakage or explosion) and each step in the chain. The risk (number of potential casualties) was calculated by multiplying the probability by the impact. We derived the scores for each supply chain by totalling the risks for each step of the chain in question. Incidents can occur in urban, rural, or industrial areas. The assessment is based on the 'worst-case' situation. In this present study, the results for ammonia from the 2024 MCA of hydrogen carriers were detailed and broken down for refrigerated and pressurised ammonia in a workshop with safety experts.

Cyber security and terrorism

Cyber security and terrorism involve the risks of a targeted cyber attack or terrorist attack. These risks are not the product of human error or technical failures. They result from intentional actions designed to disrupt society. As with external safety, we draw upon the regional risk profile method and the country-wide national security risk analysis. Together with a panel of experts, we assessed the risks of cyber incidents and terrorist attacks for various hydrogen carriers in each step of the chain. We integrated these probabilities with the potential impacts previously identified in the environmental risk indicator, yielding a cyber risk and terrorism risk for every step of the chain. The scores for each supply chain were calculated by adding together the individual chain steps. In this present study, the results for ammonia from the 2024 MCA of hydrogen carriers were detailed and broken down for refrigerated and pressurised ammonia in a workshop with safety experts.

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

Transport safety

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

The shadow costs, as established by CE Delft, are also used in the KiM Freight transport knowledge base.[81] The costs cover medical expenses, production losses, handling charges, and material costs linked to fatalities, as well as to individuals with severe and minor injuries. Benchmark figures are available for transport by road, water, and rail. Transport by pipeline is expected to eliminate traffic accidents entirely, allowing us to avoid any expenses related to transport safety.

5. SUSTAINABLE

The public interest Sustainable comprises three indicators: 1) Greenhouse gas emissions, 2) Energy loss and 3) (critical raw) Material usage.

Greenhouse gas emissions

Across the various hydrogen supply chains, small quantities of carbon dioxide, methane, hydrogen, and/or nitrous oxide (N_2O) are released during production, conversion, storage, and transport. These emissions drive climate change, either directly (carbon dioxide, methane, nitrous oxide) or indirectly (hydrogen). Emission types and volumes vary greatly from one chain to another. Emission level estimates for various steps in the chain are drawn primarily from the literature, particularly JRC2.[82]

Transport-related CO_2 emissions result from the use of fossil fuels (expected to remain dominant in 2030, but will be mostly phased out by 2050). Small amounts of hydrogen escape during the conversion of various hydrogen carriers to hydrogen and while it is being transported in liquid or gaseous form. In addition, JRC2 indicated that small amounts of N_2O are emitted during ammonia conversion.

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

Energy loss

Energy loss can be broken down into two components. The first of these involves the energy needed to produce hydrogen in the exporting country, convert it with nitrogen to ammonia, ship it and store it within the Netherlands, transport it onward, and convert it back into hydrogen or another product for end use. The second component is the energy required to replenish the

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

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

amount of hydrogen or ammonia that is lost throughout the process, whether from unintended emissions or from its planned use as fuel in various steps of the chain, making it inaccessible for end use. Together, these components make up the total energy input required to supply 1 kt of hydrogen to the end user. We express this total energy input in terms of the energy contained in 1 kt of hydrogen.

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

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

Material usage

We gauged material usage by examining the impact on limited resources needed within the hydrogen supply chain. This covers various catalysts and carrier materials sourced from raw materials designated as critical by the EU[83]. In an ideal situation, the loss of scarce materials would also be factored in. However, information on this topic remains limited. Accordingly, we have restricted our focus to the amount of material (in grams per kilogramme of hydrogen) required to meet annual demand (source: JRC2). This range of materials is unified under a common denominator by multiplying each by its current market price. Thus, the comparative indicator for each chain is the value of the demand for scarce materials per kt of hydrogen equivalent.

6. ADAPTABLE

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

The level of adaptability is expressed in terms of the value of extra investments that cannot be repurposed. This is the 'value at risk'. We re-used the results from the 2024 MCA of hydrogen carriers assessed by a panel of experts; we assessed the extra investments required as a proportion of total investments and determined their potential for reallocation. For each chain, the final indicator is the scale of investment needed that cannot be reallocated at a later stage, expressed as kt per hydrogen equivalent. The higher the level of high-risk investments, the lower the adaptability score. Details of the investments needed for each chain were mainly sourced from JRC1.

7. FAIR

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

The distribution of benefits and burdens becomes less equitable when a significant portion of the unpriced (external) effects of imports – such as their environmental impact and greenhouse gas emissions – falls on the producer countries, or when a relatively large number of external effects

[83] European Commission website on Critical Raw Materials.

from the hydrogen carrier supply chain are felt in the Netherlands. In this case, the 'true costs' is significantly higher than the invoiced cost.[84]

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

External costs passed on to producer countries

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

The import costs are assessed against the public interest Affordable. The external effects of imports are partly derived from the LCA study in JRC2[85], along with environmental cost factors from CE Delft.[86]

Passing on the external costs of chains within the Netherlands

As an indicator of fairness for the Netherlands (or its residents), we calculated the total value of external effects per chain within its borders and divided this by the associated costs of chain activities in the country. This means the costs of transshipment and storage, transport, and the conversion steps[87]. These costs are assessed against Affordable. In the Netherlands, external costs consist of:

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

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

8. ACCESSIBLE

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

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

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

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

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

Accessible by cost parity (inland versus port of entry)

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

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

Accessible network / proximity for end users

To determine the accessibility of hydrogen and ammonia for end users inland, we employed a methodology inspired by the proximity factor used in other domains (see CBS proximity statistics). We quantify this indicator by defining it as the proportion of industrial estates linked to the transport mode. In terms of delivery by road and through the natural gas network, this is 100 percent. Delivery by rail and water is based on data from the IBIS database.[88] We estimated the percentage of industrial estates expected to have access to specific pipelines or the hydrogen transport network by identifying the municipalities along the planned routes of the Delta Rhine Corridor and the national hydrogen transport network. To provide a rough approximation, we use the number of industrial estates in these municipalities as a percentage of the total number of industrial estates in the Netherlands (see Annex D for the relevant figures).

9. SPATIAL FOOTPRINT

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

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

10. ENVIRONMENT

Here, the term Environment includes the impacts of various emissions that damage the environment as well as the health of people and animals. For this comparison, the public interest Environment covers the costs associated with nitrogen emissions, particulate matter, ammonia emissions, habitat degradation, noise pollution, ecotoxicity, and methane-induced smog, including,

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

where possible, the costs of environmental impacts in case of incidents such as spills. Insofar as they occur in the Netherlands, these costs are factored into the public interest Environment. Fair is the only public interest that takes account of environmental impacts in other countries.

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

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

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

Transport causes a range of adverse effects on nature and landscapes, classified as habitat degradation (damage to the natural habitats of animal and plant species). This involves habitat loss resulting from the encroachment of transport infrastructure, as well as habitat fragmentation or barrier effects due to major and expansive primary infrastructure (such as motorways and railways). This is in addition to the habitat degradation caused by environmentally harmful substances other than NO_x and particulate matter. Where they contribute to climate change, greenhouse gas emissions, both direct and indirect (carbon dioxide, methane, hydrogen, and nitrous oxide), are included in the assessment of the public interest Sustainable. To this end, methane's effects are divided into climate-related impacts and those arising from ecotoxicity and methane-induced smog.

Inland transport by road, water, and rail generates NO_x, particulate matter emissions, and noise pollution, as well as causing habitat degradation. There is also the potential for environmental incidents. As inland shipping operates farther away from residential areas, it is not expected to generate any noise pollution. Benchmark figures are available for these effects (source: KiM), which we integrate with data on transported tonne-kilometres per supply chain. The use of electric pumps, means that pipeline transport generates no NO_x, particulate matter emissions, or noise emissions.[89]

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

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

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

ANNEX D: DATA USED FOR CALCULATING SCORES FOR PUBLIC INTERESTS

This annex explains the underlying assumptions and figures for each public interest. The order in which these are given is identical to that in the National Energy System Plan.

For each public interest, we provide an explanation of the data concerning ammonia. We refer to the annexes of the 2024 MCA of hydrogen carriers[90] for all other data that were used. Few changes were made in those data, noteworthy are the following:

- We used the KEV 2024 dataset in the 2024 MCA of hydrogen carriers and the 2025 update for the present study.
- We use the ISPT safe & compliant ammonia pipeline study as the reference for the pressurised ammonia pipeline instead of the Delta Rhine Corridor cost-benefit study.
- We used the Antea study on incidents with hydrogen carriers (draft 2025) to refine the Safe & secure assessment in a separate expert session on External safety and Cyber security and terrorism.
- We verified some of the emissions data from a new study by the Environmental Defense Fund on the nitrogen compound emissions (NH_3, NOx, N_2O) in the ammonia supply chain.

1. AFFORDABLE

As for the 2024 MCA of hydrogen carriers, we use the 2022 HyDelta study[91] as the basis for the import and conversion (cracking) costs of (refrigerated) ammonia, see Table 8. We selected Morocco as the exporting country. It was mentioned in the interviews that green ammonia is becoming more widely available for imports and the price is decreasing rapidly (from 800 euro per ton a few years ago to 600 euro per ton now, helped by the emergence of a spot market), but we did not update the HyDelta costs with this information.

[90] Stratelligence (2024). Vergelijking waterstofdragers. Multicriteria-analyse van leveringsketens in Nederland. In opdracht van het Ministerie van Klimaat en Groene Groei.

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

Table 8: Costs of ammonia imported from Morocco to the Netherlands in 2030, in euro per ton H_2 equivalent.

Morocco 2030 HyDelta	H_2 via NH_3
Local H_2 production	€ 2,691
Compressed H_2 storage	€ 33
H_2 to ammonia conversion (synthesis)	€ 1,047; *synthesis in the Netherlands: € 1,014**
Ammonia export and storage	€ 216
Transport: ocean shipping	€ 33
Ammonia import and storage at port of entry	€ 187
Ammonia to H_2 conversion	€ 300**
Total import costs	€ 4,018

*) One supply chain involves synthesis of ammonia in the Netherlands using hydrogen from the national hydrogen network. We take the costs of this conversion in the United Kingdom according to HyDelta, assuming that of the countries HyDelta examined, the UK most closely resembles the Netherlands.

**) HyDelta does not include the use of DeNOx aftertreatment in ammonia cracking, but this study assumes it will be used. We calculate the costs of DeNOx using data from the feasibility study for the Rotterdam ammonia cracker (production capacity size, amount of emissions to be treated) and from IPLO - Information Point for the Environment (cost indicators for investment and operational costs).[92]

Table 9: Composite costs per tonkm for ammonia transport by road, rail and inland vessel. Source: Panteia and market information.

Transport costs Costs per tonkm	Road Chemicals	Rail Chemicals	Inland waterway transport Liquid bulk
Fixed costs	€ 0.018	€ 0.007	€ 0.018
Variable costs	€ 0.051	€ 0.005	€ 0.006
Personnel costs	€ 0.050	€ 0.002	€ 0.014
Modality-specific costs	€ 0.001	€ 0.004	€ 0.001
General operational costs	€ 0.018	€ 0.003	€ 0.001
Total costs per tonkm	€ 0.138	€ 0.021	€ 0.039
Pressurised ammonia	*€ 0.138*	*€ 0.021*	*€ 0.039*
Additional fixed costs refrigerated ammonia	*€ 0.008*	*€ 0.011*	*€ 0.004*
Refrigerated ammonia	*€ 0.146*	*€ 0.032*	*€ 0.043*
Correction for capacity	--	*€ 0.006*	*- € 0.006*
Refrigerated ammonia	*€ 0.146*	*€ 0.038 **	*€ 0.037 ***

*) The investment for the refrigerated ammonia rail tank car is 2,5 times higher than for the pressurised version, that also holds 20% more ammonia (source: VTG).

**) The investment for the pressurised barge is 15 M€ and for the refrigerated barge 18 M€; the refrigerated barge holds 15% more ammonia due to higher density (more mass in the same cargo space).

[92] In the MCA study of hydrogen carriers, CAPEX for DeNOx were calculated as €5-18/tonH_2, and OPEX € 0,021-0,28 /tonH_2 for reagentia en 0,058 €/tonH_2 for the catalyst, i.e. negligible compared to CAPEX.

Domestic transport costs are added to this, calculated using Panteia key figures (integral costs per tonkm for road, rail, and barge).[93] The following Table 9 shows the breakdown of these integral costs. The fixed costs consist of: depreciation, insurance, interest, and maintenance and repair. The difference between pressurised and refrigerated ammonia concerns the fixed costs due to the higher investment costs of cryogenic transport equipment (sources: market information, see Table 10). The total costs per km therefore also differ.

Table 10: Investments for transport means in million euros.

Input	Pipeline / H_2 network	Semi-trailer truck	Rail tank car	Barge
H_2	172 (200 km, partly existing, 1 compression station)	Out of scope	Out of scope	Out of scope
Pressurised NH_3	807 (200 km, pumping stations included)	0,295	0,22	15,00
Refrigerated NH_3	N/A	0,430	0,55	18,00

Sources: 2024 MCA of hydrogen carriers, market information Essent Hydrogen, VTG, Schenk Tanktransport, Koninklijke Binnenvaart Nederland

This leads to the following overview of storage and transport costs of ammonia (and hydrogen by pipeline) in Table 11.

Table 11: Transport costs in euro per ton ammonia (H_2 equivalent) by road, rail, barge and pipeline.

Cost of storage and transport per ton H_2eq				Modality			
Drager	Import	Storage/ transfer	Storage at end user	Pipeline/H_2 network	Road	Rail tank car	Barge
H_2-gas				€ 34			
Pressurised NH_3	N/A	N/A	€ 26***	€ 92	€ 155	€ 24	€ 44
Refrigerated NH_3	€ 3.116*	€ 145**	€ 36***	N/A	€ 164	€ 43	€ 42

*) Calculated as 78% (conversion efficiency of ammonia cracking) of € 4,018 (total import costs of ammonia according to HyDelta, see Table 8.

**) 78% of € 187 (Ammonia import and storage at port of entry according to HyDelta, see Table 8).

***) € 145 divided by 14 days x 3 days x cost factor. Factor refrigerated ammonia storage +15% due to smaller capacity, factor pressurised ammonia storage -17% because of lower installation costs storage tank.

Transport costs are based on reference figures for road transport, rail transport, and transport (liquid bulk) per inland waterway vessel per tonkm (see Table 9 multiplied by the representative distance of 200 km and the hydrogen content of ammonia (5.63 kg NH_3 per kg H_{2eq}).

In the 2024 MCA of hydrogen carriers, we calculated the transport costs of ammonia by pipeline using data from Delta-Rhine-Corridor and JRC (team analysis based on public sources and information from companies, see Table 12).[94] For CAPEX, we selected the data for the planned

[93] Panteia (2023), Cost Figures for Freight Transport – final report, commissioned by Kennisinstituut voor Mobiliteitsbeleid (KiM), January 2023.

[94] JRC1: JRC, Assessment of Hydrogen Delivery Options Feasibility of Transport of Green Hydrogen within Europe, 2022; en JRC2: European Commission, Joint Research Centre, Arrigoni, A. et al (2024), Environmental life cycle

Delta-Rhine Corridor pipeline. This cost estimate is considerably higher than according to JRC1, mainly because the pipeline diameter is larger (24 inches vs. 18 inches) and the requested market quote will have taken into account rising raw material prices and thus higher costs per km of pipeline. For OPEX, we followed JRC1 estimates. We assumed three pumping stations, each with two pumps, to be connected to the route.

This study uses the data from the 2025 ISPT study on safe & compliant ammonia pipeline, because this is a more transparent and recent set of data. The cost estimate in the ISPT study was drawn up for the entire pipeline, including all the necessary valve and pumping stations as well as the required risk reduction measures. The CAPEX does not include import terminal facilities. The CAPEX estimate is based on 2025 cost levels and has been factorised at a budgetary (Class V) level according to AACE guidelines. The estimates' accuracy range lies between -50% and +100%. The cost estimates include a 50% contingency as this accounts for risks such as delays and uncertainties (e.g. permit issuing, design changes).

Table 12: Transport costs for hydrogen and ammonia by 200 km pipelines.

Transport costs with pipelines	H_2 36"	NH_3 24" (DRC)	NH_3 20" (ISPT)
Throughput route (kton/jr.)	1,578	8,884	7,000
CAPEX pipeline (MEUR/km)	€ 0.8	€ 4.0	€ 3.8
CAPEX pipeline 200 km (MEUR)	€ 160	€ 800	€ 760
Lifetime (a)	50	50 (1)	50
OPEX pipeline, % of CAPEX per year (2)	1%	0.04%	15%
Number of compression/pumping stations	1	3	3 (for 550 km)
CAPEX compression/pumping stat. (MEUR)	€ 12	€ 6.60	included in CAPEX of pipeline
Lifetime (a)	20	20	20
OPEX compression/pumping stations (2)	1,2%	4%	included in OPEX of pipeline
Energy input compression/pumps (MWh/a)	577,548	122,400	26,280
Energy cost (MEUR) (3)	€ 42.2	€ 8.9	€ 2.0 included in OPEX
Interest	5%	5%	5% included in 15% OPEX
Annuity per year per kton carrier	€ 33,987	€ 6,064	€ 16,286
Annuity per year per kton H_2 equivalent	€ 33,987	€ 34,139	€ 91,689

1) JRC1 and DRC specify 40 years, and the LNG study specified 30 years, but we assume equal lifespans for all pipelines.
(2) JRC1 provides higher OPEX for gas pipelines than for liquid pipelines.
(3) Calculated at €73/MWh in 2030, in accordance with KEV 2025.

The costs for decentralised ammonia storage were calculated as 3/14ths of the costs of centralised storage (3 days of decentralised inventory, 14 days of centralised inventory in the port of entry).

assessment (LCA) comparison of hydrogen delivery options within Europe, Publications Office of the European Union, Luxembourg; Decisio (2023), MKBA Delta Rhine Corridor Fase 2, voor Ministerie van Economische Zaken en Klimaat, 22 december 2023.

For centralised storage, a 14-day inventory of average daily end use was assumed, and for decentralised storage, a 3-day inventory of average daily end use was assumed.

2. ECONOMICALLY ROBUST

For the public interest Economically Robust, we use a composite indicator, which consists of the added value minus the social costs of congestion and the social costs of public infrastructure.

- Added value is defined as revenue minus purchase costs. Purchase costs for different hydrogen carriers are taken from the public interest Affordable. For the calculation of revenue, we assume an indicative price for hydrogen per kilogramme upon delivery to end users (either as hydrogen or as hydrogen carrier such as ammonia). We choose a sales price for hydrogen and deduct the conversion costs for ammonia per hydrogen equivalent to determine the sales prices for other hydrogen carriers / ammonia, see Table 13. The precise level of the chosen sales price for hydrogen is not important because the difference between purchasing and selling determines the score on this indicator, along with the following cost items.
- The costs of road congestion are calculated by multiplying the transport volumes (tonkm) by key figures from KiM/CE Delft.
- The costs of using space and public infrastructure are also calculated by multiplying transport volumes (tonkm) by key figures from KiM/CE Delft.

The difference between the sales price of hydrogen or ammonia and the import costs of ammonia is decisive. Congestion and infrastructure costs are negligible in this case.

Table 13: Assumed revenue per ton H_2 equivalent for hydrogen and ammonia in 2030

	Indicative sales price per ton H_2 eq	
H_2-gas	€ 12,000	
Refrigerated and pressurised NH_3	€ 11,700	Adjusted for conversion to H_2

3. RELIABLE

By reliable, we mean the extent to which hydrogen or ammonia supply chains are robust and offer security of supply. If supply is less secure, this will be compensated for by incorporating more storage capacity. Therefore, as an indicator of reliability, we use the required additional storage capacity that must be incorporated into the chain to offer the same security of supply as the current supply chains for fossil fuels.

The 2024 MCA of hydrogen carriers used this method in which the degree of reliability of the supply chain is expressed in the need for (additional) storage capacity within the chain. For each chain component, we estimated its reliability compared to the fossil fuel chain. For each chain, we add up the reliability (expressed in the estimated additional storage needs of the end user) of the chain components to arrive at a total estimate.

The following Table 14 provides a summary of the TRLs (Technology Readiness Levels) of the components of the ammonia supply chains to and within (and through) the Netherlands. We now differentiate between refrigerated and pressurised ammonia. Most chain components are classified at TRL 9, but some are classified lower. These 'weak links' are highlighted in bold. The assessment of the individual components of the chain is described separately after Table 14.

Table 14: TRL (Technology Readiness Levels) of components of ammonia supply chains to and within the Netherlands. 'Weak links' in the chains (TRLs below 9) are highlighted in bold.

	TRL of ammonia production in exporting country	TRL of ocean transport	TRL of storage	TRL of national transport (road, rail, barge, pipeline)	TRL of conversion installations
H_2-gas			TRL9, salt caverns (USA)	TRL9, pipelines	
Refrigerated NH_3	TRL9, large-scale production usually with H_2 from natural gas but also electrolysis	TRL9, dedicated NH_3 tankers	TRL9, large scale	Each mode TRL9, apart from **refrigerated rail tank car TRL8**	Cracking: TRL9 small-/ medium-scale, **TRL7 large-scale, demonstrations planned** Synthesis: TRL9
Pressurised NH_3	N/A	N/A	TRL9, small scale	Each mode TRL9, apart from **pipeline TRL7-8**	Cracking: TRL9 small-/ medium-scale, **TRL7 large-scale, demonstrations planned** Synthesis: TRL9

For most aspects that impact the public interest Reliable, there are no differences between refrigerated and pressurised ammonia. Differences (see Table 15, Table 16 and Table 17) do exist for:

- Stability/'shelf life' of the carrier: ammonia can be stored indefinitely under pressure or at atmospheric refrigeration, provided the low boil-off with refrigerated ammonia is controlled. Pressurised ammonia has a longer 'shelf life' than refrigerated ammonia (it takes longer for vapour build-up to lead to venting into the atmosphere). There is sufficient experience in transporting and storing ammonia to ensure security of supply for both variations.
- Transport means with TRL9 are available for both pressurised and refrigerated ammonia transport, with the exception of long-distance, large-diameter ammonia pipelines through built-up areas and refrigerated inland tankers. However, there is experience with refrigerated ammonia barges in the USA (and the Netherlands last century) and with cryogenic gas tankers that can be utilised.

Table 15: Reliability of ammonia supply chains: import to the Netherlands (refrigerated transport and storage)

	TRL of ammonia production in exporting country	TRL of ocean transport	TRL of storage	Stability/longevity of carrier	**Additional storage**
H_2 gas			TRL9 salt caverns (VS)	Stable and indefinitely storable under pressure	0 (2030)+ 0 (2050)
Refrigerated NH_3	TRL9, large-scale production usually with H_2 from natural gas but also electrolysis	TRL9, dedicated NH_3 tankers	TRL9, large scale	Stable and indefinitely storable if boil-off is controlled	1 (2030)+ 0 (2050)
Pressurised NH_3	N/A	N/A	TRL9, small scale	Stable and indefinitely storable under pressure	N/A

Table 16: Reliability of ammonia supply chains: distribution in/via the Netherlands

Chain component	**Semi-trailer truck**	**Extra storage**	**Rail tank car**	**Extra storage**	**Gas tanker (barge)**	**Extra storage**	**Pipelines incl. pumps/ compressors**	**Extra storage**
H_2 gas							TRL9 – no detour options – 99,99%	0
Refrigerated NH_3	TRL9 – many detour options – 98,5%	0	TRL9 – few detour options – 98,6%	0	**TRL7-8 –** few/no detour options – 98,0%	*7*	**N/A**	0
Pressurised NH_3	TRL9 – many detour options – 98,5%	0	TRL9 – few detour options – 98,6%	0	TRL9 – few/no detour options – 98,0%	*7*	**TRL7-8 –** no detour options **–** 99,99%	0

Table 17: Reliability of ammonia supply chains: conversion installations

	TRL conversion installations	**Additional storage need**
H_2 gas		
Pressurised and refrigerated NH_3	Cracking: small/medium scale TRL9, **large scale TRL7, demonstrations** planned Synthesis: TRL9	Centralised 0; decentralised +2 Synthesis: 0

4. SAFE & SECURE

Three indicators are used for the public interest Safe: 1) External safety, 2) Cyber security and terrorism, and 3) Transport safety.

External safety

Supply chains of ammonia and other hydrogen carriers pose risks to society due to unintended incidents during the transport and processing of (hazardous) hydrogen carriers. This risk is defined as the *probability* of incidents occurring, multiplied by the *severity of the effect* (consequence) of these incidents. As in the 2024 MCA of hydrogen carriers, the methodology used to assess the risk of incidents is the combined *Regional risk profile* and *Nationwide security risk analysis*.[95] This methodology is very comprehensive and was therefore applied in a simplified manner, for a limited number of incident scenarios within the Dutch chain components, excluding end use, and for abstract rather than specific geographic locations.

The probabilities of incidents occurring depend on the number of installations or the number of transport movements and the distance travelled, and on the specific probability of an incident. The effects (consequences), expressed as the number of fatalities in an incident, depend on the hazard of the substance. The focus of the assessment was on the most serious incident, but other impacts were also taken into account.

Probability classification	% per 5 years
Very improbable	< 0.05%
Improbable	0.05-0.5%
Somewhat probable	0.5-5%
Probable	5-50%
Very probable	50-100%
Consequences classification	**E.g. number of fatalities**
Limited	1
Considerable	1-4
Serious (low) (high)	4-16 16-40
Very serious (low) (high)	40-160 160-400
Catastrophic	> 400

Note: logarithmic scale

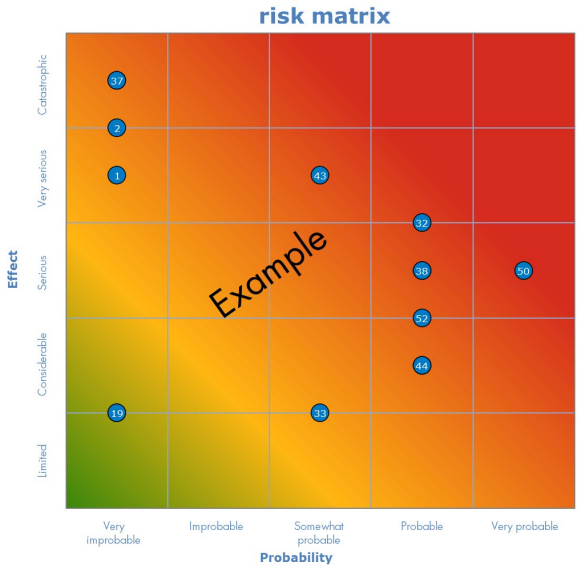


Figure 25: Scaling from the Regional risk profiles and example of a risk matrix

The 2024 MCA of hydrogen carriers assessed the environmental risk of the supply chains by evaluating six types of incidents in two expert sessions and completing risk matrices for these

[95] Analistennetwerk Nationale Veiligheid (2022). Rijksbrede Risicoanalyse Nationale Veiligheid. Arcadis, Gemini Consultants, Houdijk Advies, Stichting Werkgemeenschap tussen Techniek en Zorg (2009). Handreiking regionaal risicoprofiel.

incidents. Experts from safety regions, environmental services, port authorities, the National Institute for Public Health and the Environment (RIVM), knowledge institutions, provinces, and the national government participated in the sessions (February 2024).

Figure 25 shows an example of such a matrix; the table explains how to interpret the scales. The scale is logarithmic: moving up one box represents a factor of 10 more or less. The experts estimated the position of each incident in the risk matrix; the risks of the various incidents were added up for each supply chain. The information on the probability and impact of the various incidents was multiplied into a risk per calamity, and the various calamities were combined for each chain. The total risk was used to determine a ranking of the various chains. This was the outcome of expert judgment based on the best estimates that experts were able to provide on-site during a structured discussion session.

The exercise was partly repeated for the present study: a group of external safety experts estimated the position of each incident in the risk matrix, for pressurised and refrigerated ammonia only. The positions of the other hydrogen carriers remained the same. As additional input for the exercise, we used the results of the study that Antea et al.[96] carried out for the ministry of Infrastructure and Water Management on the hazards, risks, events, possible consequences and the effects of incidents involving hydrogen carriers (for people and the environment) and the (im)possibilities for incident response.

Incident scenarios

Table 18 shows the most serious effects for the six incident scenarios discussed below, for ammonia only. An effect category may be a toxic cloud, an explosion, or a pool fire. For ammonia, the most serious effect is the formation of a toxic cloud. An incident scenario describes a potential calamity.

Table 18: Most serious effect category per calamity (incident scenario)

	Most serious effect category per calamity					
Carrier	Road	Rail	Barge	Pipeline	Storage	Conversion
Pressurised and refrigerated NH_3	toxic cloud	toxic cloud	toxic cloud, damage above waterline	toxic cloud	toxic cloud	toxic cloud

Because these are incident scenarios, a calamity occurs by definition.

1. Road transport calamity

For ammonia, this calamity could result in a toxic cloud due to a rupture or leak in the tank of the road tanker, e.g. after a collision. In addition to human casualties, there may also be material damage and environmental emissions. The risk has been classified for the most serious effect. The probability of occurrence is related to the number of transport journeys per standard route of 200 km. Because the domestic route is the same length for each chain, differences in distance play no role in the comparison of the transport modes.

The *probability* of occurrence is determined by the likelihood of a specific incident (for example, how likely is an accident involving a truck) and is also related to, among other things, the number

[96] Antea Group SAVE, NIPV, GB Rotterdam & H2K (draft 2025). Incidenten waterstofdragers. Voor Ministerie van Infrastructuur en Waterstaat. Projectnummer 0502980.100, concept revisie 1.0, 18 december 2025.

of journeys (the more transport movements, the higher the probability). The probability is the same with refrigerated liquid ammonia as with pressurised ammonia due to the same number of trips required to transport the same amount of ammonia. A tanker truck transports 25 tons of pressurised liquid ammonia or 25 tons of refrigerated liquid ammonia.

The *severity* of the effect is estimated to be largest for a toxic cloud of ammonia. A rupture or leak in an ammonia tanker will cause a toxic cloud to form immediately (when transported under pressure) or after evaporation (when transported as a refrigerated liquid). The impact with refrigerated ammonia is lower than with pressurised ammonia because the toxic cloud spreads less quickly; on the other hand, the evaporation of a pool of ammonia results in a longer duration of the incident. The exposure of people in the vicinity is greater to a toxic cloud than to a pool fire or explosion as the cloud spreads over a much larger area. A road incident is usually easily accessible for emergency response, but the response time will likely be longer than the cloud formation.

2. Rail transport calamity

This type of calamity, which is largely similar to a road calamity, can result in a toxic cloud when the tank of an ammonia rail tank car ruptures or leaks, e.g. after a collision. Besides casualties, there may also be material damage and environmental emissions. The risk was classified for the most serious effect.

The *probability* of a railway incident is lower than a road incident because there are fewer transport movements due to the larger volume per rail tank car, and because the average probability of an incident per km on the railway is lower than on the road. The probability is the same with refrigerated liquid ammonia as with pressurised ammonia due to the similar number of railcar trips required to transport the same amount of ammonia. A railcar transports 50 tons of pressurised liquid ammonia or 40 tons of refrigerated liquid ammonia. The experts judge that this difference falls within the uncertainty margin of this exercise.

The *severity* of the effect is estimated to be largest for a toxic cloud of ammonia. The severity of the effect will be less in case of refrigerated ammonia. There will be less flash effect and less pool evaporation. Compared to road transport, the effect of a railway incident is smaller because leaking fluids are absorbed into the track ballast bed; on the other hand, this adds heat to the ammonia so that it evaporates more quickly. A railway incident may be more difficult to access for emergency response.

3. Inland waterway transport calamity

This type of incident could result in a toxic cloud when one of the tanks of an ammonia barge ruptures or leaks above the waterline, e.g. after a collision with a bridge. Besides casualties, there can also be material damage and environmental emissions. The risk was classified for the most serious effect.

The *probability* of an incident occurring with barges is lower than for road tankers of rail tank cars because the number of voyages is smaller and because rivers are much less busy than roads or railways. Compared to road and rail transport, the impact of an incident on water is greater because the transported volumes are larger (even though the cargo tanks consist of compartments). The risk of this occurring is the same with refrigerated liquid ammonia as with pressurised ammonia due to the same number of voyages required to transport the same amount of ammonia. An inland tanker of the same class transports 1,500 tons of pressurised liquid ammonia and 1,700

tons of refrigerated liquid ammonia. The experts judge that this difference falls within the uncertainty margin of this exercise.

The *severity* of the effect will be less with refrigerated ammonia. With pressurised ammonia, a leak above the waterline will lead to rapid cloud formation, while the remaining ammonia in the cargo tank will boil. If the leak is below the waterline (in either the tank or the ship's hull), the ammonia will leak into the water, partially dissolve, and partially diffuse through the water, where it evaporates and forms a thinner and less dangerous toxic cloud than in the case of a pipeline rupture. On the other hand, water can enter the cargo tank, accelerating evaporation and increasing the pressure inside the tank. Access for fireboats capable of deploying a water barrier to reduce the ammonia concentration in the cloud will take some time, by which time the initial cloud may already have formed. There will be less of a flash effect (rapid initial evaporation of liquid due to a drop in pressure), and more ammonia will dissolve in the water. This leads to less evaporation and less serious consequences.

The impact of a refrigerated liquid ammonia spill compared to a pressurised ammonia spill in inland shipping is based on results from large-scale field trials by Air Products (Red Squirrel Tests, 2022).[97] These trials measured and calculated the distances from a spill that could cause very serious health effects for both forms of ammonia. They showed that the zone in which such effects are possible extends more than twice as far for pressurised ammonia as for refrigerated ammonia. When this effect distance is translated into the corresponding exposed area, the result is an impact zone that is approximately 4–5 times larger for pressurised ammonia.

4. Calamity with pipeline

Two kinds of calamities are possible for pipelines: the first is the failure of a compressor or pump in a compressor station. The number of compressor stations determines the risk classification per chain. Failure of a compressor can result in, for example, a jet fire (e.g., hydrogen) with low emissions or a toxic cloud (e.g., ammonia). Material damage consists of replacing the installation in the event of a fire or is limited in the event of a toxic cloud. The second calamity is a rupture of the main pipeline. Per km of pipeline, there is a risk of leakage due to rupture or excavation damage. Material damage consists of repair or replacement of the pipeline. It was decided to combine these two calamities in the assessment. The risk has been classified for the most serious effect, which in the case of ammonia is a toxic cloud.

Pipeline transport is the mode of transport with the lowest *probability* of incidents occurring, for all hydrogen carriers. The likelihood of compressor or pump failure is greater than that of a rupture in the main pipeline, but the impact of the rupture is greater.

The present study investigated the existence and theoretical feasibility of a refrigerated long-distance ammonia pipeline, and concludes that this is not a realistic alternative to be considered (see annex H). Such pipelines do exist for short distances of up to about 5 km. Therefore, we do not compare pressurised and refrigerated liquid ammonia here, but merely consider the pressurised ammonia pipeline's position in the risk matrix.

There is uncertainty about what exactly happens in the event of an ammonia leak in a pipeline. The *severity* of the impact of a rupture or compressor failure in the pipeline is estimated to be

[97] S. Dharmavaram, M. J. Carroll, E. M. Lutostansky, D. McCormack, A. Chester, D. Allason, 'Red Squirrel Tests: Air Products ammonia field experiments'. *Process Safety Progress* 2023 (**42**), 481–498. DOI: 10.1002/prs.12454

largest for a toxic ammonia cloud. The impact is greater as the diameter of the pipeline increases. The impact can be limited by using safety valves in the pipeline to stop the outflow, known as compartmentalisation.

In order to increase safety, ISPT has developed guidelines for safe and standard-compliant state-of-the-art ammonia pipeline design.[98] This safety approach results in a risk contour for a 20-inch pipeline below the legally required 5 meters, and 1,800 meters for the pumping stations. The guidelines include:

- Intermediate pumping (booster) stations and a smaller pipeline diameter (20 inches instead of 32 inches). This reduces the ammonia volume in the pipeline to one third, thus reducing the potential ammonia outflow in the event of a leak.
- Thermal expansion protection is applied between the segments, with shut-off valves between the pipeline segments and emergency shut-off valves (ESD valves) for a fast response time. Current European regulations do not specify the exact locations between the shut-off valves; a distance of 5 km between them was considered the safest in view of the formation of toxic clouds.
- Choosing a smaller diameter results in a higher ammonia flow rate (for the same volume to be transported), and this increases the risk of damage to valves due to liquid hammer.
- Other risk-mitigating measures include burial to a minimum depth of 2 meters and partially covering the pipeline with protective plates to prevent (excavation) damage.

The scenario book assumes 10 km compartments for an ammonia pipeline, and the 2024 MCA of hydrogen carriers assumes a 24-inch diameter pipeline, which was considered for the Delta-Rhine Corridor variant with mitigation. The ISPT design study considers 20 inches and 5 km. The impact of a disaster with direct closure is proportional to the length of the compartment and the square of its diameter.

While the amount of ammonia released from a gas tanker and a compartmentalised pipeline will be of the same order of magnitude, the impact is larger on land because the cloud is not partly dissolved in the water.

5. Calamity with storage tank

In the event of an instantaneous failure of a storage tank, the entire tank is destroyed and the stored substance escapes into the environment, a quantity that can be an order of magnitude higher as a pipe rupture. Ammonia can produce a toxic cloud. It is assumed that material damage will be limited to tank replacement. The risk has been clasified for the most serious effect per hydrogen carrier.

We do not compare with centralised storage of pressurised liquid ammonia because in practice, pressurised ammonia storage is limited to 1 kton (and at most two such tanks within a Seveso establishment), while refrigerated storage is available from small capacities (cylinder tanks ranging from tens of tons to full-containment tanks of 60 ktons).

The *probability* of an instantaneous failure of a storage tank is (very) small. Storage is a static situation that requires no transport or handling, resulting in lower risks. The *severity* of the effect

[98] ISPT (2025). Design and Safety Aspects for large-scale Clean Ammonia Pipelines. Clean Ammonia Innovation Platform. Public report.

with decentralised storage is smaller due to the lower volume per tank, but not proportionally smaller. DCMR compared the effects of a calamity (toxic cloud) with different sizes and types of ammonia storage. We used these calculations for the present study.

The probability of a calamity occurring varies. Less ammonia is stored decentrally than centrally (3 days' supply instead of 14 days). However, because the tanks are smaller, there are more tanks needed (distributed among customers). The more tanks, the greater the probability of an incident. Due to differences in tank type, the probability of a calamity occurring for pressurised liquid storage is greater per tank than for refrigerated liquid storage.

The effect of a calamity with decentralised refrigerated liquid ammonia storage (50 ktons) is lower than with centralised refrigerated liquid ammonia (10 ktons), and the effect of a calamity with decentralised pressurised liquid ammonia (1 kton storage) is lower still.

6. Calamity with conversion installation

High operating temperatures and high required or emitted heat can cause safety risks due to overheating during conversion processes such as ammonia cracking. The basic principle is that installations and equipment are designed and implemented according to the highest safety standards and procedures, and that the required precautions are observed. These standards, procedures and measures are more advanced for hydrogen carriers that have been used in the industry for some time (e.g. ammonia) than for newer carriers. Nevertheless, incidents can occur: in the event of a disaster, an external fire can occur with limited impact on the surrounding area (limited emissions of hydrogen carriers, as well as soot, CO, CO_2, and possibly toxic fumes, etc.). The material damage may be significant (requiring replacement of the installation).

In the 2024 MCA of hydrogen carriers as well as this present study, the number of conversion installations determines the risk classification per chain, as the volume is only slightly different. The risk has been classified for the most serious effect, which is the formation of a toxic ammonia cloud if an ammonia cracker fails. This effect extends over a large area, therefore resulting in higher exposure than a fire or explosion in an evaporator or steam reformer, the impact of which is usually limited to a sparsely populated industrial site.

Ammonia is split into nitrogen and hydrogen through catalytic cracking. The ammonia can be supplied in either refrigerated or pressurised form, depending on the location and logistics. Refrigerated ammonia is used if the cracker is located adjacent to a storage terminal, and alternatively, a pipeline with pressurised buffer tanks is required for operational reliability if the cracker is located remotely. Both options are included in the plans for cracking plants in the Port of Rotterdam. Before the ammonia enters the cracking reactor, it vaporises with the help of ambient heat. The reaction takes place at temperatures between 500 and 900°C without a catalyst, or at a lower temperature of 400 to 700°C with a catalyst. For these reasons, when it comes to risk assessment, we do not differentiate between the two forms of ammonia in the event of an incident at a cracker.

Cyber security and terrorism

The second indicator for the public interest Safe & Secure is cyber security and terrorism. Ammonia and other hydrogen carrier supply chains may be targeted by cyber and terrorist attacks. The risk is assessed by combining probability and effect. By probability, we mean the vulnerability or sensitivity of the supply chains to a cyberattack or terrorist attack. This involves an assessment of vulnerability without any other mitigating measures beyond those already implemented or

legally required. A group of external safety experts assessed the vulnerability to a cyberattack or terrorist attack for various parts of the supply chain. Due to the sensitivity of the topic, it was decided not to publish the results of this discussion.

Probability is also determined by the (periodic/variable) threat assessment: which organisations are seeking to make victims, disrupt society, or commit economic blackmail. Threats to the energy supply, particularly pipelines and industrial installations, potentially arise from state actors, activist groups, and criminal organisations engaged in blackmail. This is the domain of the security services and is not taken into account. For the scores, this means that the overall probability can decrease as the threat level decreases or increase as the threat level increases. This likely will not change the rankings.

The *severity* of the impact of an incident in hydrogen supply chains was determined in the aforementioned sessions with experts in the field of external safety, and reviewed in another expert session for the present study. We added the distinction between pressurised and refrigerated ammonia for each chain component. External safety concerns the probability of an incident occurring during regular operations, while cyber security and terrorism concern the vulnerability of the chain to deliberate disruption. How easy is it for third parties to cause an incident? The basic principle is that the effect is the same in both cases, but the effect can vary between physical (fatalities, material damage) and economic consequences (e.g., disruption of the energy system).

Transport safety

The third indicator of public interest Safe & Secure is Transport safety. The transport of ammonia and other hydrogen carriers by road, rail, and waterways can lead to an increase in the number of traffic accidents.[99] The Netherlands Institute for Transport Policy Analysis (KiM) and CE Delft have expressed the societal costs of traffic accidents as average amounts per transported volume in tonkm.[100] The societal costs for the Transport safety indicator are calculated by multiplying these valuation factors by the transport volumes in tonkm for each supply chain. Logically, no costs from traffic accidents are calculated for pipelines.

5. SUSTAINABLE

Greenhouse gas emissions

Greenhouse gases are released at various stages in the ammonia supply chain. For CO_2 emissions during transport in the Netherlands, we use the same key figures as in the 2024 MCA of hydrogen carriers. Losses during transport and storage of hydrogen (from ammonia) have already been described above. According to JRC2, ammonia cracking releases a small amount of nitrous oxide (N_2O) (4.89 mg per kg of hydrogen), in addition to NOx and ammonia. Hydrogen is released during ammonia synthesis (0.77 g of hydrogen per kg of ammonia). We assume no difference between pressurised and refrigerated ammonia here.

[99] Over time, the transport of hydrogen carriers will eventually replace the transport of other fuels. This could reduce the transport of fossil fuels. We have not included this effect in our modelling.

[100] O. Jonkeren en J. Francke, Kennisinstituut voor Mobiliteitsbeleid | KiM, Kennisbasis Goederenvervoer, Notitie, Februari 2023. CE Delft, Toekomstverkenning, De prijs van een reis, Verkennende analyse richting 2050, mei 2022. The following societal costs are included in the assessment of transport safety: medical costs, handling costs, material costs, costs of production loss, immaterial costs, and traffic jam costs.

Greenhouse gas emissions from transport are not included in Table 19; this is calculated by combining the transported volume (tons per year), the capacity of the transport means (ton), and the emissions per transport means (kg per tonkm) according to Panteia (2023). The emissions of the transport means are assumed to decrease due to emissions reductions policies. Furthermore, there will still be greenhouse gas emissions from the electricity used throughout the supply chain, as the Netherlands will not have achieved a fully renewable (with some nuclear) energy mix in 2030 yet.

Table 19: Greenhouse gas emissions from ammonia storage and conversion (JRC2)

Emissions from storage and conversion in g/kg H_2eq in the Dutch part of the supply chain			
Carrier	chain component	type of emission	g/kg H_2eq
Pressurised or refrigerated NH_3	synthesis	H_2	4.3
Pressurised or refrigerated NH_3	Cracking	N_2O	0.00489

Elizondo et al. (2025)[101] on behalf of Environmental Defense Fund studied the impact of both direct and indirect N_2O emissions across the ammonia marine fuel value chain, including production, compression or liquefaction, distribution, storage, bunkering, and combustion. Their model incorporates N_2O, NO_x, and NH_3 emissions at each value chain stage under different scenarios, ranging from low to high emissions, and with various nitrogen-to-indirect-N_2O conversion rates.[102] We have decided to disregard the indirect N_2O emissions discussed in this present study and use the NOx and NH_3 emissions for the public interest Environment only. Direct N_2O emissions in the production chain are absent, but are substantial from engine fuel combustion (which is outside the scope of this study).

Energy loss

Various steps in the hydrogen carrier supply chains require energy input. This can be considered as energy loss. The energy input can be supplied externally (e.g., electricity for pumps or fuel for ships) or extracted from ammonia (during cracking). Leakage is also included in the energy loss.

Table 20 shows the energy losses per step in the ammonia chain up to its arrival in the Netherlands. The energy efficiency of the chains is determined by adding all energy losses of the steps and comparing them to the energy content of the final product: one kilogramme of hydrogen

[101] Sofia Esquivel-Elizondo, Blake Walkowiak, Stavroula S. Sartzetakis, and Brian Buma (2025). Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain. *Environ. Sci. Technol.* **59**, 9037–9048. https://doi.org/10.1021/acs.est.4c13135

[102] NH_3 engine slip and other NH_3 releases to the environment throughout the value chain, such as leaks, spills, and vented boil-off gas, are naturally removed by water bodies and atmospheric moisture and deposited on terrestrial and aquatic surfaces, where they undergo chemical and biological transformations into N_2O (and other nitrogen compounds). Similarly, NO*x* can be converted into N_2O in soil and water bodies. The nitrogen compound to indirect N_2O (N-to-N2Oi) conversion across various environments is still relatively poorly understood. Current data on N-to-N2Oi conversion, primarily derived from agricultural studies, estimate that 0.1–7.3% (depending on context) of the nitrogen in NH_3-based fertilisers is converted into N_2O, with some measured rates as high as 21%. Additionally, volatile NH_3 emissions that enter the atmosphere can react with OH radicals, converting ~1% of the nitrogen in ammonia into N_2O, driving ~8% of global anthropogenic N_2O emissions.

(equivalent). We assume no difference between pressurised or refrigerated ammonia for the import portion and for conversion, but only for storage.

Table 20: Energy loss or energy input per chain component until entry into the Netherlands (JRC1+2).

Carrier	H_2 production MJ/kgH_2	Ammonia production MJ/kgH_2	Storage before export MJ/kgH_2	3,000 km transport to the Netherlands, MJ/kgH_2
Refrigerated NH_3	180			2.5
Electricity		16.3	1.38	
Consumption of H_2 / carrier		0		
Losses			0.14	0.0

Table 21 and Table 22 show the energy input for the chain components within the Netherlands. Energy consumed for transportation is not included in the tables; this is calculated by combining the transported volume (tons per year), the capacity of the transport means (ton), and the energy use per transport means (MJ per tonkm) according to Panteia (2023).

Table 21: Energy loss (electricity and ammonia as fuel) for cracking in MJ/kg H_2 equivalent

Energy loss (electricity) in MJ/kg H_2 equivalent	Output	
input	H_2	NH_3
H_2		16.34
Refrigerated and pressurised NH_3	17.50	
Energy loss (ammonia as fuel for cracking) in MJ/kg H_2 equivalent	**Output**	
Input	H_2	NH_3
H_2		0.00
Refrigerated and pressurised NH_3	34.74	

There is also energy input during centralised refrigerated storage: this mainly concerns energy for stirring, transfer and re-liquefaction of ammonia vapour (boil-off). This is not applied in decentralised tanks, either pressurised spheres or cryogenic.

Table 22: Energy loss (electricity) for centralised (refrigerated) and decentralised (pressurised or refrigerated) storage in MJ/kg hydrogen equivalent (JRC)

Type of storage	Energy loss	
Refrigerated NH_3 - centralised	1.38	MJ per kg H_2eq
Refrigerated NH_3 - decentralised	0	MJ per kg H_2eq
Pressurised NH_3 - decentralised	0	MJ per kg H_2eq
Change from refrigerated to pressurised NH_3	0.03	MJ per kg H_2eq

Included in the table is also the change from refrigerated ammonia to pressurised ammonia, which requires energy input too. This occurs during the transfer of ammonia from refrigerated storage tanks to compressed storage tanks before loading rail tank cars, road tankers, or tanker vessels. It also occurs when ammonia is fed into a pipeline. The ammonia is heated by admitting ambient heat (from surface water or wastewater) through a heat exchanger. It takes 46 kWh to heat 1 ton of NH_3 from -33°C to +5°C, i.e. 0.03 MJ/kgH_2eq (market information).

Any change from pressurised to refrigerated ammonia elsewhere in the supply chain (at an inland receiving terminal) occurs through expansion (from a pressure storage tank to a refrigerated tank).

During this process, some of the liquid ammonia converts to a gas, which can be captured and utilised. This energy demand has already been factored into the energy used for storage (Table 22).

Therefore, there is a small energetic advantage in avoiding the changes between refrigerated and pressurised in the supply chain.

(Critical raw) material usage

This concerns the use of materials for installations, processes, and as raw materials for hydrogen carriers. If the hydrogen carrier supply chains require a large number of scarce or critical materials, we consider this less sustainable. We multiply the material requirements per unit of hydrogen equivalent by the volumes per chain, as follows from the calculations outlined earlier. We multiply the material requirements per chain by the market price, because we assume this price reflects the degree of scarcity of the materials (see Table 23). Market prices are, of course, snapshots. We assume no difference between pressurised and refrigerated ammonia.

Table 23: Values for (critical) material usage according to JRC2. Critical materials according to the European Commission list are in bold.

Conversion	Amount*	Market price**	Cost per kgH_2
NH_3 cracking			
Magnesium oxide (94%) and **Nickel oxide (6%)**	1.46 g/kgH_2, of which 6 mass% Nickel oxide with 78,6 mass% Nickel (Ni)	€ 16.79/kgNi	€ 0.0012/kgH_2

*) Source amount: JRC2

**) Source market price Nickel: www.lme.com (London Metal Exchange), https://www.lme.com/Metals/Non-ferrous/LME-Nickel#Summary

Table 24 shows the results of this exercise. If multiple conversion and synthesis steps occur in a chain, the corresponding values are added up.

Table 24: Calculated values for material usage in conversions from ammonia to hydrogen and vice versa

price of critical material usage per kton H_2 equivalent		H_2-eq output
Input	H_2	NH_3
H_2		€ -
NH_3	€ 1,156	

6. ADAPTABLE

By adaptable, we mean the extent to which hydrogen supply chains are future-proof. Technological and market developments can increase or decrease demand for hydrogen or ammonia, as well as for supply modalities. To quantify this indicator, we look at the additional, inflexible investments associated with the supply chains. The lower these investments, the more adaptable the supply chain.

For each supply chain, we add up the investments in components to arrive at a total investment amount. We do this based on literature and our own calculations of the required volumes: we determine how much ammonia must be stored, converted, and transported per supply chain by

applying weight percentages of hydrogen in ammonia and efficiencies within the supply chain. We calculate the required number of installations and transport vehicles based on assumptions about capacities and associated investment costs (from literature) and transport duration.

For the 2024 MCA of hydrogen carriers we have, together with experts, estimated the following for each chain component:

1. For each supply chain, the sum of investments in the chain components to arrive at a total investment amount. We do this based on literature and our own calculations of the required volumes supplied by the chains.
2. The portion that will not require investment in 2030 because there is already sufficient capacity, installations, or transport resources available for import flows; and
3. The portion of the investment value that can be reused or repurposed after 2030 if the market opts for other hydrogen carriers or modes.

We use these estimates also in this study, with the addition of refrigerated ammonia supply chains.

1. Total investment need

The total investment required to transport the volume of ammonia is determined by dividing the end-use by the annual volume to be transported per mode of transport, and multiplying the number of required modes of transport by the estimated investment per means of transport. There are differences between pressurised and refrigerated ammonia, see Table 25. We assume differences between pressurised and refrigerated ammonia for investments in transport equipment and storage, but not for conversion.

Table 25: Investments for transport of 100% end use in a single supply chain in 2030.

Chain component	Semi-trailer truck	Rail tank car	Barge	Pipeline incl. pumps/compressors
H_2	Out of scope	Out of scope	Out of scope	€ 260 million
Pressurised NH_3	1460 semis, total € 431 million	1460 tank cars, total € 326 million	65 barges, total € 974 million	€ 1024 million
Refrigerated NH_3	1460 semis, total € 628 million	1826 tank cars, total € 1004 million	57 barges, total € 1031 million	N/A

The total investment for the storage facilities and conversion plants was determined by multiplying the ammonia capacity by the investment per kiloton of carrier, see Table 26. This figure reflects the difference between the costs of centralised (refrigerated) and decentralised storage (pressurised or refrigerated).

Table 26: Investments for ammonia storage and conversion in million euro per kton ammonia (JRC)

	Conversion		Storage		
	Centralised	Decentralised	Centralised (refrigerated)	Decentralised (pressurised)	Decentralised (refrigerated)
NH_3 cracking	€ 0.69	€ 1.56	€ 0.65	€ 0.54	€ 0.75
NH_3 synthesis	€ 1.49	€ 1.49			

The next Table 27 shows the investments required for 100% end-use in a single chain by 2030.

Table 27: Investment needed for 100% ammonia end use in a single supply chain in 2030.

Chain component	Centralised storage port of entry	Centralised cracking to H_2	Decentralised storage	Decentralised cracking to H_2	Decentralised ammonia synthesis from H_2
Pressurised NH_3	N/A	8,884 ktons, total € 1,087 million	73 ktons, total € 39 million	8,884 ktons, total € 2,461 million	8,884 ktons NH_3, total € 2,345 million
Refrigerated NH_3	341 ktons, total € 221million		73 ktons, total € 55 million		

2. Part of investment present in 2030

Table 28 shows whether the required transport means are already available and whether they are available for importing hydrogen carriers. Many of the transport means are listed as being occupied. This indicates that although suitable transport means are available, they cannot be deployed because their capacity is being used for other purposes.

Table 28: Part of investments for transport means present in 2030

Chain component	Semi-trailer truck	Rail tank car	Barge	Pipeline incl. pumps/compressors
H_2 gaseous	Out of scope	Out of scope	Out of scope	Investment in H_2 network booked, to clusters
NH_3	Hundreds, occupied	Available, occupied	83 G type, occupied	Not committed in plans yet

Table 29 shows the current or planned availability of assets that can be used for the storage and conversion of ammonia. There is existing storage capacity for ammonia in several ports. Large-scale ammonia storage and transfer are not yet available anywhere except at existing production and consumption sites. For large-scale use, both as a feedstock and as a hydrogen carrier, significant expansion is required, as well as a dense distribution network. Few decentralised ammonia storage facilities are currently available, except at companies with ammonia refrigeration (pressurised).

Table 29: Part of investments for storage and conversion present in 2030.

Chain component	Centralised refrigerated storage in port of entry or at ammonia plant	Centralised cracking to H_2	Decentralised storage	Decentralised cracking to H_2	Decentralised conversion of H_2 to ammonia (synthesis)
NH_3	Refrigerated: 2 x 15 ktons OCI (today); 2 x 15 ktons Yara (today); 60 ktons new-build OCI (permitted, no FID); 2 x 20 ktons repurposing Vesta (permitted); 30 ktons new-build Vesta (permitted); various others with plans; pressurised buffer tanks at production sites	Not available, but there are initiatives	Pressurised at companies with ammonia refrigeration	Not available, but there are initiatives	Not available, no initiatives

The conclusion, as for the transport means, is that largely new installed base of storage and cracking facilities will have to be built for ammonia. Initial investments for this will be made shortly. For example, the company OCI has received a permit to build a 60 ktons storage tank for refrigerated ammonia in Rotterdam, scheduled for completion in 2030 and therefore counted as an investment already made.

3. Part of investment that is reusable for other purposes

The following Table 30 shows the share of transport assets that, according to expert judgment (for the 2024 MCA of hydrogen carriers), can be reused for a different product if ammonia as a hydrogen carrier proves less successful. In principle, all assets are occupied, but individual parties can redeploy transport resources.

- Transport means for ammonia are specifically designed and classified for ammonia, but they can in principle be repurposed for transporting LPG or CO_2. Reinspection and declassification of the vehicles or tank rail cars is possible but not done in practice. In practice, much transport is dedicated, meaning that a tank container is only used for the same substance and not for different substances throughout the year, to save the costs and time of cleaning between shipments. Furthermore, transporting a different substance in the cargo tank can lead to exceeding the axle load, preventing the tank from being completely filled; this latter point is not an issue for barges.
- Barges can be modified to transport substances other than those for which they were designed. The hull, engines, wheelhouse, etc., can be reused, while the storage tanks and piping must be replaced. Of the investment in pressurised ammonia tankers, 30% will then be reusable as dry cargo ships, or 25% in case of a cryogenic ammonia tank barge. For tank trucks and tank wagons, we assume that such a modification is not cost-effective for the owners.

- An ammonia pipeline can be reused for liquids, but stringent safety precautions are required for ammonia, making the pipeline more expensive than necessary for 'easier' products. Therefore, we calculate 50% of the investment as reusable (50% capital destruction).[103]

Table 30: Part of investment that is reusable for other purposes

Chain component	Tractor-semitrailer	Rail tank car	Barge	Pipelines incl. pumps/compressors
H_2 gas	Out of scope	Out of scope	Out of scope	100% reusable (biomethane)*
Refrigerated NH_3	0% reusable	No; 75%[104]	25% reusable	50% reusable
Pressurised NH_3	0% reusable	No; 75%	30% reusable	50% reusable

Ammonia storage tanks and ammonia cracking installations will be specifically designed and classified for these substances (0% of the investment is reusable). The choice of materials, process components and safety features are tailored to the properties of the substance for which they are intended (pressures, temperatures, corrosiveness, etc.).

7. FAIR

The public interest Fair is elaborated in two indicators: fairness for production countries and fairness for the people in the Netherlands.

- As an indicator for Fair with respect to the producing countries, we use the total value of the external effects in those countries (prior to importing into the Netherlands) per supply chain, and divide this by the costs of importing into the Netherlands for that supply chain. The higher the score, the more external costs are shifted to the producing countries and therefore the less fair it is. External effects included are environmental costs and greenhouse gas emissions abroad. The costs of importing are taken from the public interest Affordable, while the external costs abroad are derived from the JRC2-LCA study combined with environmental cost factors from CE Delft.
- The second indicator for Fair relates to external effects in the Netherlands. Dutch people experience impacts from the transport and conversion of hydrogen carriers, such as traffic emissions and noise, and the risk of accidents and incidents involving hydrogen carriers. The more these externalities are incorporated into the costs of hydrogen carriers for the end user, the fairer the situation from a 'polluter pays' perspective. We use the total value of the externalities (greenhouse gases, pollutant emissions, transport safety costs) in the Netherlands per chain and divide this by the costs of the Dutch chain components as determined for the public interest Affordable.

[103] Ammonia storage tanks can in principle also be reused for liquids such as methanol and some LOHCs, but even then excessive safety precautions are required, resulting in higher storage costs than when using tanks designed for these liquids.
[104] A 75% reusability rating for these specialty tank wagons only applies if there are not too many of them, otherwise the market will be flooded. The score was calculated based on 0%.

For both indicators, no additional data are needed for the exercise.

8. ACCESSIBLE

The public interest Accessible is expressed in two indicators: 1) Cost parity and 2) Physical proximity to the supply chains.

- An accessible cost level (cost parity) exists when companies throughout the land can participate in the hydrogen economy. The extent to which this is the case depends, among other things, on the cost level of the hydrogen carriers they can receive. The indicator for this public interest is the ratio of costs of hydrogen in the Dutch (or German) hinterland compared to the ports of entry. The variables for this comparison are derived from the public interest Affordable and need no additional data.
- Physical accessibility to hydrogen carriers is crucial to participate in the hydrogen economy, besides cost. Companies must be able to get hydrogen carriers to their location. To determine the accessibility of various hydrogen carriers in the hinterland, we use a methodology inspired by the factor of proximity in other domains.[105] We define this indicator as the number of industrial estates in the Netherlands connected by a road, railway station, inland port, or pipeline connection. Differences between pressurised and refrigerated ammonia do not matter for this exercise.

9. SPATIAL FOOTPRINT

We distinguish between refrigerated atmospheric tanks and pressure tanks for pressurised ammonia. Pressure tanks are available up to approximately 2-3 ktons.[106]

For the 2024 MCA of hydrogen carriers, the MKBV study on hydrogen carriers (2024) provided the space requirement for refrigerated ammonia storage terminals in m² per kton. This was determined by measuring the terminal surface area using aerial photographs. Additional information was obtained from experts at storage companies. One storage company estimated the space requirement for a new ammonia terminal at half the MKBV's estimate because new tanks are being built higher than before, and that is the figure we went with.

We have updated these figures based on a study by Haskoning (2025) that among other things assessed the spatial implications of hydrogen carrier terminals and conversion facilities in the port of Rotterdam.[107] Based on a generic layout of ammonia terminals and cracking facilities, the required surface area for different throughputs and capacities was estimated including storage area (the tanks with each 25-meter maintenance and safety zone), process area (e.g. for warming the ammonia before send-out) and offices and parking, see Table 31. Surface needed for the jetty and loading of rail tank cars or truck is not included. The surface required is higher than assumed in the 2024 MCA of hydrogen carriers, because it now includes the complete terrain. For pressurised ammonia tanks, the spatial needs were derived from the layout of an ammonia cracking facility

[105] See CBS proximity statistics.
[106] A 2,000-ton spherical tank with a recommended maximum filling of 85% has a volume of 4,000 m³, a radius of 10 m, and a surface area of 100 m². Adding an additional 10 m² of space around it results in a footprint of 200 m² per kton of ammonia and 1,126 m² per kton of H²-eq.
[107] Haskoning (2025). Systeembeschrijving waterstofketens. Ontwikkelingen in beeld voor NOVEX-traject Havengebied Rotterdam. 4 februari 2025.

with such storage onsite (2 pressurised buffer tanks for 3 kton NH_3 on 3,600 m^2 results in 1,200 m^2/ktonNH$_3$ and 6,756 m^2/ktonH$_2$eq, see bold in Table 31).

The MKBV study also provided the footprint of ammonia conversion facilities (79 m^2/kton of hydrogen equivalent), based on the feasibility study for ammonia cracking in Rotterdam.[108] The Haskoning study confirms this value (see bold in Table 31).

Table 31: Use of space for storage and cracking of ammonia in m^2 per kton (Haskoning)

Storage terminal					
Throughput kton/a	**Capac-ity kton**	**Facilities**	**Surface m^2**	**m^2/ktonNH$_3$**	**m^2/ktonH$_2$eq**
500	14	2 full containment tanks, Ø25m, height 30m	7,700 total; 1,500 process area, 5,500 storage area, 700 offices/parking	total: 550 storage area: 393	**3,097** 2,212
2,000	55	2 full containment tanks, Ø45m, height 30m	18,700 total; 6,000 process area, 11,000 storage area, 1,700 offices parking	total: 340 storage area: 200	**1,914** 1,126
5,000	136	2 full containment tanks, Ø69m, height 30m	37,500 total; 15,000 process area, 19,000 storage area, 3,500 offices/parking	total: 275 storage area: 140	1,552 787
Cracking facility with buffer storage					
Throughput kton/a	**Capac-ity kton**	**Facilities**	**Surface m^2**	**m^2/ktonNH$_3$ (through-put)**	**m^2/ktonH$_2$eq (throughput)**
500	**3**	1 cracking unit **2 pressurised buffer tanks Ø17m**	8,700 total; 4,400 process area, **3,600 storage area**, 700 of-fices/parking	total: 17.4 process area: 8.8 storage area: 7.2	98.0 49.5 40.5
2,000	7	2 cracking units 5 pressurised buffer tanks Ø17m	29,500 total; 18,000 process area, 9,000 storage area, 2,500 offices/parking	total: 14.8 process area: 9.0 storage area: 4.5	83.0 50.7 25.3
5,000	18	5 cracking units 12 pressurised buffer tanks Ø17m	70,000 total; 44,000 process area, 20,000 storage area, 6,000 offices/parking	total: 14.0 process area: 8.8 storage area: 4.0	**78.8** 49.5 22.5

Subsequently, the required storage space (in m^2) for each chain was determined for a volume of 14 days' supply/transit at import and 3 days at the end user. The required spatial investment for this was determined by multiplying the square meters by the industrial land price (304 euros/m^2). This industrial land price is based on the MKBV and adjusted for price levels and site preparation. The required footprint for the conversions (in m^2) per chain is determined by multiplying the annual hydrogen equivalent volume. The spatial investment required for this is determined by multiplying the surface in square meters by the industrial land price.

[108] The Executive summary pre-feasibility study large-scale industrial ammonia cracking plant mentions a higher footprint of 200-450 m^2 per kton of hydrogen capacity, but this also includes storage space.

For pipelines, we calculate a representative route of 200 km, see Table 32. The footprint is 5 meters on both sides, resulting in 10,000 m² per km of pipeline length.[109] The route runs 180 km through rural (agricultural or nature) areas and 20 km through or alongside built-up areas. A pipeline for ammonia must be newly constructed. The national hydrogen network largely uses existing natural gas pipelines; 40 km of new pipelines must be constructed to connect industrial estates, 20 km of which will be through rural areas and 20 km through industrial areas. We assume that the spatial investment for new pipelines on agricultural land is €8/m² and on industrial land €304/m². We assume no difference in the space required for a pipeline for pressurised or refrigerated ammonia.

Table 32: Summary of values for determining the spatial investment in pipelines for hydrogen carriers

	existing pipeline	new on agricultural land	new on industrial land	unit
NH_3 pipeline	0	180	20	km
H_2 network	160	20	20	km
land value		8	304	€ / m²
Surface	10,000			m² per km length

10. ENVIRONMENT

JRC2 provides emissions per kilogramme of hydrogen equivalent for the various chain components, including cracking of ammonia to hydrogen or the reverse synthesis. The following emissions occur with ammonia (Table 33). No distinction is made between pressurised and refrigerated ammonia as no such data are available.

Emissions during transport are not included in the table; these are calculated by combining the transported volume (tons per year), the capacity of the transport means (ton), and the emissions per transport means (kg per tonkm) according to Panteia (2023).

The assumption for all modes of transport including the ammonia pipeline designed and modelled by ISPT is that there are no regular losses, emissions or leakages from the system (pipeline, valves, and pumping stations), as the monitoring, design, and safeguarding are aimed at avoiding and preventing regular (and incidental) losses, emissions and leakages. In the event of an incident, the Emergency Shutdown limits the loss to the content of a 5 km segment, which is app. 500 tons of ammonia. The segment will be empty within 1,800 seconds. For comparison, the maximum loss is 25 tons from one tank truck, 50 tons from one rail tank car, and 600 tons from one cargo tank on a barge. A collapsing storage tank may release 15 ktons of ammonia.

[109] Ministerie van Economische Zaken en Klimaat, Ontwerp-Programma Energiehoofdstructuur, Ruimte voor een klimaatneutraal energiesysteem van nationaal belang, 2023.

Table 33: Emissions from storage and conversion of refrigerated and pressurised ammonia (JRC2, EDF)

Emissions from ammonia storage and conversion in g/kg H_2eq in Dutch part of the chain			
chain step	**type of emission**	**g/kg H_2eq**	**source**
storage	NH_3	0.0011	JRC, EDF****
Cracking	NH_3	0.007*	JRC
Cracking	NOx	0.14**	Feasibility study cracker
Synthesis	NH_3	9.18***	JRC
Synthesis	NOx (after DeNOx)	0.39	JRC
Emissions from ammonia storage and conversion in g/kg H_2eq in producing countries			
Storage	NH_3	0.0011	JRC
Synthesis	NH_3	9.18***	JRC
Synthesis	NOx (without DeNOx)	5.63	JRC

*) Based on JRC2. Antea (2025) calculate an emission of 0.0563 g/kgH2eq, almost tenfold higher, based on various calculations performed confidentially for a number of companies. Therefore, we decided not to change the input to our modelling.

**) Based on the feasibility study for the Rotterdam ammonia cracker. This study assumes an emission standard that, at a production rate of 1 Mton of H_2, leads to an annual NOx emission of 140 ton/year (93% reduction). This value was also used in the MKBV study (2024). We assume that ammonia synthesis also uses post-treatment that reduces NOx emissions by 93%. Antea (2025) calculate an emission of 0.076 g/kgH_2eq, roughly half, based on various calculations performed confidentially for a number of companies. Therefore, we decided not to change the input to our modelling.

***) JRC estimates that for 1 kg ammonia produced, up to 1.63 g of ammonia is emitted (0.16%). Esquivel-Elizondo et al. assign an NH_3 emission rate of 0.01–0.5% of the ammonia produced in the emissions, based on satellite observations quantifying site-level NH_3 emissions. As the JRC figure is in this range, we decided to keep using it for our modelling.

****) A recent study on emissions across the ammonia marine fuel value chain for the Environmental Defense Fund confirms the JRC value. [110]

A disaster involving the storage, transport, or conversion of ammonia may impact the environment as well as people. We investigated whether a spill constitutes a significant effect beyond the environmental impacts discussed previously. The calculation method is to multiply the probability of the incident according to the national risk manual by the released volume and by the environmental price of the substance according to the CE Delft environmental price manual. The effect of the environmental disaster was found to be just 0.1% of the total environmental costs. Due to this result, and while the impact on the habitat in the vicinity of the disaster is potentially very significant ('dead zones'), we disregard the environmental impact of disasters such as spills. [111]

To provide further context, total ammonia emissions in the Netherlands in 2023 amounted to 116 million kg ammonia. 90% is caused by agriculture, and 2,1% is from the industry and waste

[110] Sofia Esquivel-Elizondo, Blake Walkowiak, Stavroula S. Sartzetakis, and Brian Buma (2025). Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain. *Environ. Sci. Technol.* **59**, 9037–9048. https://doi.org/10.1021/acs.est.4c13135

[111] Another study for the Environmental Defense Fund assessed the impacts for various types of habitats of acute large-event spills of ammonia used as a shipping fuel during bunkering or after a ship's collision or sinking. The study concluded that estuaries, mangroves and wetlands are particularly sensitive, and typically the fish. It calls for the development of a robust regulatory framework for ammonia as a shipping fuel including suitable mitigation measures. EDF (2022). Ammonia as a Shipping Fuel: Impacts of large spill scenarios. Environmental Assessment Report. With Ricardo and Lloyd's Register. November 2022.

sectors, i.e. 2.4 ktons. Behind glass wool producer Rockwool, ammonia producers Yara and OCI are leading the top-100 list of individual ammonia emitters (259, 254 and 114 tons in 2019, respectively, which is mainly made up of cattle farmers. [112] A spill from a pipeline, barge, bunker barge or even more so an ocean gas tanker would be high up in this top-100 list.

Reported emissions by Yara and OCI are 0.01% of their production capacity of 1.9 and 1.2 million tons per year. Both companies are investing in measures to reduce their ammonia emissions further, including diffuse emissions involving ammonia attaching itself to the products that are made with ammonia. Minimising the ammonia emissions is essential for the license to operate of ammonia companies, as even the smallest emissions will cause penetrant smell and nuisance for the population.

[112] Sources: CBS website; Natuur & Milieu (2025). Schade aan de leefomgeving door de Nederlandse industrie; Top 100 ammoniakuitstoters 2019.

ANNEX E: SCORES FOR PUBLIC INTERESTS

This annex presents the results for all the public interests and indicators. It first shows the normalised scores for each public interest for the baseline situation in 2030. The results for the baseline situation and sensitivity analysis for decentralised storage are followed by the results for the variants: 1) end use in the port of entry, and 2) transit and export. Further details about the calculations are given in Annex D.

1. SCORES FOR PUBLIC INTEREST AFFORDABLE

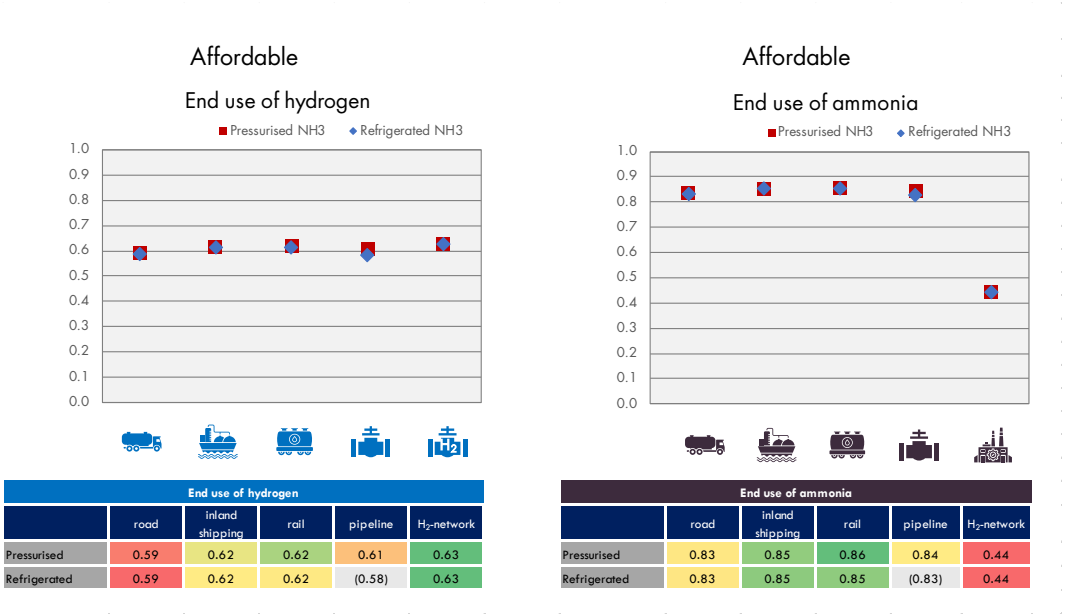
Figure 26 shows the normalised scores for the affordability of hydrogen and ammonia for the various supply chains for inland use. The higher the score, the lower the cost price per kilogramme of hydrogen equivalent. The bandwidth used is 2.50 euros (score 1) to 8 euros (score 0).

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

Results for baseline situation (2030, inland end use)

Ammonia has the highest scores if this substance is used directly (right-hand chart, Figure 26), without cracking. The scores are lower when conversion to hydrogen is necessary (left-hand chart). A combination of centralised cracking and synthesis to ammonia at the end user results in the lowest scores. This is due to the costs for cracking and conversion back (synthesis) to ammonia and the use of ammonia as fuel for the cracking process.

The choice of inland transport mode has little effect on the overall costs due to low transport and storage costs compared to the import costs. As differences between refrigerated and pressurised ammonia only affect the domestic transport costs and subsequent storage, the differences are small and do not result in different values. Only the colour coding indicates that pressurised ammonia chains have a (slightly) higher score than refrigerated ammonia chains (less than one percent point) due to the more costly equipment needed for storing and transporting refrigerated ammonia. This outweighs the costs of heating the stored refrigerated ammonia before transporting it in pressurised form (ambient heat is generally used). The exception is the value between brackets for the chain with fictitious refrigerated ammonia pipeline transport. The maximum difference for Affordable is 3 percent points even though the domestic transport costs of refrigerated ammonia by pipeline are assumed to be twice as high. That is because the import costs make up the largest part of the costs for the end user.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.59	0.62	0.62	0.61	0.63
Refrigerated	0.59	0.62	0.62	(0.58)	0.63

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.83	0.85	0.86	0.84	0.44
Refrigerated	0.83	0.85	0.85	(0.83)	0.44

Figure 26: Scores for Affordable for inland supply chains in 2030; hydrogen end use and ammonia end use

- Pressurised ammonia supply chains have overall slightly higher scores than refrigerated ammonia chains, as domestic transport and decentralised storage of refrigerated ammonia have higher costs than of pressurised ammonia.
- Rail transport and inland shipping have the highest scores for ammonia transport due to the lowest transport costs per hydrogen equivalent. Transport of hydrogen through the hydrogen network requires less costs and has the highest scores in case of hydrogen end use, but the differences between the alternateives are small, because import costs are much higher than domestic transport costs.

Results for variants

Port of entry

End use in the port of entry improves the Affordable score compared to the baseline situation. There are no longer any differences between the transport modes, as there are no inland transport and storage costs.

Since the only differences between refrigerated and pressurised ammonia supply chains occur due to differences in domestic transport costs and storage, there is no difference in scores between the two forms.

Transit and export

The scores for Affordable for transit to Germany or Belgium are the same as in the baseline situation, because the costs for the end user do not change.

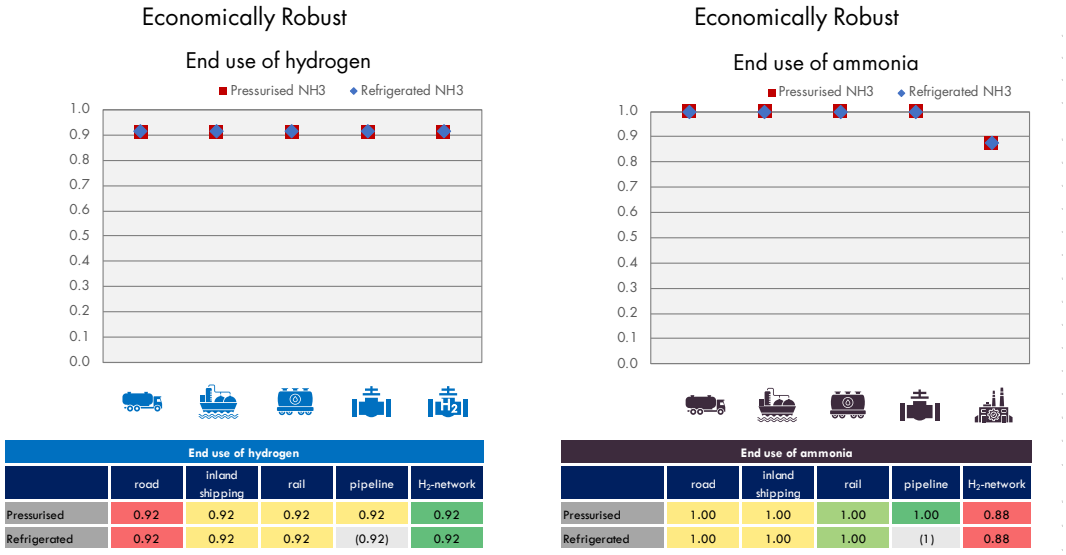
2. SCORES FOR PUBLIC INTEREST ECONOMICALLY ROBUST

Figure 27 shows the normalised scores for the public interest Economically Robust for the various supply chains for inland use. The higher the score, the higher the added value in the Netherlands. The scores are corrected for congestion and public infrastructure costs. The bandwidth used is 1.30 euros (score 0) to 8.60 euros (score 1) per kilogramme of hydrogen equivalent.

Results for baseline situation (2030, inland end use)

The scores for Economically Robust correlate strongly with those for Affordable, even though the costs of transport in the Netherlands do not apply. These costs are part of the added value, but they are small compared to other costs, as are the costs of congestion and the use of public infrastructure. The latter two cost types collectively account for less than 1 percent of the added value and therefore have little effect on the differences between the supply chains. Loss of ammonia during cracking is decisive: chains without cracking score highest (right-hand vs. left-hand chart).

Though there is a difference in the domestic transport costs of pressurised and refrigerated ammonia, the difference between the sales value (corrected for congestion and infrastructure costs) and import value is exactly the same. Therefore, there is no difference in the scores between pressurised and refrigerated ammonia. In both chains, ammonia is imported in refrigerated state.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.92	0.92	0.92	0.92	0.92
Refrigerated	0.92	0.92	0.92	(0.92)	0.92

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	1.00	1.00	1.00	1.00	0.88
Refrigerated	1.00	1.00	1.00	(1)	0.88

Figure 27: Scores for Economically Robust for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains.
- Road transport has lower scores than other transport modalities due to costs of congestion and infrastructure use, but the differences are small and visible only in the ranking colours.

Results for variants

Port of entry

End use in the port of entry improves the score compared to the baseline situation, except for the supply chains based on pipeline transport. For end use in the port of entry, there are no differences between the transport modes. This is because the social costs of congestion and use of public infrastructure do not apply. The effect of this is limited and the differences between the baseline and use in the port of entry do not lead to noticeable changes in the scores. Since there were no differences between refrigerated and pressurised ammonia in the baseline, there are none in this variant either.

Transit and export

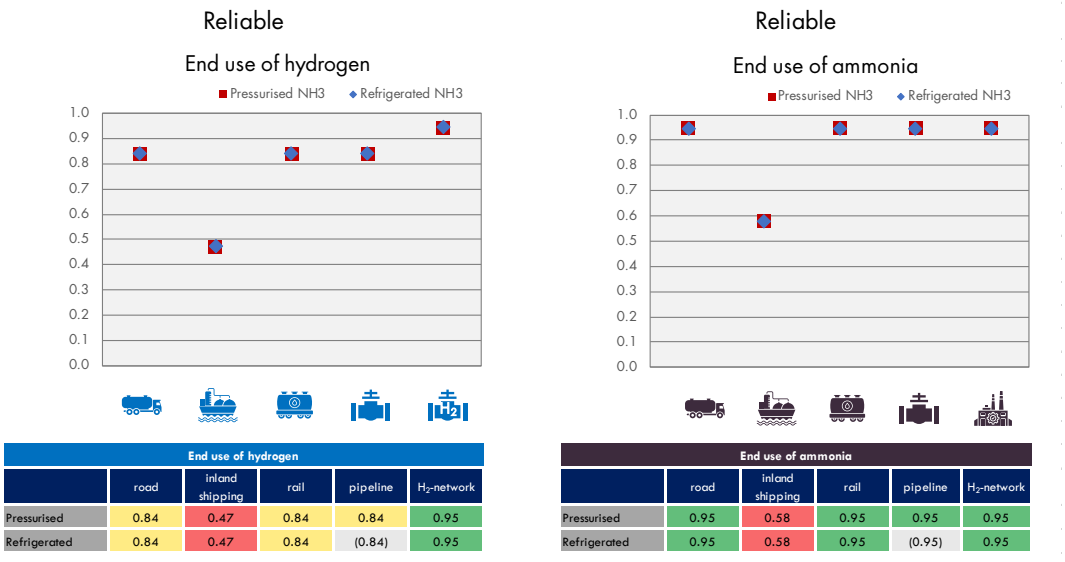
The scores for transit and export to Germany are lower than in the baseline situation. This is because the added value of storage and conversion at the end user's site does not apply. The added value is assigned in proportion to the division of costs between the Netherlands and Germany or Belgium. This means that, if 30 percent of the costs between import and the end user for transit and export are incurred in Germany, we assume that 30 percent of the added value between import and the end user will also end up in Germany. Because most of the transit costs are assumed in the Netherlands and the decentralised storage costs occur abroad and both cost items are not the same for refrigerated and pressurised ammonia, minimal differences arise. For road transport and transport by barge, the balance is favourable for pressurised ammonia. For refrigerated ammonia, the balance is favourable for rail and pipeline transport.

3. SCORES FOR PUBLIC INTEREST RELIABLE

Figure 28 shows the normalised scores for Reliable. The higher the score, the more reliable the supply chain is in the opinion of the consulted experts. The scores are relative. The supply chain assessed as worst is awarded a score of 0. A supply chain that is no less reliable than the existing natural gas network is awarded a score of 1.

Results for baseline situation (2030, inland end use)

The resulting scores for pressurised and refrigerated ammonia chains are equal: equipment and chains are mature/TRL9 in 2030 for both.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.84	0.47	0.84	0.84	0.95
Refrigerated	0.84	0.47	0.84	(0.84)	0.95

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.95	0.58	0.95	0.95	0.95
Refrigerated	0.95	0.58	0.95	(0.95)	0.95

Figure 28: Scores for Reliable for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains.
- Inland waterway transport has lower scores than other transport modalities due to reliability risks from prolonged low water periods.

The choice of transport mode sometimes results in a difference in scores for the public interest Reliable. Road, rail, and pipeline are comparably reliable, but transport by water has a lower score and transport through the hydrogen network a higher score.

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

Transport through the hydrogen network has the highest score in the left-hand chart, as decentralised conversion to hydrogen is not required; the conversion takes place in the port of entry. If a supply chain includes decentralised conversion, this will result in slightly lower reliability in the opinion of the experts. Centralised cracking to hydrogen is considered to have no negative impact on reliability.

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

Results for variants

Port of entry

Since the resulting scores for pressurised and refrigerated ammonia chains are equal in the baseline, the variants show no differences between the two forms of ammonia.

End use in the port of entry improves the reliability of various supply chains compared to the baseline situation. This is particularly the case for transport by inland shipping, as the transport process is no longer affected by high and low water levels. The drawbacks associated with decentralised conversion are also eliminated, as all conversion is centralised.

Transit and export

For end use in Germany or Belgium, the reliability of decentralised storage and conversion is not affected. There are no differences between scores for refrigerated and pressurised ammonia.

4. SCORES FOR PUBLIC INTEREST SAFE & SECURE

We have analysed the public interest Safe & Secure using three indicators: 1) External safety (non-deliberate accidents), 2) Cyber security and terrorism i.e. protection against cyber attacks and terrorism (deliberate disruptions and incidents) and 3) Transport safety. The scores for External safety and Cyber security and terrorism dominate, due to the high weighting factors. This chapter begins with a description of the combined and weighted results for the public interest Safe & Secure. The results for each indicator with differences for refrigerated and pressurised ammonia are then explained.

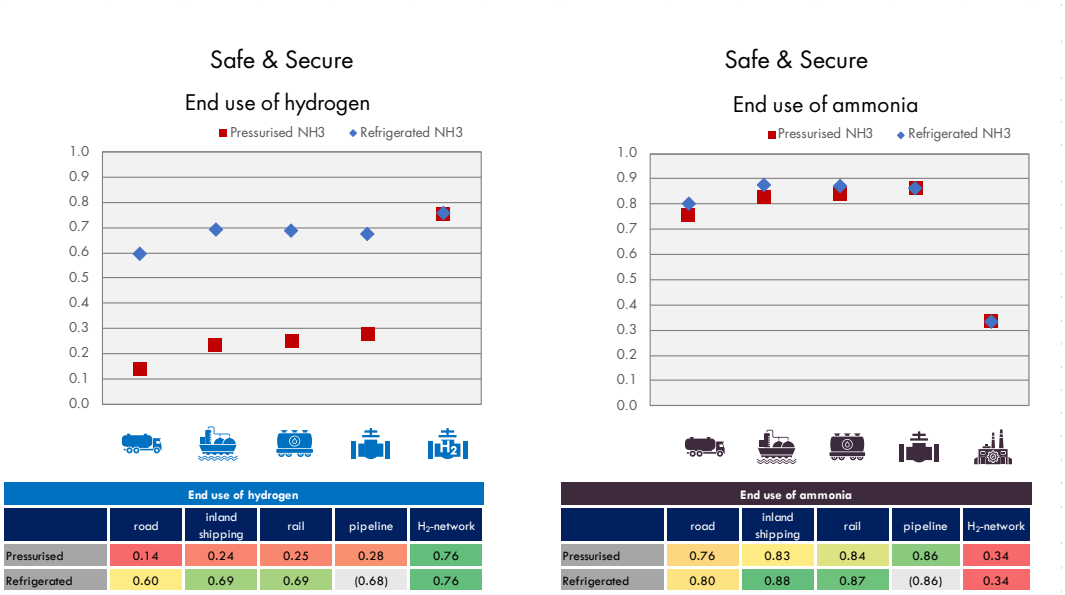
The higher the score, the safer the supply chain is based on the opinion of the experts. The scores are relative. The supply chain assessed as least safe is assigned a score of 0. A supply chain without any safety and security risks is assigned a score of 1.

Results for baseline situation (2030, inland end use)

The combined and weighted results for the public interest Safe & Secure[113] are shown in Figure 29. This consistently shows lower scores for supply chains for pressurised ammonia than for refrigerated ammonia, due to the potential larger impact of a toxic gas leak. In accidents involving pressurised ammonia, a toxic gas cloud almost always forms immediately, while for refrigerated ammonia a pool of ammonia forms first before a toxic gas cloud arises. It takes the cold liquid time to evaporate into a toxic gas cloud.

The lowest scores are for supply chains that include decentralised pressurised ammonia storage (the first four supply chains in the left-hand chart). That is because the risk score of decentralised pressurised storage dominates the supply chain risk score.

Transport by road has the lowest score, as it has the highest probability of traffic accidents (indicator Transport safety, part of the composite indicator Safe & Secure) and the highest External safety risk classification according to the experts, in spite of a lower risk classification for Cyber security and terrorism (being a less attractive target than trains, barges and pipelines which transport larger volumes).



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.14	0.24	0.25	0.28	0.76
Refrigerated	0.60	0.69	0.69	(0.68)	0.76

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.76	0.83	0.84	0.86	0.34
Refrigerated	0.80	0.88	0.87	(0.86)	0.34

Figure 29: Scores for Safe & Secure for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have higher scores than pressurised ammonia, because in the event of an incident (breach or leak), refrigerated ammonia must first evaporate before a toxic cloud forms, giving more time to respond.
- Road transport has the lowest scores due to the highest probability of accidents (indicator Transport safety) and the highest External safety risk classification according to the experts, in spite of lower risk classification for Cyber security and terrorism.

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

The scores for transport by rail are higher than for transport by road, because the probability of traffic accidents is lower (Transport safety) and because experts assessed the external safety risk classification as lower.

Rail transport also has higher scores than inland waterways in most situations in Figure 29. Although inland waterway transport has a lower external safety risk classification, this advantage is insufficient to compensate for its higher Transport safety and Cybersecurity and terrorism risks classification.[114] The exception is end use of ammonia in refrigerated supply chains, where the External safety advantage of inland waterways is decisive and results in a higher combined Safe & Secure score than rail.

The score for ammonia pipeline transport is only slightly higher than for rail and waterway transport despite no probability of traffic accidents (by definition) and the low risk classification for External safety. This is because it has a higher risk classification for cyber attacks or terrorist attacks, according to the experts. Plants and pipelines containing ammonia are – more than is the case for other hydrogen carriers – seen as attractive and probable targets for cyber attacks and terrorist attacks in the eyes of the experts.

Sensitivity analysis: all decentralised storage refrigerated and normalisation scale is adjusted

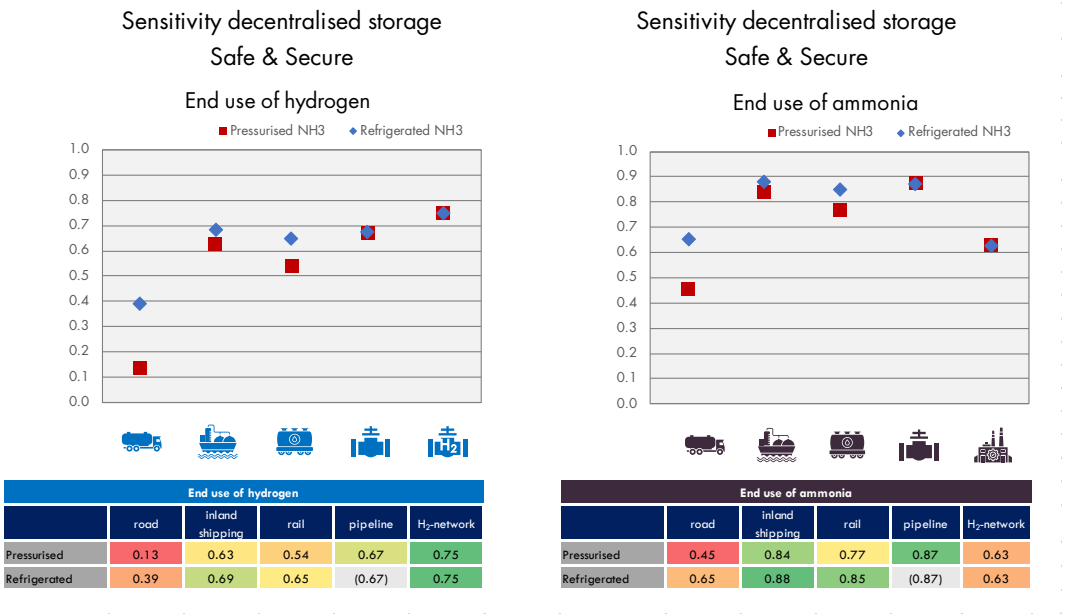
Decentralised storage has a dominant impact on the scores. We are also interested in the impact due to the other elements of the supply chain such as transport modalities. That is why a sensitivity analysis is done to discover how large the differences are due to variations in transport modalities if the decentralised pressurised storage component were replaced by refrigerated storage, for supply chains with transport of pressurised ammonia.[115]

Figure 30 shows that refrigerated ammonia supply chains still have higher scores than pressurised ammonia chains, but the difference with pressurised supply chains is now smaller than in Figure 29 (baseline), due to elimination of differences in decentralised storage.

The differences in scores between the transport modalities for one type of ammonia are larger in Figure 30 than in Figure 29. The differences between transport modalities now have more impact on the Safe & Secure score because the differences are not overshadowed by the major impact of decentralised storage on the normalisation scale. Road transport has the lowest scores.

[114] In the expert session of 2024, a worst-case scenario was considered, namely the outflow of the entire cargo. Ammonia tankers consist of multiple compartments (typically 4). This impact is also used to determine the Cyber security and terrorism risk. Another scenario is that one compartment leaks, with higher probability but smaller impact. We cannot determine retrospectively whether this leads to a higher total risk. The experts at the time did not consider this alternative scenario to be the worst case.

[115] In the 2024 MCA of hydrogen carriers, the risk of decentralised storage was assumed to be 3/14 of the risk of centralised storage (refrigerated). When distinguishing between refrigerated and pressurised ammonia, this turns out to be incorrect. Storage under pressure has a higher risk classification than refrigerated storage. As a result, in the present analysis, the difference between the ideal score (zero risk) and the chain with the worst score has increased, expanding the normalisation scale. This means that the same difference in risk classification as in the 2024 MCA of hydrogen carriers now results in a smaller difference in score.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.13	0.63	0.54	0.67	0.75
Refrigerated	0.39	0.69	0.65	(0.67)	0.75

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.45	0.84	0.77	0.87	0.63
Refrigerated	0.65	0.88	0.85	(0.87)	0.63

Figure 30: Scores for Safe & Secure for inland supply chains in 2030; hydrogen end use and ammonia end use (all decentralised storage refrigerated)

- Refrigerated ammonia supply chains still have higher scores than pressurised ammonia chains, but the difference with pressurised supply chains is smaller than in the baseline, as differences in decentralised storage are eliminated.
- Road transport still has the lowest scores. The differences between the modalities are larger in the sensitivity analysis with all decentralised storage refrigerated than in the baseline. The reason is that the expansion of the normalisation scale which was needed to accommodate the decentralised storage scores is now reversed.

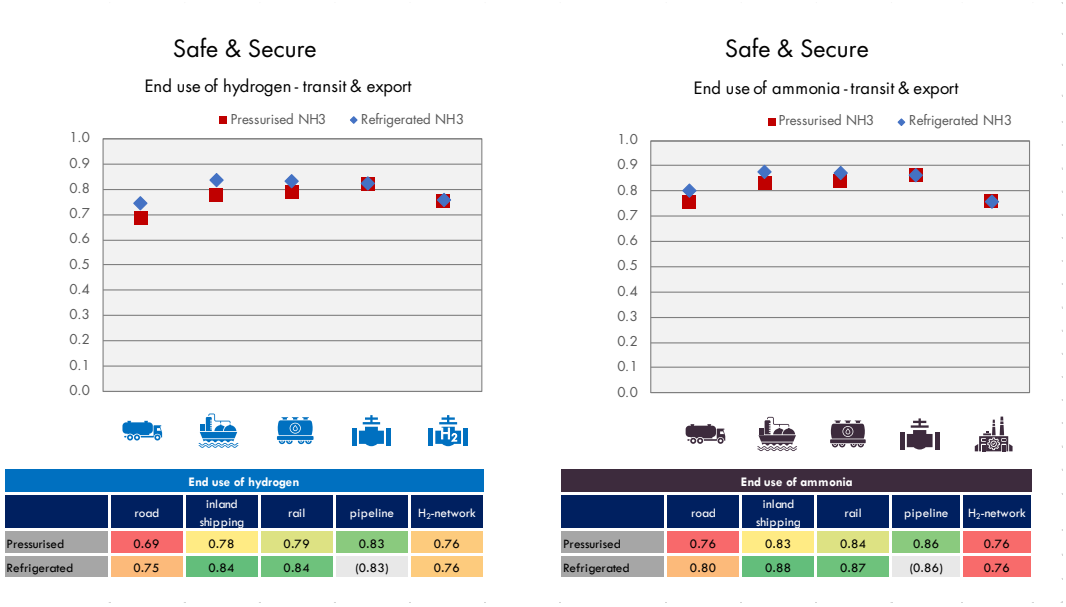
Results for variants

Port of entry

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

Transit and export

For end use in Germany or Belgium, the safety and security risks (risk to Dutch society) of decentralised storage and conversion are not taken into account. This improves the score for the supply chains that include decentralised conversion and/or storage compared to end use in the Netherlands, see Figure 31. Since decentralised storage of pressurised ammonia is dominant for the safety risks and the difference between pressurised and refrigerated ammonia scores, this results in a smaller difference between supply chains with pressurised and refrigerated ammonia. Only the differences that can be attributed to the transport means remain.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.69	0.78	0.79	0.83	0.76
Refrigerated	0.75	0.84	0.84	(0.83)	0.76

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.76	0.83	0.84	0.86	0.76
Refrigerated	0.80	0.88	0.87	(0.86)	0.76

Figure 31: Scores for Safe & Secure for transit and export supply chains in 2030; hydrogen end use and ammonia end use

External safety (indicator for Safe & Secure)

For all incidents, there is a very small probability of occurrence. However, refrigerated ammonia supply chains have much higher scores than pressurised ammonia chains due to the lower impact in case of a toxic gas leak, in particular if decentralised storage is part of the supply chain (first four columns in the left-hand chart).

The supply chain with the lowest score for External safety is the supply chain with pressurised ammonia transported by road. The supply chain with the highest score for External safety is the supply chain without cracking/conversion and without decentralised storage and transport by pipeline.[116]

The difference between these two extremes is explained by the following:

- The storage of *pressurised* ammonia determines the difference in external safety risk score. This risk score dominates the score for Safe & Secure. Supply chains which include decentralised storage of pressurised ammonia have a low score while chains without this kind of storage have a much higher score, sometimes even rounded to 1.00. This does not mean that there is no risk, but the risk score is less than 1/200th of the risk score of the chain with decentralised storage and cracking and road transport of pressurised ammonia.
- Of all supply chains with decentralised storage and cracking, road transport has the lowest score. The modalities in descending order of risk classification are road, rail, inland shipping, and pipeline.

[116] There are no detailed results for pipeline transport of refrigerated ammonia. Therefore, the supply chain with the highest score is pipeline transport of pressurised ammonia. For all modalities where both pressurised as refrigerated ammonia are assessed, the supply chains with refrigerated ammonia have a higher score.

The risk classification for transport of *refrigerated* ammonia by road, rail or inland shipping is significantly lower because the refrigerated ammonia needs to evaporate first in the event of an incident (breach, leak). The scores in Figure 32 show that the differences in risk classification between the modalities are smaller for refrigerated ammonia (maximum spread 11 percent point) than for pressurised ammonia (maximum spread 21 percent point).



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.00	0.20	0.16	0.21	0.99
Refrigerated	0.88	0.99	0.97	(0.99)	0.99

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.84	1.00	0.96	1.00	0.37
Refrigerated	0.92	1.00	0.98	(1.00)	0.37

Figure 32: Scores for External safety for inland supply chains in 2030; hydrogen end use and ammonia end use

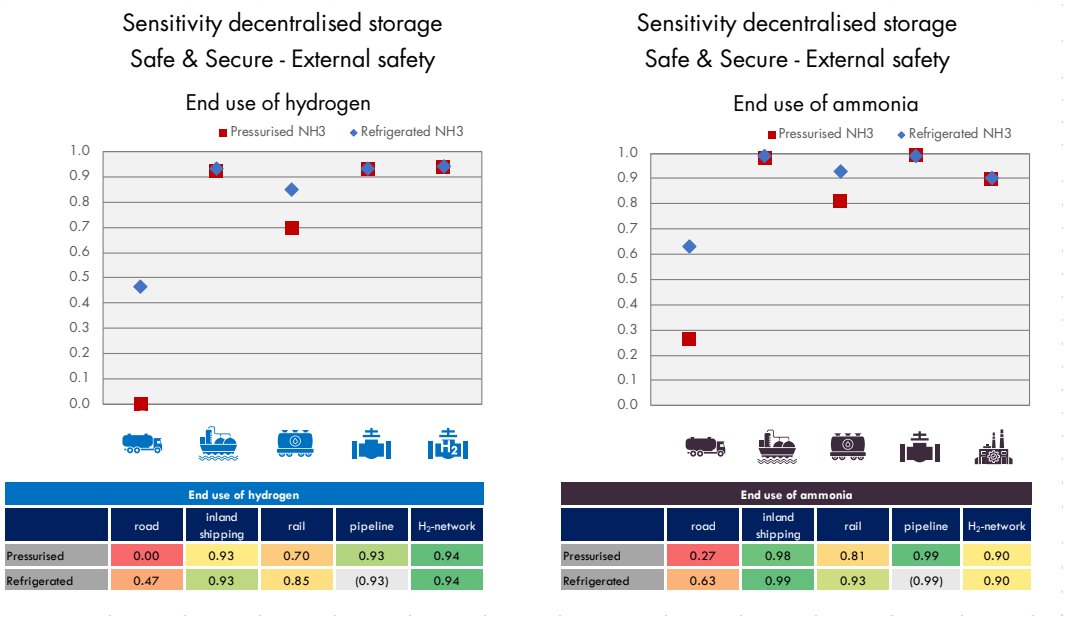
- Refrigerated ammonia supply chains have much higher scores than pressurised ammonia chains due to the lower impact in case of a toxic gas leak, in particular if decentralised storage is part of the supply chain.
- Road transport has the lowest scores due to the highest external safety risk, despite the smaller volume compared to other transport modes.

Sensitivity analysis: if all decentralised storage is refrigerated and normalisation scale is adjusted

Because of the dominant impact of the decentralised storage, a sensitivity analysis is done to discover how large the differences are due to variations in chains and transport modalities if there are no differences in the decentralised storage chain component.

In the baseline situation it is assumed that domestically transported refrigerated ammonia is stored refrigerated before cracking to hydrogen and domestically transported pressurised ammonia is stored pressurised before cracking to hydrogen. If decentralised storage is assumed not to differ between the chains but done refrigerated across the board, Figure 33 shows that there are indeed significant differences between the transport modalities (maximum spread 47 percent point for refrigerated ammonia and 93 percent point for pressurised ammonia), compared to Figure 32. The external safety risk classifications are lowest for pipeline transport and inland shipping. In these cases, the risk score of domestic transport does not determine the risk score of the whole supply chain. The risk score of decentralised refrigerated storage determines the total risk. In case of transport by road or rail, the contribution of domestic transport to the total risk classification is larger than of the decentralised storage of refrigerated ammonia.

For inland waterway transport, the difference in external safety scores between pressurised and refrigerated ammonia is negligible for both hydrogen and ammonia end use. This is because the external safety risk classification per barge is inherently low compared to road and rail transport. Although refrigerated ammonia is safer than pressurised ammonia, partly because approximately half of any spill dissolves in water, the absolute difference in risk classification between the two forms is small relative to the differences observed for road transport.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.00	0.93	0.70	0.93	0.94
Refrigerated	0.47	0.93	0.85	(0.93)	0.94

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.27	0.98	0.81	0.99	0.90
Refrigerated	0.63	0.99	0.93	(0.99)	0.90

Figure 33: Scores for External safety for inland supply chains in 2030; hydrogen end use and ammonia end use (all decentralised storage refrigerated)

- Refrigerated ammonia supply chains have higher scores than pressurised ammonia chains, but the difference with pressurised supply chains is smaller compared to the baseline, as differences in decentralised storage are eliminated.
- Road transport still has the lowest scores. The differences between the modalities are larger than in the baseline because these differences are not overshadowed by the major impact of decentralised storage on the normalisation scale.
- The differences between refrigerated and pressurised ammonia via inland waterway transport seem negligible as the external safety risks are small compared to rail and road transport.

Cyber security and terrorism (indicator for Safe & Secure)

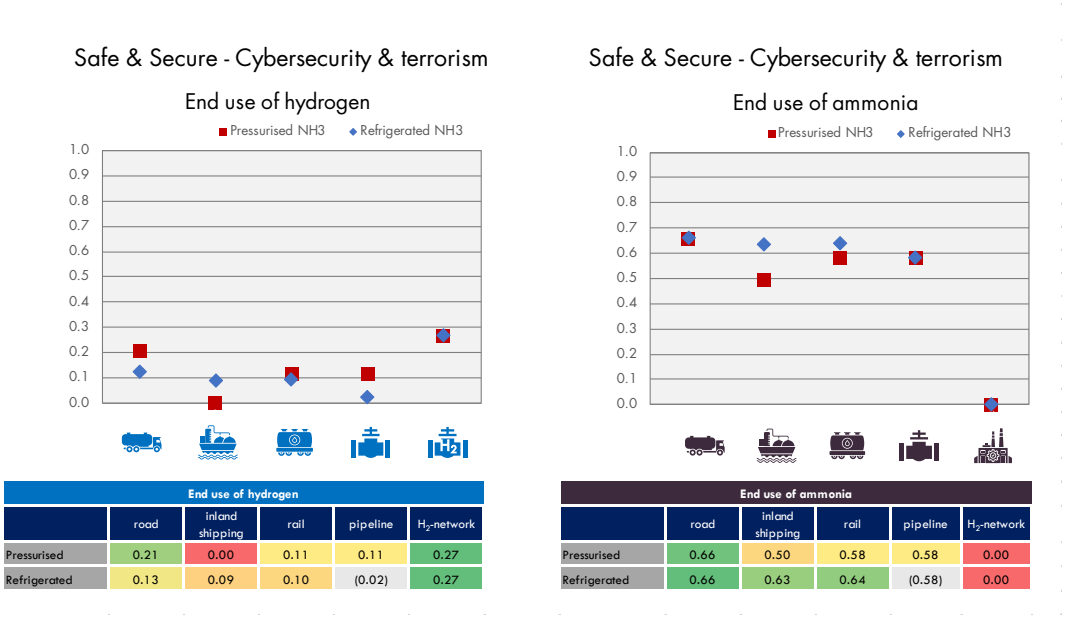
The experts expect that any cyber or terrorist attacks will probably be targeted at supply chain assets and substances with the largest negative impact, rather than on supply chain assets and substances with less catastrophic effects. Therefore, the likelihood of an incident or attack on a storage tank is larger than on a truck. However, the experts estimate there is no difference in the likelihood of an attack on pressurised or refrigerated ammonia assets.

Consequently, the scores of refrigerated ammonia chains are higher (see Figure 34) if there is no decentralised storage because the risks are lower.The likelihood for pressurised and refrigerated supply chain elements is the same, and the impact is lower for refrigerated ammonia as per tank trailer, rail tank car or barge the volume of refrigerated and pressurised ammonia is about the same.

However, if decentralised storage is part of the supply chain, pressurised ammonia chains have higher Cyber security and terrorism scores because the impact of an incident is smaller due to smaller decentralised storage volume of an individual pressurised ammonia tank (and the likelihood is the same for refrigerated and pressurised).

The exception is inland shipping, where in spite of the decentralised storage, refrigerated ammonia has a higher score than pressurised. Although refrigerated ammonia requires larger decentralised storage volumes, its lower transport risk classification outweighs this disadvantage for the cyber and terrorism risk. The advantage for refrigerated ammonia is relatively large as in case of spill half the refrigerated ammonia dissolves in water.

Road transport has higher scores than other transport modalities due to the assumed lower probability of a cyber attack as it is less sensitive to IT issues. An incident also causes less societal disruption because of dispersed transport of relatively small volumes. The centralised storage in the port of entry determines these scores for all supply chains in equal measure.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.21	0.00	0.11	0.11	0.27
Refrigerated	0.13	0.09	0.10	(0.02)	0.27

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.66	0.50	0.58	0.58	0.00
Refrigerated	0.66	0.63	0.64	(0.58)	0.00

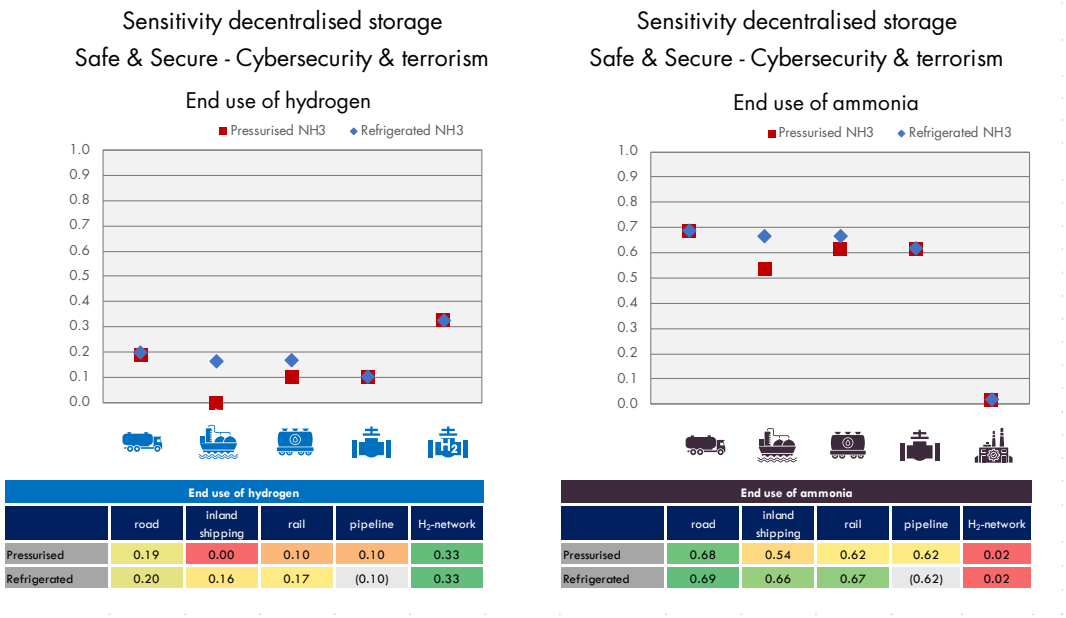
Figure 34: Scores for Cyber security and terrorism for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have overall higher scores than pressurised ammonia chains, if there is no decentralised storage. The probability of an incident is the same but the impact is lower for refrigerated ammonia.
- Pressurised ammonia supply chains have higher scores than refrigerated ammonia chains, if the impact of decentralised storage is included. The impact is smaller because of the smaller volume of a pressurised storage tank than a refrigerated tank.
- Road transport has higher scores than other transport modalities due to the assumed lower probability of a cyber attack and the small volume per truck.
- An exception is inland shipping: despite the higher cyber security and terrorism risk classification of larger decentralised refrigerated storage volumes, refrigerated ammonia still has higher scores than pressurised ammonia. This is because in the event of a spill during transport, approximately half of the refrigerated ammonia dissolves in water, substantially reducing its impact, an advantage that outweighs the storage disadvantage.

Supply chains with end use of hydrogen (left-hand chart Figure 34) have lower scores than those with end use of ammonia (right-hand chart Figure 34). With the end use of ammonia, less ammonia is needed because the ammonia is not required as fuel and cracking does not pose an additional risk.

Sensitivity analysis: if all decentralised storage is refrigerated and normalisation scale is adjusted

Figure 35 shows the results assuming that all decentralised ammonia storage is done refrigerated. The scores for supply chains with domestic pressurised ammonia (first four supply chains in left-hand chart) transport become lower compared to Figure 34 (baseline). This is because the advantage of the smaller pressurised storage tanks compared to refrigerated storage disappears. Refrigerated ammonia has higher scores than pressurised ammonia because of the lower transport risks. Road transport still has higher scores than other transport modalities.



End use of hydrogen

	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.19	0.00	0.10	0.10	0.33
Refrigerated	0.20	0.16	0.17	(0.10)	0.33

End use of ammonia

	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.68	0.54	0.62	0.62	0.02
Refrigerated	0.69	0.66	0.67	(0.62)	0.02

Figure 35: Scores for Cyber security and terrorism for inland supply chains in 2030; hydrogen end use and ammonia end use (all decentralised storage refrigerated)

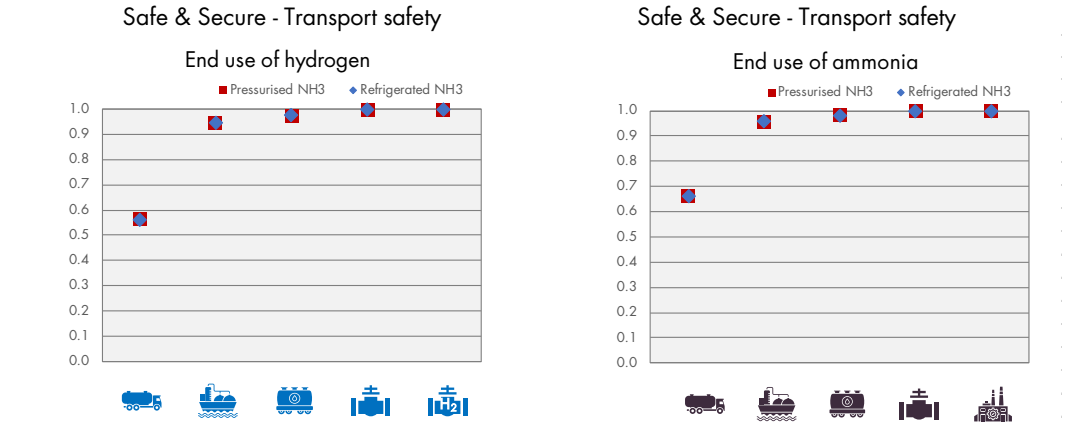
- In this sensitivity analysis, pressurised ammonia supply chains also have overall lower scores than refrigerated ammonia chains, as domestic transport determines the differences in scores and refrigerated ammonia has lower risks than pressurised ammonia transport.
- Road transport has higher scores than other transport modalities, just like in the baseline, due to the assumed lower probability of a cyber attack and the small volume per truck.

Transport safety (indicator Safe & Secure)

There is no difference in Transport safety scores for refrigerated and pressurised ammonia, see Figure 36. Transport by road runs the highest risk of traffic accidents, followed by transport by water and then by rail. Pipeline transport does not cause traffic accidents, which means there is no such risk associated with this transport mode.

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

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



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.56	0.95	0.98	1.00	1.00
Refrigerated	0.56	0.95	0.98	(1.00)	1.00

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.66	0.96	0.98	1.00	1.00
Refrigerated	0.66	0.96	0.98	(1.00)	1.00

Figure 36: Scores for Transport safety for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains.
- Road transport has lower scores than other transport modalities due to the highest risks of traffic accidents.

5. SCORES FOR PUBLIC INTEREST SUSTAINABLE

The public interest Sustainable has been quantified using three indicators: 1) Greenhouse gas emissions, 2) Energy loss and 3) (critical raw) Material usage. Greenhouse gas emissions were assigned the highest weighting in this analysis. The supply chain assessed as least sustainable is assigned a score of 0. A theoretical supply chain that does not require any critical materials, that does not produce greenhouse gas emissions and that does not require any additional energy to produce a kilogramme of hydrogen would have a score of 1.

Results for baseline situation (2030, inland end use)

The weighted results for the public interest Sustainable are shown in Figure 37. Ammonia supply chains have a high score. That is because there are few greenhouse gas emissions compared to other hydrogen carriers that make up the normalisation scale. The same holds for material usage. Combination shows no difference for supply chains of pressurised and refrigerated ammonia, although supply chains with pressurised ammonia require slightly more energy than refrigerated

supply chains in case the imported refrigerated ammonia needs to be heated before domestic transport. This energy loss is so small that it is negligible compared to other energy losses in the chain. Differences between the supply chains arise from the choice of transport mode and the number of conversions.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.91	0.91	0.91	0.91	0.91
Refrigerated	0.91	0.91	0.91	(0.91)	0.91

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.96	0.97	0.97	0.97	0.89
Refrigerated	0.96	0.97	0.97	(0.97)	0.89

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

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains.
- Road transport has lower scores than other transport modalities due to the highest greenhouse gas emissions and energy loss.

Results for variants

Port of entry

End use in the port of entry slightly improves the score for Sustainable for various supply chains compared to the baseline situation. However, these effects are small compared to the other supply chain steps (< 1 percent point), which means that the overall effect on the scores is minor. There are no visible differences between pressurised and refrigerated ammonia.

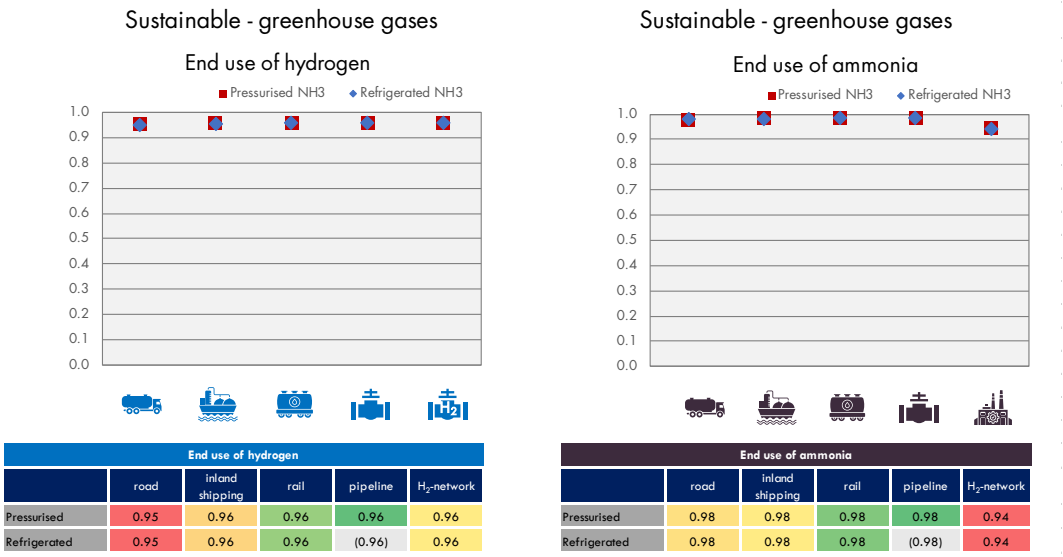
Transit and export

For end use in Germany or Belgium, the scores for Sustainable are exactly equal to the baseline situation. This is because we count the sustainability aspects (Greenhouse gas emissions, Energy loss and Material usage) across the entire supply chain.

Greenhouse gas emissions (indicator Sustainable)

Scores for pressurised and refrigerated ammonia chains are equal: both type of chains emit the same amount of greenhouse gases, with small differences due to transport mode, see Figure 38. Compared to other carriers that determine the normalisation scale (max 18-19 kilogrammes of

CO_2 per kilogramme of hydrogen equivalent) the level of CO_2 emissions is small. They are the result of the logistical movements and electricity consumption.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.95	0.96	0.96	0.96	0.96
Refrigerated	0.95	0.96	0.96	(0.96)	0.96

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.98	0.98	0.98	0.98	0.94
Refrigerated	0.98	0.98	0.98	(0.98)	0.94

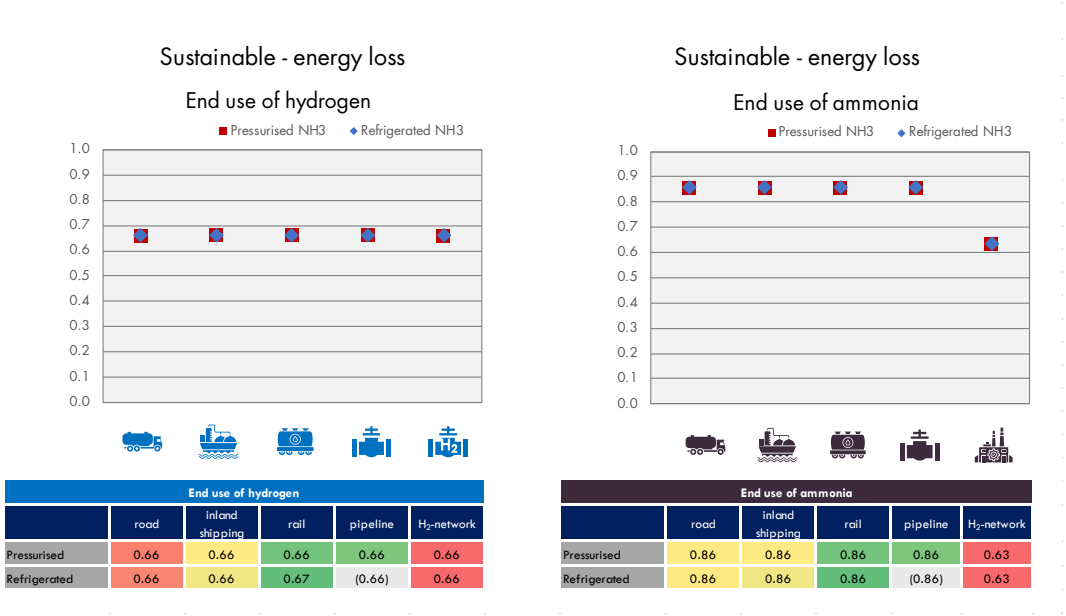
Figure 38: Scores for greenhouse gas emissions for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains.
- Road transport has lower scores than other transport modalities due to the highest greenhouse gas emissions.

Energy loss (indicator Sustainable)

The energy losses per kilogramme of hydrogen equivalent include energy for electrolysis and ammonia synthesis (in the producing country), cracking, transport and losses due to leakage and boil-off. The theoretically most efficient supply chain, in which the total energy use is exactly equal to the energy content of a kilogramme of hydrogen (no losses), is assigned a score of 1. The supply chain with the highest energy losses per kilogramme of hydrogen is assigned a score of 0.

Use of the hydrogen carrier to fuel the conversion process results in lower scores, see Figure 39. Some of the ammonia is consumed during cracking. This contributes to the energy losses for these supply chains, as larger volumes of ammonia must be produced in the exporting countries to supply comparable quantities of hydrogen equivalent for end use. This is the same for pressurised and refrigerated ammonia.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.66	0.66	0.66	0.66	0.66
Refrigerated	0.66	0.66	0.67	(0.66)	0.66

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.86	0.86	0.86	0.86	0.63
Refrigerated	0.86	0.86	0.86	(0.86)	0.63

Figure 39: Scores for Energy loss for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia chains have slightly higher scores than pressurised supply chains because the imported refrigerated ammonia must first be heated before it can be transported as pressurised ammonia. This difference is barely visible in the ranking colours. as the differences in energy loss, if any, are negligible.
- Rail transport and pipeline transport have the highest scores, but the differences with other modalities are small and visible only in the ranking colours.

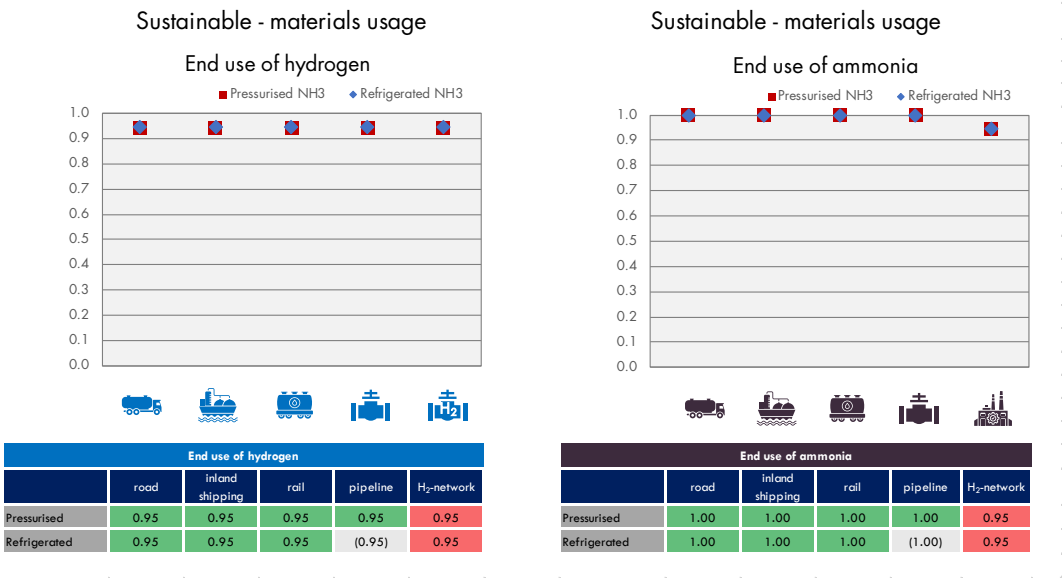
The only difference is that pressurised ammonia chains have slightly higher energy loss than refrigerated ammonia chains because the imported refrigerated ammonia must first be heated before it can be transported as pressurised ammonia. This is generally done using heat exchangers with ambient heat, but can also involve external energy input. Either way, the effect is small compared to other energy losses and within rounding (except for the chain with rail transport in the left-hand chart). Consequently, the differences between refrigerated and pressurised ammonia chains are only visible due to the slightly different colours that indicate the ranking. The yellow colour of transport of refrigerated ammonia by barge has a green touch, while the colour of transport of pressurised ammonia by barge is plain yellow. Ambient heating is generally used for evaporating the ammonia before cracking.

Material usage (indicator Sustainable)

The score for material usage reflects the extent to which scarce materials are required in each hydrogen supply chain, either as catalysts or as carrier materials. Supply chains that do not use scarce materials are assigned a score of 1. Supply chains with a 2.1 cents material usage per kilogramme of hydrogen equivalent are assigned a score of 0.[117]

[117] Normalisation scale is derived from the 2024 MCA of hydrogen carriers, ignoring the sodium borohydride data.

The supply chains with transport of pressurised and refrigerated ammonia require the same critical raw material use, that is small by comparison to the supply chain that has the lowest score, see Figure 40. All ammonia chains with cracking to hydrogen have (almost) equal use of catalysts with precious metals. Conversion to hydrogen at the port of entry requires a small amount of additional ammonia because a fraction of the hydrogen is lost during transport via the hydrogen network. More ammonia must be converted to deliver the same amount of final product.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.95	0.95	0.95	0.95	0.95
Refrigerated	0.95	0.95	0.95	(0.95)	0.95

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	1.00	1.00	1.00	1.00	0.95
Refrigerated	1.00	1.00	1.00	(1.00)	0.95

Figure 40: Scores for material usage for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains.
- All modalities have the same scores.

6. SCORES FOR PUBLIC INTEREST ADAPTABLE

Figure 41 shows the normalised scores for the public interest Adaptable for the various supply chains for inland use. The scores that resulted from expert sessions for the 2024 MCA of hydrogen carriers were reviewed for the present study, with differentiation between pressurised and refrigerated liquid ammonia assets. Supply chains that require fewer high-risk investments are assigned a higher score. The bandwidth used is 26 euros (score 0) to 0 euros (score 1) of high-risk investments per kilogramme of hydrogen equivalent. High-risk means that additional investments must be made and that these have no other applications if the supply chain for the hydrogen or ammonia is not successful.[118]

Results for baseline situation (2030, inland end use)

The investments in conversion have the largest effect on the scores. Supply chains with one or more conversion steps (cracking, synthesis back to ammonia) have the lowest score, as conversion

[118] The possibility for stepwise expansion has not been considered in the operationalisation of Adaptable.

plants cannot generally be reused for other processes (other than recycling for parts/scrap). Neither are there existing facilities available for use (they do not exist or they are already in use).

Although investments in means of transport are higher[119] for refrigerated than for pressurised ammonia, the difference in scores between supply chains is small, and is often visible only in the ranking colours. This is due to two factors:

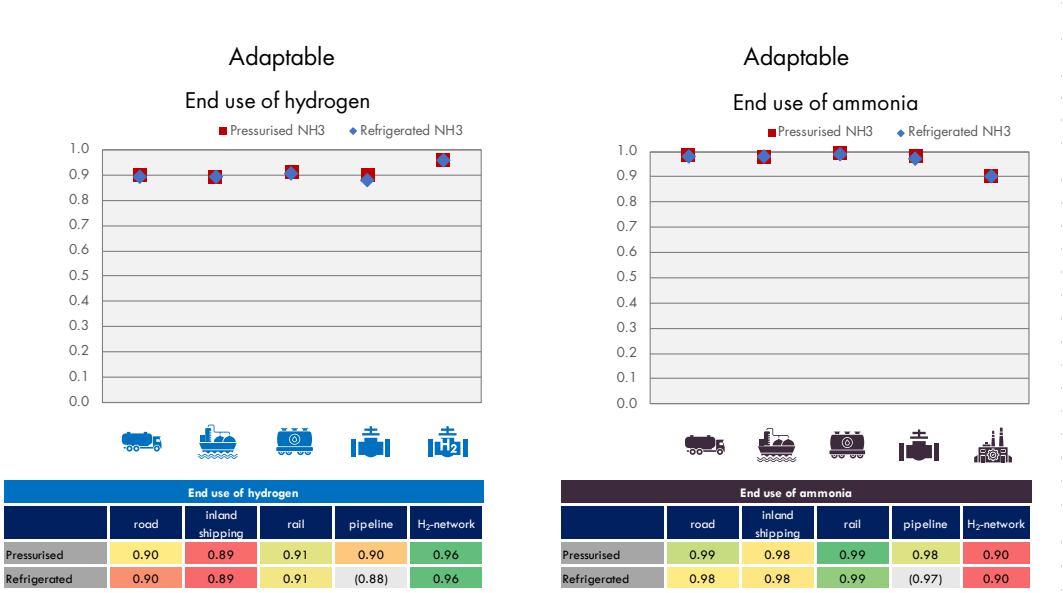
- The investments in means of transport are part of the total investments at risk. The required investments at risk in conversion facilities (maximum 2.01 million euro per kton hydrogen equivalent decentralised cracking) are larger than the investments required in means of transport (up to 0.60 million euro per kton hydrogen equivalent) or storage facilities (maximum 0.05 million euro per kton hydrogen equivalent for decentralised storage). Differences between means of transport for refrigerated and pressurised ammonia are even smaller up to 0.16 million euro per kton hydrogen equivalent.
- The normalisation scale, equal to the one used in the 2024 MCA of hydrogen carriers, is much larger than the maximum difference in the ammonia supply chains. Therefore, differences in investment at risk only correspond to 11 percentage points of the normalisation scale and differences between refrigerated and pressurised ammonia for the same means of transport are less than 1 percentage point.

A substantial part of the required investments in centralised ammonia storage has already received a building permit or concerns retrofit of existing facilities. This means that less additional risky investments are needed in the target year 2030 but the centralised storage does not differ between refrigerated and pressurised ammonia supply chains. Centralised storage is always refrigerated in the supply chains that we compare.

The means of transport with the highest scores is use of the hydrogen network. The investment decision was already taken and there are few additional high-risk investments needed. Inland shipping has the lowest scores (except the fictitious refrigerated pipeline) due to the highest high-risk investments per hydrogen equivalent.

In relation to the scores for Adaptable, note that the extent to which the investments are reusable is based on an expert judgement and that the values for the required investments in the literature are uncertain.

[119] 6% higher investment costs per kton hydrogen equivalent for transport by inland waterways, 46% for transport by road and 208% for transport by rail.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.90	0.89	0.91	0.90	0.96
Refrigerated	0.90	0.89	0.91	(0.88)	0.96

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.99	0.98	0.99	0.98	0.90
Refrigerated	0.98	0.98	0.99	(0.97)	0.90

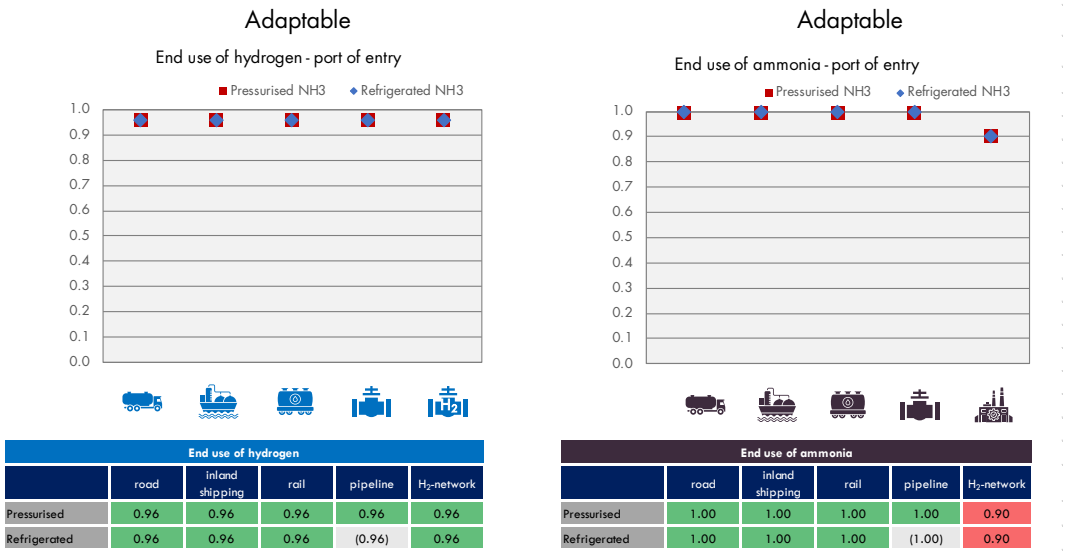
Figure 41: Scores for Adaptable for inland supply chains in 2030; hydrogen end use and ammonia end use

- Pressurised ammonia supply chains have overall slightly higher scores (visible in the ranking colours) than refrigerated ammonia chains, as the means of transport for refrigerated ammonia require more high-risk investments than for pressurised ammonia.
- Inland shipping has the lowest scores for ammonia transport (besides the fictitious refrigerated pipeline) due to the highest high-risk investments per hydrogen equivalent. The hydrogen network has the lowest additional high-risk investments as the investment decision was already taken.

Results for variants

Port of entry

End use in the port of entry slightly improves the score for Adaptable compared to the baseline situation, see Figure 42. This is because no high-risk investments in means of inland transport are required, and because decentralised high-risk investments in conversion are generally estimated to be higher than if a centralised conversion plant is built in the port, which results in economies of scale. As the only minor differences between refrigerated and pressurised ammonia are caused by differences in transport mode investments or decentralised storage there are no differences between the two forms of ammonia.



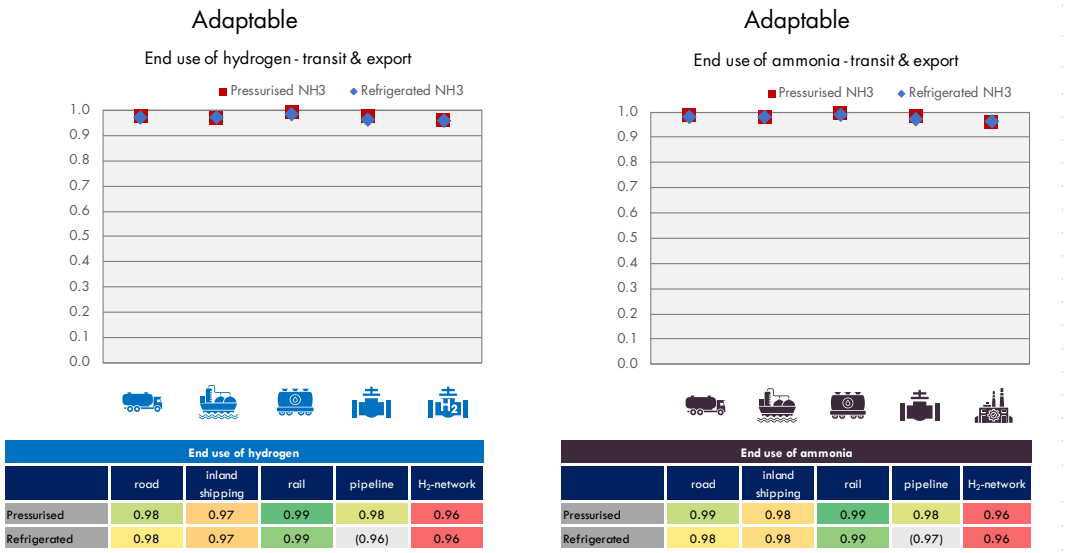
End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.96	0.96	0.96	0.96	0.96
Refrigerated	0.96	0.96	0.96	(0.96)	0.96

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	1.00	1.00	1.00	1.00	0.90
Refrigerated	1.00	1.00	1.00	(1.00)	0.90

Figure 42: Scores for Adaptable for supply chains that involve use in the port of entry in 2030; hydrogen end use and ammonia end use

Transit and export

For end use in Germany or Belgium, the high-risk investments in conversion and storage are not taken into account. This improves the score for the supply chains with decentralised conversion or storage compared to end use in the Netherlands, see Figure 43. This applies to the first four supply chains in the left-hand chart and the fifth in the right-hand chart. The only minor differences between refrigerated and pressurised ammonia are caused by differences in transport mode investments. Pressurised ammonia has slightly higher scores than refrigerated ammonia.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.98	0.97	0.99	0.98	0.96
Refrigerated	0.98	0.97	0.99	(0.96)	0.96

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.99	0.98	0.99	0.98	0.96
Refrigerated	0.98	0.98	0.99	(0.97)	0.96

Figure 43: Scores for Adaptable for transit and export supply chains in 2030; hydrogen end use and ammonia end use

7. SCORES FOR PUBLIC INTEREST FAIR

The normalised scores for the public interest Fair are a combination of two indicators: 1) Fair for exporting countries and 2) Fair for Dutch society. The stakeholders assessed these indicators as approximately equally important.

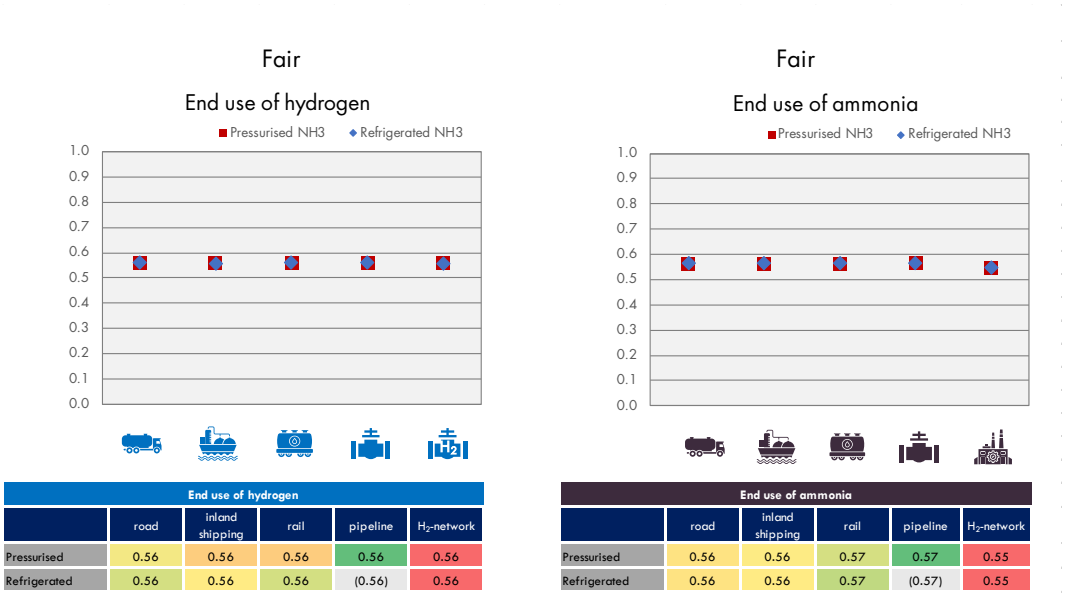
The higher the score, the smaller the difference between the 'true costs' and the private costs, and the less the external effects are shifted onto the exporting country or Dutch society. A supply chain is assigned a score of 1 if there is no difference between the true costs and the private costs; in this case, the true costs divided by the private costs is 100 percent. The supply chain with the largest percentage difference is assigned a score of 0.

Results for baseline situation (2030, inland end use)

The weighted results for the public interest Fair are shown in Figure 44. The table shows moderate scores for ammonia. This score for ammonia is due to a combination of the low private costs and higher environmental costs, particularly due to ammonia emissions and leaks.

There are no differences between refrigerated and pressurised ammonia chains in terms of import, but within the Netherlands, the refrigerated ammonia chains have a slightly higher score than pressurised ammonia due to higher costs while the external costs are the same. The differences are barely visible.

Important to note is that costs of external safety and the costs of cyber security and terrorism are not factored in. If this had been possible the advantage of refrigerated ammonia would be higher.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.56	0.56	0.56	0.56	0.56
Refrigerated	0.56	0.56	0.56	(0.56)	0.56

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.56	0.56	0.57	0.57	0.55
Refrigerated	0.56	0.56	0.57	(0.57)	0.55

Figure 44: Scores for Fair for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have overall slightly higher scores (visible in the ranking colours) than pressurised ammonia chains, as the private costs of domestic supply chain are slightly higher than for pressurised ammonia, while the external costs are the same.
- Pipeline transport has the highest scores, due to the favourable ratio between the true costs and private costs of domestic transport, but the differences with other modalities are small.

Results for variants

Port of entry

For end use in the port of entry, differences due to the use of inland transport and decentralised storage (Fair supply chain in the Netherlands) do not apply, see Figure 45. The scores for fairness for the producer countries remain the same and are the same for all chains. There are no differences between refrigerated and pressurised ammonia.



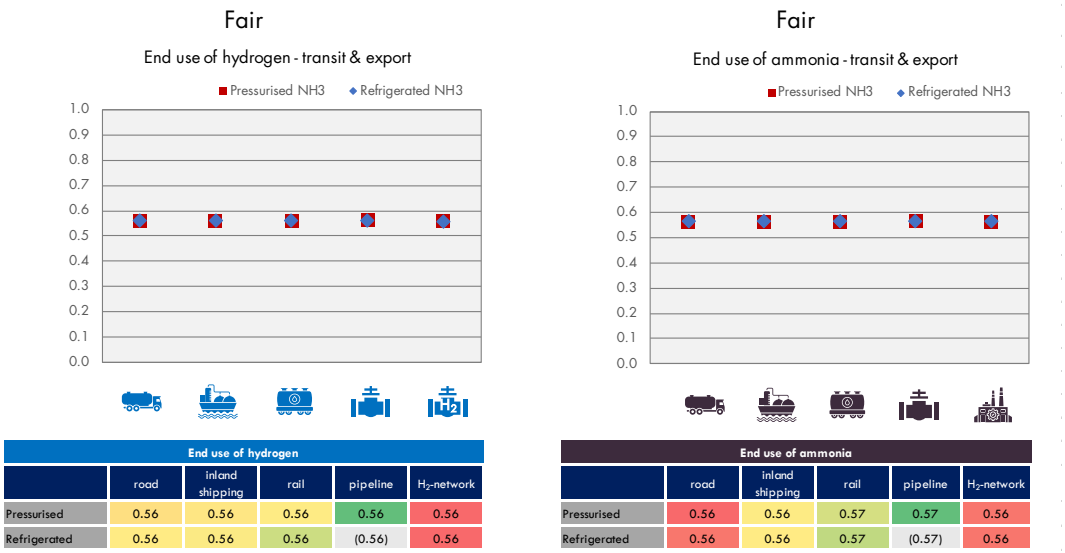
End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.56	0.56	0.56	0.56	0.56
Refrigerated	0.56	0.56	0.56	(0.56)	0.56

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.57	0.57	0.57	0.57	0.55
Refrigerated	0.57	0.57	0.57	(0.57)	0.55

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

Transit and export

For end use in Germany or Belgium, the contribution from decentralised conversion and storage is not taken into account. This affects the fairness of the supply chain in the Netherlands. As is the case for end use in the port of entry, the fairness of the supply chain in the producing countries remains the same, see Figure 46. The effect of eliminating the contributions from decentralised storage and conversion varies for refrigerated and pressurised ammonia. The scores remain unchanged for supply chains without decentralised conversion or storage (use of hydrogen network in the left-hand chart, and first four columns in the right-hand chart).



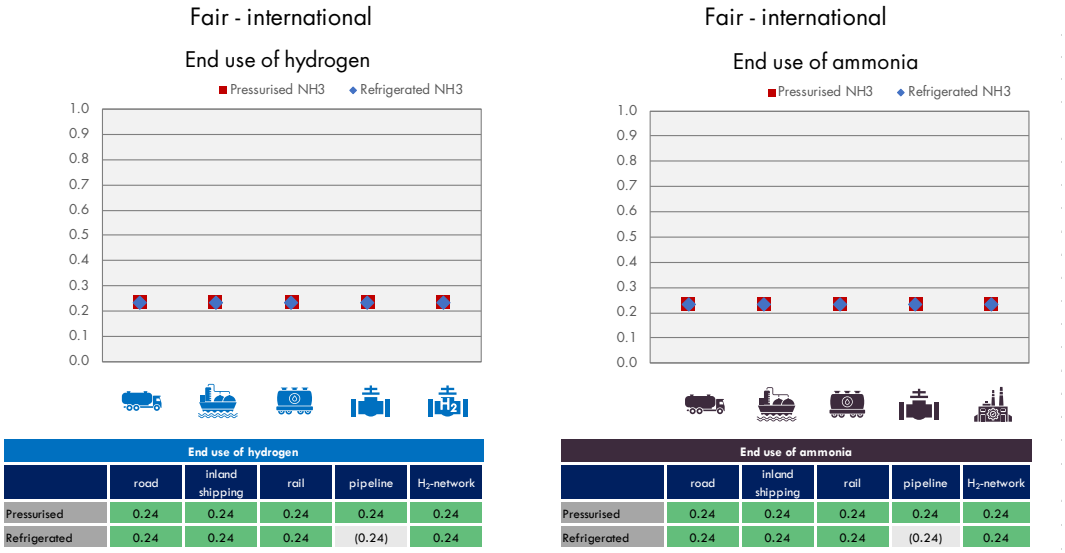
End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.56	0.56	0.56	0.56	0.56
Refrigerated	0.56	0.56	0.56	(0.56)	0.56

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.56	0.56	0.57	0.57	0.56
Refrigerated	0.56	0.56	0.57	(0.57)	0.56

Figure 46: Scores for Fair for transit and export supply chains in 2030; hydrogen end use and ammonia end use

Fair for exporting countries (indicator Fair)

The import supply chains with the smallest differences between the true costs and the private costs have the highest scores: these are the fairest. Ammonia has a large environmental impact abroad (emissions of NOx and ammonia during synthesis), while the import price is relatively low. This means the chains have low scores, see Figure 47. There are no differences between the chains as the import chain to the Netherlands is the same.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.24	0.24	0.24	0.24	0.24
Refrigerated	0.24	0.24	0.24	(0.24)	0.24

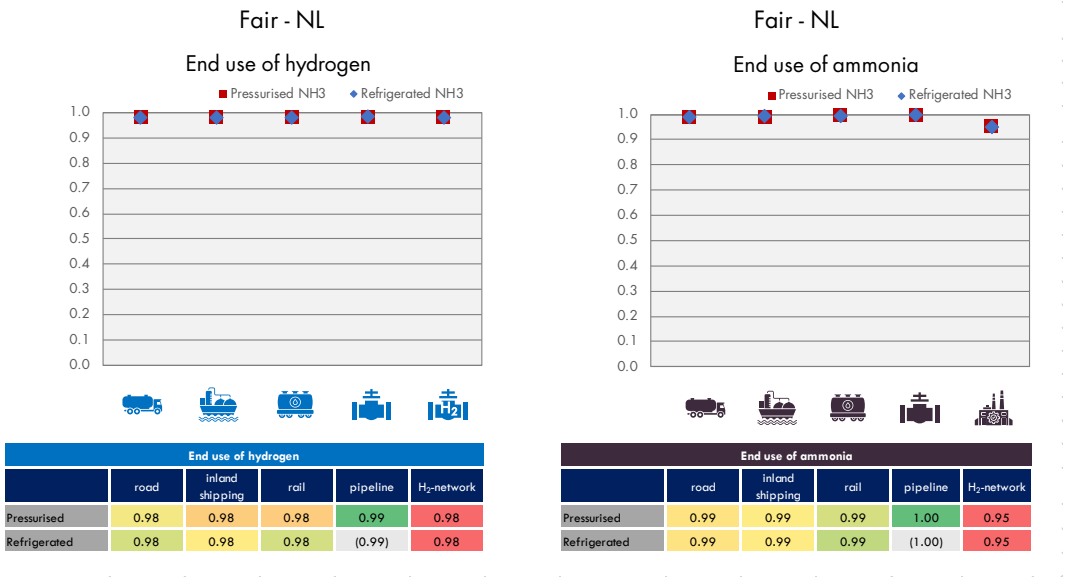
End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.24	0.24	0.24	0.24	0.24
Refrigerated	0.24	0.24	0.24	(0.24)	0.24

Figure 47: Scores for Fair for producing countries for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains and all transport modalities have the same scores, because the supply chain up to the port of entry is the same.

Fair for Dutch Society (indicator Fair)

The score for Fair for Dutch society is determined by the supply chain steps from import and storage up to and including conversion at the end user's site. The difference between true costs and private costs for the domestic ammonia supply chains in the Netherlands is small compared to the normalisation scale. The maximum difference of the true and private costs in the ammonia supply chains is 48 percent. This corresponds to 5 percentage points of the normalisation scale, resulting in a high score for Fair for Dutch society, see Figure 48. The scores for refrigerated ammonia chains are slightly higher than for pressurised ammonia chains because the private costs are somewhat higher while the external costs are the same. The differences between refrigerated and pressurised ammonia are equal to a maximum difference of the ratio between true and private costs of two percent.[120] This difference is so small that the difference in the normalised scores is visible only in the ranking colours. Due to the favourable ratio between the true costs and private costs of domestic transport, pipeline transport has the highest scores, but the differences with other modalities are small.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.98	0.98	0.98	0.99	0.98
Refrigerated	0.98	0.98	0.98	(0.99)	0.98

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.99	0.99	0.99	1.00	0.95
Refrigerated	0.99	0.99	0.99	(1.00)	0.95

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

- Refrigerated ammonia supply chains have overall slightly higher scores (visible in the ranking colours) than pressurised ammonia chains, as the private costs are slightly higher than for pressurised ammonia, while the external costs are the same (by definition excluding External safety and Cyber security and terrorism).
- Pipeline transport has the highest scores, due to the favourable ratio between the true costs and private costs of domestic transport, but the differences with other modalities are small.

[120] Excluding differences in External safety and Cyber Security and terrorism.

8. SCORES FOR PUBLIC INTEREST ACCESSIBLE

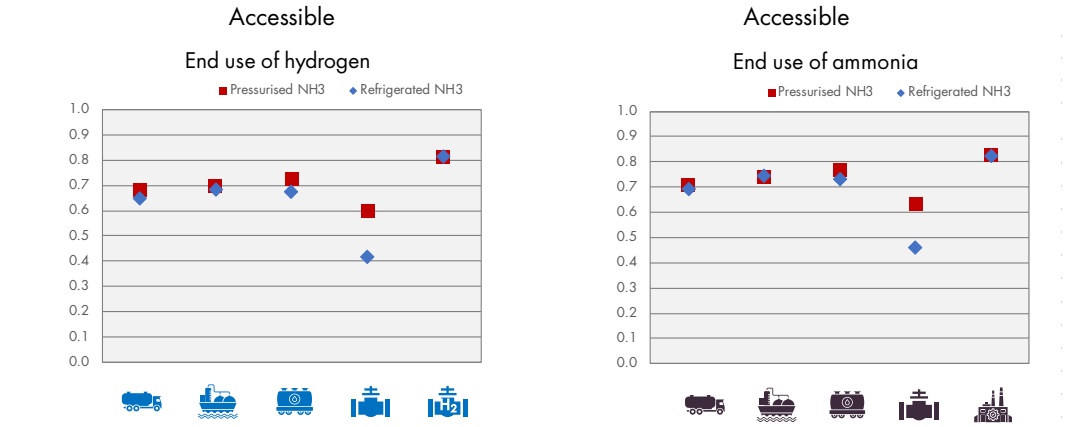
The public interest Accessible consists of two indicators: 1) Cost parity (level playing field) for end users both inland and in the port of entry, and 2) Proximity of the supply chain to inland consumers. Of these two indicators, an Accessible cost level for end users has the highest weighting. A supply chain that is accessible to all inland companies, with inland costs that are the same as those incurred by companies in the port of entry, is assigned a score of 1. A supply chain is assigned a score of 0 if it is accessible to no inland companies (0 percent) and has the highest additional costs (around 10%) in this analysis compared to companies in the port of entry.

Results for baseline situation (2030, inland end use)

Figure 49 shows the weighted results for the public interest Accessible. Although road delivery is possible to all industrial estates, the higher costs result in a lower total score, lower for refrigerated ammonia, which has slightly higher inland transport costs than pressurised ammonia.

Because of the lower score for the proximity indicator, the combined score for water, rail and pipeline transport is lower than for road transport.

Highest scores are for chains via the hydrogen network, mainly due to limited additional costs compared to the costs in the port of entry.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.68	0.70	0.73	0.60	0.82
Refrigerated	0.65	0.69	0.68	(0.42)	0.82

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.71	0.74	0.77	0.63	0.82
Refrigerated	0.69	0.74	0.73	(0.46)	0.82

Figure 49: Scores for Accessible for inland supply chains in 2030; hydrogen end use and ammonia end use

- Pressurised ammonia supply chains have overall higher scores for Accessible than refrigerated ammonia chains, as the costs of domestic transport are lower than for refrigerated ammonia.
- Transport by hydrogen network has the highest scores, due to the assumed low domestic transport costs and the absence of decentralised storage, despite limited proximity compared to road transport.

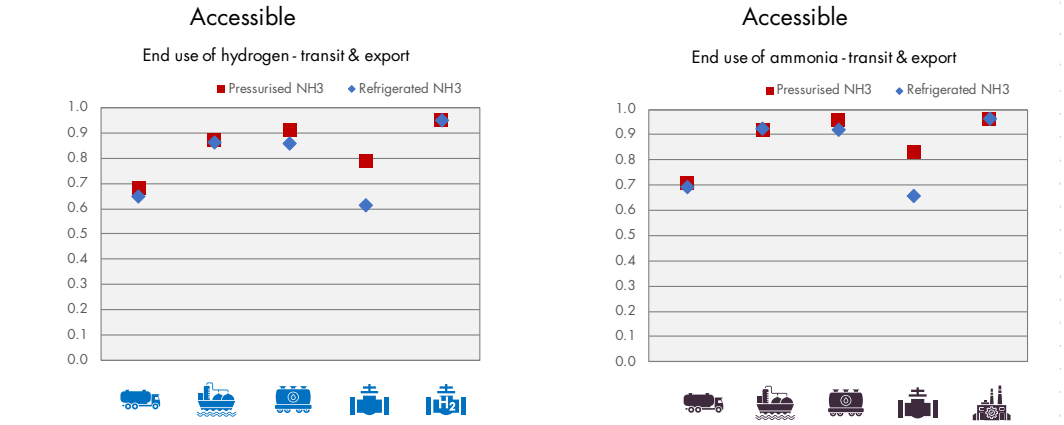
Results for variants

Port of entry

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

Transit and export

Following discussion with the client, the proximity indicator was deemed to be irrelevant in the case of end use in Germany or Belgium. This is because the indicator concerns the proximity for companies based in the Netherlands, which do not play a role in this variant. We have therefore assigned all supply chains a score of 1 in the model. This results in an improvement to all scores for supply chains with a proximity score below 100 percent in the baseline situation, see Figure 50. Because of the lower domestic transport costs, the supply chains of pressurised ammonia have slightly higher scores than those with refrigerated ammonia.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.68	0.88	0.91	0.79	0.95
Refrigerated	0.65	0.86	0.86	(0.62)	0.95

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.71	0.92	0.96	0.83	0.96
Refrigerated	0.69	0.92	0.92	(0.66)	0.96

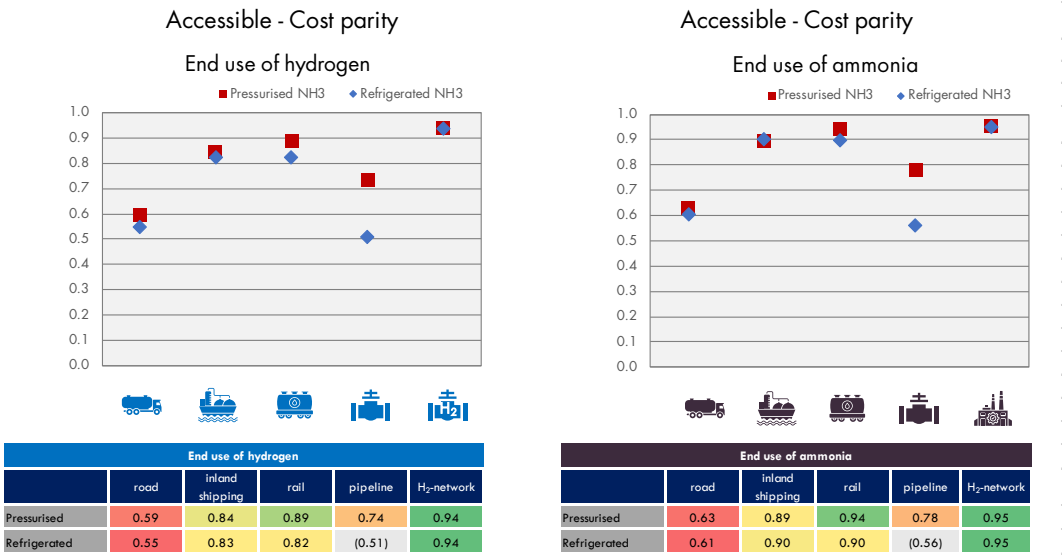
Figure 50: Scores for Accessible for transit and export supply chains in 2030; hydrogen end use and ammonia end use

Cost parity (level playing field indicator for Accessible)

Refrigerated ammonia supply chains scores are lower than for pressurised ammonia due to somewhat higher transport costs (more expensive transport equipment).

The supply chains that use the hydrogen network for transport in the Netherlands have the highest scores for this indicator due to a small price difference between the port of entry and the end user inland, based on the assumed hydrogen network transport fees, see Figure 51. The supply chains with high additional transport costs have the lowest score (road transport). Pipeline transport with the ISPT safe & compliant design adds more costs for an inland end user than transport by inland shipping or rail.

The scores for the fictitious pipeline with refrigerated ammonia are the lowest. These are based on the rough assumption of twice the costs of the pipeline with pressurised ammonia.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.59	0.84	0.89	0.74	0.94
Refrigerated	0.55	0.83	0.82	(0.51)	0.94

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.63	0.89	0.94	0.78	0.95
Refrigerated	0.61	0.90	0.90	(0.56)	0.95

Figure 51: Scores for Accessible by Cost parity for inland supply chains in 2030; hydrogen end use and ammonia end use

- Pressurised ammonia supply chains have overall higher scores than refrigerated ammonia chains, as the costs of domestic transport are lower for pressurised than for refrigerated ammonia.
- Transport by hydrogen network has the highest scores, due to the assumed low domestic transport costs and the absence of decentralised storage.

Proximity (indicator for Accessible)

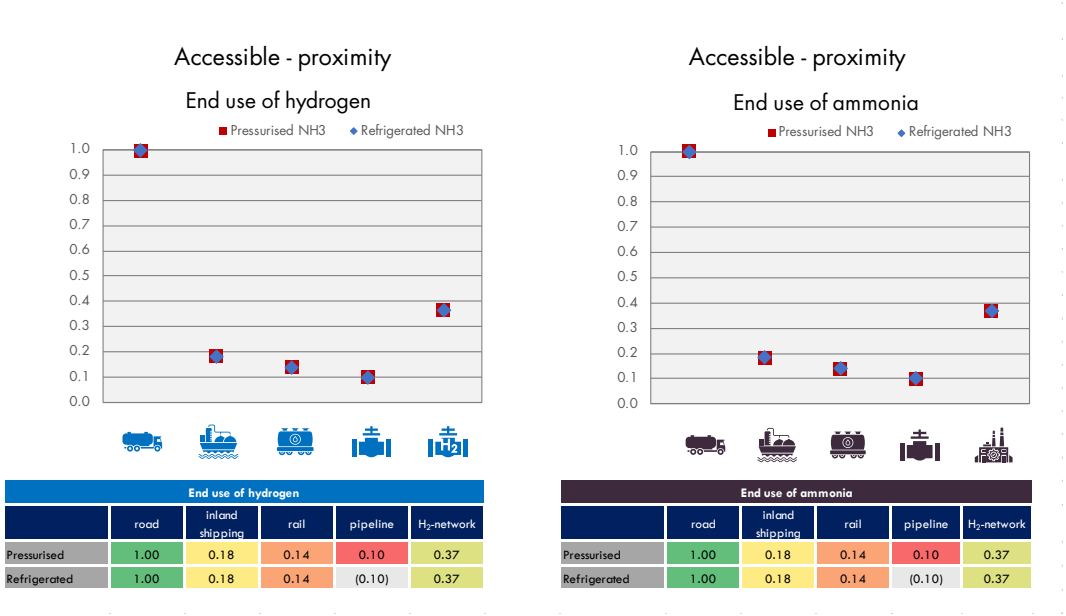
The scores for this indicator depend only on the transport mode and not on the form of ammonia. All supply chains of the same type therefore have the same score in the charts, see Figure 52.

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

The lowest score was assigned to a specific pipeline, similar to the Delta Rhine Corridor, which passes only a limited number of industrial sites.

A small percentage of industrial estates in the Netherlands will have direct access to such pipelines. We estimated this to be 10 percent, see Annex D. If 10 percent of industrial estates have access, this results in a score of 0.1.

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



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	1.00	0.18	0.14	0.10	0.37
Refrigerated	1.00	0.18	0.14	(0.10)	0.37

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	1.00	0.18	0.14	0.10	0.37
Refrigerated	1.00	0.18	0.14	(0.10)	0.37

Figure 52: Scores for Proximity for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains, as scores depend only on the means of transport.
- Road transport has the highest scores because every industrial estate has direct access, while pipeline transport has the lowest scores as we assume only 10 percent of industrial estates has direct access.

9. SCORES FOR PUBLIC INTEREST SPATIAL FOOTPRINT

To assign a score for the public interest Spatial Footprint, we assessed the physical space that each supply chain occupies. A supply chain with no additional spatial requirements is assigned a score of 1. A supply chain with a score of 0 has spatial requirements valued at 0.4 euros per kilogramme of hydrogen equivalent.

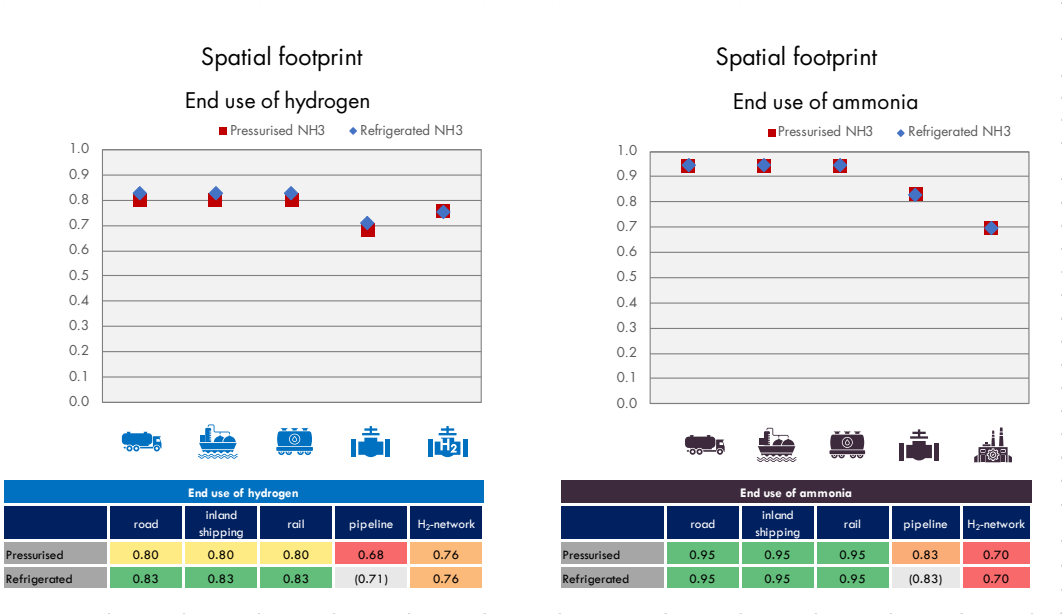
Results for baseline situation (2030, inland end use)

Differences between the supply chains are due to the different spatial requirements for pressurised or refrigerated decentralised storage, due to the spatial need for additional pipelines and due to the differences in volume (expressed in hydrogen equivalent). The cause for the latter, in case of end use of hydrogen, is that ammonia is used as fuel for cracking.

Refrigerated ammonia has a higher score than pressurised ammonia in supply chains for hydrogen end use that include decentralised storage, because pressurised ammonia requires more storage space (multiple tanks with lower capacity each) than refrigerated ammonia. The overall differences are small.

The spatial needs are by definition higher for end use of hydrogen because the chains then include decentralised storage and cracking within the system boundaries. No decentralised storage is assumed in the modelling of supply chains for end use as ammonia, even though end users may have storage on their site.

The supply chains with the highest scores are those that do not require new pipelines, have modest spatial requirements for storage facilities and do not involve cracking, see Figure 53. No supply chain has a score of 1, because every supply chain requires at least space for centralised storage.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.80	0.80	0.80	0.68	0.76
Refrigerated	0.83	0.83	0.83	(0.71)	0.76

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.95	0.95	0.95	0.83	0.70
Refrigerated	0.95	0.95	0.95	(0.83)	0.70

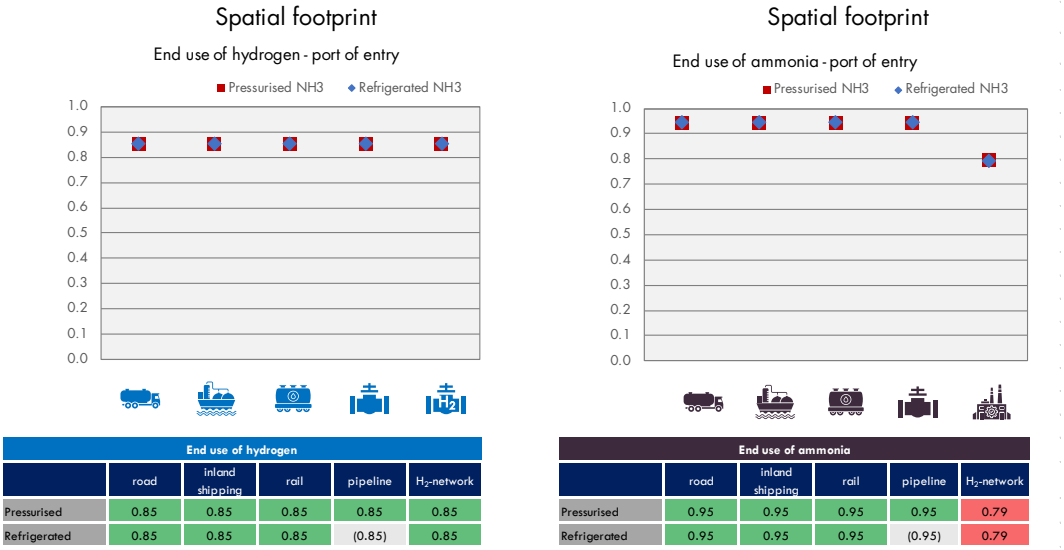
Figure 53: Scores for Spatial Footprint for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have higher scores than pressurised ammonia chains if decentralised storage is included, because the spatial footprint of decentralised pressurised storage is higher than for decentralised refrigerated ammonia storage.
- Transport by pipeline has the lowest scores, due to the substantial spatial need for additional pipelines.

Results for variants

Port of entry

For end use in the port of entry, the spatial requirements are lower (see Figure 54), as no new pipelines are required for inland transport. Decentralised storage is also not required. In this variant, many supply chains have the same score. The differences primarily depend on whether the end user consumes hydrogen or ammonia, and how many conversions are needed.



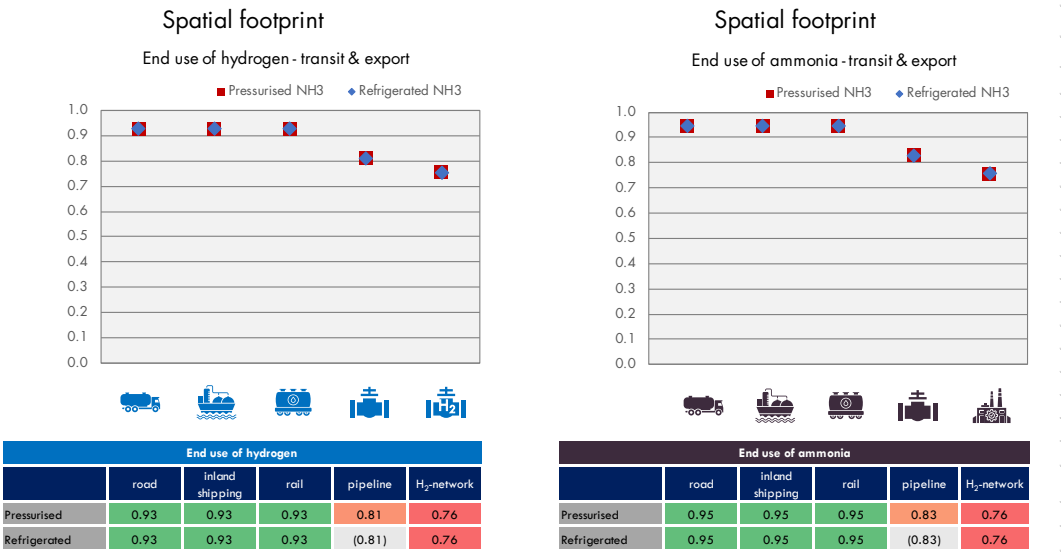
End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.85	0.85	0.85	0.85	0.85
Refrigerated	0.85	0.85	0.85	(0.85)	0.85

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.95	0.95	0.95	0.95	0.79
Refrigerated	0.95	0.95	0.95	(0.95)	0.79

Figure 54: Scores for Spatial Footprint for supply chains that involve use in the port of entry in 2030; hydrogen end use and ammonia end use

Transit and export

For end use in Germany or Belgium, the space required for decentralised storage and conversion is not taken into account. This slightly improves the score for the supply chains with decentralised conversion compared to end use in the Netherlands, see Figure 55. The spatial requirements for pipelines still have a major impact on the score. There is no difference between pressurised and refrigerated supply chains. They only differ in the space use of decentralised storage and this is out of scope in this variant.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.93	0.93	0.93	0.81	0.76
Refrigerated	0.93	0.93	0.93	(0.81)	0.76

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.95	0.95	0.95	0.83	0.76
Refrigerated	0.95	0.95	0.95	(0.83)	0.76

Figure 55: Scores for Spatial Footprint for transit and export supply chains in 2030; hydrogen end use and ammonia end use

10. SCORES FOR PUBLIC INTEREST ENVIRONMENT

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

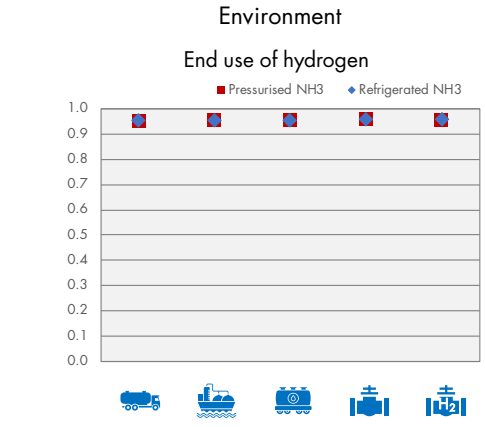
The supply chain with the highest environmental impact is assigned a score of 0 in this analysis. We have monetised this environmental impact using established shadow cost parameters. The various emissions are therefore grouped together. The lowest score equates to environmental costs of around 50 cents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

Results for baseline situation (2030, inland end use)

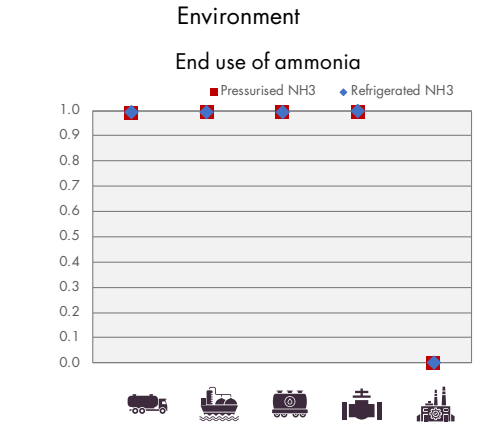
Figure 56 shows the results for the public interest Environment. Ammonia leakage from decentralised synthesis using hydrogen from the national network in the Netherlands proves to have the largest effect. The leakage from ammonia synthesis is 1.63 grammes per kilogramme of ammonia (JRC). With shadow costs of almost 50 euros per kilogramme of ammonia, this results in an environmental impact of more than 45 cents per kilogramme of hydrogen equivalent for the ammonia chain that includes conversion and decentralised synthesis in the Netherlands (far right in Figure 56). In addition to these costs, there are some environmental costs of the NO_X emissions: around 2 cents per kilogramme of hydrogen equivalent for conversions (based on the assumed use of $DeNO_X$ plants) and 3 cents for the NO_X emissions due to the electricity consumed in the Netherlands. These numbers are the same for refrigerated and pressurised ammonia. As a result, there are no differences in the scores.

It is worth noting in this context that these emissions already occur during the existing production of ammonia from natural gas, which is used to produce artificial fertiliser. If we assume that equal volumes of fertiliser are produced, emissions will not increase compared to existing production if this production is replaced by ammonia synthesis using hydrogen from the transport network. However, emissions will worsen if ammonia is used for electricity generation. The minor NO_X emissions from transport are negligible, but the NO_X emissions from the electricity used in the Netherlands do cause distinctive environmental costs.

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



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.96	0.96	0.96	0.96	0.96
Refrigerated	0.96	0.96	0.96	(0.96)	0.96

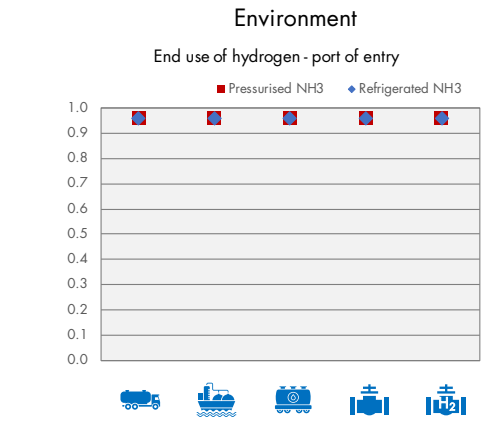


End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.99	1.00	0.99	1.00	0.00
Refrigerated	0.99	1.00	0.99	(1.00)	0.00

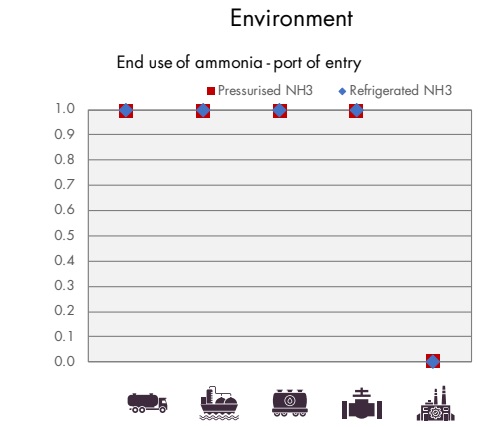
Figure 56: Scores for Environment (nature and people) for inland supply chains in 2030; hydrogen end use and ammonia end use

- Refrigerated ammonia supply chains have the same scores as pressurised ammonia chains.
- Pipeline transport has the highest scores because there are no noise pollution, habitat and environmental damage assumed except for the electricity used.

Results for variants



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.96	0.96	0.96	0.96	0.96
Refrigerated	0.96	0.96	0.96	(0.96)	0.96



End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	1.00	1.00	1.00	1.00	0.00
Refrigerated	1.00	1.00	1.00	(1.00)	0.00

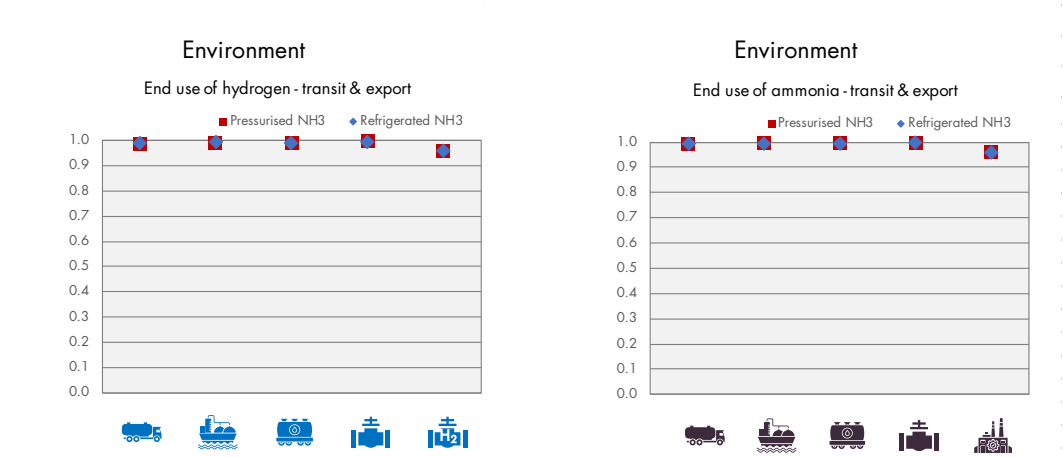
Figure 57: Scores for Environment for supply chains that involve use in the port of entry in 2030; hydrogen end use and ammonia end use

Port of entry

End use in the port of entry results in almost no improvement to the score for Environment compared to the baseline situation, see Figure 57. This is because the environmental impact of transport is very small compared to the environmental emissions during conversion and synthesis.

Transit and export

For end use in Germany or Belgium, the environmental emissions from conversion and decentralised storage are not taken into account. This improves the score for the supply chains with decentralised conversion (the first four columns in the left-hand chart and the last column in the right-hand chart of Figure 58) compared to end use in the Netherlands. It results in a higher score for the ammonia supply chain that includes both conversion and decentralised synthesis in particular. This is because the effects of ammonia leakage and NO_X emissions during synthesis are moved abroad. These emissions arise in other countries.



End use of hydrogen	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.99	0.99	0.99	1.00	0.96
Refrigerated	0.99	0.99	0.99	(1.00)	0.96

End use of ammonia	road	inland shipping	rail	pipeline	H_2-network
Pressurised	0.99	1.00	0.99	1.00	0.96
Refrigerated	0.99	1.00	0.99	(1.00)	0.96

Figure 58: Scores for Environment for transit and export supply chains in 2030; hydrogen end use and ammonia end use

ANNEX F: EXPLANATION OF NORMALISATION METHOD

For normalisation, this study adhered as much as possible to the method of global normalisation as in the MCA hydrogen carriers. This means that a fixed normalisation scale was used between the highest (possible) score and the lowest (possible) score. The highest (possible) score was given a value of 1 and the lowest (possible) score a value of 0. Global normalisation is based on the theoretical minimum and maximum scores and thus guarantees that all calculated scores for all interests will be within the bandwidth used for normalisation.

The normalisation bandwidth between the lowest and highest score is important, because when the weighting factors are applied, it matters what the absolute difference is between the supply chains assessed as worst and best; for Affordable, for example, is the difference 1 cent, 1 euro or 10 euros per kilogramme? In the Delphi questionnaire, a bandwidth was given for the values for each public interest. This gave the participants a reference to compare alternatives. It should be noted that most of the participants will not consciously have taken the bandwidth into account when assigning a weighting to the public interests.

The best (theoretical) score for each public interest is generally easy to determine. For instance, a situation with zero emissions, no spatial requirements, or 100 percent proximity. For the public interest Affordable, we assume that the best possible score equates to a cost price of 2.50 euros per kilogramme of hydrogen.

The lowest possible score cannot generally be determined theoretically, except for proximity. The lowest possible score for proximity was set at zero (0%), as this is the worst possible score (if no industrial estates whatsoever have access to this hydrogen supply chain).

For the other public interests, we used the lowest score for that public interest as determined in the MCA hydrogen carriers, after excluding sodium borohydride alternatives. The reason the scores of sodium borohydride were excluded, is that this carrier has extreme scores compared to the other carriers. This is likely due to the early-stage, pre-commercial nature of this carrier, which results in extreme scores relative to the other carriers assessed.

This bandwidth was applied in the present analyses. Two exceptions apply: for External safety and Spatial Footprint, the bandwidth has been increased, as the more detailed analysis of decentralised storage options yields higher risk and Spatial Footprint scores than those found in the MCA hydrogen carriers, see Table 34. For External safety it concerns a fivefold increase in scale, for Spatial Footprint less than 5% expansion.

Table 34: Bandwidth used for normalisation

Public interest	Worst score	Best score
Affordable	Lowest score in MCA hydrogen carriers*	2.50 euros per kg hydrogen, this value is achieved by the supply chain with the highest score in 2050 (benchmark)
Economically Robust	Lowest score in MCA hydrogen carriers*	Highest score in model
Reliable	Lowest score in MCA hydrogen carriers*	No additional storage compared with existing flows of current energy carriers (benchmark)
Safe & Secure – External safety	Lowest score in MCA ammonia supply chains	No risk (theoretical score)
Safe & Secure – Cyber security and terrorism	Lowest score in MCA hydrogen carriers/ammonia supply chains	No risk (theoretical score)
Safe & Secure – Transport safety	Lowest score in MCA hydrogen carriers*	No risk (theoretical score)
Sustainable – Greenhouse gas emissions	Lowest score in MCA hydrogen carriers*	No emissions (theoretical score)
Sustainable – Material usage	Lowest score in MCA hydrogen carriers*	No critical materials consumed (theoretical score)
Sustainable – Energy loss	Lowest score in MCA hydrogen carriers*	100% (no additional energy needed above 120 MJ/kg H_2) (theoretical score)
Adaptable	Lowest score in MCA hydrogen carriers*	0 (theoretical score)
Fair – for producing countries	Lowest score in MCA hydrogen carriers*	0% (true costs equal to import costs) (theoretical score)
Fair – for Dutch society	Lowest score in MCA hydrogen carriers*	0% (true costs equal to private costs of supply chain in the Netherlands) (theoretical score)
Accessible – cost parity	Lowest score in MCA hydrogen carriers*	100% no additional costs inland (theoretical score)
Accessible – proximity	0% (theoretical score)	100% of companies have access to the supply chain (theoretical score and also the best score in the model)
Spatial Footprint	Lowest score in MCA ammonia supply chains	No spatial requirements (theoretical score)
Environment	Lowest score in MCA hydrogen carriers*	No environmental impact (theoretical score)

* Excluding sodium borohydride alternatives

ANNEX G: EXPLANATION OF DELPHI AND AHP

In order to assign weightings to the public interests, a Delphi process with various stakeholders was carried out in the 2024 MCA of hydrogen carriers. The Delphi approach was combined with the AHP method to guarantee a structured decision-making process. The Delphi approach and the AHP are explained below in brief.

MODIFIED DELPHI APPROACH

The Delphi method is a research method in which a large number of participants (experts or stakeholders) are asked for their opinions about a subject for which no consensus exists. The method aims to generate a consensus by holding several rounds, in which the answers of other participants are (anonymously) fed back to participants. The Delphi method resolves several of the shortcomings of traditional forecasting methods (including the theoretical approach, quantitative modelling or extrapolation) in areas that lack accurate scientific laws. The method works by recognising the value of the opinion, experience and intuition of participants and using these in the absence of comprehensive scientific knowledge. Comparisons with traditional methods have shown that the Delphi method produces more accurate forecasts than these methods.[121]

The Modified Delphi method is derived from the original Delphi method.[122] The traditional Delphi method is very time consuming, due to the many written iterations required to reach a consensus. There may also be questions that cannot easily be distilled into hypotheses, or that give the stakeholders/experts too little opportunity and freedom to add new ideas and points of view outside the realm of the ideas prepared by the research team. The Modified Delphi method addresses these problems. In this method, only the scoring is carried out anonymously and in writing, not the entire process. The differences identified from the written questionnaire are discussed during the group discussion(s). This saves time. To ensure that participants with particular personality traits do not excessively influence the discussion, amendments to previous answers must be properly justified and be logically related to the discussion, for example because new arguments are presented.

The various steps in the Modified Delphi approach used in this study are as follows:

1. Preparing and testing a briefing on strategy, indicators, alternatives to be considered and an evaluation form. To avoid misunderstandings and ambiguities, we first tested

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

[122] RAND developed the Delphi method between 1950 and 1960 to address the shortcomings of traditional forecasting methods. Various studies have been carried out since then. Shankar Basu & Roger G. Schroeder (1977), "Incorporating Judgments in Sales Forecasts: Application of the Delphi Method at American Hoist & Derrick", Interfaces, INFORMS, vol. 7(3), pp. 18-27, May. Dalkey. N. and Helmer, O. (1963). An experimental application of the DELPHI Method to the use of experts. Management Science, 9, 3: 458-467. https:/ /doi.org/10.1287/mnsc.9.3.458

the form and explanation (comprehensibility, size, balance, neutrality, etc.) with the advisory group.
2. Written round with a broadly composed group, in which participants give and motivate their opinion on the pairwise comparison of the public interests based on various indicators.
3. Analysis of the answers by the research team and aggregation of the respondents' individual scores to produce an overall picture.
4. Discussion of the aggregation of the individual scores and accompanying arguments during the physical Delphi meeting. The goal is to identify differences in answers that result from an incomplete picture, unfamiliarity with relevant arguments and aspects or ambiguities in the methodology, for example about how something should be interpreted.
5. Opportunity for the participants to amend the individual scores in response to new information and insights.
6. Analysis of the final answers by the research team and aggregation of the respondents' individual scores to produce a set of weighting factors for use in the multi-criteria analysis.

ANALYTICAL HIERARCHY PROCESS (AHP)

AHP is a method designed to guarantee a structured decision-making process.[123] The method is used to assign a value to the criteria that are important when making the correct decision. The potential solutions can then be determined and calculations carried out for these solutions. We use the method to produce an accurate estimate of the weightings of various public interests. The knowledge and experience of the participants in the Modified Delphi method described above are used to estimate the relative size of the weighting factors using pairwise comparisons. Each respondent compares the relative importance of each pair of public interests or indicators and gives a score on a 9-point scale, see Table 35.

[123] R.W. Saaty, The analytic hierarchy process-what it is and how it is used, Mat/d Modelling, Vol. 9, No. 3-5, pp. 161-176, 1987. R.W. Saaty, Relative Measurement and Its Generalization in Decision Making. Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors, The Analytic Hierarchy/Network Process, vol. 102 (2), 2008, pp. 251–318.

Table 35: Scale used for scores

9-point scale (Saaty's 9-point scale)	Numerical score
Absolutely more important than	9
(between very much more important than and absolutely more important than)	8
Very much more important than	7
(between more important than and very much more important than)	6
More important than	5
(between somewhat more important than and more important than)	4
Somewhat more important than	3
(between equally important and somewhat more important than)	2
Equally important	1

In the example below, the participants assessed that the greenhouse gas emissions indicator is 4.2 x more important than energy consumption.

Not all 21 participants assessed all comparisons. However, at least 19 usable scores were available for each comparison.

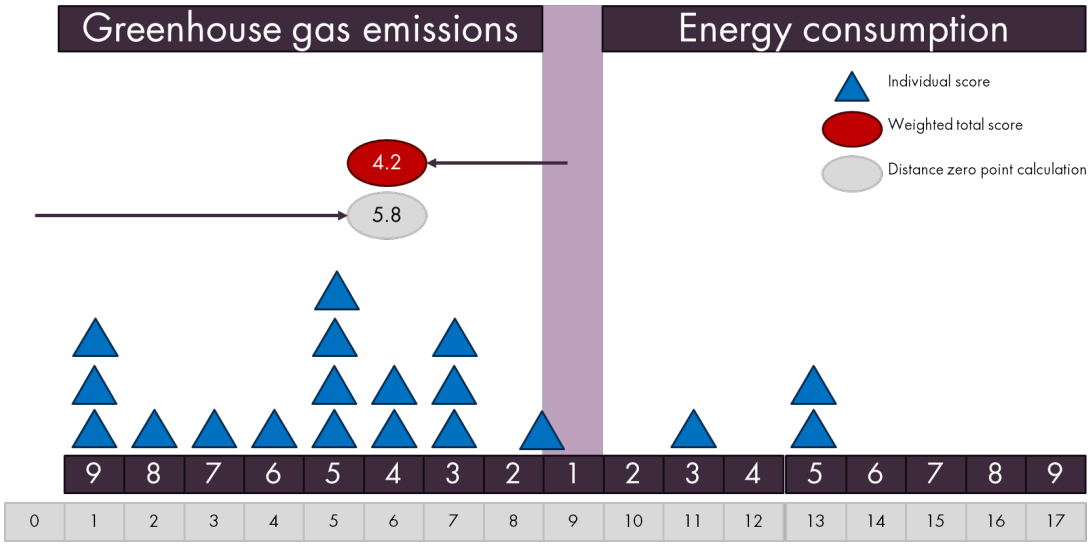


Figure 59: Illustration of individual scores and weighted total scores of 19 participants in AHP pairwise comparison

The centroid of all the scores (4.2 in this example, Figure 59) is determined by solving the following formula for x:

$$\sum_{i=1}^{n}(vi - x)$$

For which:
i = score for all participants,
n = number of participants with a usable score for the comparison
v_i = distance of the score from the left side of the chart for participant i; the first '9' has a distance of 1, the last '9' has a distance of 17
x = distance between the centroid and the left side of the chart.
In this case, the calculated value of x = 5.8. This means the centroid represents a score of 4.2 for greenhouse gas emissions.

ANNEX H: EXPLANATION OF VIKOR METHOD

The total scores for the various alternatives are a combination of the weighting factors that emerged from the Delphi process and the scores for the individual public interests. Annex G explains how the weighting factors were determined.

We ranked the total scores using the VIKOR ('Multicriteria Optimisation and Compromise Solution') method.[124] This results in a nuanced picture: we consider not just the highest score for the combination of the Delphi weighting and the scores for the ammonia supply chains for the individual public interests, but also whether a given supply chain has a very low score for one or more of the individual public interests. For those who attach great importance to that public interest, the ammonia supply chain with the lowest score of all for that public interest will probably be unacceptable.

METHOD

The VIKOR method determines the attractiveness of a supply chain based on:

1) the distance to the ideal score for each public interest
2) the distance to the least ideal/worst possible score for each public interest

The 'ideal score' is for a *notional* supply chain with the best score for all public interests (value 1), such as the combination of ammonia for Affordable and pipeline transport for Transport safety.

The 'worst possible score' is for a *notional* supply chain with the worst possible score for all public interests (value 0), for example the combination of the Transport safety score for road transport and the Affordable score for sodium borohydride (the most costly hydrogen carrier in the 2024 MCA of hydrogen carriers).

The distance to these two scores can be compared in any given relative proportion, although a 50-50 weighting is generally used. We have used that weighting in this study:

1) Half of the total score is determined by the standard multi-criteria calculation ('Utility'): weighting factor x score for each public interest ('what we want the most').
2) Half of the total score is determined by the 'regret' method: this penalises alternatives with relatively low scores for one or more public interests (comparable to the right of veto: 'what we don't want').

The supply chain that performs best for this combination achieves the best overall score. This is a chain that is reasonably close to the best score for each public interest and reasonably far from the lowest score for each of those interests. If three alternatives achieve the same score for the Utility value (e.g. 0.5), then the alternative that scores closest to the worst possible score for one

[124] In Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje

of the public interests will have the highest regret deduction, and the alternative that scores furthest from the worst possible score will have the lowest regret deduction, and thus the smallest points deduction.

EXAMPLE

To illustrate, we will show the method with a simple example.

Imagine that we consider only the public interests Affordable and Safe & Secure and that we consider these public interests to be equally important (i.e., the weighting factors are both 50%).

There are three alternatives with various scores for these two public interests, as shown in Table 36. If we follow the standard MCA method (Utility score), then all three will obtain the same score: 0.5. For the chosen weighting factors, none of the three alternatives is favoured.

Table 36: Score for 3 alternatives using the standard MCA method

Alternative	Score Affordable (weighting 50%)	Score Safe & Secure (weighting 50%)	Utility score
A	1	0	0.5 (50% x 1 + 50% x 0)
B	0.5	0.5	0.5 (50% x 0.5 + 50% x 0.5)
C	0	1	0.5 (50% x 0 + 50% x 1)

With the VIKOR method, the normalised distance to the ideal utility score counts for half of the overall score and the maximum regret score counts for the other half. This is the maximum normalised distance between an alternative and the best score for one of the public interests.

- For alternative A, this distance is 1 x 50%, because A has a distance of 1 for Safe & Secure and a weighting factor of 50%.
- For alternative C, this distance is 1 x 50%, because C has a distance of 1 for Affordable and a weighting factor of 50%.
- For alternative B, the maximum distance is 0.5 x 50%, because B has a distance of 0.5 for Safe & Secure and Affordable and a weighting factor of 50%.

The lowest overall score is thus the best alternative identified by the VIKOR method.

The VIKOR score is calculated using the following formula:

$$VIKOR = factor * \frac{S._i - S.^+}{S.^- - S.^+} + (1 - factor) * \frac{R_i - R^+}{R^- - R^+}$$

For which:

factor = 50%, i.e., the Utility score and the Regret score count equally
S_i = Utility score for supply chain i
S^+ = Best Utility score of all supply chains (the ideal utility score)
S^- = Worst Utility score of all supply chains
R_i = Regret score for supply chain i
R^+ = Best Regret score of all supply chains
R- = Worst Regret score of all supply chains

In this example (see Table 37), the lowest score is the best. To avoid confusion in the presentation of the total scores in the main text, we have inverted the scores produced by the VIKOR method: 1 rather than 0 is the best score. Alternative B performs better than A and C because it has a more 'average' score and does not have the worst score for any public interest.

Table 37: Score for 3 alternatives using the VIKOR method (standard and inverted)

Alternative	Distance to ideal Utility score	Regret score Affordable	Regret Score Safe & Secure	Maximum Regret (Ri)	VIKOR score Standard (lowest = best)	VIKOR score reversed (highest = best)
A	0 (0.5 – 0.5)	0 x 50%	1 x 50%	0.5	50% x 0 + 50% x 0.25/0.25 = 0.5	0.5 (1 - 0.5)
B	0 (0.5 – 0.5)	0.5 x 50%	0.5 x 50%	0.25	50% x 0 + 50% x 0/0.25 = 0	1 (1 - 0)
C	0 (0.5 – 0.5)	1 x 50%	0 x 50%	0.5	50% x 0 + 50% x 0.25/0.25 = 0.5	0.5 (1 - 0.5)

The calculation is visualised in Figure 60. It is important to note that all weighted public interests contribute to the Utility score, while only the largest weighted distance for one of the public interests counts for the Regret score.

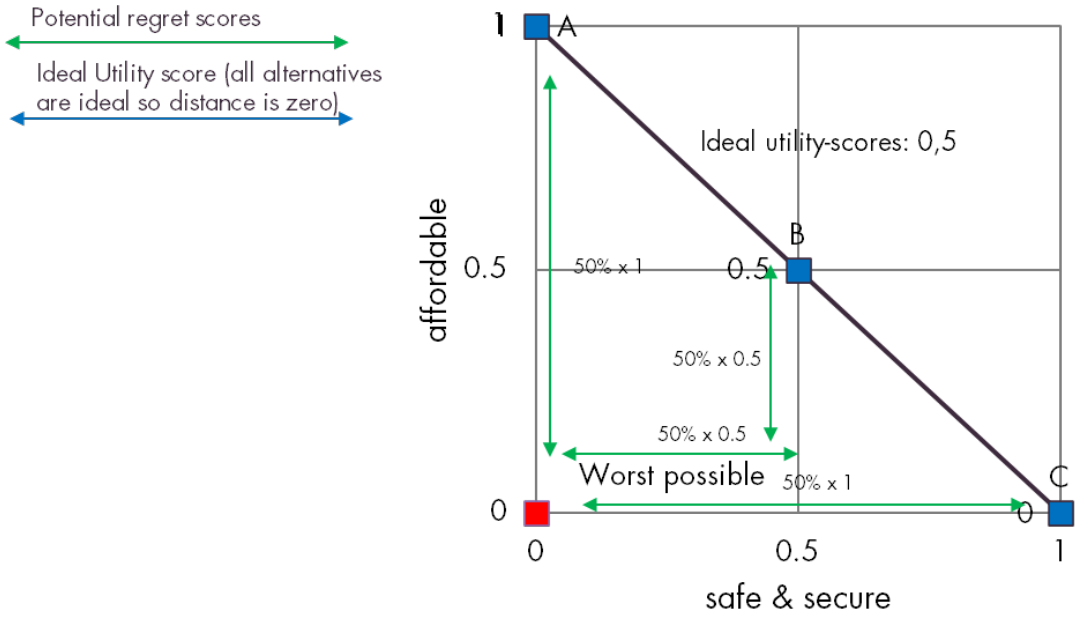


Figure 60: Visualisation of VIKOR method for example

ANNEX I: LONG-DISTANCE REFRIGERATED AMMONIA PIPELINE

Pipelines for refrigerated liquid ammonia (-33°C and 2-5 barg) are generally only used over distances of less than 5 km, as the refrigeration infrastructure would be very expensive and higher pressures are required for transport over longer distances.[125] Very strong insulation is required, both to keep the ammonia cold and to avoid freezing of the soil. Gezerman[126] analysed the kinetic energy of anhydrous ammonia transported under cryogenic conditions (–33°C) and discussed solutions to minimise risks such as cracking and corrosion occurring in the materials that form the structure of transportation and storage systems due to cryogenic conditions. The tendency of refrigerated ammonia to evaporate continuously causes temperature changes in the pipelines during the transfer. These temperature changes cause volumetric differences in the transfer lines, which can damage the pipelines with the corrosive effect of ammonia. Therefore, material selection is an important issue in the design of transfer lines due to the cryogenic environment and corrosive properties.

The company ITP offers refrigerated pipe-in-pipe technology for the transfer of liquid gas products that require temperatures as low as -60°C, including refrigerated ammonia.[127] The company distinguishes refrigerated from cryogenic pipelines, the latter able to withstand temperatures down to -253°C. The technology is positioned to enable import/export terminal architectures, rather than long-distance pipelines.

LONG DISTANCE LNG PIPELINE AS PROXY

Although not currently in operation anywhere, we have attempted to include a rough theoretical approximation of a long-distance cryogenic ammonia pipeline in this comparative study. We took data from a Chinese academic article[128] that discussed the theoretical feasibility of a liquefied natural gas long-distance pipeline (300 and 600 km) in comparison with a gaseous natural gas pipeline. We are fully aware that LNG and refrigerated ammonia are different substances. As LNG and refrigerated ammonia both have very low viscosity at low temperatures (both in the order of 10^{-1} centipoise), we assumed nevertheless that the LNG pipeline could be a plausible proxy for a refrigerated ammonia pipeline.

LNG pipeline transportation would require the construction of a specialised low-temperature system, including low-temperature pipelines, insulation facilities, low-temperature pressurisation

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[125] ISPT (2024). Clean Ammonia Roadmap.

[126] A. O. Gezerman (2021). Industrial Scale Ammonia Pipeline Transfer System and Exergy Analysis, *Kem. Ind.* 70,11-12, 711–716.

[127] ITP Interpipe website.

[128] Bo Zhang, Bin Xu, Ning Xu, Rui Qiu, Qi Liao, Haoran Zhang, Yongtu Liang (2025). Economic Viability of Liquefied Natural Gas Pipeline Construction: Influence of Cascaded Utilization of Cold Energy and Distance - Volume Factors. *Journal of Pipeline Science and Engineering,* pre-proof, accepted date 15 July 2025.

equipment, etc. The construction technology requirements are expected to be high, resulting in high capital investment costs. Also, a large amount of energy is consumed to maintain the liquid state of LNG for refrigeration and maintaining a low-temperature environment. The maintenance, inspection of pipelines, and equipment renewal also incur high costs, so the operation cost is expected to be relatively high. It should be noted that the article assumes overhead laying, and does not discuss other long-distance LNG pipeline laying methods such as buried and corridor laying, each with distinct features and applications.

The study assumed for the 300 km pipeline a transport capacity of 2 billion m^3 of natural gas per year (1660 ktons), resulting in a pipeline diameter of 281 mm or 11 inches.[129] This corresponds to 0.42 kton hydrogen equivalent and to 2.348 ktons ammonia.

It is assumed in the theoretical study that along the 300 km LNG pipeline, three pump stations are constructed, and five along the 600 km LNG pipeline. We assume there would be two pump stations for the 200 km route. Since insultation cannot be perfect, the LNG temperature will rise during the transport, but it does not require additional 'cold stations' to lower the temperature (two such stations would be required for a 600 km route, with six times the energy consumption of a pump station).

Table 38 below summarises the costs for 300 km in million Chinese yuan (CNY) and for 200 km in euros (1 CNY = 0,12 euro).

[129] As the thickness of the insulation layer of the LNG pipeline is 130 mm, the outer diameter of the LNG pipeline would be 541 mm or 21 inch, which is larger than that of the compressed natural gas pipeline under the same transportation volume (470 mm).

Table 38: Assumptions and costs for cryogenic transport pipelines for 1,660 ktons LNG.[130]

Scenario	300 km; million CNY	200 km; million euro
Number of pump stations	3	2
Number of cold stations	0	0
Pipeline diameter (mm)	281.0	281.0
Pipeline thickness (mm)	9.2	9.2
Cooling layer thickness (mm)	130.0	130.0
Design pressure (MPa = 10 bar)	7.7	7.7
Pipeline material costs	353	28.24
Pipeline laying costs	1,059	84.72
Costs of insulation layer	201	16.08
Total cost of pipeline construction	1,613	129.0
Pump station power (kW)	373.7	2.696
Construction cost of the pump stations	73.5	5.88
Engineering cost	1,686	134.9
Other construction costs	202.4	16.19
Prepare fee	283.3	22.66
Investment in project construction	2,172	173.76
Interest investment	63.9	5.11
Original value of fixed assets	2,034	162.7
Operation and maintenance cost	49.2	3.94
Energy consumption of pump stations	8.9	0.71
Gas loss	12.0	0.96
Material cost	0.4	0.03
Personal expenditures	12.8	1.02
Other expenses	1.2	0.096
Total operating expenses	84.6	6.77
Circulating assets	40.7	3.26
Depreciation cost	67.8	5.42
Amortisation cost	30.4	2.43
Interest expense	27.1	2.17
Total investment (annual total cost)	209.8	16.78

Based on these figures the CAPEX of the pipeline would be just € 0,87 MEUR/km (see table: 173,76 million euro / 200 km), surprisingly a factor 4 cheaper than the investment cost in the pressurised ammonia pipeline according to the ISPT safe & compliant study. This is very unlikely. Also, we would expect a refrigerated ammonia pipeline to be even cheaper than a refrigerated LNG pipeline because of the lower temperature of LNG.

In addition, we have questions about some of the figures in the table and how they relate. For instance, the last five lines in the table do not add up. In conclusion, we do not feel comfortable with using these figures for the study. Also, data are lacking to assess the Safe & Secure public interest for this transport mode. In conclusion, we decided together with the client not to use these data for the present study.

To gain insight in the potential impact of a refrigerated ammonia pipeline on the scores, we did model a fictitious 200 km refrigerated ammonia pipeline that has the same Safety level as pressurised and twice the cost of pressurised.

[130] Whereas the distance is 300 km or 600 km throughout the text, only the table in the article mentions 400 km and 600 km. We assume that this is an error. Other figures in the table do correspond to the text.